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Solid Waste Disposal Facility Criteria

Technical Manual

MSW Landfill Criteria Technical Manual

Updated Version of Key Technical Manual Released

This manual was originally published in November, 1993 as a companion to the Criteria for Municipal Solid Waste Landfills (MSWLF Criteria) that were promulgated on October 9, 1991 as 40 CFR Part 258. The technical manual was developed to assist owners/operators of MSWLFs in achieving compliance with the revised MSWLF Criteria. The manual is now available in electronic format and can be accessed below in Adobe Acrobat PDF and ASCII text formats.

The manual's newly revised Introduction discusses briefly state and tribal processes for implementing the Part 258 Criteria and changes in the Criteria since their promulgation. The manual then focuses on providing owners/operators with guidance for complying with the Criteria. Its six chapters are arranged to follow the order of the Criteria. This document does not include a section on the financial assurance requirements; questions regarding these requirements may be addressed to EPA's RCRA/Superfund Call Center at 800 424-9346 or TDD 800 553-7672 (hearing impaired).

The PDF version of the Introduction now contains a new table of contents spanning all six chapters. Each entry is hypertext-linked to the corresponding section in the chapter for quick navigation. Each chapter's PDF file also has its own table of contents with hypertext links.

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NOTICE

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TABLE OF CONTENTS

APPENDICES

INTRODUCTION

This manual was originally published in November, 1993 as a companion to the Criteria for Municipal Solid Waste Landfills (MSWLF Criteria) that were promulgated on October 9, 1991 as 40 CFR Part 258. Since that time the MSWLF Criteria have been modified several times due to statutory revisions and court decisions that are discussed below. Most of the modifications delayed the effective dates but all provisions are now effective. All changes to the rule are included in the text of the manual. The technical content of the manual did not require revision and only typographical errors were corrected.

The manual is now available in electronic format and can be accessed on the Environmental Protection Agency's (EPA) web site <**www.epa.gov/osw**>.

Purpose of This Manual

This technical manual has been developed to assist owners/operators of MSWLFs in achieving compliance with the revised MSWLF Criteria. This manual is not a regulatory document, and does not provide mandatory technical guidance, but does provide assistance for coming into compliance with the technical aspects of the revised landfill Criteria.

Implementation of the Landfill Criteria

The EPA fully intends that States and Tribes maintain the lead role in implementing and enforcing the revised Criteria. States will achieve this through approved State permit programs. Due to recent decisions by the courts, Tribes will do so using a case-by-case review process.[1] Whether in a State or in Indian Country, landfill owners/operators must comply with the revised[2] MSWLF Criteria.

Example of Technical and Performance Standards in 40 CFR Part 258: Liners

Technical standard:
MSWLFs must be built with a composite liner consisting of a 30 mil flexible membrane liner over 2 feet compacted soil with a hydraulic conductivity of no more than 1×10^{-7} cm/sec.

Performance standard:
MSWLFs must be built in accordance with a design approved by the Director of an approved State or as specified in 40 CFR § 258.40(e) for unapproved States. The design must ensure that the concentration values listed in Table 1 of 40 CFR § 258.40 will not be exceeded in the uppermost aquifer at the relevant point of compliance, as specified by the Director of an approved State under paragraph 40 CFR § 258.40(d).

State Process

The Agency's role in the regulation of MSWLFs is to establish national minimum standards that the states are to incorporate into their MSWLF permitting programs. EPA evaluates state

[1] The Agency originally intended to extend to Indian Tribes the same opportunity to apply for permit program approval as is available to States, but a court decision blocked this approach. See the **Tribal Process** section below for complete details.

[2] EPA finalized several revisions to 40 CFR Part 258 on October 1, 1993 (58 *FR* 51536) and issued a correction notice on October 14, 1993 (58 *FR* 53136). Questions regarding the final rule and requests for copies of the *Federal Register* notices should be made to the RCRA/Superfund Hotline at 800 424-9346.

MSWLF permitting programs under the procedures set out in 40 CFR Part 239, "Requirements for State Permit Program Determination of Adequacy," proposed on January 26, 1996 (61 *FR* 2584), to determine whether programs are adequate to ensure that MSWLF owners/operators comply with the federal standards. As of early 1998, 40 States and Territories had received full approval and another seven had received partial approval.

If their permitting programs have been approved by EPA, States can allow the use of flexible performance standards established in 40 CFR Part 258 in addition to the self-implementing technical standards for many of the Criteria. Approved States can provide owners/operators flexibility in satisfying the location restrictions, operating criteria, and requirements for liner design, ground-water monitoring, corrective action, closure and post-closure care, and financial assurance. This flexibility allows for the consideration of site-specific conditions in designing and operating a MSWLF at the lowest cost possible while ensuring protection of human health and the environment. In unapproved states, owners/operators must follow the self-implementing technical standards.

EPA continues to work with States toward approval of their programs and recommends that owners/operators stay informed of the approval status of the programs in their State. States may be in various stages of the program approval process. The majority of states have received full program approval and others have received "partial" program approval (i.e., only some portions of the State program are approved while the remainder of the program is pending approval). Regardless of a State's program approval status, landfill owners/operators must comply with the Criteria. States can grant flexibility to owners/operators only in the areas of their program that have been approved. For example, a state in which only the ground-water monitoring area of the permitting program has been approved by EPA cannot grant owners/operators flexibility to use alternative liner designs.

States are free to enact landfill regulations that are *more* stringent than the MSWLF Criteria. Certain areas of flexibility provided by the Criteria (e.g., the small landfill exemption) may not be reflected in a State program. In such instances, the owner/operator must comply with the more stringent provisions (e.g., no exemption). These regulations would be enforced by the State independently from the Criteria. **NOTE: The program requirements for approved States may differ from those described in this manual, which are based specifically on the Federal Criteria. Therefore, owners/operators are urged to work closely with their approved State in order to ensure that they are fully in compliance with all applicable requirements.**

State regulatory personnel will find this document helpful when reviewing permit applications for landfills. This manual presents technical information to be used in siting, designing, operating, and closing landfills, but does not present a mandatory approach for demonstrating compliance with the Criteria. This manual also outlines the types of information relevant to make the demonstrations required by the Criteria, including demonstrations for restricted locations and performance-based designs in approved States.

Tribal Process

From the beginning of EPA's development of the permitting program approval process, the Agency planned to offer permitting program approval to tribes as well as to states. In a 1996 court decision[3], however, the court ruled that EPA cannot approve tribal permitting programs. The Agency has therefore developed a site-specific rulemaking process to meet its goal of quickly and efficiently providing owners/operators in Indian Country[4] the same flexibility that is available to landfill owners/operators in states with EPA-approved MSWLF permitting programs. The process is described in *Site-Specific Flexibility Requests for Municipal Solid Waste Landfills in Indian Country—Draft Guidance* (EPA530-R-97-016).

Under this process, an owner or operator can request to use certain alternative approaches at a specific MSWLF site to meet the 40 CFR Part 258 performance standards. Unless the tribal government is the owner/operator, the tribal government should review the request for consistency with tribal law and policy and forward it to EPA with a recommendation. If EPA approves a request, it will issue a site-specific rule allowing the use of the requested alternative approaches. Owners/operators in Indian Country should therefore understand that when this manual refers to areas of flexibility that can be granted by a "State Director," they would instead seek such flexibility in the form of a site-specific rulemaking from EPA after tribal government review of their petition for rulemaking. Although tribes will not issue permits as EPA-approved permitting entities under the Criteria, they are free to enact separate tribal landfill regulations that are more stringent than the Criteria. Tribal regulations are enforced by the tribe independently of the Criteria.

The site-specific process encourages active dialogue among tribes, MSWLF owners/operators, EPA, and the public. The guidance is designed so that the Agency works in partnership with tribes. Because EPA recognizes tribal sovereignty, EPA will respect tribal findings concerning consistency of proposed approaches with tribal law and policy.

Revisions to Part 258

Some important changes have been made to Part 258 since its original promulgation. In addition, other regulations that affect solid waste management have been implemented.

Ground-Water Monitoring Exemption for Small, Dry, and Remote Landfills (40 CFR § 258.1(f)(1))

The Land Disposal Program Flexibility Act (LDPFA) of 1996 reestablished an exemption for ground-water monitoring for owners/operators of certain small MSWLFs. EPA revised 40 CFR § 258.1(f)(1) on September 25, 1996 (61 *FR* 50409) to codify the LDPFA ground-water monitoring exemption. To qualify for an exemption, owners/operators must accept less than 20 tons per day of MSW (based on an annual average), have no evidence of ground-water contamination, and be located in either a dry or remote location. This exemption eases the burden on certain small MSWLFs without compromising ground-water quality.[5]

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[3] *Backcountry Against Dumps v. EPA*, 100 F.3d 147 (D.C. Cir. 1996).

[4] This manual uses the term "Indian Country" as defined in 40 CFR § 258.2.

[5] In the original 40 CFR Part 258 rulemaking, promulgated October 9, 1991, the Agency provided an exemption from ground-water monitoring for small MSWLF units located in dry or remote locations. In 1993, the U.S. Court of Appeals for the District of Columbia set aside this ground-water monitoring exemption. *Sierra Club v. EPA*, 992 F.2d 337 (D.C. Cir. 1993).

New Flexibility for Small Landfills (40 CFR §§ 258.21, 258.23, 258.60)

In addition to reestablishing the ground-water exemption for small, dry, and remote MSWLFs, the LDPFA provided additional flexibility to approved states for any small landfill that receives 20 tons or less of MSW per day. EPA revised 40 CFR Part 258 to allow approved states to grant the use of alternative frequencies of daily cover, alternative frequencies of methane monitoring, and alternative infiltration layers for final cover (62 *FR* 40707 (July 29, 1997)). The LDPFA also authorized flexibility to establish alternative means for demonstrating financial assurance, and this flexibility was granted in another action. The additional flexibility will allow owners and operators of small MSWLFs the opportunity to reduce their costs of MSWLF operation while still protecting human health and the environment.

Added Financial Assurance Options (40 CFR § 258.74)

A revision to 40 CFR Part 258, published November 27, 1996 (61 *FR* 60328), provided additional options to the menu of financial assurance instruments that MSWLF owners/operators can use to demonstrate that adequate funds will be readily available for the costs of closure, post-closure care, and corrective action for known releases associated with their facilities. The existing regulations specify several mechanisms that owners and operators may use to make that demonstration, such as trust funds and surety bonds. The additional mechanisms are a financial test for use by local government owners and operators, and a provision for local governments that wish to guarantee the closure, post-closure, and corrective action costs for an owner or operator. These financial assurance options allow local governments to use their financial strength to avoid incurring the expenses associated with the use of third-party financial instruments. This action granted the flexibility to all owners and operators (including owners and operators of small facilities) to establish alternative means for demonstrating financial assurance as envisioned in the LDPFA.

Additionally, EPA promulgated a regulation allowing corporate financial tests and corporate guarantees as financial assurance mechanisms that private owners and operators of MSWLFs may use to demonstrate financial assurance (63 *FR* 17706 (April 10, 1998)). This test extends to private owners and operators the regulatory flexibility already provided to municipal owners or operators of MSWLFs. These regulations allow firms to demonstrate financial assurance by passing a financial test. For firms that qualify for the financial test, this mechanism will be less costly than the use of a third party financial instrument such as a trust fund or a surety bond.

How to Use This Manual

This document is subdivided into six chapters arranged to follow the order of the Criteria. The first chapter addresses the general applicability of the Part 258 Criteria; the second covers location restrictions; the third explains the operating requirements; the fourth discusses design standards; the fifth covers ground-water monitoring and corrective action; and the sixth chapter addresses closure and post-closure care. Each chapter contains an introduction to that section of the Criteria. This document does not include a section on the financial responsibility requirements;

questions regarding these requirements may be addressed to EPA's RCRA/Superfund Hotline at 800 424-9346.

Within each chapter, the Criteria have been subdivided into smaller segments. The *Statement of Regulation* section provides a verbatim recital of the regulatory language. The second section, entitled *Applicability*, provides a general explanation of the regulations and who must comply with them. Finally, for each segment of the regulation, a *Technical Considerations* section identifies key technical issues that may need to be addressed to ensure compliance with a particular requirement. Each chapter ends with a section entitled *Further Information*, which provides references, addresses, organizations, and other information that may be of use to the reader.

Limitations of This Manual

The ability of this document to provide current guidance is limited by the technical literature that was available at the time of preparation. Technology and product development are advancing rapidly, especially in the areas of geosynthetic materials and design concepts. As experience with new waste management techniques expands in the engineering and science community, an increase in published literature, research, and technical information will follow. The owners and operators of MSWLFs are encouraged to keep abreast of innovation through technical journals, professional organizations, and technical information developed by EPA. Many of the Criteria contained in Part 258 are performance-based. Future innovative technology may provide additional means for owners/operators to meet performance standards that previously could not be met by a particular facility due to site-specific conditions.

Deadlines and Effective Dates

The original effective date for the Criteria, October 9, 1993, was revised for several categories of landfills, in response to concerns that a variety of circumstances was hampering some communities' abilities to comply by that date. Therefore, the Agency provided additional time for certain landfills to come into compliance, especially small units and those that accepted waste from the 1993 Midwest floods. As the accompanying table indicates, the extended general effective dates for all MSWLF categories have passed, and all units should now be in compliance.

SUMMARY OF CHANGES TO THE EFFECTIVE DATES OF THE MSWLF CRITERIA

	MSWLF Units Accepting Greater than 100 TPD	MSWLF Units Accepting 100 TPD or Less; Are Not on the NPL; and 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.[1,2,3] This is the effective date for location, operation, design, and closure/post-closure.	October 9, 1993	April 9, 1994	October 9, 1997; exempt from the design requirements	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.[2,3]	October 9, 1994	October 9, 1994	October 9, 1998	Within one year of date determined by State; no later than October 9, 1995
Effective date of ground-water monitoring and corrective action.[2,3]	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	Exempt from the ground-water monitoring requirements.[5]	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.[3,4]	April 9, 1997	April 9, 1997	October 9, 1997	April 9, 1997

[1] If a MSWLF unit receives waste after this date, the unit must comply with all of Part 258.
[2] See the final rule and preamble published on October 1, 1993 (58 FR 51536) for a full discussion of all changes and related conditions.
[3] See the final rule and preamble published on October 6, 1995 (60 FR 52337) for a full discussion of all changes and related conditions.
[4] See the final rule and preamble published on April 7, 1995 (60 FR 17649) for a discussion of this delay.
[5] See the final rule and preamble published on September 25, 1990 (61 FR 50409) for a discussion of the ground-water monitoring exemption.

settlements of the ground surface (Winterkorn and Fang, 1975).

Well-compacted cohesionless embankments or reasonably flat slopes in insensitive clay are less likely to fail under moderate seismic shocks (up to 0.15g and 0.20g acceleration). Embankments made of insensitive cohesive soils founded on cohesive soils or rock may withstand even greater seismic shocks. For earthen embankments in seismic regions, designs with internal drainage and core material most resistant to fracturing should be considered. Slope materials vulnerable to earthquake shocks are described below (U.S. Navy, 1983):

- Very steep slopes of weak, fractured and brittle rocks or unsaturated loess are vulnerable to transient shocks caused by tensional faulting;
- Loess and saturated sand may be liquefied by seismic shocks causing the sudden collapse of structures and flow slides;
- Similar effects are possible in sensitive cohesive soils when natural moisture exceeds the soil's liquid limit; and
- Dry cohesionless material on a slope at an angle of repose will respond to seismic shock by shallow sloughing and slight flattening of the slope.

In general, loess, deltaic soils, floodplain soils, and loose fills are highly susceptible to liquefaction under saturated conditions (USEPA, 1992).

Geotechnical stability investigations frequently incorporate the use of computer models to reduce the computational time of well-established analytical methods. Several computer software packages are available that approximate the anticipated dynamic forces of the design earthquake by resolving the forces into a static analysis of loading on design cross sections. A conservative approach would incorporate both vertical and horizontal forces caused by bedrock acceleration if it can be shown that the types of material of interest are susceptible to the vertical force component. Typically, the horizontal force caused by bedrock acceleration is the major force to be considered in the seismic stability analysis. Examples of computer models include PC-Slope by Geoslope Programming (1986), and FLUSH by the University of California.

Design modifications to accommodate an earthquake may include shallower waste sideslopes, more conservative design of dikes and run-off controls, and additional contingencies for leachate collection should primary systems be disrupted. Strengths of the landfill components should be able to withstand these additional forces with an acceptable factor of safety. The use of professionals experienced in seismic analysis is strongly recommended for design of facilities located in areas of high seismic risk.

2.7 UNSTABLE AREAS
40 CFR §258.15

2.7.1 Statement of Regulation

(a) Owners or operators of new MSWLF units, existing MSWLF units, and lateral expansions located in an unstable area must demonstrate that engineering measures have been incorporated into the MSWLF unit's

design to ensure that the integrity of the structural components of the MSWLF unit will not be disrupted. The owner or operator must place the demonstration in the operating record and notify the State Director that it has been placed in the operating record. The owner or operator must consider the following factors, at a minimum, when determining whether an area is unstable:

(1) On-site or local soil conditions that may result in significant differential settling;

(2) On-site or local geologic or geomorphologic features; and

(3) On-site or local human-made features or events (both surface and subsurface).

(b) For purposes of this section:

(1) <u>Unstable area</u> means a location that is susceptible to natural or human-induced events or forces capable of impairing the integrity of some or all of the landfill structural components responsible for preventing releases from a landfill. Unstable areas can include poor foundation conditions, areas susceptible to mass movements, and Karst terrains.

(2) <u>Structural components</u> means liners, leachate collection systems, final covers, run-on/run-off systems, and any other component used in the construction and operation of the MSWLF that is necessary for protection of human health and the environment.

(3) <u>Poor foundation conditions</u> means those areas where features exist which indicate that a natural or man-induced event may result in inadequate foundation support for the structural components of a MSWLF unit.

(4) <u>Areas susceptible to mass movement</u> means those areas of influence (i.e., areas characterized as having an active or substantial possibility of mass movement) where the movement of earth material at, beneath, or adjacent to the MSWLF unit, because of natural or man-induced events, results in the downslope transport of soil and rock material by means of gravitational influence. Areas of mass movement include, but are not limited to, landslides, avalanches, debris slides and flows, solifluction, block sliding, and rock fall.

(5) <u>Karst terrains</u> means areas where karst topography, with its characteristic surface and subterranean features, is developed as the result of dissolution of limestone, dolomite, or other soluble rock. Characteristic physiographic features present in karst terrains include, but are not limited to, sinkholes, sinking streams, caves, large springs, and blind valleys.

<u>2.7.2 Applicability</u>

Owners/operators of new MSWLF units, existing MSWLF units, and lateral expansions of units that are located in unstable areas must demonstrate the structural integrity of the unit. Existing units for which a successful demonstration cannot be made must be closed. The regulation applies to new units, existing units, and lateral expansions that are located on sites classified as unstable areas. Unstable areas are areas susceptible to natural or human-induced events or forces that are capable of impairing or destroying the integrity of some or all of the structural components. Structural components consist of liners, leachate collection systems, final cover systems, run-on and run-off control systems, and any other component necessary for protection of human health and the environment.

MSWLF units can be located in unstable areas, but the owner or operator must demonstrate that the structural integrity of the MSWLF unit will not be disrupted. The demonstration must show that engineering measures have been incorporated into the design of the unit to ensure the integrity of the structural components. Existing MSWLF units that do not meet the demonstration must be closed within 5 years in accordance with §258.60, and owners and operators must undertake post-closure activities in accordance with §258.61. The Director of an approved State can grant a 2-year extension to the closure requirement under two conditions: (1) no disposal alternative is available, and (2) no immediate threat is posed to human health and the environment.

2.7.3 Technical Considerations

Again, for the purposes of this discussion, natural unstable areas include those areas that have poor soils for foundations, are susceptible to mass movement, or have karst features.

- **Areas with soils that make poor foundations** have soils that are expansive or settle suddenly. Such areas may lose their ability to support a foundation when subjected to natural (e.g., heavy rain) or man-made events (e.g., explosions).

  — Expansive soils usually are clay-rich soils that, because of their molecular structure, tend to swell and shrink by taking up and releasing water and thus are sensitive to a variable hydrologic regime. Such soils include: smectite (montmorillonite group) and vermiculite clays; bentonite is a smectite-rich clay. In addition, soils rich in "white alkali" (sodium sulfate), anhydrite (calcium sulfate), or pyrite (iron sulfide) also may exhibit swelling as water content increases. Such soils tend to be found in the arid western states.

  — Soils that are subject to rapid settlement (subsidence) include loess, unconsolidated clays, and wetland soils. Loess, which is found in the central states, is a wind-deposited silt that is moisture-deficient and tends to compact upon wetting. Unconsolidated clays, which can be found in the southwestern states, can undergo considerable compaction when fluids such as water or oil are removed. Similarly, wetland soils, which by their nature are water-bearing, also tend to be subject to subsidence when water is withdrawn.

- Another type of unstable area is an **area that is subject to mass movement**. Such areas can be situated on steep or gradual slopes. They tend to have rock or soil conditions that are conducive to downslope movement of soil, rock, and/or debris (either alone or mixed with water) under the influence of gravity. Examples of mass movements include avalanches, landslides, debris slides and flows, and rock slides.

- **Karst terrains** tend to be subject to extreme incidents of differential settlement, namely complete ground collapse. Karst is a term used to describe areas that are underlain by soluble bedrock, such as limestone, where solution of the rock by water creates subterranean drainage systems that may include areas of rock collapse. These areas tend to be characterized by large subterranean and surficial voids (e.g., caverns and sinkholes) and unpredictable surface and ground-water flow (e.g., sinking streams and large springs). Other rocks such as dolomite or gypsum also may be subject to solution effects.

Examples of human-induced unstable areas are described below:

- The presence of cut and/or fill slopes during construction of the MSWLF unit may cause slippage of existing soil or rock.

- Excessive drawdown of ground water increases the effective overburden on the foundation soils underneath the MSWLF unit, which may cause excessive settlement or bearing capacity failure on the foundation soils.

- A closed landfill as the foundation for a new landfill ("piggy-backing") may be unstable unless the closed landfill has undergone complete settlement of the underlying wastes.

As part of their demonstration to site a landfill in an unstable area, owners/operators must assess the ability of the soils and/or rock to serve as a foundation as well as the ability of the site embankments and slopes to maintain a stable condition. Once these factors have been evaluated, a MSWLF design should be developed that will address these types of concerns and prevent possible associated damage to MSWLF structural components.

In designing a new unit or lateral expansion or re-evaluating an existing MSWLF unit, a **stability assessment** should be conducted in order to avoid or prevent a destabilizing event from impairing the structural integrity of the landfill component systems. A stability assessment involves essentially three components: an evaluation of subsurface conditions, an analysis of slope stability, and an examination of related design needs. An evaluation of subsurface conditions requires:

- Assessing the stability of foundation soils, adjacent embankments, and slopes;

- Investigating the geotechnical and geological characteristics of the site to establish soil strengths and other engineering properties by performing standard penetration tests, field vane shear tests, and laboratory tests; and

- Testing the soil properties such as water content, shear strength, plasticity, and grain size distribution.

A stability assessment should consider (USEPA, 1988):

- The adequacy of the subsurface exploration program;
- The liquefaction potential of the embankment, slopes, and foundation soils;
- The expected behavior of the embankment, slopes, and foundation soils when they are subjected to seismic activity;
- The potential for seepage-induced failure; and
- The potential for differential settlement.

In addition, a qualified professional must assess, at a minimum, natural conditions (e.g., soil, geology, geomorphology) as well as human-made features or events (both subsurface and surface) that could cause differential settlement of ground. Natural conditions can be highly unpredictable and destructive, especially if amplified by human-induced changes to the environment. Specific examples of natural or human-induced phenomena include: debris flows resulting from heavy rainfall in a small watershed; the rapid formation of a sinkhole as a result of excessive local or regional ground water withdrawal in a limestone region; earth displacement by faulting activity; and rockfalls along a cliff face caused by vibrations resulting from the detonation of explosives or sonic booms.

Information on natural features can be obtained from:

- The USGS National Atlas map entitled "Engineering Aspects of Karst," published in 1984;
- Regional or local soil maps;
- Aerial photographs (especially in karst areas); and
- Site-specific investigations.

To examine an area for possible sources of human-induced ground instability, the site and surrounding area should be examined for activities related to extensive withdrawal of oil, gas, or water from subsurface units as well as construction or other operations that may result in ground motion (e.g., blasting).

Types of Failures

Failures occur when the driving forces imposed on the soils or engineered structures exceed the resisting forces of the material. The ratio of the resisting force to the driving force is considered the factor of safety (FS). At an FS value less than 1.0, failure will occur by definition. There is a high probability that, due to natural variability and the degree of accuracy in measurements, interpreted soil conditions will not be precisely representative of the actual soil conditions. Therefore, failure may not occur exactly at the calculated value, so factors of safety greater than 1.0 are required for the design. For plastic soils such as clay, movement or deformation (creep) may occur at a higher factor of safety prior to catastrophic failure.

Principal modes of failure in soil or rock include:

- Rotation (change of orientation) of an earthen mass on a curved slip surface approximated by a circular arc;
- Translation (change of position) of an earthen mass on a planar surface whose length is large compared to depth below ground;
- Displacement of a wedge-shaped mass along one or more planes of weakness;
- Earth and mud flows in loose clayey and silty soils; and
- Debris flows in coarse-grained soils.

For the purposes of this discussion, three types of failures can occur at a landfill unit: settlement, loss of bearing strength, and sinkhole collapse.

- If not properly engineered, a landfill in an unstable area may undergo extreme **settlement**, which can result in structural failure. Differential settlement is a particular mode of failure that generally occurs beneath a landfill in response to consolidation and dewatering of the foundation soils during and following waste loading.

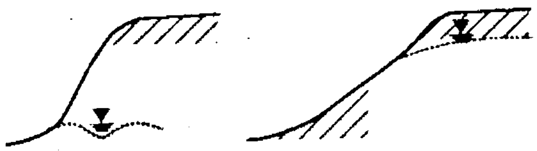
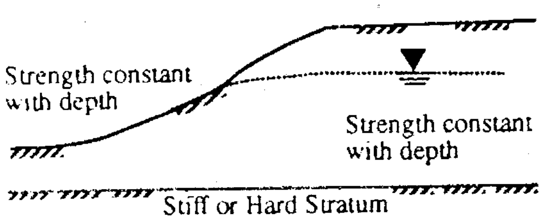
  Settlement beneath a landfill unit, both total and differential, should be assessed and compared to the elongation strength and flexure properties of the liner and leachate collection pipe system. Even small amounts of settlement can seriously damage leachate collection piping and sumps. The analysis will provide an estimate of maximum settlement, which can be used to aid in estimating differential settlement.

  Allowable settlement is typically expressed as a function of total settlement because differential settlement is more difficult to predict. However, differential settlement is a more serious threat to the integrity of the structure than total settlement. Differential settlement also is discussed in Section 6.3 of Chapter 6.

- **Loss of bearing strength** is a failure mode that tends to occur in areas that have soils that tend to expand, rapidly settle, or liquefy, thereby causing failure or reducing performance of overlying MSWLF components. Another example of loss of bearing strength involves failures that have occurred at operating sites where excavations for landfill expansions adjacent to the filled areas reduced the mass of the soil at the toe of the slope, thereby reducing the overall strength (resisting force) of the foundation soil.

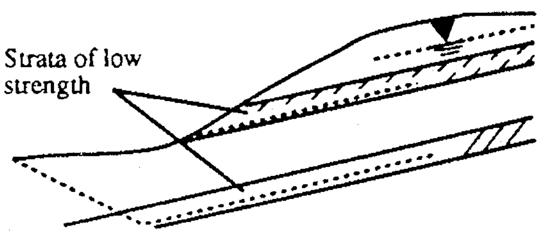
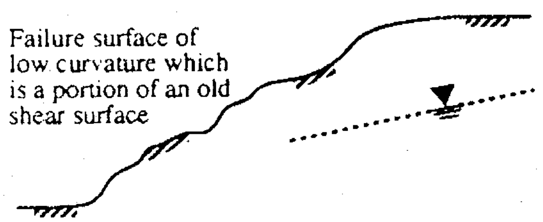
- **Catastrophic collapse in the form of sinkholes** is a type of failure that occurs in karst regions. As water, especially acidic water, percolates through limestone (calcium carbonate), the soluble carbonate material dissolves, forming cavities and caverns. Land overlying caverns can collapse suddenly, resulting in sinkhole features that can be 100 feet or more in depth and 300 feet or more in width.

Tables 2-2 and 2-3 provide examples of analytical considerations for mode of failure assessments in both natural and human-made slopes.

1. Slope in Coarse-Grained Soil with Some Cohesion *Low Groundwater* Failure of thin wedge, position influenced by tension cracks *High Groundwater* Failure at relatively shallow toe circles 	• With low groundwater, failure occurs on shallow, straight, or slightly curved surface. Presence of a tension crack at the top of the slope influences failure location. With high groundwater, failure occurs on the relatively shallow toe circle whose position is determined primarily by ground elevation. • Analyze with effective stress using strengths C' and Ø' from CD tests. Pore pressure is governed by seepage condition. Internal pore pressures and external water pressures must be included.
2. Slope in Coarse-Grained, Soil Cohesion *Low Groundwater* Stable slope angle = effective friction angle *High Groundwater* Stable slope angle = ½ effective friction angle 	• Stability depends primarily on groundwater conditions. With low groundwater, failures occur as surface sloughing until slope angle flattens to friction angle. With high groundwater, stable slope is approximately 1/2 friction angle. • Analyze with effective stress using strengths C' and Ø' from CD tests. Slight cohesion appearing in test envelope is ignored. Special consideration must be given to possible flow slides in loose, saturated fine sands.
3. Slope in Normally Consolidated or Slightly Preconsolidated Clay *Location of failure depends on variation of shear strength with depth.* 	• Failure occurs on circular arcs whose position is governed by theory. Position of groundwater table does not influence stability unless its fluctuation changes strength of the clay or acts in tension cracks. • Analyze with total stresses, zoning cross section for different values of shear strengths. Determine shear strength from unconfined compression test, unconsolidated undrained triaxial test or vane shear.

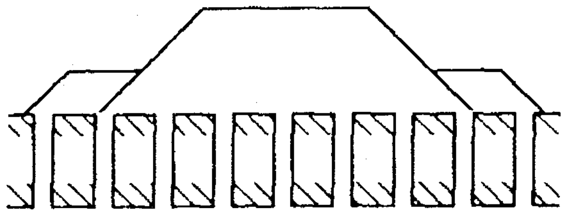
Source: Soil Mechanics, NAVFAC Design Manual 7.01

Table 2-2. Analysis of Stability of Natural Slopes

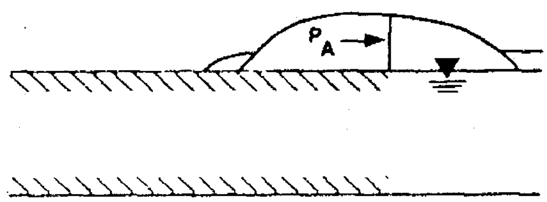
4. Slope in Stratified Soil Profile *Location of failure depends on relative strength and orientation of layers.*  	• Location of failure plane is controlled by relative strength and orientation of strata. Failure surface is combination of active and passive wedges with central sliding block chosen to conform to stratification. • Analyze with effective stress using strengths C' and Ø' for fine-grained strata and Ø' for cohesionless material.
5. Depth Creep Movements in Old Slide Mass *Bowl-shaped area of low slope (9 to 11%) bounded at top by old scarp.*  	• Strength of old slide mass decreases with magnitude of movement that has occurred previously. Most dangerous situation is in stiff, over-consolidated clay which is softened, fractured, or slickensided in the failure zone.

Source: Soil Mechanics, NAVFAC Design Manual 7.01

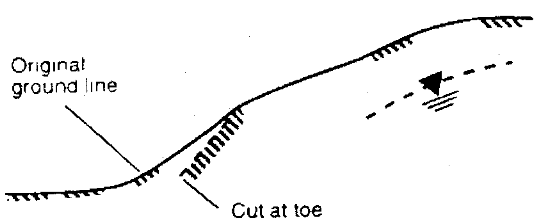
Table 2-2. Analysis of Stability of Natural Slopes (Continued)

<table>
<tr>
<td>1. Failure of Fill on Soft Cohesive Foundation with Sand Drains

Location of failure depends on geometry and strength of cross section.</td>
<td>

- Usually, minimum stability occurs during placing of fill. If rate of construction is controlled, allow for gain in strength with consolidation from drainage.
- Analyze with effective stress using strengths C' and Ø' from CU tests with pore pressure measurement. Apply estimated pore pressures or piezometric pressures. Analyze with total stress for rapid construction without observation of pore pressures, use shear strength from unconfined compression or unconsolidated undrained triaxial.

</td>
</tr>
<tr>
<td>2. Failure of Stiff Compacted Fill on Soft Cohesive Foundation

Failure surface may be rotation on circular arc or translation with active and passive wedges.</td>
<td>

- Usually, minimum stability obtained at end of construction. Failure may be in the form of rotation or translation, and both should be considered.
- For rapid construction ignore consolidation from drainage and utilize shear strengths determined from U or UU tests or vane shear in total stress analysis. If failure strain of fill and foundation materials differ greatly, safety factor should exceed one, ignoring shear strength of fill. Analyze long-term stability using C and Ø from CU tests with effective stress analysis, applying pore pressures of

</td>
</tr>
<tr>
<td>3. Failure Following Cut in Stiff Fissured Clay

Failure surface depends on pattern of fissures or depth of softening.</td>
<td>

- Release of horizontal stresses by excavation causes expansion of clay and opening of fissures, resulting in loss of cohesive strength.
- Analyze for short-term stability using C' and Ø' with total stress analysis. Analyze for long-term stability with C'_r and $Ø'_m$ based on residual strength measured in consolidated drained tests.

</td>
</tr>
</table>

Source: Soil Mechanics, NAVFAC Design Manual 7.01

Table 2-3. Analysis of Stability of Cut and Fill Slopes, Conditions Varying With Time

Subsurface Exploration Programs

Foundation soil stability assessments for non-catastrophic failure require field investigations to determine soil strengths and other soil properties. *In situ* field vane shear tests commonly are conducted in addition to collection of piston samples for laboratory testing of undrained shear strengths (biaxial and triaxial). Field vanes taken at depth provide a profile of soil strength. The required field vane depth intervals vary, based on soil strength and type, and the number of borings required depends on the variability of the soils, the site size, and landfill unit dimensions. Borings and field vane testing should consider the anticipated design to identify segments of the facility where critical cross sections are likely to occur. Critical sections are where factors of safety are anticipated to be lowest.

Other tests that are conducted to characterize a soil include determination of water content, Atterberg limits, grain size distribution, consolidation, effective porosity, and saturated hydraulic conductivity. The site hydrogeologic conditions should be assessed to determine if soils are saturated or unsaturated.

Catastrophic failures, such as sinkhole collapse in karst terrains or fault displacement during an earthquake, are more difficult to predict. Subsurface karst structures may have surface topographic expressions such as circular depressions over subsiding solution caverns. Subsurface borings or geophysical techniques may provide reliable means of identifying the occurrence, depth, and size of solution cavities that have the potential for catastrophic collapse.

Methods of Slope Stability Analysis

Slope stability analyses are performed for both excavated side slopes and aboveground embankments. The analyses are performed as appropriate to verify the structural integrity of a cut slope or dike. The design configuration is evaluated for its stability under all potential hydraulic and loading conditions, including conditions that may exist during construction of an expansion (e.g., excavation). Analyses typically performed are slope stability, settlement, and liquefaction. Factor of safety rationale and selection for different conditions are described by Huang (1983) and Terzaghi and Peck (1967). Table 2-4 lists recommended minimum factor of safety values for slopes. Many States may provide their own minimum factor of safety requirements.

There are numerous methods currently available for performing slope stability analyses. Method selection should be based on the soil properties and the anticipated mode of failure. Rationale for selecting a specific method should be provided.

The majority of these methods may be categorized as "limit equilibrium" methods in which driving and resisting forces are determined and compared. The basic assumption of the limit equilibrium approach is that the failure criterion is satisfied along an assumed failure surface. This surface may be a straight line, circular arc, logarithmic spiral, or other irregular plane. A free body diagram of the driving forces acting on the slope is constructed using assumed or known values of the forces. Next, the soil's shear resistance as it pertains to establishing equilibrium is calculated. This calculated shear resistance

Table 2-4

Recommended Minimum Values of Factor of Safety for Slope Stability Analyses

	Uncertainty of Strength Measurements	
Consequences of Slope Failure	Small[1]	Large[2]
No imminent danger to human life or major environmental impact if slope fails	1.25 (1.2)*	1.5 (1.3)
Imminent danger to human life or major environmental impact if slope fails	1.5 (1.3)	2.0 or greater (1.7 or greater)

[1] The uncertainty of the strength measurements is smallest when the soil conditions are uniform and high quality strength test data provide a consistent, complete, and logical picture of the strength characteristics.

[2] The uncertainty of the strength measurements is greatest when the soil conditions are complex and when available strength data do not provide a consistent, complete, and logical picture of the strength characteristics.

* Numbers without parentheses apply for static conditions and those within parentheses apply to seismic conditions.

Source: EPA Guide to Technical Resources for the Design of Land Disposal Facilities.

then is compared to the estimated or available shear strength of the soil to give an indication of the factor of safety (Winterkorn and Fang, 1975).

Methods that consider only the whole free body as a single unit include the Culmann method and the friction circle method. Another approach is to divide the free body into vertical slices and to consider the equilibrium of each slice. Several versions of the slice method are available; the best known are the Swedish Circle method and the Bishop method. Discussions of these and other methods may be found in Winterkorn and Fang (1975), Lambe and Whitman (1969), and U.S. Navy (1986).

A computer program that is widely used for slope stability analysis is PC STABL, a two-dimensional model that computes the minimum critical factors of safety between layer interfaces. This model uses the method of vertical slices to analyze the slope and calculate the factor of safety. PC STABL can account for heterogeneous soil systems, anisotropic soil strength properties, excess pore water pressure due to shear, static ground water and surface water, pseudostatic earthquake loading, surcharge boundary loading, and tieback loading. The program is written in FORTRAN IV and can be run on a PC. Figure 2-7 presents a typical output from the model.

Design for Slope Stabilization

Methods for slope stabilization are presented in Table 2-5 and are summarized below.

- The first illustration shows that stability can be increased by changing the slope geometry through reduction of the slope height, flattening the slope angle, or excavating a bench in the upper part of the slope.

- The second illustration shows how compacted earth or rock fill can be placed in the form of a berm at and beyond the slope's toe to buttress the slope. To prevent the development of undesirable water pressure behind the berm, a drainage system may be placed behind the berm at the base of the slope.

- The third illustration presents several types of retaining structures. These structures generally involve drilling and/or excavation followed by constructing cast-in-place concrete piles and/or slabs.

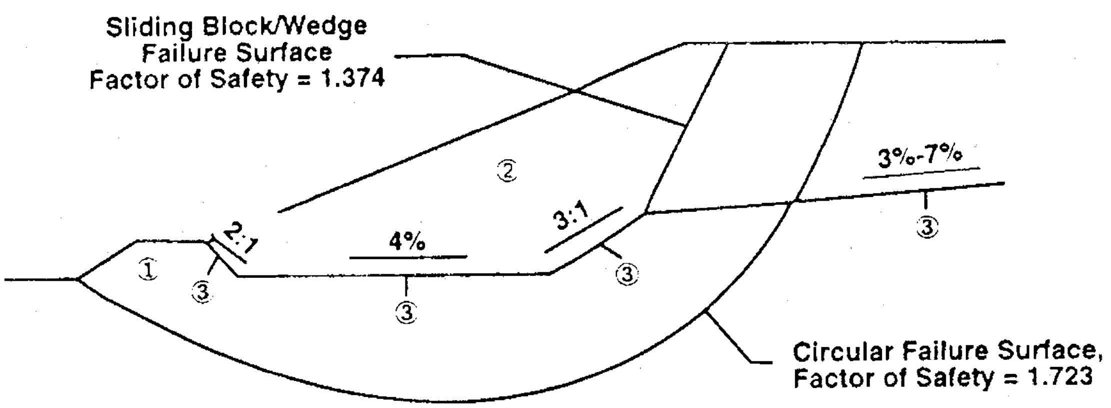
  — The T-shaped cantilever wall design enables some of the retained soil to contribute to the stability of the structure and is advisable for use on slopes that have vertical cuts.

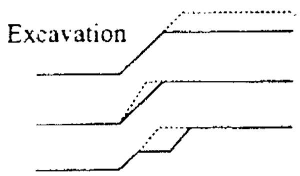
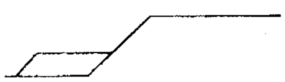
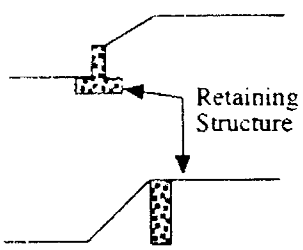
  — Closely-spaced vertical piles placed along the top of the slope area provide reinforcement against slope failure through a soil arching effect that is created between the piles. This type of retaining system is advisable for use on steeply cut slopes.

  — Vertical piles also may be designed with a tie back component at an angle to the vertical to develop a high resistance to lateral forces. This type of wall is recommended for use in areas

Figure 2-7
Sample Output from PC STABL Model

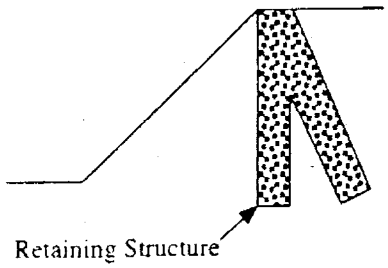
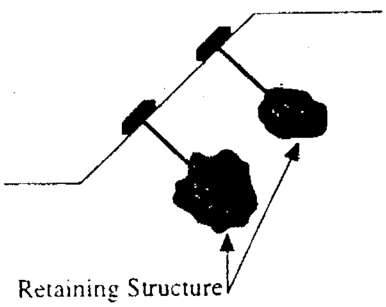
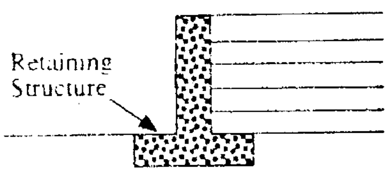
① Subgrade: Internal friction angle = 32 degrees
② Refuse: Internal friction angle of waste = 25 degrees
③ Refuse: Internal friction angle of waste = 25 degrees



Scheme	Applicable Methods	Comments
1. Changing Geometry 	1. Reduce slope height by excavation at top of slope 2. Flatten the slope angle. 3. Excavate a bench in upper part of slope.	1. Area has to be accessible to construction equipment. Disposal site needed for excavated soil. Drainage sometimes incorporated in this method.
2. Earth Berm Fill 	1. Compacted earth or rock berm placed at end beyond the toe. Drainage may be provided behind the berm.	1. Sufficient width and thickness of berm required so failure will not occur below or through the berm.
3. Retaining Structures 	1. Retaining wall: crib or cantilever type. 2. Drilled, cast-in-place vertical piles and/or slabs founded well below bottom slide plane. Generally 18 to 36 inches in diameter and 4- to 8-foot spacing. Larger diameter piles at closer spacing may be required in some cases with mitigate failures of cuts in highly fissured clays.	1. Usually expensive. Cantilever walls might have to be tied back. 2. Spacing should be such that soil can arch between piles. Grade beam can be used to tie piles together. Very large diameter (6 feet±) piles have been used for deep slide.

Source: Soil Mechanics, NAVFAC Design Manual 7.01

Table 2-5
Methods of Stabilizing Excavation Slopes

Scheme	Applicable Methods	Comments
	3. Drilled, cast-in-place vertical piles tied back with battered piles or a deadman. Piles founded well below slide plane. Generally, 12 to 30 inches in diameter and at least 4- to 8-foot spacing.	3. Space close enough so soil will arch between piles. Piles can be tied together with grade beam.
	4. Earth and rock anchors and rock bolts.	4. Can be used for high slopes, and in very restricted areas. Conservative design should be used, especially for permanent support. Use may be essential for slopes in rocks where joints dip toward excavation, and such joints daylight in the slope.
	5. Reinforced earth.	5. Usually expensive
4. Other methods	See TABLE 7, NAVFAC DM-7.2, Chapter 1	

Source: Soil Mechanics, NAVFAC Design Manual 7.01

Table 2-5 (continued)
Methods of Stabilizing Excavation Slopes

with steeply cut slopes where soil arching can be developed between the piles.

— The last retaining wall shown uses a cantilever setup along with soil that has been reinforced with geosynthetic material to provide a system that is highly resistant to vertical and lateral motion. This type of system is best suited for use in situations where vertically cut slopes must have lateral movement strictly controlled.

Other potential procedures for stabilizing natural and human-made slopes include the use of geotextiles and geogrids to provide additional strength, the installation of wick and toe drains to relieve excess pore pressures, grouting, and vacuum and wellpoint pumping to lower ground-water levels. In addition, surface drainage may be controlled to decrease infiltration, thereby reducing the potential for mud and debris slides in some areas. Lowering the ground-water table also may have stabilizing effects. Walls or large-diameter piling can be used to stabilize slides of relatively small dimension or to retain steep toe slopes so that failure will not extend back into a larger mass (U.S. Navy, 1986). For more detailed information regarding slope stabilization design, refer to Winterkorn and Fang (1975), U.S. Navy (1986), and Sowers (1979). Richardson and Koerner (1987) and Koerner (1986) provide design guidance for geosynthetics in both landfill and general applications.

Monitoring

During construction activities, it may be appropriate to monitor slope stability because of the additional stresses placed on natural and engineered soil systems (e.g., slopes, foundations, dikes) as a result of excavation and filling activities. Post-closure slope monitoring usually is not necessary.

Important monitoring parameters may include settlement, lateral movement, and pore water pressure. Monitoring for pore water pressure is usually accomplished with piezometers screened in the sensitive strata. Lateral movements of structures may be detected on the surface by surveying horizontal and vertical movements. Subsurface movements may be detected by use of slope inclinometers. Settlement may be monitored by surveying ground surface elevations (on several occasions over a period of time) and comparing them with areas that are not likely to experience changes in elevations (e.g., USGS survey monuments).

Engineering Considerations for Karst Terrains

The principal concern with karst terrains is progressive and/or catastrophic failure of subsurface conditions due to the presence of sinkholes, solution cavities, and subterranean caverns. The unpredictable and catastrophic nature of subsidence in these areas makes them difficult to develop as landfill sites. Before situating a MSWLF in a karst region, the subject site should be characterized thoroughly.

The first stage of demonstration is to characterize the subsurface. Subsurface drilling, sinkhole monitoring, and geophysical testing are direct means that can be used to characterize a site. Geophysical techniques include tests using electromagnetic conductivity, seismic refraction, ground-penetrating radar, gravity, and electrical resistivity. Interpretation and applicability of different geophysical techniques should be reviewed by a qualified geophysicist. Often more than one technique should be employed to confirm and correlate findings and anomalies. Subsurface drilling is recommended highly for verifying the results of geophysical investigations.

Additional information on karst conditions can come from remote sensing techniques, such as aerial photograph interpretation. Surface mapping of karst features can help to provide an understanding of structural patterns and relationships in karst terrains. An understanding of local carbonate geology and stratigraphy can aid in the interpretation of both remote sensing and geophysical techniques.

A demonstration that engineering measures have been incorporated into a unit located in a karst terrain may include both initial design and site modifications. A relatively simple engineering modification that can be used to mitigate karst terrain problems is ground-water and surface water control and conveyance. Such water control measures are used to minimize the rate of dissolution within known near-surface limestone. This means of controlling karst development may not be applicable to all karst situations. In areas where development of karst topography tends to be minor, loose soils overlying the limestone may be excavated or heavily compacted to achieve the needed stability. Similarly, in areas where the karst voids are relatively small and limited in extent, infilling of the void with slurry cement grout or other material may be an option.

In general, due to the unpredictable and catastrophic nature of ground failure in such areas, engineering solutions that try to compensate for the weak geologic structures by constructing manmade ground supports tend to be complex and costly. For example, reinforced raft (or mat) foundations could be used to compensate for lack of ground strength in some karst areas. Raft foundations are a type of "floating foundation" that consist of a concrete footing that extends over a very large area. Such foundations are used where soils have a low bearing capacity or where soil conditions are variable and erratic; these foundations are able to reduce and distribute loads. However, it should be noted that, in some instances, raft foundations may not necessarily be able to prevent the extreme type of collapse and settlement that can occur in karst areas. In addition, the construction of raft foundations can be very costly, depending on the size of the area.

2.8 CLOSURE OF EXISTING MUNICIPAL SOLID WASTE LANDFILL UNITS 40 CFR §258.16

2.8.1 Statement of Regulation

(a) Existing MSWLF units that cannot make the demonstration specified in §§258.10(a), pertaining to airports, 258.11(a), pertaining to floodplains, and 258.15(a), pertaining to unstable areas,

must close by October 9, 1996, in accordance with §258.60 of this part and conduct post-closure activities in accordance with §258.61 of this part.

(b) The deadline for closure required by paragraph (a) of this section may be extended up to two years if the owner or operator demonstrates to the Director of an approved State that:

(1) There is no available alternative disposal capacity;

(2) There is no immediate threat to human health and the environment.

2.8.2 Applicability

These requirements are applicable to all MSWLF units that receive waste after October 9, 1993 and cannot meet the airport safety, floodplain, or unstable area requirements. The owner or operator is required to demonstrate that the facility: (1) will not pose a bird hazard to aircraft under §258.10(a); (2) is designed to prevent washout of solid waste, will not restrict floodplain storage capacity, or increase floodwater flow in a 100-year floodplain under §258.11(a); and 3) can withstand damage to landfill structural component systems (e.g., liners, leachate collection, and other engineered structures) as a result of unstable conditions under §258.15(a). If any of these demonstrations cannot be made, the landfill must close by October 9, 1996. In approved States, the closure deadline may be extended up to two additional years if it can be shown that alternative disposal capacity is not available and that the MSWLF unit does not pose an immediate threat to human health and the environment.

2.8.3 Technical Considerations

The engineering considerations that should be addressed for airport safety, 100-year floodplain encroachment, and unstable areas are discussed in Sections 2.2, 2.3, and 2.7 of this chapter. Information and evaluations necessary for these demonstrations also are presented in these sections. If applicable demonstrations are not made by the owners or operators, the landfill unit(s) must be closed according to the requirements of section §258.60 by October 9, 1996.

For MSWLF units located in approved States, this deadline may be extended if there is no immediate threat to human health and the environment and no waste disposal alternative is available. The demonstration of no disposal alternative should consider all waste management facilities, including landfills, municipal waste combustors, and recycling facilities. The demonstration for the two-year extension should consider the impacts on human health and the environment as they relate to airport safety, 100-year floodplains, or unstable areas.

§§258.17-258.19 [Reserved].

2.9 FURTHER INFORMATION

2.9.1 References

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2.9.2 Organizations

American Institute of Architects
Washington, D.C.
(202) 626-7300

Aviation Safety Institute (ASI)
Box 304
Worthington, OH 43085
(614) 885-4242

American Society of Civil Engineers
345 East 47th St.
New York, NY 10017-2398
(212) 705-7496

Building Seismic Safety Council
201 L Street, Northwest Suite 400
Washington, D.C. 20005
(202) 289-7800

Bureau of Land Management
1849 C St. N.W.
Washington, D.C. 20240
(202) 343-7220 (Locator)
(202) 343-5717 (Information)

3.2 PROCEDURES FOR EXCLUDING THE RECEIPT OF HAZARDOUS WASTE 40 CFR §258.20

3.2.1 Statement of Regulation

(a) Owners or operators of all MSWLF units must implement a program at the facility for detecting and preventing the disposal of regulated hazardous wastes as defined in Part 261 of this title and polychlorinated biphenyls (PCB) wastes as defined in Part 761 of this title. This program must include, at a minimum:

(1) Random inspections of incoming loads unless the owner or operator takes other steps to ensure that incoming loads do not contain regulated hazardous wastes or PCB wastes;

(2) Records of any inspections;

(3) Training of facility personnel to recognize regulated hazardous waste and PCB wastes; and

(4) Notification of State Director of authorized States under Subtitle C of RCRA or the EPA Regional Administrator if in an unauthorized State if a regulated hazardous waste or PCB waste is discovered at the facility.

(b) For purposes of this section, regulated hazardous waste means a solid waste that is a hazardous waste, as defined in 40 CFR 261.3, that is not excluded from regulation as a hazardous waste under 40 CFR 261.4(b) or was not generated by a conditionally exempt small quantity generator as defined in §261.5 of this title.

3.2.2 Applicability

This regulation applies to all MSWLF units that receive wastes on or after October 9, 1993.

The owner or operator must develop a program to detect and prevent disposal of regulated hazardous wastes or PCB wastes at the MSWLF facility. Hazardous wastes may be gases, liquids, solids, or sludges that are listed or exhibit the characteristics described in 40 CFR Part 261. Household hazardous wastes are excluded from Subtitle C regulation, and wastes generated by conditionally exempt small quantity generators (CESQGs) are not considered regulated hazardous wastes for purposes of complying with §258.20; therefore, these wastes may be accepted for disposal at a MSWLF unit.

The MSWLF hazardous waste exclusion program should be capable of detecting and preventing disposal of PCB wastes. PCB wastes may be liquids or non-liquids (sludges or solids) and are defined at 40 CFR Section 761.60. PCB wastes do not include small capacitors found in fluorescent light ballast, white goods (e.g., washers, dryers, refrigerators) or other consumer electrical products (e.g., radio and television units).

The hazardous waste exclusion program is not intended to identify whether regulated hazardous waste or PCB waste was received at the MSWLF unit or facility prior to the effective date of the Criteria.

3.2.3 Technical Considerations

A solid waste is a regulated hazardous waste if it: (1) is listed in Subpart D of 40 CFR

Part 261 (termed a "listed" waste); (2) exhibits a characteristic of a hazardous waste as defined in Subpart C of 40 CFR Part 261; or (3) is a mixture of a listed hazardous waste and a non-hazardous solid waste. Characteristics of hazardous wastes as defined in Subpart C of 40 CFR Part 261 include ignitability, corrosivity, reactivity, and toxicity. The toxicity characteristic leaching procedure (TCLP) is the test method used to determine the mobility of organic and inorganic compounds present in liquid, solid, and multiphase wastes. The TCLP is presented in Appendix II of Part 261.

The MSWLF Criteria exclude CESQG waste (as defined in 40 CFR §261.5) from the definition of "regulated hazardous wastes." CESQG waste includes listed hazardous wastes or wastes that exhibit a characteristic of a hazardous waste that are generated in quantities no greater than 100 kg/month, or for acute hazardous waste, 1 kg/month. Under 40 CFR §261.5(f)(3)(iv) and (g)(3)(iv), conditionally exempt small quantity generator hazardous wastes may be disposed at facilities permitted, licensed, or registered by a State to manage municipal or industrial solid waste.

Other solid wastes are excluded from regulation as a hazardous waste under 40 CFR §261.4(b) and may be accepted for disposal at a MSWLF unit. Refer to §261.4(b) for a listing of these wastes.

PCBs are regulated under the Toxic Substances Control Act (TSCA), but PCB-containing wastes are considered hazardous wastes in some States. PCBs typically are not found in consumer wastes except for fluorescent ballast and small capacitors in white goods and electrical appliances. These sources are not regulated under 40 CFR Part 761 and, therefore, are not part of the detection program required by §258.20. Commercial or industrial sources of PCB wastes that should be addressed by the program include:

- Mineral oil and dielectric fluids containing PCBs;
- Contaminated soil, dredged material, sewage sludge, rags, and other debris from a release of PCBs;
- Transformers and other electrical equipment containing dielectric fluids; and
- Hydraulic machines.

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

- Random inspections of incoming loads or other prevention methods;
- Maintenance of inspection records;
- Facility personnel training; and
- Notification to appropriate authorities if hazardous wastes or PCB wastes are detected.

Each of these program elements is discussed separately on the following pages.

Inspections

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

Ideally, all loads should be screened; however, it is generally not practical to inspect in detail all incoming loads. Random inspections, therefore, can be used to provide a reasonable means to adequately control the receipt of inappropriate wastes. Random inspections are simply inspections made on less than every load.

The frequency of random inspections may be based on the type and quantity of wastes received daily, and the accuracy and confidence desired in conclusions drawn from inspection observations. Because statistical parameters are not provided in the regulation, a reasoned, knowledge-based approach may be taken. A random inspection program may take many forms such as inspecting every incoming load one day out of every month or inspecting one or more loads from transporters of wastes of unidentifiable nature each day. If these inspections indicate that unauthorized wastes are being brought to the MSWLF site, then the random inspection program should be modified to increase the frequency of inspections.

Inspection frequency also can vary depending on the nature of the waste. For example, wastes received predominantly from commercial or industrial sources may require more frequent inspections than wastes predominantly from households.

Inspection priority also can be given to haulers with unknown service areas, to loads brought to the facility in vehicles not typically used for disposal of municipal solid waste, and to loads transported by previous would-be offenders. For wastes of unidentifiable nature received from sources other than households (e.g., industrial or commercial establishments), the inspector should question the transporter about the source/composition of the materials.

Loads should be inspected prior to actual disposal of the waste at the working face of the landfill unit to provide the facility owner or operator the opportunity to refuse or accept the wastes. Inspections can be conducted on a tipping floor of a transfer station before transfer of the waste to the disposal facility. Inspections also may occur at the tipping floor located near the facility scale house, inside the site entrance, or near, or adjacent to, the working face of the landfill unit. An inspection flow chart to identify, accept, or refuse solid waste is provided as Figure 3-1.

Inspections of materials may be accomplished by discharging the vehicle load in an area designed to contain potentially hazardous wastes that may arrive at the facility. The waste should be carefully spread for observation using a front end loader or other piece of equipment. Personnel should be trained to identify suspicious wastes. Some indications of suspicious wastes are:

- Hazardous placards or marking;
- Liquids;
- Powders or dusts;

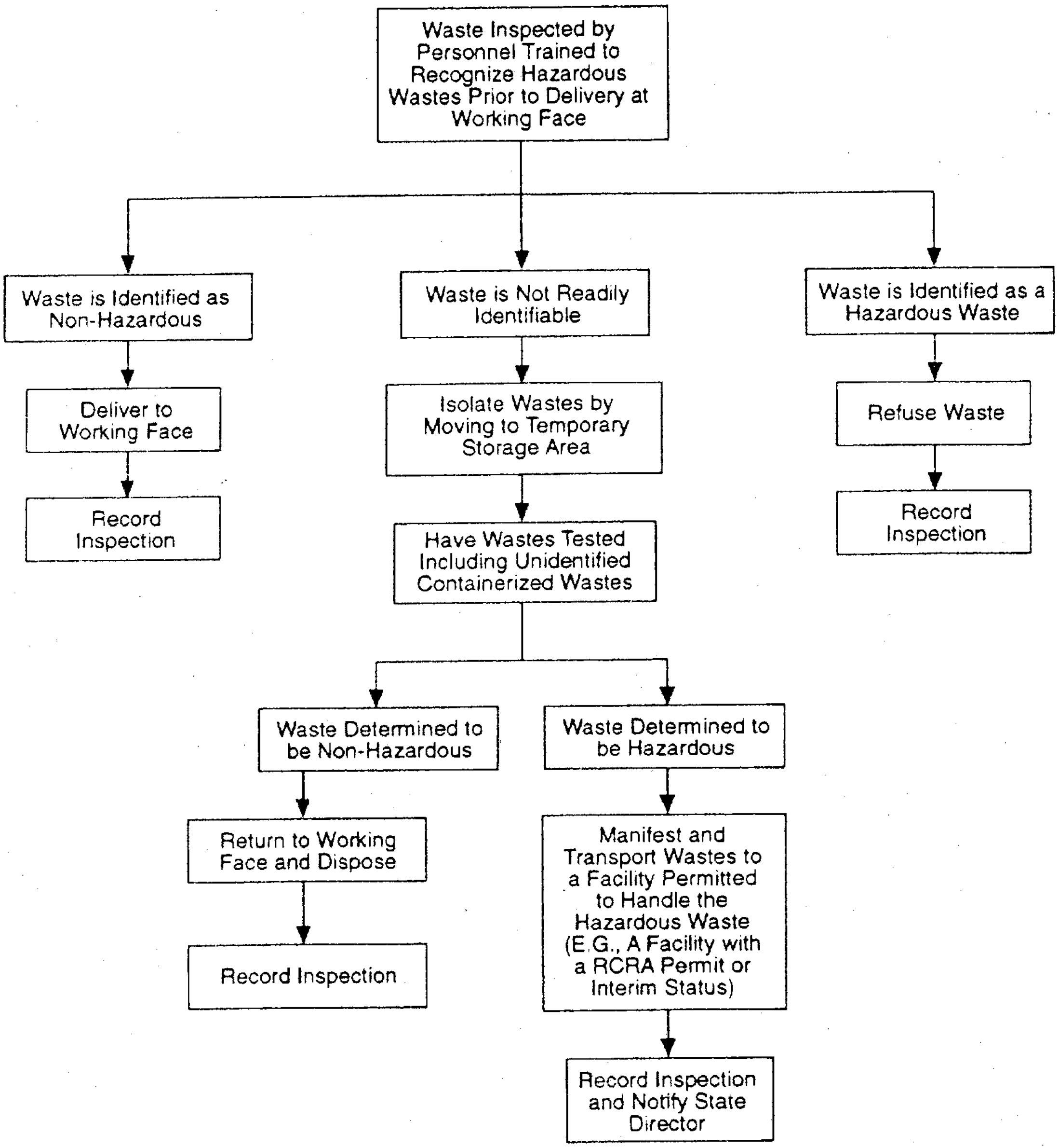


Figure 3-1
Hazardous Waste Inspection Decision Tree
Inspection Prior to Working Face

- Sludges;
- Bright or unusual colors;
- Drums or commercial size containers; or
- Chemical odors.

The owner or operator should develop specific procedures to be followed when suspicious wastes are discovered. The procedure should include the following points:

- Segregate the wastes;
- Question the driver;
- Review the manifest (if applicable);
- Contact possible source;
- Call the appropriate State or Federal agencies;
- Use appropriate protective equipment;
- Contact laboratory support if required; and
- Notify a response agency if necessary.

Containers with contents that are not easily identifiable, such as unmarked 55-gallon drums, should be opened only by properly trained personnel. Because these drums could contain hazardous waste, they should be refused whenever possible. Upon verifying that the solid waste is acceptable, it may then be transferred to the working face for disposal.

Some facilities may consider it reasonable to test unidentified waste, store it, and see that it is disposed of properly. Most facilities would not consider this reasonable.

Testing typically would include The Toxicity Characteristic Leaching Procedure (TCLP) and other tests for characteristics of hazardous wastes including corrosivity, ignitability, and reactivity. Wastes that are suspected of being hazardous should be handled and stored as a hazardous waste until a determination is made.

If the wastes temporarily stored at the site are determined to be hazardous, the owner or operator is responsible for the management of the waste. If the wastes are to be transported from the facility, the waste must be: (1) stored at the MSWLF facility in accordance with requirements of a hazardous waste generator, (2) manifested, (3) transported by a licensed transporter, and (4) sent to a permitted Treatment, Storage, or Disposal (TSD) facility for disposal. These requirements are discussed further in this section.

Alternative Methods for Detection and Prevention

While the regulations explicitly refer to inspections as an acceptable means of detecting regulated hazardous wastes and PCB wastes, preventing the disposal of these wastes may be accomplished through other methods. These methods may include receiving only household wastes and processed (shredded or baled) wastes that are screened for the presence of the excluded wastes prior to processing. A pre-acceptance agreement between the owner or operator and the waste hauler is another alternative method. An example of a pre-acceptance agreement is presented as Appendix I. The owner or operator should keep any such agreements concerning these alternatives in the operating record.

Recordkeeping

A record should be kept of each inspection that is performed. These records should be included and maintained in the facility operating record. Larger facilities that take large amounts of industrial and commercial wastes may use more detailed procedures than smaller facilities that accept household wastes. Inspection records may include the following information:

- The date and time wastes were received for inspection;
- Source of the wastes;
- Vehicle and driver identification; and
- All observations made by the inspector.

The Director of an approved State may establish alternative recordkeeping locations and requirements.

Training

Owners or operators must ensure that personnel are trained to identify potential regulated hazardous waste and PCB wastes. These personnel could include supervisors, designated inspectors, equipment operators, and weigh station attendants who may encounter hazardous wastes. Documentation of training should be placed in the operating record for the facility in accordance with §258.29.

The training program should emphasize methods to identify containers and labels typical of hazardous waste and PCB waste. Training also should address hazardous waste handling procedures, safety precautions, and recordkeeping requirements. This information is provided in training courses designed to comply with the Occupational Safety and Health Act (OSHA) under 29 CFR §1910.120. Information covered in these courses includes regulatory requirements under 40 CFR Parts 260 through 270, 29 CFR Part 1910, and related guidance documents that discuss such topics as: general hazardous waste management; identification of hazardous wastes; transportation of hazardous wastes; standards for hazardous waste treatment; storage and disposal facilities; and hazardous waste worker health and safety training and monitoring requirements.

Notification to Authorities and Proper Management of Wastes

If regulated quantities of hazardous wastes or PCB wastes are found at the landfill facility, the owner or operator must notify the proper authorities. Proper authorities are either the Director of a State authorized to implement the hazardous waste program under Subtitle C of RCRA, or the EPA Regional Administrator, in an unauthorized State.

If the owner or operator discovers regulated quantities of hazardous waste or PCB waste while it is still in the possession of the transporter, the owner or operator can refuse to accept the waste at the MSWLF facility, and the waste will remain the responsibility of the transporter. If the owner or operator is unable to identify the transporter who brought the hazardous waste, the owner or operator must ensure that the waste is managed in accordance with all applicable Federal and State regulations.

Operators of MSWLF facilities should be prepared to handle hazardous wastes that are inadvertently received at the MSWLF facility. This may include having containers such as 55-gallon drums available on-site and retaining a list of names and telephone numbers of the nearest haulers licensed to transport hazardous waste.

Hazardous waste may be stored at the MSWLF facility for 90 days, provided that the following procedures required by 40 CFR §262.34, or applicable State requirements, are followed:

- The waste is placed in tanks or containers;
- The date of receipt of the waste is clearly marked and visible on each container;
- The container or tank is marked clearly with the words "Hazardous Waste";
- An employee is designated as the emergency coordinator who is responsible for coordinating all emergency response measures; and
- The name and telephone number of the emergency coordinator and the number of the fire department is posted next to the facility phone.

Extensions to store the waste beyond 90 days may be approved pursuant to 40 CFR 262.34.

If the owner or operator transports the wastes off-site, the owner or operator must comply with 40 CFR Part 262 or the analogous State/Tribal requirements. The owner or operator is required to:

- Obtain an EPA identification number (EPA form 8700-12 may be used to apply for an EPA identification number; State or Regional personnel may be able to provide a provisional identification number over the telephone);
- Package the waste in accordance with Department of Transportation (DOT) regulations under 49 CFR Parts 173, 178, and 179 (The container must be labeled, marked, and display a placard in accordance with DOT regulations on hazardous wastes under 49 CFR Part 172); and
- Properly manifest the waste designating a permitted facility to treat, store, or dispose of the hazardous waste.

If the owner or operator decides to treat, store (for more than 90 days), or dispose of the hazardous waste on-site, he or she must comply with the applicable State or Federal requirements for hazardous waste treatment, storage, and disposal facilities. This may require a permit.

PCB wastes detected at a MSWLF facility must be stored and disposed of according to 40 CFR Part 761. The owner or operator is required to:

- Obtain an EPA PCB identification number;
- Properly store the PCB waste;
- Mark containers or items with the words "Caution: contains PCBs"; and

- Manifest the PCB waste for shipment to a permitted incinerator, chemical waste landfill, or high efficiency boiler (depending on the nature of the PCB waste) for disposal.

3.3 COVER MATERIAL REQUIREMENTS 40 CFR §258.21

3.3.1 Statement of Regulation

(a) Except as provided in paragraph (b) of this section, the owners or operators of all MSWLF units must cover disposed solid waste with six inches of earthen material at the end of each operating day, or at more frequent intervals if necessary, to control disease vectors, fires, odors, blowing litter, and scavenging.

(b) Alternative materials of an alternative thickness (other than at least six inches of earthen material) may be approved by the Director of an approved State if the owner or operator demonstrates that the alternative material and thickness control disease vectors, fires, odors, blowing litter, and scavenging without presenting a threat to human health and the environment.

(c) The Director of an approved State may grant a temporary waiver from the requirement of paragraph (a) and (b) of this section if the owner or operator demonstrates that there are extreme seasonal climatic conditions that make meeting such requirements impractical.

3.3.2 Applicability

The regulation applies to all MSWLF units receiving waste after October 9, 1993. The regulation requires MSWLF unit owners and operators to cover wastes with a 6-inch layer of earthen material at the end of each operating day. More frequent application of soil may be required if the soil cover does not control:

- Disease vectors (e.g., birds, flies and other insects, rodents);
- Fires;
- Odors;
- Blowing litter; and
- Scavenging.

The Director of an approved State may allow an owner or operator to use alternative cover material of an alternative thickness or grant a temporary waiver of this requirement. An alternative material must not present a threat to human health and the environment, and must continue to control disease vectors, fires, odors, blowing litter, and scavenging. The only basis for a temporary waiver from the requirement to cover at the end of each operating day would be where extreme seasonal climatic conditions make compliance impractical.

3.3.3 Technical Considerations

Owners and operators of new MSWLF units, existing MSWLF units, and lateral expansions are required to cover solid waste at the end of each operating day with six inches of earthen material. This cover protection of human health and the environment.

3.4.3 Technical Considerations

Disease vectors such as rodents, birds, flies, and mosquitoes typically are attracted by putrescent waste and standing water, which act as a food source and breeding ground. Putrescent waste is solid waste that contains organic matter (such as food waste) capable of being decomposed by micro-organisms. A MSWLF facility typically accepts putrescent wastes.

Application of cover at the end of each operating day generally is sufficient to control disease vectors; however, other vector control alternatives may be required. These alternatives could include: reducing the size of the working face; other operational modifications (e.g., increasing cover thickness, changing cover type, density, placement frequency, and grading); repellents, insecticides or rodenticides; composting or processing of organic wastes prior to disposal; and predatory or reproductive control of insect, bird, and animal populations. Additional methods to control birds are discussed in Chapter 2 (Airport Safety).

Mosquitoes, for example, are attracted by standing water found at MSWLFs, which can provide a potential breeding ground after only three days. Water generally collects in surface depressions, open containers, exposed tires, ponds resulting from soil excavation, leachate storage ponds, and siltation basins. Landfill operations that minimize standing water and that use an insecticide spraying program ordinarily are effective in controlling mosquitoes.

Vectors may reach the landfill facility not only from areas adjacent to the landfill, but through other modes conducive to harborage and breeding of disease vectors. Such modes may include residential and commercial route collection vehicles and transfer stations. These transport modes and areas also should be included in the disease vector control program if disease vectors at the landfill facility become a problem. Keeping the collection vehicles and transfer stations covered; emptying and cleaning the collection vehicles and transfer stations; using repellents, insecticides, or rodenticides; and reproductive control are all measures available to reduce disease vectors in these areas.

3.5 EXPLOSIVE GASES CONTROL 40 CFR §258.23

3.5.1 Statement of Regulation

(a) Owners or operators of all MSWLF units must ensure that:

(1) The concentration of methane gas generated by the facility does not exceed 25 percent of the lower explosive limit for methane in facility structures (excluding gas control or recovery system components); and

(2) The concentration of methane gas does not exceed the LEL for methane at the facility property boundary.

(b) Owners or operators of all MSWLF units must implement a routine methane monitoring program to ensure that the standards of paragraph (a) of this section are met.

(1) The type and frequency of monitoring must be determined based on the following factors:

(i) Soil conditions;

(ii) The hydrogeologic conditions surrounding the facility;

(iii) The hydraulic conditions surrounding the facility; and

(iv) The location of facility structures and property boundaries.

(2) The minimum frequency of monitoring shall be quarterly.

(c) If methane gas levels exceeding the limits specified in paragraph (a) of this section are detected, the owner or operator must:

(1) Immediately take all necessary steps to ensure protection of human health and notify the State Director;

(2) Within seven days of detection, place in the operating record the methane gas levels detected and a description of the steps taken to protect human health; and

(3) Within 60 days of detection, implement a remediation plan for the methane gas releases, place a copy of the plan in the operating record, and notify the State Director that the plan has been implemented. The plan shall describe the nature and extent of the problem and the proposed remedy.

(4) The Director of an approved State may establish alternative schedules for demonstrating compliance with paragraphs (2) and (3).

(d) For purposes of this section, <u>lower explosive limit</u> (LEL) means the lowest percent by volume of a mixture of explosive gases in air that will propagate a flame at 25°C and atmospheric pressure.

<u>3.5.2 Applicability</u>

The regulation applies to existing MSWLF units, lateral expansions, and new MSWLF units. The accumulation of methane in MSWLF structures can potentially result in fire and explosions that can endanger employees, users of the disposal site, and occupants of nearby structures, or cause damage to landfill containment structures. These hazards are preventable through monitoring and through corrective action should methane gas levels exceed specified limits in the facility structures (excluding gas control or recovery system components), or at the facility property boundary. MSWLF facility owners and operators must comply with the following requirements:

- Monitor at least quarterly;
- Take immediate steps to protect human health in the event of methane gas levels exceeding 25% of the lower explosive limit (LEL) in facility structures, such as evacuating the building;
- Notify the State Director if methane levels exceed 25% of the LEL in facility structures or exceed the LEL at the facility property boundary;

- Within 7 days of detection, place in the operating record documentation that methane gas concentrations exceeded the criteria, along with a description of immediate actions taken to protect human health; and

- Within 60 days of detection, implement a remediation plan for the methane gas releases, notify the State Director, and place a copy of the remediation plan in the operating record.

The compliance schedule for monitoring and responding to methane levels that exceed the criteria of this regulation can be changed by the Director of an approved State.

3.5.3 Technical Considerations

To implement an appropriate routine methane monitoring program to demonstrate compliance with allowable methane concentrations, the characteristics of landfill gas production and migration at a site should be understood. Landfill gases are the result of microbial decomposition of solid waste. Gases produced include methane (CH_4), carbon dioxide (CO_2), and lesser amounts of other gases (e.g., hydrogen, volatile organic compounds, and hydrogen sulfide). Methane gas, the principal component of natural gas, is generally the primary concern in evaluating landfill gas generation because it is odorless and highly combustible. Typically, hydrogen gas is present at much lower concentra-tions. Hydrogen forms as decomposition progresses from the acid production phase to the methanogenic phase. While hydrogen is explosive and is occasionally detected in landfill gas, it readily reacts to form methane or hydrogen sulfide. Hydrogen sulfide is toxic and is readily identified by its "rotten egg" smell at a threshold concentration near 5 ppb.

Landfill gas production rates vary spatially within a landfill unit as a result of pockets of elevated microbial activity but, due to partial pressure gradients, differences in gas composition are reduced as the gases commingle within and outside the landfill unit. Although methane gas is lighter than air and carbon dioxide is heavier, these gases are concurrently produced at the microbial level and will not separate by their individual density. The gases will remain mixed and will migrate according to the density gradients between the landfill gas and the surrounding gases (i.e., a mixture of methane and carbon dioxide in a landfill unit or in surrounding soil will not separate by rising and sinking respectively, but will migrate as a mass in accordance with the density of the mixture and other gradients such as temperature and partial pressure).

When undergoing vigorous microbial production, gas pressures on the order of 1 to 3 inches of water relative to atmospheric pressure are common at landfill facilities, with much higher pressures occasionally reported. A barometric pressure change of 2 inches of mercury is equivalent to 27.2 inches of water. Relative gauge pressures at a particular landfill unit or portion of a landfill unit, the ability of site conditions to contain landfill gas, barometric pressure variations, and the microbial gas production rate control pressure-induced landfill gas migration. Negative gas pressures are commonly observed and are believed to occur as a result of the delayed response within a landfill unit to the passage of a high pressure system outside the landfill unit. Barometric highs will tend to introduce atmospheric oxygen into surface soils in shallow portions of the landfill unit, which may alter microbial activity, particularly methane production and gas composition.

Migration of landfill gas is caused by concentration gradients, pressure gradients, and density gradients. The direction in which landfill gas will migrate is controlled by the driving gradients and gas permeability of the porous material through which it is migrating. Generally, landfill gas will migrate through the path of least resistance.

Coarse, porous soils such as sand and gravel will allow greater lateral migration or transport of gases than finer-grained soils. Generally, resistance to landfill gas flow increases as moisture content increases and, therefore, an effective barrier to gas flow can be created under saturated conditions. Thus, readily drained soil conditions, such as sands and gravels above the water table, may provide a preferred flowpath, but unless finer-grained soils are fully saturated, landfill gases also can migrate in a "semi-saturated" zone. Figure 3-2 illustrates the potential effects of surrounding geology on gas migration.

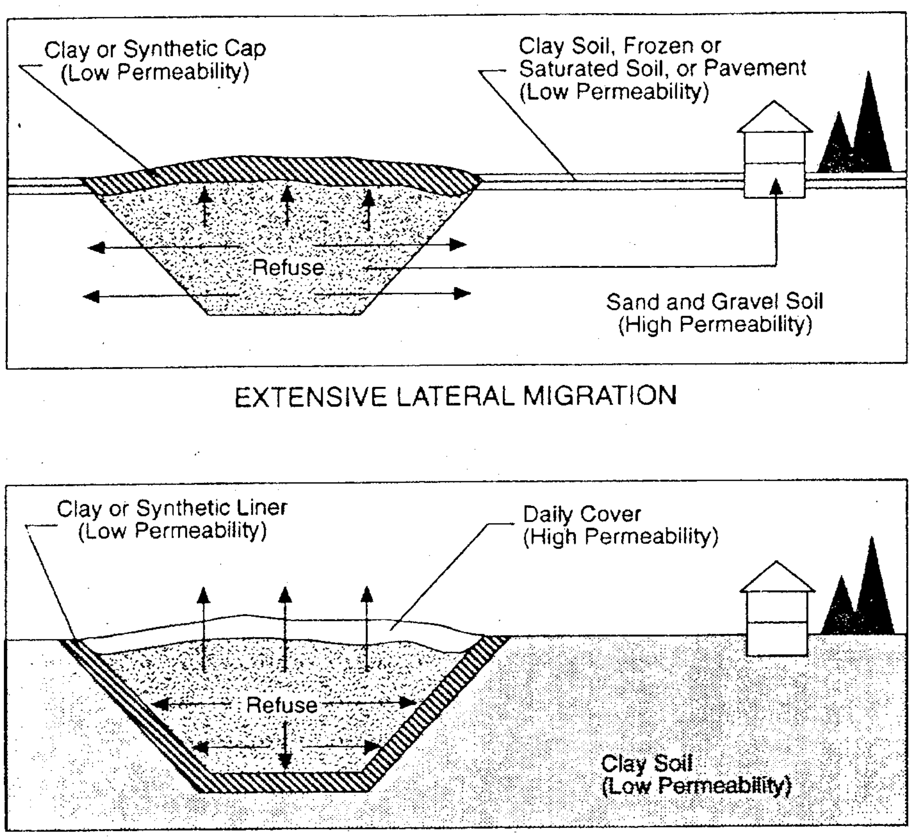
While geomembranes may not eliminate landfill gas migration, landfill gas in a closed MSWLF unit will tend to migrate laterally if the final cover contains a geomembrane and if the side slopes of the landfill do not contain an effective gas barrier. Lateral gas migration is more common in older facilities that lack appropriate gas control systems. The degree of lateral migration in older facilities also may depend on the type of natural soils surrounding the facility.

Stressed vegetation may indicate gas migration. Landfill gas present in the soil atmosphere tends to make the soil anaerobic by displacing the oxygen, thereby asphyxiating the roots of plants. Generally, the higher the concentration of combustible gas and/or carbon dioxide and the lower the amount of oxygen, the greater the extent of damage to vegetation (Flowers, et. al, 1982).

Gas Monitoring

The owner or operator of a MSWLF unit/facility must implement a routine methane monitoring program to comply with the lower explosive limit (LEL) requirements for methane. Methane is explosive when present in the range of 5 to 15 percent by volume in air. When present in air at concentrations greater than 15 percent, the mixture will not explode. This 15 percent threshold is the Upper Explosive Limit (UEL). The UEL is the maximum concentration of a gas or vapor above which the substance will not explode when exposed to a source of ignition. The explosive hazard range is between the LEL and the UEL. Note, however, that methane concentrations above the UEL remain a significant concern; fire and asphyxiation can still occur at these levels. In addition, even a minor dilution of the methane by increased ventilation can bring the mixture back into the explosive range.

To demonstrate compliance, the owner/operator would sample air within facility structures where gas may accumulate and in soil at the property boundary. Other monitoring methods may include: (1) sampling gases from probes within the landfill unit or from within the leachate collection system; or (2) sampling gases



Source: Emcon, 1981.

Figure 3-2
Potential Effects of
Surrounding Geology on Gas Migration

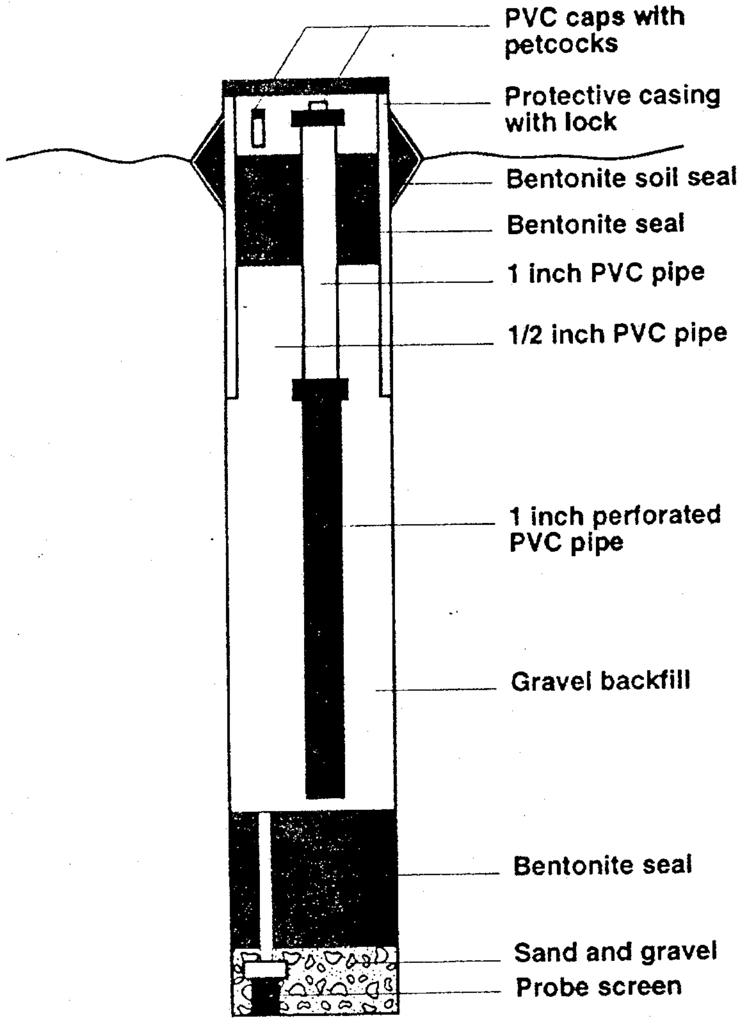
from monitoring probes installed in soil between the landfill unit and either the property boundary or structures where gas migration may pose a danger. A typical gas monitoring probe installation is depicted in Figure 3-3.

Although not required by the regulations, collection of data such as water presence and level, gas probe pressure, ambient temperature, barometric pressure, and the occurrence of precipitation during sampling, provides useful information in assessing monitoring results. For example, falling barometric pressure may cause increased subsurface (gas) pressures and corresponding increased methane content as gas more readily migrates from the landfill. Gas probe pressure can be measured using a portable gauge capable of measuring both vacuum and pressure in the range of zero to five inches of water pressure (or other suitable ranges for pressure conditions); this pressure should be measured prior to methane measurement or sample collection in the gas probe. A representative sample of formation (subsurface) gases can be collected directly from the probe. Purging typically is not necessary due to the small volume of the probe. A water trap is recommended to protect instrumentation that is connected directly to the gas probe. After measurements are obtained, the gas probe should be capped to reduce the effects of venting or barometric pressure variations on gas composition in the vicinity of the probe.

The frequency of monitoring should be sufficient to detect landfill gas migration based on subsurface conditions and changing landfill conditions such as partial or complete capping, landfill expansion, gas migration control system operation or failure, construction of new or replacement structures, and changes in landscaping or land use practices. The rate of landfill gas migration as a result of these anticipated changes and the site-specific conditions provides the basis for establishing monitoring frequency. Monitoring is to be conducted at least quarterly.

The number and location of gas probes is also site-specific and highly dependent on subsurface conditions, land use, and location and design of facility structures. Monitoring for gas migration should be within the more permeable strata. Multiple or nested probes are useful in defining the vertical configuration of the migration pathway. Structures with basements or crawl spaces are more susceptible to landfill gas infiltration. Elevated structures are typically not at risk.

Measurements are usually made in the field with a portable methane meter, explosimeter, or organic vapor analyzer. Gas samples also may be collected in glass or metal containers for laboratory analysis. Instruments with scales of measure in "percent of LEL" can be calibrated and used to detect the presence of methane. Instruments of the hot-wire Wheatstone bridge type (i.e., catalytic combustion) directly measure combustibility of the gas mixture withdrawn from the probe. The thermal conductivity type meter is susceptible to interference as the relative gas composition and, therefore, the thermal conductivity, changes. Field instruments should be calibrated prior to measurements and should be rechecked after each day's monitoring activity.



Source: Warzyn Inc.

Figure 3-3
Typical Gas Monitoring Probe

Laboratory measurements with organic vapor analyzers or gas chromatographs may be used to confirm the identity and concentrations of gas.

In addition to measuring gas composition, other indications of gas migration may be observed. These include odor (generally described as either a "sweet" or a rotten egg (H_2S) odor), vegetation damage, septic soil, and audible or visual venting of gases, especially in standing water. Exposure to some gases can cause headaches and nausea.

If methane concentrations are in excess of 25 percent of the LEL in facility structures or exceed the LEL at the property boundary, the danger of explosion is imminent. Immediate action must be taken to protect human health from potentially explosive conditions. All personnel should be evacuated from the area immediately. Venting the building upon exit (e.g., leaving the door open) is desirable but should not replace evacuation procedures.

Owners and operators in unapproved States have 60 days after exceeding the methane level to prepare and implement a remediation plan. The remediation plan should describe the nature and extent of the methane problem as well as a proposed remedy.

To comply with this 60-day schedule, an investigation of subsurface conditions may be needed in the vicinity of the monitoring probe where the criterion was exceeded. The objectives of this investigation should be to describe the frequency and lateral and vertical extent of excessive methane migration (that which exceeds the criterion). Such an investigation also may yield additional characterization of unsaturated soil within the area of concern. The investigation should consider possible causes of the increase in gas concentrations such as landfill operational procedures, gas control system failure or upset, climatic conditions, or closure activity. Based on the extent and nature of the excessive methane migration, a remedial action should be described, if the exceedance is persistent, that can be implemented within the prescribed schedule. The sixty-day schedule does not address the protection of human health and the environment. The owner or operator still must take all steps necessary to ensure protection of human health, including interim measures.

Landfill Gas Control Systems

Landfill gas may vent naturally or be purposely vented to the atmosphere by vertical and/or lateral migration controls. Systems used to control or prevent gas migration are categorized as either passive or active systems. Passive systems provide preferential flowpaths by means of natural pressure, concentration, and density gradients. Passive systems are primarily effective in controlling convective flow and have limited success controlling diffusive flow. Active systems are effective in controlling both types of flow. Active systems use mechanical equipment to direct or control landfill gas by providing negative or positive pressure gradients. Suitability of the systems is based on the design and age of the landfill unit, and on the soil, hydrogeologic, and hydraulic conditions of the facility and surrounding environment. Because of these variables, both systems have had varying degrees of success.

Passive systems may be used in conjunction with active systems. An example of this may be the use of a low-permeability passive system for the closed portion of a landfill unit (for remedial purposes) and the installation of an active system in the active portion of the landfill unit (for future use).

Selection of construction materials for either type of gas control system should consider the elevated temperature conditions within a landfill unit as compared to the ambient air or soil conditions in which gas control system components are constructed. Because ambient conditions are typically cooler, water containing corrosive and possibly toxic waste constituents may be expected to condense. This condensate should be considered in selecting construction materials. Provisions for managing this condensate should be incorporated to prevent accumulation and possible failure of the collection system. The condensate can be returned to the landfill unit if the landfill is designed with a composite liner and leachate collection system per §258.40(a)(2). See Chapter 4 for information regarding design. See Section 3.10 of this Chapter for information regarding liquids in landfills.

Additional provisions (under the Clean Air Act) were proposed on May 30, 1991 (56 FR 24468), that would require the owners/operators of certain landfill facilities to install gas collection and control systems to reduce the emissions of nonmethane organic compounds (NMOCs). The proposed rule amends 40 CFR Parts 51, 52, and 60. For new municipal solid waste landfill units (those for which construction was begun after May 30, 1991), and for those units that have a design capacity greater than 111,000 tons, a gas collection and control system must be installed if emissions evaluations indicate that the NMOC emissions rate is 150 megagrams per year (167 tons per year) or greater. Allowable control systems include open and enclosed flares, and on-site or off-site facilities that process the gas for subsequent sale or use. EPA believes that, depending on landfill design, active collection systems may be more cost-effective than passive systems in ensuring that the system effectively captures the gas that is generated within the landfill unit. The provisions for new landfill units are self-implementing and will be effective upon promulgation of the rule.

In addition to the emissions standards for new municipal solid waste landfill units, the regulations proposed on May 30, 1991 establish guidelines for State programs for reducing NMOC emissions from certain existing municipal landfill units. These provisions apply to landfill units for which construction was commenced before May 30, 1991, and that have accepted waste since November 8, 1987 or that have remaining capacity. Essentially, the State must require the same kinds of collection and control systems for landfill units that meet the size criteria and emissions levels outlined above for new landfill units. The requirements for existing facilities will be effective after the State revises its State Implementation Plan and receives approval from EPA.

The rule is scheduled to be promulgated in late 1993; the cutoff numbers for landfill size and emission quantity may be revised in the final rule. EPA expects that the new regulations will affect less than 9% of the municipal landfill facilities in the U.S.

Passive Systems

Passive gas control systems rely on natural pressure and convection mechanisms to vent landfill gas to the atmosphere. Passive systems typically use "high-permeability" or "low-permeability" techniques, either singularly or in combination at a site. High-permeability systems use conduits such as ditches, trenches, vent wells, or perforated vent pipes surrounded by coarse soil to vent landfill gas to the surface and the atmosphere. Low-permeability systems block lateral migration through barriers such as synthetic membranes and high moisture-containing fine-grained soils.

Passive systems may be incorporated into a landfill design or may be used for remedial or corrective purposes at both closed and active landfills. They may be installed within a landfill unit along the perimeter, or between the landfill and the disposal facility property boundary. A detailed discussion of passive systems for remedial or corrective purposes may be found in U.S. EPA (1985).

A passive system may be incorporated into the final cover system of a landfill closure design and may consist of perforated gas collection pipes, high permeability soils, or high transmissivity geosynthetics located just below the low-permeability gas and hydraulic barrier or infiltration layer in the cover system. These systems may be connected to vent pipes that vent gas through the cover system or that are connected to header pipes located along the perimeter of the landfill unit. Figure 3-4 illustrates a passive system. The landfill gas collection system also may be connected with the leachate collection system to vent gases in the headspace of leachate collection pipes.

Some problems have been associated with passive systems. For example, snow and dirt may accumulate in vent pipes, preventing gas from venting. Vent pipes
at the surface are susceptible to clogging by vandalism. Biological clogging of the system is also more common in passive systems.

Active Systems

Active gas control systems use mechanical means to remove landfill gas and consist of either positive pressure (air injection) or negative pressure (extraction) systems. Positive pressure systems induce a pressure greater than the pressure of the migrating gas and drive the gas out of the soil and/or back to the landfill unit in a controlled manner. Negative pressure systems extract gas from a landfill by using a blower to pull gas out of the landfill. Negative pressure systems are more commonly used because they are more effective and offer more flexibility in controlling gas migration. The gas may be recovered for energy conversion, treated, or combusted in a flare system. Typical components of a flare system are shown in Figure 3-5. Negative pressure systems may be used as either perimeter gas control systems or interior gas collection/recovery systems. For more information regarding negative pressure gas control systems, refer to U.S. EPA (1985).

An active gas extraction well is depicted in Figure 3-6. Gas extraction wells may be installed within the landfill waste or, as depicted in Figure 3-7A and Figure 3-7B, perimeter extraction trenches could be used. One possible configuration of an interior gas collection/recovery system is illustrated in

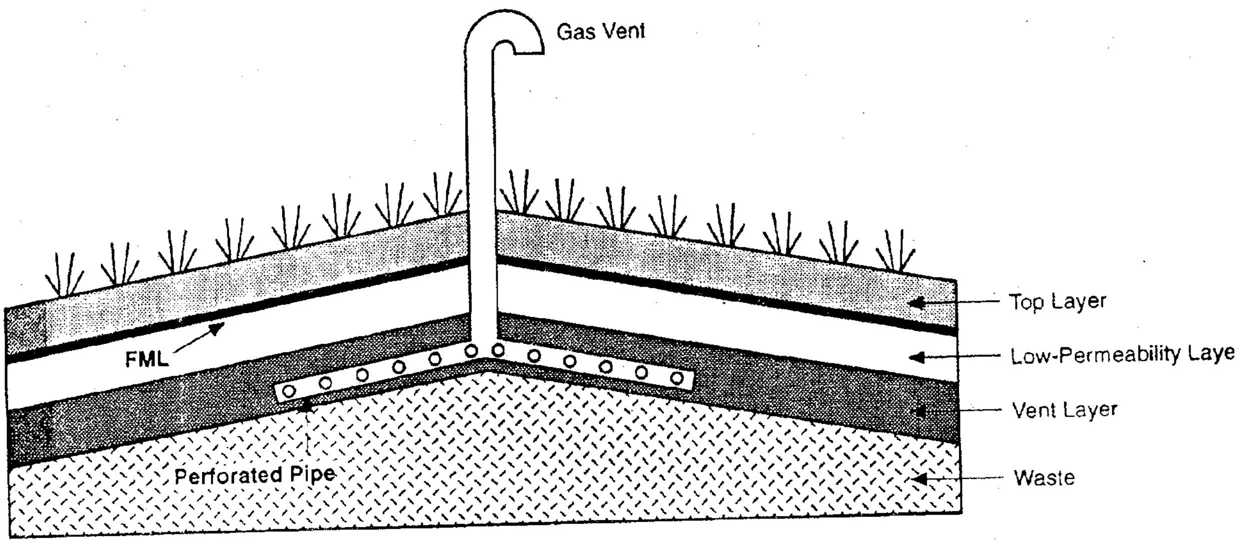


Figure 3-4
Passive Gas Control System
(Venting to Atmosphere)

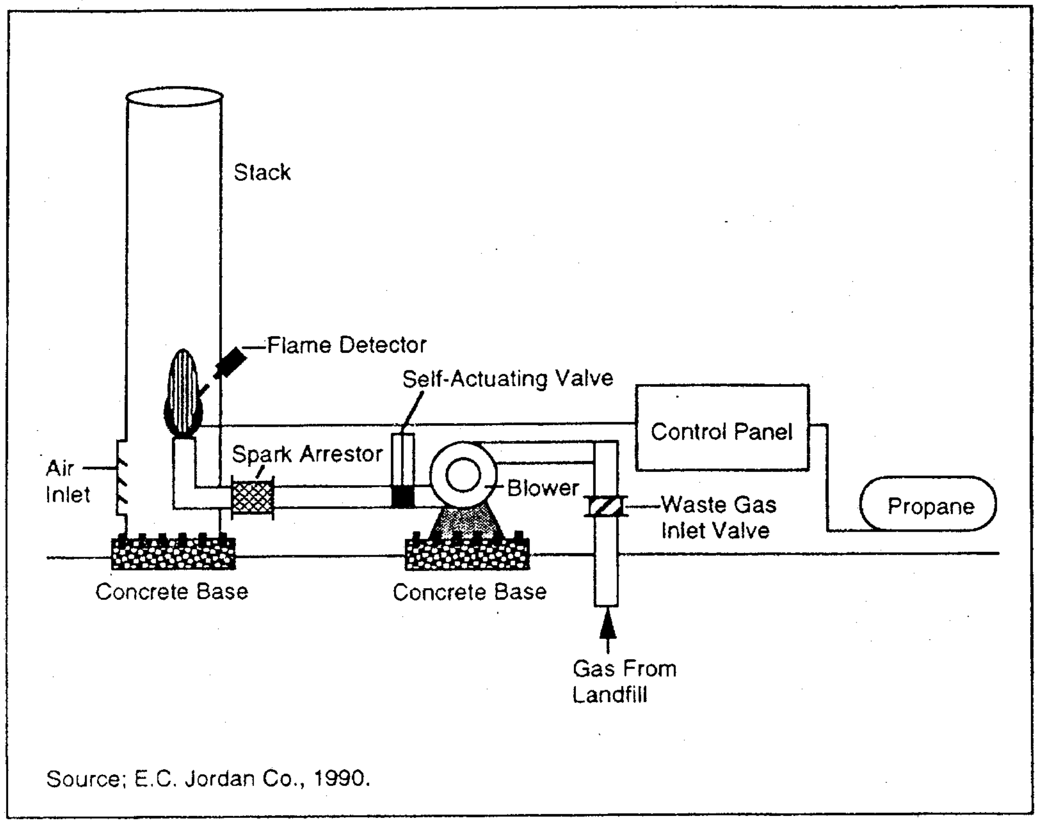


Figure 3-5. Example Schematic Diagram of a Ground-based Landfill Gas Flare

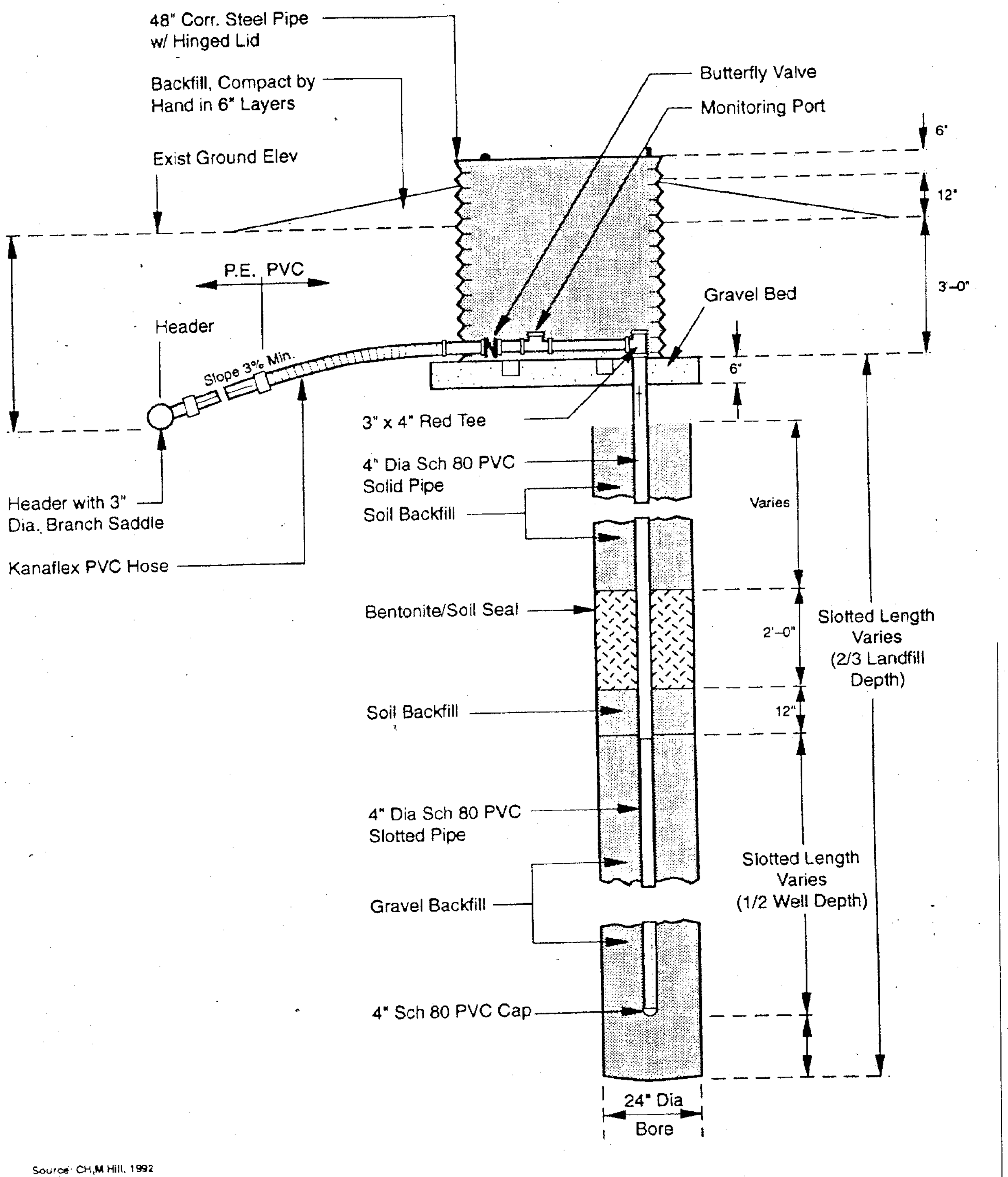


Figure 3-6 Example of a Gas Extraction Well

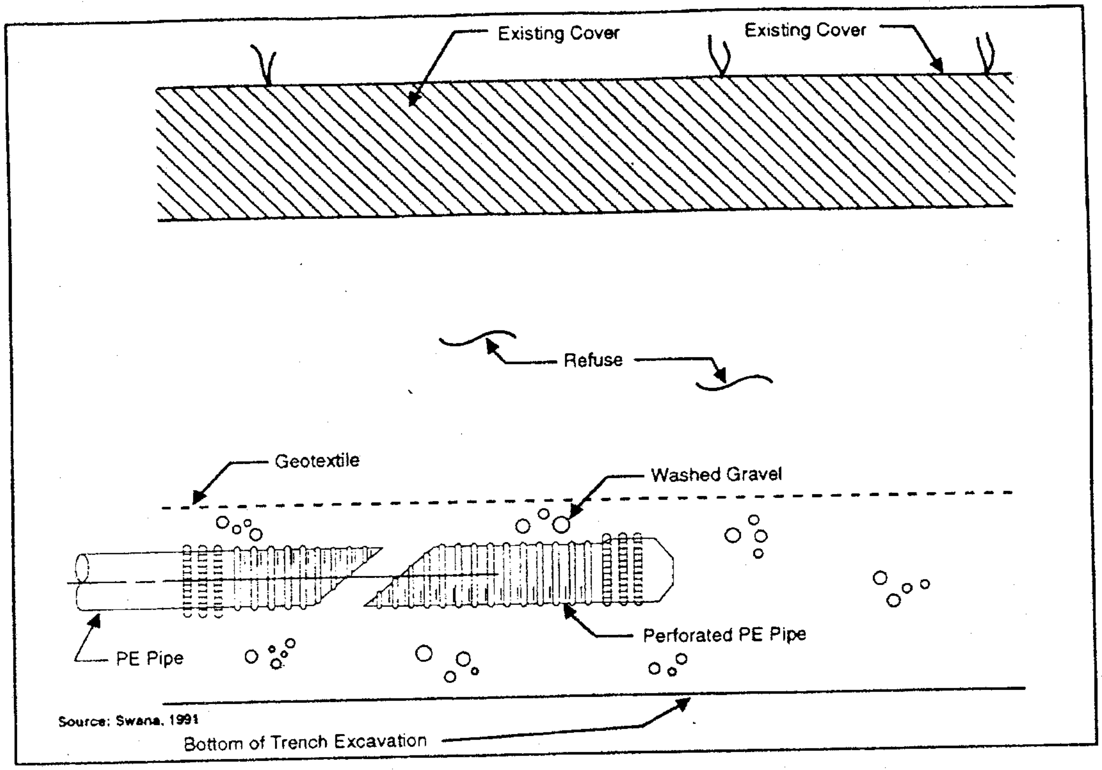


Figure 3-7A. Perimeter Extraction Trench System

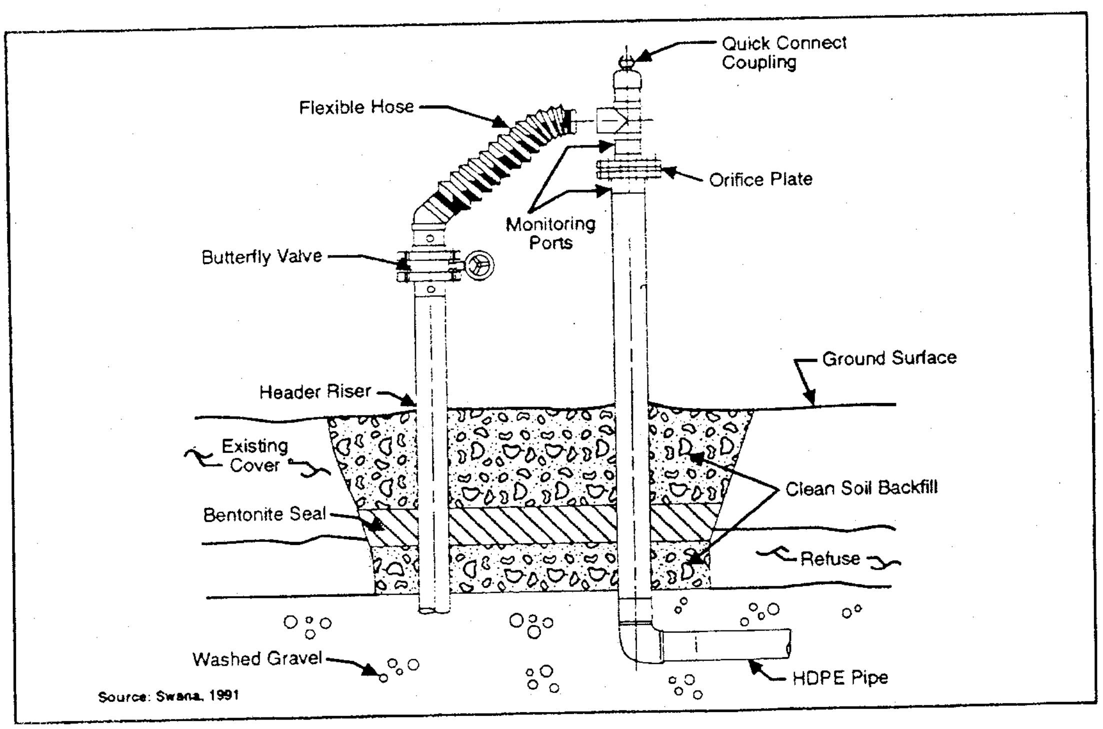


Figure 3-7B. Perimeter Extraction Trench System

Figure 3-8. The performance of active systems is not as sensitive to freezing or saturation of cover soils as that of passive systems. Although active gas systems are more effective in withdrawing gas from the landfill, capital, operation, and maintenance costs of such systems will be higher and these costs can be expected to continue throughout the post-closure period. At some future time, owners and operators may wish to convert active gas controls into passive systems when gas production diminishes. The conversion option and its environmental effect (i.e., gas release causing odors and health and safety concerns) should be addressed in the original design.

There are many benefits to recovering landfill gas. Landfill gas recovery systems can reduce landfill gas odor and migration, can reduce the danger of explosion and fire, and may be used as a source of revenue that may help to reduce the cost of closure. Landfill gas can be used with a minimal amount of treatment or can be upgraded to pipeline standards (SWANA, 1992). An upgraded gas is one which has had the carbon dioxide and other noncombustible constituents removed.

Raw landfill gas may be used for heating small facilities and water, and may require removal of only water and particulates for this application. A slightly upgraded gas can be used for both water and space heating as well as lighting, electrical generation, cogeneration, and as a fuel for industrial boilers-burners. Landfill gas also may be processed to pipeline quality to be sold to utility companies and may even be used to fuel conventional vehicles. The amount of upgrading and use of landfill gas is dependent on the landfill size.

3.6 AIR CRITERIA
40 CFR §258.24

3.6.1 Statement of Regulation

(a) Owners or operators of all MSWLFs must ensure that the units do not violate any applicable requirements developed under a State Implementation Plan (SIP) approved or promulgated by the Administrator pursuant to section 110 of the Clean Air Act, as amended.

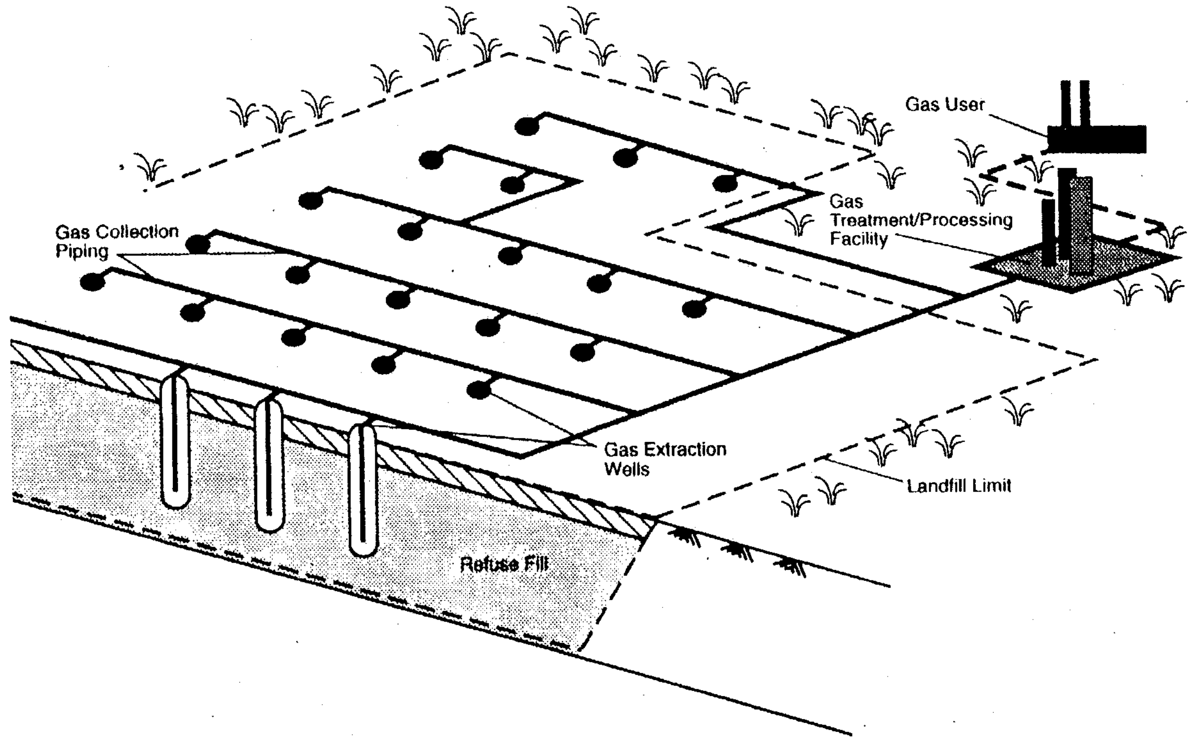
(b) Open burning of solid waste, except for the infrequent burning of agricultural wastes, silvicultural wastes, land-clearing debris, diseased trees, or debris from emergency clean-up operations, is prohibited at all MSWLF units.

3.6.2 Applicability

The regulation applies to existing MSWLF units, lateral expansions to existing MSWLF units, and new MSWLF units. Routine open burning of municipal solid waste is prohibited. Infrequent burning of agricultural and silvicultural wastes, diseased trees, or debris from land clearing or emergency clean-up operations is allowed when in compliance with any applicable requirements developed under a State Implementation Plan (SIP) of the Clean Air Act. Agricultural waste does not include empty pesticide containers or waste pesticides.

3.6.3 Technical Considerations

Air pollution control requirements are developed under a SIP, which is developed by the State and approved by the EPA Administrator. The owner or operator of a



Source: Emcon, 1981

Figure 3-8
Example of an Interior Gas Collection/Recovery System

MSWLF unit should consult the State or local agency responsible for air pollution control to ascertain that the burning of wastes complies with applicable requirements developed under the SIP. The SIP may include variances, permits, or exemptions for burning agricultural wastes, silvicultural wastes, land-clearing debris, diseased trees, or debris from emergency clean-up operations. Routine burning of wastes is banned in all cases, and the SIP may limit burning of waste such as agricultural wastes to certain hours of the day; days of the year; designated burn areas; specific types of incinerators; atmospheric conditions; and distance from working face, public thoroughfares, buildings, and residences.

Requirements under the SIP also may include notifying applicable State or local agencies whose permits may: (1) restrict times when limited burning of waste may occur; (2) specify periods when sufficient fire protection is deemed to be available; or (3) limit burning to certain areas.

Open burning is defined under §258.2 as the combustion of solid waste: (1) without control of combustion air to maintain adequate temperature for efficient combustion; (2) without containment of the combustion reaction in an enclosed device to provide sufficient residence time and mixing for complete combustion; and (3) without the control of the emission of the combustion products. Trench or pit burners, and air curtain destructors are considered open burning units because the particulate emissions are similar to particulate emissions from open burning, and these devices do not control the emission of combustion products.

[Note: The Agency plans to issue regulations under the Clean Air Act to control landfill gas emissions from large MSWLF units in 1993. These regulations are found at 40 CFR Parts 51, 52, and 60.]

3.7 ACCESS REQUIREMENT 40 CFR §258.25

3.7.1 Statement of Regulation

Owners or operators of all MSWLF units must control public access and prevent unauthorized vehicular traffic and illegal dumping of wastes by using artificial barriers, natural barriers, or both, as appropriate to protect human health and the environment.

3.7.2 Applicability

The regulation applies to existing MSWLF units, lateral expansions, and new MSWLF units. The owner or operator is required to prevent public access to the landfill facility, except under controlled conditions during hours when wastes are being received.

3.7.3 Technical Considerations

Owners and operators are required to control public access to prevent illegal dumping, public exposures to hazards at MSWLF units, and unauthorized vehicular traffic. Frequently, unauthorized persons are unfamiliar with the hazards associated with landfill facilities, and consequences of uncontrolled access may include injury and even death. Potential hazards are related to inability of equipment operators to see unauthorized individuals during operation of equipment and haul vehicles; direct exposure to waste (e.g., sharp objects and pathogens);

TABLE 4-2
ISSUES TO BE CONSIDERED
BEFORE APPLYING MULTIMED
(from Sharp-Hansen et al., 1990)

Objectives of the Study

- Is a "screening level" approach appropriate?
- Is modeling a "worst-case scenario" acceptable?

Significant Processes Affecting Contaminant Transport

- Does MULTIMED simulate all the significant processes occurring at the site?
- Is the contaminant soluble in water and of the same density as water?

Accuracy and Availability of the Data

- Have sufficient data been collected to obtain reliable results?
- What is the level of uncertainty associated with the data?
- Would a Monte Carlo simulation be useful? If so, are the cumulative probability distributions for the parameters with uncertain values known?

Complexity of the Hydrogeologic System

- Are the hydrogeologic properties of the system uniform?
- Is the flow in the aquifer uniform and steady?
- Is the site geometry regular?
- Does the source boundary condition require a transient or steady-state solution?

MULTIMED may be run in either a deterministic or a Monte Carlo mode. The Monte Carlo method provides a means of estimating the uncertainty in the results of a model, if the uncertainty of the input variables is known or can be estimated. However, it may be difficult to determine the cumulative probability distribution for a given parameter. Assuming a parameter probability distribution when the distribution is unknown does not help reduce uncertainty. Furthermore, to obtain a valid estimate of the uncertainty in the output, the model must be run numerous times (typically several hundred times), which can be time-consuming. These issues should be considered before utilizing the Monte Carlo technique.

4.3 COMPOSITE LINER AND LEACHATE COLLECTION SYSTEM 40 CFR §258.40

4.3.1 Statement of Regulation

(a) New MSWLF units and lateral expansions shall be constructed:

(1) *See Statement of Regulation in Section 4.2.1 of this guidance document for performance-based design requirements.*

(2) With a composite liner, as defined in paragraph (b) of this section and a leachate collection system that is designed and constructed to maintain less than a 30-cm depth of leachate over the liner,

(b) For purposes of this section, <u>composite liner</u> means a system consisting of two components; the upper component must consist of a minimum 30-mil flexible

membrane liner (FML), and the lower component must consist of at least a two-foot layer of compacted soil with a hydraulic conductivity of no more than 1 x 10^{-7} cm/sec. FML components consisting of high density polyethylene (HDPE) shall be at least 60-mil thick. The FML component must be installed in direct and uniform contact with the compacted soil component.

4.3.2 Applicability

New MSWLF units and expansions of existing MSWLF units in States without approved programs must be constructed with a composite liner and a leachate collection system (LCS) that is designed to maintain a depth of leachate less than 30 cm (12 in.) above the liner. A composite liner consists of a flexible membrane liner (FML) installed on top of, and in direct and uniform contact with, two feet of compacted soil. The FML must be at least 30-mil thick unless the FML is made of HDPE, which must be 60-mil thick. The compacted soil liner must be at least two feet thick and must have a hydraulic conductivity of no more than 1 x 10^{-7} cm/sec.

Owners and operators of MSWLF units located in approved States have the option of proposing a performance-based design provided that certain criteria can be met (see Section 4.2.2).

4.3.3 Technical Considerations

This section provides information on the components of composite liner systems including soils, geomembranes, and leachate collection systems.

Standard Composite Liner Systems

The composite liner system is an effective hydraulic barrier because it combines the complementary properties of two different materials into one system: 1) compacted soil with a low hydraulic conductivity; and 2) a FML (FMLs are also referred to as geomembranes). Geomembranes may contain defects including tears, improperly bonded seams, and pinholes. In the absence of an underlying low-permeability soil liner, flow through a defect in a geomembrane is essentially unrestrained. The presence of a low-permeability soil liner beneath a defect in the geomembrane reduces leakage by limiting the flow rate through the defect.

Flow through the soil component of the liner is controlled by the size of the defect in the geomembrane, the available air space between the two liners into which leachate can flow, the hydraulic conductivity of the soil component, and the hydraulic head. Fluid flow through soil liners is calculated by Darcy's Law, where discharge (Q) is proportional to the head loss through the soil (dh/dl) for a given cross-sectional flow area (A) and hydraulic conductivity (K) where:

$$Q = KA(dh/dl)$$

Leakage through a geomembrane without defects is controlled by Fick's first law, which describes the process of liquid diffusion through the membrane liner. The diffusion process is similar to flow governed by Darcy's law for soil liners except that diffusion is driven by concentration gradients and not by hydraulic head. Although diffusion rates in geomembranes are several orders of magnitude lower than comparable hydraulic flow rates in low-permeability soil liners, construction of a completely impermeable geomembrane is difficult. The factor that most strongly influences geomembrane performance is the presence of imperfections such as improperly bonded seams, punctures and pinholes. A detailed discussion of leakage through geomembranes and composite liners can be found in Giroud and Bonaparte (1989 (Part I and Part II)). A geomembrane installed with excellent control over defects may yield the equivalent of a one-centimeter-diameter hole per acre of liner installed (Giroud and Bonaparte, 1989 (Part I and Part II)). If the geomembrane were to be placed over sand, this size imperfection under one foot of constant hydraulic head could be expected to account for as much as 3,300 gal/acre/day (31,000 liters/hectare/ day) of leakage. Based upon measurements of actual leakage through liners at facilities that have been built under rigorous control, Bonaparte and Gross (1990) have estimated an actual leakage rate, under one foot of constant head, of 200 liters/hectare/day or about 21 gallons/acre/day for landfill units.

The uniformity of the contact between the geomembrane and the soil liner is extremely important in controlling the effective flow area of leachate through the soil liner. Porous material, such as drainage sand, filter fabric, or other geofabric, should not be placed between the geomembrane and the low permeability soil liner. Porous materials will create a layer of higher hydraulic conductivity, which will increase the amount of leakage below an imperfection in the geomembrane. Construction practices during the installation of the soil and the geomembrane affect the uniformity of the geomembrane/soil interface, and strongly influence the performance of the composite liner system.

Soil Liner

The following subsections discuss soil liner construction practices including thickness requirements, lift placement, bonding of lifts, test methods, prerequisite soil properties, quality control, and quality assurance activities.

Thickness

Two feet of soil is generally considered the minimum thickness needed to obtain adequate compaction to meet the hydraulic conductivity requirement. This thickness is considered necessary to minimize the number of cracks or imperfections through the entire liner thickness that could allow leachate migration. Both lateral and vertical imperfections may exist in a compacted soil. The two-foot minimum thickness is believed to be sufficient to inhibit hydraulic short-circuiting of the entire layer.

Lift Thickness

Soil liners should be constructed in a series of compacted lifts. Determination of appropriate lift thickness is dependent on the soil characteristics, compaction equipment, firmness of the foundation materials, and the anticipated compactive effort needed to achieve the required soil hydraulic conductivity. Soil liner lifts should be thin enough to allow adequate compactive effort to reach the lower portions of the lift. Thinner lifts also provide greater assurance that sufficient compaction can be achieved to provide good, homogeneous bonding between subsequent lifts. Adequate compaction of lift thickness between five and ten inches is possible if appropriate equipment is used (USEPA, 1988). Nine-inch loose lift thicknesses that will yield a 6-

inch soil layer also have been recommended prior to compaction (USEPA, 1990a).

Soil liners usually are designed to be of uniform thickness with smooth slopes over the entire facility. Thicker areas may be considered wherever recessed areas for leachate collection pipes or collection sumps are located. Extra thickness and compactive efforts near edges of the side slopes may enhance bonding between the side slopes and the bottom liner. In smaller facilities, a soil liner may be designed for installation over the entire area, but in larger or multi-cell facilities, liners may be designed in segments. If this is the case, the design should address how the old and new liner segments will be bonded together (U.S. EPA, 1988).

Bonding Between Lifts

It is not possible to construct soil liners without some microscopic and/or macroscopic zones of higher and lower hydraulic conductivity. Within individual lifts, these preferential pathways for fluid migration are truncated by the bonded zone between the lifts. If good bonding between the lifts is not achieved during construction, the vertical pathways may become connected by horizontal pathways at the lift interface, thereby diminishing the performance of the hydraulic barrier.

Two methods may be used to ensure proper bonding between lifts. Kneading or blending a thinner, new lift with the previously compacted lift may be achieved by using a footed roller with long feet that can fully penetrate a loose lift of soil. If the protruding rods or feet of a sheepsfoot roller are sufficient in length to penetrate the top lift and knead the previous lift, good bonding may be achieved. Another method includes scarifying (roughening), and possibly wetting, the top inch or so of the last lift placed with a disc harrow or other similar equipment before placing the next lift.

Placement of Soil Liners on Slopes

The method used to place the soil liner on side slopes depends on the angle and length of the slope. Gradual inclines from the toe of the slope enable continuous placement of the lifts up the slopes and provide better continuity between the bottom and sidewalls of the soil liner. When steep slopes are encountered, however, lifts may need to be placed and compacted horizontally due to the difficulties of operating heavy compaction equipment on steeper slopes.

When sidewalls are compacted horizontally, it is important to tie in the edges with the bottom of the soil liner to reduce the probability of seepage planes (USEPA, 1988). A significant amount of additional soil liner material will be required to construct the horizontal lifts since the width of the lifts has to be wide enough to accommodate the compaction equipment. After the soil liner is constructed on the side slopes using this method, it can be trimmed back to the required thickness. The trimmed surface of the soil liner should be sealed by a smooth-drum roller. The trimmed excess materials can be reused provided that they meet the specified moisture-density requirements.

Hydraulic Conductivity

Achieving the hydraulic conductivity standard depends on the degree of compaction, compaction method, type of clay, soil moisture content, and density of the soil during liner construction. Hydraulic conductivity is the key design parameter when evaluating the acceptability of the constructed soil liner. The hydraulic conductivity of a soil depends, in part, on the viscosity and density of the fluid flowing through it. While water and leachate can cause different test results, water is an acceptable fluid for testing the compacted soil liner and source materials. The effective porosity of the soil is a function of size, shape, and area of the conduits through which the liquid flows. The hydraulic conductivity of a partially saturated soil is less than the hydraulic conductivity of the same soil when saturated. Because invading water only flows through water-filled voids (and not air-filled voids), the dryness of a soil tends to lower permeability. Hydraulic conductivity testing should be conducted on samples that are fully saturated to attempt to measure the highest possible hydraulic conductivity.

EPA has published Method 9100 in publication SW-846 (Test Methods for Evaluating Solid Waste) to measure the hydraulic conductivity of soil samples. Other methods appear in the U.S. Army Corps of Engineers Engineering Manual 1110-2-1906 (COE, 1970) and the newly published "Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter" (ASTM D-5084). To verify full saturation of the sample, this latter method may be performed with back pressure saturation and electronic pore pressure measurement.

Soil Properties

Soils typically possess a range of physical characteristics, including particle size, gradation, and plasticity, that affect their ability to achieve a hydraulic conductivity of 1 x 10^{-7} cm/sec. Testing methods used to characterize proposed liner soils should include grain size distribution (ASTM D-422), Atterberg limits (ASTM D-4318), and compaction curves depicting moisture and density relationships using the standard or modified Proctor (ASTM D-698 or ASTM D-1557), whichever is appropriate for the compaction equipment used and the degree of firmness of the foundation materials.

Liner soils usually have at least 30 percent fines (fine silt- and clay-sized particles). Some soils with less than 30 percent fines may be worked to obtain hydraulic conductivities below 1 x 10^{-7} cm/sec, but use of these soils requires greater control of construction practices and conditions.

The soil plasticity index (PI), which is determined from the Atterberg limits (defined by the liquid limit minus the plastic limit), should generally be greater than 10 percent. However, soils with very high PI, (greater than 30 percent), are cohesive and sticky and become difficult to work with in the field. When high PI soils are too dry during placement, they tend to form hard clumps (clods) that are difficult to break down during compaction. Preferential flow paths may be created around the clods allowing leachate to migrate at a relatively high rate.

Soil particles or rock fragments also can create preferential flow paths. For this reason, soil particles or rock fragments should be less than 3 inches in diameter so as not to affect the overall hydraulic performance of the soil liner (USEPA, 1989).

The maximum density of a soil will be achieved at the optimum water content, but this point generally does not correspond to the point at which minimum hydraulic conductivity is achieved. Wet soils, however, have low shear strength and high potential for desiccation cracking. Care should be taken not to compromise other engineering properties such as shear strengths of the soil liner by excessively wetting the soil liner. Depending on the specific soil characteristics, compaction equipment and compactive effort, the hydraulic conductivity criterion may be achieved at moisture values of 1 to 7 percent above the optimum moisture content.

Although the soil may possess the required properties for successful liner construction, the soil liner may not meet the hydraulic conductivity criterion if the construction practices used to install the liner are not appropriate and carefully controlled. Construction quality control and quality assurance will be discussed in a later section.

Amended Soils

If locally available soils do not possess properties to achieve the specified hydraulic conductivity, soil additives can be used. Soil additives, such as bentonite or other clay materials, can decrease the hydraulic conductivity of the native soil (USEPA, 1988b).

Bentonite may be obtained in a dry, powdered form that is relatively easy to blend with on-site soils. Bentonite is a clay mineral (sodium-montmorillonite) that expands when it comes into contact with water (hydration), by absorbing the water within the mineral matrix. This property allows relatively small amounts of bentonite (5 to 10 percent) to be added to a noncohesive soil (sand) to make it more cohesive (U.S. EPA, 1988b). Thorough mixing of additives to cohesive soils (clay) is difficult and may lead to inconsistent results with respect to complying with the hydraulic conductivity criterion.

The most common additive used to amend soils is sodium bentonite. The disadvantage of using sodium bentonite includes its vulnerability to degradation as a result of contact with chemicals and waste leachates (U.S. EPA, 1989).

Calcium bentonite, although more permeable than sodium bentonite, also is used as a soil amendment. Approximately twice as much calcium bentonite typically is needed to achieve a hydraulic conductivity comparable to that of sodium bentonite.

Soil/bentonite mixtures generally require central plant mixing by means of a pugmill, cement mixer, or other mixing equipment where water can be added during the process. Water, bentonite content, and particle size distribution must be controlled during mixing and placement. Spreading of the soil/bentonite mixture may be accomplished in the same manner as the spreading of natural soil liners, by using scrapers, graders, bulldozers, or a continuous asphalt paving machine (U.S. EPA, 1988).

Materials other than bentonite, including lime, cement, and other clay minerals such as atapulgite, may be used as soil additives (U.S. EPA, 1989). For more information concerning soil admixtures, the reader is referred to the technical resource document on the design and construction of clay liners (U.S. EPA, 1988).

Testing

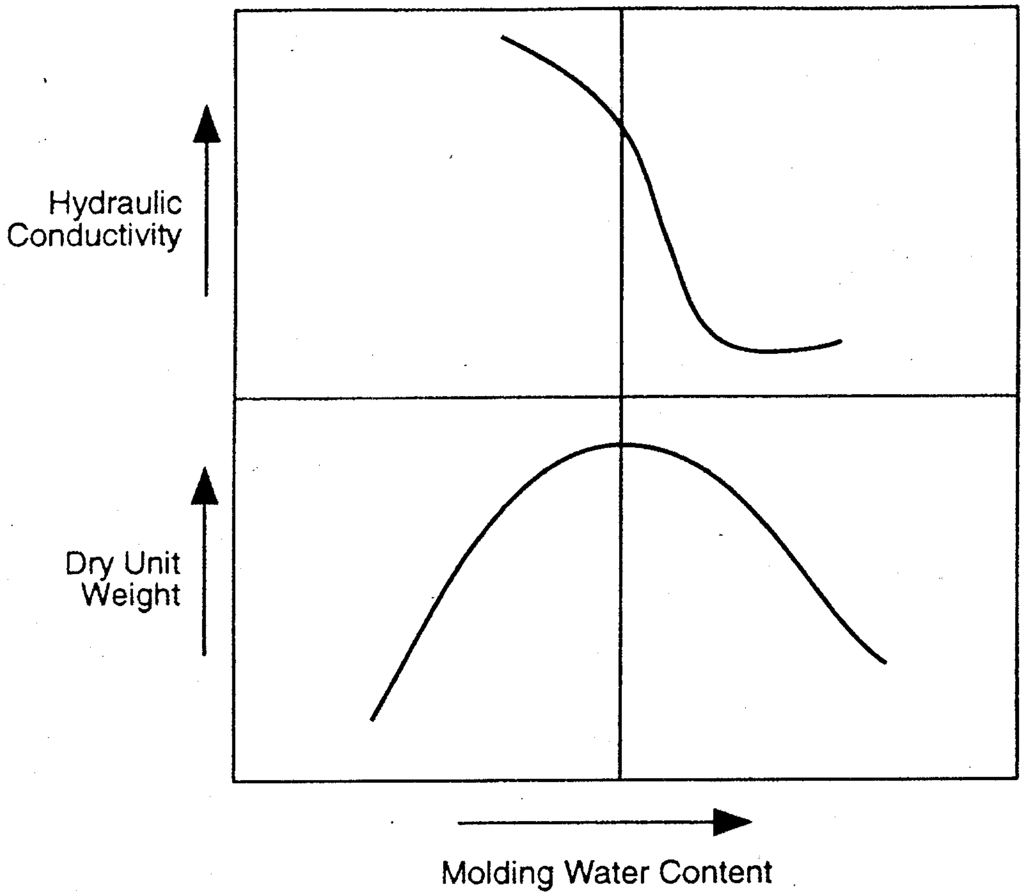
Prior to construction of a soil liner, the relationship between water content, density, and hydraulic conductivity for a particular soil should be established in the laboratory. Figure 4-5 shows the influence of molding water content (moisture content of the soil at the time of compaction) on hydraulic conductivity of the soil. The lower half of the diagram is a compaction curve and shows the relationship between dry unit weight, or dry density of the soil, and water content of the soil. The optimum moisture content of the soil is related to a peak value of dry density known as maximum dry density. Maximum dry density is achieved at the optimum moisture content.

The lowest hydraulic conductivity of compacted clay soil is achieved when the soil is compacted at a moisture content slightly higher than the optimum moisture content, generally in the range of 1 to 7 percent (U.S. EPA, 1989). When compacting clay, water content and compactive effort are the two factors that should be controlled to meet the maximum hydraulic conductivity criterion.

It is impractical to specify and construct a clay liner to a specific moisture content and a specific compaction (e.g., 5 percent wet of optimum and 95 percent modified Proctor density). Moisture content can be difficult to control in the field during construction; therefore, it may be more appropriate to specify a range of moisture contents and corresponding soil densities (percent compaction) that are considered appropriate to achieve the required hydraulic conductivity. Benson and Daniel (U.S. EPA, 1990) propose water content and density criteria for the construction of clay liners in which the moisture-density criteria ranges are established based on hydraulic conductivity test results. This type of approach is recommended because of the flexibility and guidance it provides to the construction contractor during soil placement. Figure 4-6 presents compaction data as a function of dry unit weight and molding water content for the construction of clay liners. The amount of soil testing required to determine these construction parameters is dependent on the degree of natural variability of the source material.

Quality assurance and quality control of soil liner materials involve both laboratory and field testing. Quality control tests are performed to ascertain compaction requirements and the moisture content of material delivered to the site. Field tests for quality assurance provide an opportunity to check representative areas of the liner for conformance to compaction specifications, including density and moisture content. Quality assurance laboratory testing is usually conducted on field samples for determination of hydraulic conductivity of the in-place liner. Laboratory testing allows full saturation of the soil samples and simulates the effects of large overburden stress on the soil, which cannot be done conveniently in the field (U.S. EPA, 1989).

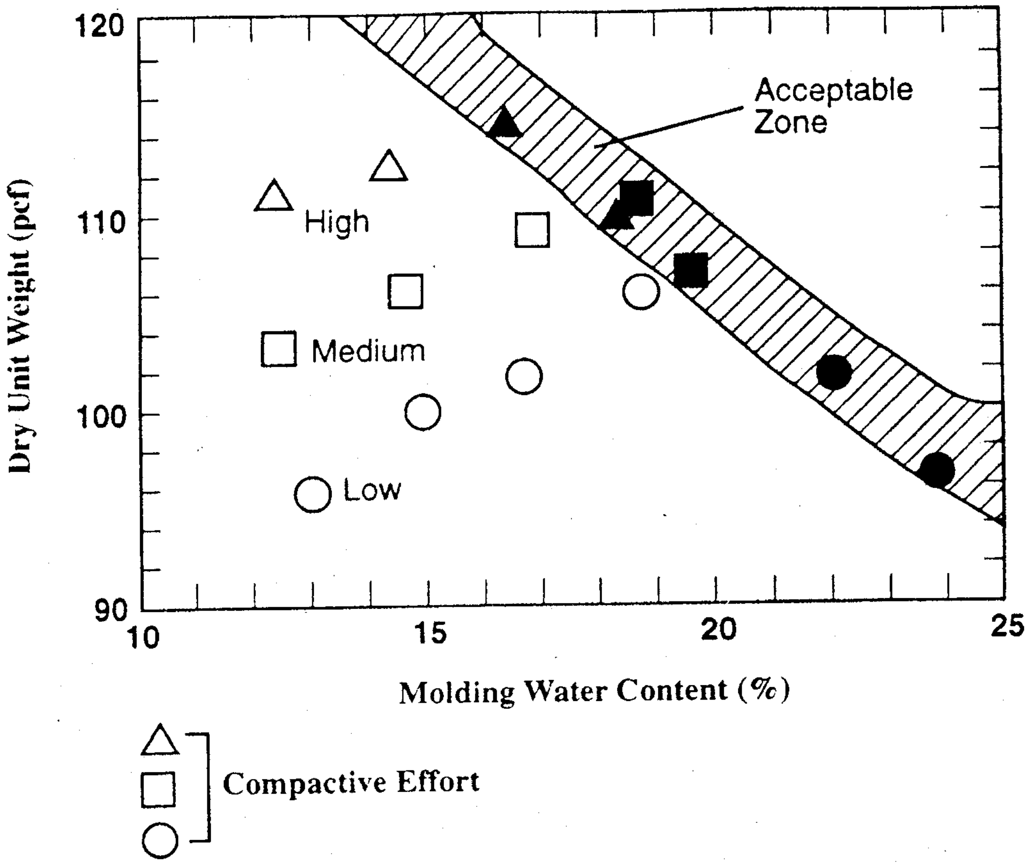
Differences between laboratory and field conditions (e.g., uniformity of material, control of water content, compactive effort, compaction equipment) may make it unlikely that minimum hydraulic conductivity values measured in the laboratory on remolded, pre-construction borrow source samples are the same as the values achieved during actual liner construction. Laboratory testing on remolded soil specimens does not account for operational problems that may result in desiccation, cracking, poor bonding of lifts, and inconsistent degree of compaction on sidewalls (U.S. EPA, 1988b). The relationship between field and laboratory hydraulic conductivity testing has been investigated by the U.S. Environmental



Source: U.S. EPA, 1989.

Note: The optimum moisture content occurs at the point at which maximum density is achieved. The lowest hydraulic conductivity generally occurs at water contents higher than optimum.

Figure 4-5
Hydraulic Conductivity and Dry Unit Weight as a Function of Molding Water Content



Compaction Data for a Silty Clay (from Mitchell et al., 1965). Solid symbols represent specimens with a hydraulic conductivity ≤ 1 x 10^{-7} cm/s and open symbols represent specimens with hydraulic conductivity > 1 x 10^{-7} cm/s.

Source: CERI 90-50 (USEPA, 1990)

Figure 4-6. Compaction Data for Silty Clay

Protection Agency using field case studies (U.S. EPA, 1990c).

In situ, or field, hydraulic conductivity testing operates on the assumption that by testing larger masses of soil in the field, one can obtain more realistic results. Four types of *in situ* hydraulic conductivity tests generally are used: borehole tests, porous probes, infiltrometer tests, and underdrain tests. A borehole test is conducted by drilling a hole, then filling the hole with water, and measuring the rate at which water percolates into the borehole. In the borehole test, water also can percolate through the sidewalls of the borehole. As a result, the measured hydraulic conductivity is usually higher than that measured by other one-dimensional field testings.

The second type of test involves driving or pushing a porous probe into the soil and pouring water through the probe into the soil. With this method, however, the advantage of testing directly in the field is somewhat offset by the limitations of testing such a small volume of soil.

A third method of testing involves a device called an infiltrometer. This device is embedded into the surface of the soil liner such that the rate of flow of a liquid into the liner can be measured. The two types of infiltrometers most widely used are open and sealed. Open rings are less desirable because, with a hydraulic conductivity of 10^{-7} cm/sec, it is difficult to detect a 0.002 inch per day drop in water level of the pond from evaporation and other losses.

With sealed rings, very low rates of flow can be measured. However, single-ring infiltrometers allow lateral flow beneath the ring, which can complicate the interpretation of test results. Single rings are also susceptible to the effects of temperature variation; as the water temperature increases, the entire system expands. As it cools down, the system contracts. This situation could lead to erroneous measurements when the rate of flow is small.

The sealed double-ring infiltrometer has proven to be the most successful method and is the one currently used. The outer ring forces infiltration from the inner ring to be more or less one-dimensional. Covering the inner ring with water insulates it substantially from temperature variation.

Underdrains, the fourth type of in situ test, are the most accurate in situ permeability testing device because they measure exactly what migrates from the bottom of the liner. However, under-drains are slow to generate data for low permeability liners, because of the length of time required to accumulate measurable flow. Also, underdrains must be installed during construction, so fewer underdrains are used than other kinds of testing devices.

Field hydraulic conductivity tests are not usually performed on the completed liner because the tests may take several weeks to complete (during which time the liner may be damaged by desiccation or freezing temperatures) and because large penetrations must be made into the liner. If field conductivity tests are performed, they are usually conducted on a test pad. The test pad should be constructed using the materials and methods to be used for the actual soil liner. The width of a test pad is usually the width of three to four construction vehicles, and the length is one to two times the width. Thickness is usually two to three feet. Test pads can be used as a means for verifying that the proposed materials and construction procedures will meet performance objectives. If a test pad is constructed, if tests verify that performance objectives have been met, and if the actual soil liner is constructed to standards that equal or exceed those used in building the test pad (as verified through quality assurance), then the actual soil liner should meet or exceed performance objectives.

Other than the four types of field hydraulic conductivity tests described earlier, ASTM D 2937 "Standard Test Method for Density of Soil in Place by the Drive-Cylinder Method" may be used to obtain in-place hydraulic conductivity of the soil liner. This test method uses a U.S. Army Corps of Engineers surface soil sampler to drive a thin-walled cylinder (typically 3-inch by 3-inch) into a completed lift of the soil liner to obtain relatively undisturbed samples for laboratory density and hydraulic conductivity testings. This test can provide useful correlation to other field and quality assurance testing results (e.g, Atterberg limits, gradation, in-place moisture and density of the soil liner) to evaluate the in-place hydraulic conductivity of the soil liner.

Soil Liner Construction

Standard compaction procedures are usually employed when constructing soil liners. The following factors influence the degree and quality of compaction:

- Lift thickness;
- Full scale or segmented lift placement;
- Number of equipment passes;
- Scarification between lifts;
- Soil water content; and
- The type of equipment and compactive effort.

The method used to compact the soil liner is an important factor in achieving the required minimum hydraulic conductivity. Higher degrees of compactive effort increase soil density and lower the soil hydraulic conductivity for a given water content. The results of laboratory compaction tests do not necessarily correlate directly with the amount of compaction that can be achieved during construction.

Heavy compaction equipment (greater than 25,000 lbs or 11,300 kg) is typically used when building the soil liner to maximize compactive effort (U.S. EPA, 1989). The preferred field compaction equipment is a sheepsfoot roller with long feet that fully penetrates loose lifts of soil and provides higher compaction while kneading the clay particles together. The shape and depth of the feet are important; narrow, rod-like feet with a minimum length of about seven inches provide the best results. A progressive change from the rod-like feet to a broader foot may be necessary in some soils after initial compaction, to allow the roller to walk out of the compacted soil. The sheepsfoot feet also aid in breaking up dry clods (see *Soil Properties* in this section). Mechanical road reclaimers, which are typically used to strip and re-pave asphalt, can be extremely effective in reducing soil clod size prior to compaction and in scarifying soil surfaces between lifts. Other equipment that has been used to compact soil includes discs and rototillers.

To achieve adequate compaction, the lift thickness (usually five to nine inches) may be decreased or the number of passes over the lift may be increased. Generally, compaction equipment should pass over the soil liner five to twenty times to attain the compaction needed to comply with the minimum hydraulic conductivity criterion (U.S. EPA, 1989).

Efforts made to reduce clod size during excavation and placement of the soil for the liner should improve the chances for achieving low hydraulic conductivity in several ways. Keeping clods in the soil liner material small will facilitate a more uniform water content. Macropores between clod remnants can result in unacceptably high field hydraulic conductivity.

Opinions differ on acceptable clod sizes in the uncompacted soil. Some suggest a maximum of one to three inches in diameter, or no larger than one-half the lift thickness. The main objective is to remold all clods in the compaction process to keep hydraulic conductivity values consistent throughout the soil liner (U.S. EPA, 1988).

Geomembranes

Geomembranes are relatively thin sheets of flexible thermoplastic or thermoset polymeric materials that are manufactured and prefabricated at a factory and transported to the site. Because of their inherent impermeability, use of geomembranes in landfill unit construction has increased. The design of the side slope, specifically the friction between natural soils and geosynthetics, is critical and requires careful review.

Material Types and Thicknesses

Geomembranes are made of one or more polymers along with a variety of other ingredients such as carbon black, pigments, fillers, plasticizers, processing aids, crosslinking chemicals, anti-degradants, and biocides. The polymers used to manufacture geomembranes include a wide range of plastics and rubbers differing in properties such as chemical resistance and basic composition (U.S. EPA, 1983 and U.S. EPA, 1988e). The polymeric materials may be categorized as follows:

- Thermoplastics such as polyvinyl chloride (PVC);
- Crystalline thermoplastics such as high density polyethylene (HDPE), very low density polyethylene (VLDPE), and linear low density polyethylene (LLDPE); and
- Thermoplastic elastomers such as chlorinated polyethylene (CPE) and chlorosulfonated polyethylene (CSPE).

The polymeric materials used most frequently as geomembranes are HDPE, PVC, CSPE, and CPE. The thicknesses of geomembranes range from 20 to 120 mil (1 mil = 0.001 inch) (U.S. EPA, 1983 and U.S. EPA, 1988e). The recommended minimum thickness for all geomembranes is 30 mil, with the exception of HDPE, which must be at least 60 mil to allow for proper seam welding. Some geomembranes can be manufactured by a calendering process with fabric reinforcement, called scrim, to provide additional tensile strength and dimensional stability.

Chemical and Physical Stress Resistance

The design of the landfill unit should consider stresses imposed on the liner by the design configuration. These stresses include the following:

- Differential settlement in foundation soils;
- Strain requirements at the anchor trench; and
- Strain requirements over long, steep side slopes.

An extensive body of literature has been developed by manufacturers and independent researchers on the physical properties of liners. Geosynthetic design equations are presented in several publications including Kastman (1984), Koerner (1990), and U.S. EPA (1988e).

The chemical resistance of a geomembrane to leachate has traditionally been considered a critical issue for Subtitle C (hazardous waste) facilities where highly concentrated solvents may be encountered. Chemical resistance testing of geomembranes may not be required for MSWLF units containing only municipal solid waste; EPA's data base has shown that leachate from MSWLF units is not aggressive to these types of materials. Testing for chemical resistance may be warranted considering the waste type, volumes, characteristics, and amounts of small quantity generator waste or other industrial waste present in the waste stream. The following guidance is provided in the event such testing is of interest to the owner or operator.

EPA's Method 9090 in SW-846 is the established test procedure used to evaluate degradation of geomembranes when exposed to hazardous waste leachate. In the procedure, the geomembrane is immersed in the site-specific chemical environment for at least 120 days at two different temperatures. Physical and mechanical properties of the tested material are then compared to those of the original material every thirty days. A software system entitled Flexible Liner Evaluation Expert (FLEX), designed to assist in the hazardous waste permitting process, may aid in interpreting EPA Method 9090 test data (U.S. EPA, 1989). A detailed discussion of both Method 9090 and FLEX is available from EPA.

It is imperative that a geomembrane liner maintain its integrity during exposure to short-term and long-term mechanical stresses. Short-term mechanical stresses include equipment traffic during the installation of a liner system, as well as thermal expansion and shrinkage of the geomembrane during the construction and operation of the MSWLF unit. Long-term mechanical stresses result from the placement of waste on top of the liner system and from subsequent differential settlement of the subgrade (U.S. EPA, 1988a).

Long-term success of the liner requires adequate friction between the components of a liner system, particularly the soil subgrade and the geomembrane, and between geosynthetic components, so that slippage or sloughing does not occur on the slopes of the unit. Specifically, the foundation slopes and the subgrade materials must be considered in design equations to evaluate:

- The ability of a geomembrane to support its own weight on the side slopes;
- The ability of a geomembrane to withstand down-dragging during and after waste placement;
- The best anchorage configuration for the geomembrane;

- The stability of a soil cover on top of a geomembrane; and

- The stability of other geosynthetic components such as geotextile or geonet on top of a geomembrane.

These requirements may affect the choice of geomembrane material, including polymer type, fabric reinforcement, thickness, and texture (e.g., smooth or textured for HDPE) (U.S. EPA, 1988). PVC also can be obtained in a roughened or file finish to increase the friction angle.

Design specifications should indicate the type of raw polymer and manufactured sheet to be used as well as the requirements for the delivery, storage, installation, and sampling of the geomembrane. Material properties can be obtained from the manufacturer-supplied average physical property values, which are published in the Geotechnical Fabrics Report's Specifier's Guide and updated annually. The minimum tensile properties of the geomembrane must be sufficient to satisfy the stresses anticipated during the service life of the geomembrane. Specific raw polymer and manufactured sheet specifications and test procedures include (U.S. EPA, 1988e, and Koerner, 1990):

Raw Polymer Specifications

- Density (ASTM D-1505);
- Melt index (ASTM D-1238);
- Carbon black (ASTM D-1603); and
- Thermogravimetric analysis (TGA) or differential scanning calorimetry (DSC).

Manufactured Sheet Specifications

- Thickness (ASTM D-1593);
- Tensile properties (ASTM D-638);
- Tear resistance (ASTM D-1004);
- Carbon black content (ASTM D-1603);
- Carbon black dispersion (ASTM D-3015);
- Dimensional stability (ASTM D-1204); and
- Stress crack resistance (ASTM D-1693).

Geomembranes may have different physical characteristics, depending on the type of polymer and the manufacturing process used, that can affect the design of a liner system. When reviewing manufacturers' literature, it is important to remember that each manufacturer may use more than one polymer or resin type for each grade of geomembrane and that the material specifications may be generalized to represent several grades of material.

Installation

Installation specifications should address installation procedures specific to the properties of the liner installed. The coefficient of thermal expansion of the geomembrane sheet can affect its installation and its service performance. The geomembrane should lie flat on the underlying soil. However, shrinkage and expansion of the sheeting, due to changes in temperature during installation, may result in excessive wrinkling or tension in the geomembrane. Wrinkles on the geomembrane surface will affect the uniformity of the soil-geomembrane interface and may result in leakage through imperfections. Excessive tautness of the geomembrane may affect its ability to resist rupture from localized stresses on the seams or at the toe of slopes where bridging over the subgrade may occur during installation. In addition to thermal expansion and contraction of the geomembrane, residual stresses from manufacturing remain in some geomembranes and can cause non-uniform expansion and contraction during construction. Some flexibility is needed in the specifications for geomembrane selection to allow for anticipated dimensional changes resulting from thermal expansion and contraction (U.S. EPA, 1988).

Technical specifications for geomembranes also should include: information for protection of the material during shipping, storage and handling; quality control certifications provided by the manufacturer or fabricator (if panels are constructed); and quality control testing by the contractor, installer, or a construction quality assurance (CQA) agent. Installation procedures addressed by the technical specifications include a geomembrane layout plan, deployment of the geomembrane at the construction site, seam preparation, seaming methods, seaming temperature constraints, detailed procedures for repairing and documenting construction defects, and sealing of the geomembrane to appurtenances, both adjoining and penetrating the liner. The performance of inspection activities, including both non-destructive and destructive quality control field testing of the sheets and seams during installation of the geomembrane, should be addressed in the technical specifications. Construction quality assurance is addressed in an EPA guidance document (USEPA, 1992).

The geomembrane sheeting is shipped in rolls or panels from the supplier, manufacturer, or fabricator to the construction site. Each roll or panel may be labeled according to its position on the geomembrane layout plan to facilitate installation. Upon delivery, the geomembrane sheeting should be inspected to check for damage that may have occurred during shipping. (U.S. EPA, 1992).

Proper storage of the rolls or panels prior to installation is essential to the final performance of the geomembrane. Some geomembrane materials are sensitive to ultraviolet exposure and should not be stored in direct sunlight prior to installation. Others, such as CSPE and CPE, are sensitive to moisture and heat and can partially crosslink or block (stick together) under improper storage conditions. Adhesives or welding materials, which are used to join geomembrane panels, also should be stored appropriately (U.S. EPA, 1992).

Visual inspection and acceptance of the soil liner subgrade should be conducted prior to installing the geomembrane. The surface of the subgrade should meet design specifications with regard to lack of protruding objects, grades, and thickness. Once these inspections are conducted and complete, the geomembrane may be installed on top of the soil liner. If necessary, other means should be employed to protect the subgrade from precipitation and erosion, and to prevent desiccation, moisture loss, and erosion from the soil liner prior to geomembrane placement. Such methods may include placing a plastic tarp on top of completed portions of the soil liner

(USEPA, 1992). In addition, scheduling soil liner construction slightly ahead of the geomembrane and drainage layer placement can reduce the exposure of the soil liner to the elements.

Deployment, or placement, of the geomembrane panels or rolls should be described in the geomembrane layout plan. Rolls of sheeting, such as HDPE, generally can be deployed by placing a shaft through the core of the roll, which is supported and deployed using a front-end loader or a winch. Panels composed of extremely flexible liner material such as PVC are usually folded on pallets, requiring workers to manually unfold and place the geomembrane. Placement of the geomembrane goes hand-in-hand with the seaming process; no more than the amount of sheeting that can be seamed during a shift or work day should be deployed at any one time (USEPA, 1988). Panels should be weighted with sand bags if wind uplift of the membrane or excessive movement from thermal expansion is a potential problem. Proper stormwater control measurements should be employed during construction to prevent erosion of the soil liner underneath the geomembrane and the washing away of the geomembrane.

Once deployment of a section of the geomembrane is complete and each section has been visually inspected for imperfections and tested to ensure that it is the specified thickness, seaming of the geomembrane may begin. Quality control/quality assurance monitoring of the seaming process should be implemented to detect inferior seams. Seaming can be conducted either in the factory or in the field. Factory seams are made in a controlled environment and are generally of high quality, but the entire seam length (100 percent) still should be tested non-destructively (U.S. EPA, 1988). Destructive testing should be done at regular intervals along the seam (see page 4-66).

Consistent quality in fabricating field seams is critical to liner performance, and conditions that may affect seaming should be monitored and controlled during installation. An inspection should be conducted in accordance with a construction quality assurance plan to document the integrity of field seams. Factors affecting the seaming process include (U.S. EPA, 1988):

- Ambient temperature at which the seams are made;
- Relative humidity;
- Control of panel lift-up by wind;
- The effect of clouds on the geomembrane temperature;
- Water content of the subsurface beneath the geomembrane;
- The supporting surface on which the seaming is bonded;
- The skill of the seaming crew;
- Quality and consistency of the chemical or welding material;
- Proper preparation of the liner surfaces to be joined;
- Moisture on the seam interface; and
- Cleanliness of the seam interface (e.g., the amount of airborne dust and debris present).

Depending on the type of geomembrane, several bonding systems are available for the construction of both factory and field seams. Bonding methods include solvents, heat seals, heat guns, dielectric seaming, extrusion welding, and hot wedge techniques. To ensure the integrity of the seams, a geomembrane should be seamed using the bonding system recommended by the manufacturer (U.S. EPA, 1988). EPA has developed a field seaming manual for all types of geomembranes (U.S. EPA, 1991a).

Thermal methods of seaming require cleanliness of the bonding surfaces, heat, pressure, and dwell time to produce high quality seams. The requirements for adhesive systems are the same as those for thermal systems, except that the adhesive takes the place of the heat. Sealing the geomembrane to appurtenances and penetrating structures should be performed in accordance with detailed drawings included in the design plans and approved specifications.

An anchor trench along the perimeter of the cell generally is used to secure the geomembrane during construction (to prevent sloughing or slipping down the interior side slopes). Run out calculations (Koerner, 1990) are available to determine the depth of burial at a trench necessary to hold a specified length of membrane, or combination of membrane and geofabric or geotextile. If forces larger than the tensile strength of the membrane are inadvertently developed, then the membrane could tear. For this reason, the geomembrane should be allowed to slip or give in the trench after construction to prevent such tearing. However, during construction, the geomembrane should be anchored according to the detailed drawings provided in the design plans and specifications (USEPA, 1988).

Geomembranes that are subject to damage from exposure to weather and work activities should be covered with a layer of soil as soon as possible after quality assurance activities associated with geomembrane testing are completed. Soil should be placed without driving construction vehicles directly on the geomembrane. Light ground pressure bulldozers may be used to push material out in front over the liner, but the operator must not attempt to push a large pile of soil forward in a continuous manner over the membrane. Such methods can cause localized wrinkles to develop and overturn in the direction of movement. Overturned wrinkles create sharp creases and localized stresses in the geomembrane that could lead to premature failure. Instead, the operator should continually place smaller amounts of soil or drainage material working outward over the toe of the previously placed material. Alternatively, large backhoes can be used to place soil over the geomembrane that can later be spread with a bulldozer or similar equipment. Although such methods may sound tedious and slow, in the long run they will be faster and more cost-effective than placing too much material too fast and having to remobilize the liner installer to repair damaged sections of the geomembrane. The QA activities conducted during construction also should include monitoring the contractor's activities on top of the liner to avoid damage to installed and accepted geomembranes.

Leachate Collection Systems

Leachate refers to liquid that has passed through or emerged from solid waste and contains dissolved, suspended, or immiscible materials removed from the solid waste. At MSWLF units, leachate is typically aqueous with limited, if any, immiscible fluids or dissolved solvents. The primary function of the leachate collection system is to collect and convey leachate out of the landfill unit and to control the depth of the leachate above the liner. The leachate collection system (LCS) should be designed to meet the regulatory performance standard of maintaining less than 30 cm (12 inches) depth of leachate, or "head," above the liner. The 30-cm head allowance is a design standard and the Agency recognizes that this design standard may be exceeded for relatively short periods of time during the active life of the unit. Flow of leachate through imperfections in the liner system increases with an increase in leachate head above the liner. Maintaining a low leachate level above the liner helps to improve the performance of the composite liner.

Leachate is generally collected from the landfill through sand drainage layers, synthetic drainage nets, or granular drainage layers with perforated plastic collection pipes, and is then removed through sumps or gravity drain carrier pipes. LCS's should consist of the following components (U.S. EPA, 1988):

- A low-permeability base (in this case a composite liner);
- A high-permeability drainage layer, constructed of either natural granular materials (sand and gravel) or synthetic drainage material (e.g., geonet) placed directly on the FML, or on a protective bedding layer (e.g., geofabric) directly overlying the liner;
- Perforated leachate collection pipes within the high-permeability drainage layer to collect leachate and carry it rapidly to a sump or collection header pipe;
- A protective filter layer over the high permeability drainage material, if necessary, to prevent physical clogging of the material by fine-grained material; and
- Leachate collection sumps or header pipe system where leachate can be removed.

The design, construction, and operation of the LCS should maintain a maximum height of leachate above the composite liner of 30 cm (12 in). Design guidance for calculating the maximum leachate depth over a liner for granular drainage systems materials is provided in the reference U.S. EPA (1989). The leachate head in the layer is a function of the liquid impingement rate, bottom slope, pipe spacing, and drainage layer hydraulic conductivity. The impingement rate is estimated using a complex liquid routing procedure. If the maximum leachate depth exceeds 30 cm for the system, except for short-term occurrences, the design should be modified to improve its efficiency by increasing grade, decreasing pipe spacing, or increasing the hydraulic conductivity (transmissivity) of the drainage layer (U.S. EPA, 1988).

Grading of Low-Permeability Base

The typical bottom liner slope is a minimum of two percent after allowances for settlement at all points in each system. A slope is necessary for effective gravity drainage through the entire operating and post-closure period. Settlement estimates of the foundation soils should set this two-percent grade as a post-settlement design objective (U.S. EPA, 1991b).

High-Permeability Drainage Layer

The high-permeability drainage layer is placed directly over the liner or its protective bedding layer at a slope of at least two percent (the same slope necessary for the composite liner). Often the selection of a drainage material is based on the on-site availability of natural granular materials. In some regions of the country, hauling costs may be very high for sand and gravel, or appropriate materials may be unavailable; therefore, the designer may elect to use geosynthetic drainage nets (geonets) or synthetic drainage materials as an alternative. Frequently, geonets are substituted for granular materials on steep sidewalls because maintaining sand on the slope during construction and operation of the landfill unit is more difficult (U.S. EPA, 1988).

Soil Drainage Layers

If the drainage layer of the leachate collection system is constructed of granular soil materials (e.g., sand and gravel), then it should be demonstrated that this granular drainage layer has sufficient bearing strength to support expected loads. This demonstration will be similar to that required for the foundations and soil liner (U.S. EPA, 1988).

If the landfill unit is designed on moderate-to-steep (15 percent) grades, the landfill design should include calculations demonstrating that the selected granular drainage materials will be stable on the most critical slopes (e.g., usually the steepest slope) in the design. The calculations and assumptions should be shown, especially the friction angle between the geomembrane and soil, and if possible, supported by laboratory and/or field testing (USEPA, 1988).

Generally, gravel soil with a group designation of GW or GP on the Unified Soils Classification Chart can be expected to have a hydraulic conductivity of greater than 0.01 cm/sec, while sands identified as SW or SP can be expected to have a coefficient of permeability greater than 0.001 cm/sec. The sand or gravel drains leachate that enters the drainage layer to prevent 30 cm (12 in) or more accumulation on top of the liner during the active life of the MSWLF unit LCS. The design of a LCS frequently uses a drainage material with a hydraulic conductivity of 1 x 10^{-2} cm/sec or higher. Drainage materials with hydraulic conductivities in this order of magnitude should be evaluated for biological and particulate clogging (USEPA, 1988). Alternatively, if a geonet is used, the design is based on the transmissivity of the geonet.

If a filter layer (soil or geosynthetic) is constructed on top of a drainage layer to protect it from clogging, and the LCS is designed and operated to avoid drastic changes in the oxidation reduction potential of the leachate (thereby avoiding formation of precipitates within the LCS), then there is no conceptual basis to anticipate that conductivity will decrease over time. Where conductivity is expected to decrease over time, the change in impingement rate also should be evaluated over the same time period because the reduced impingement rate and hydraulic conductivity may still comply with the 30 cm criterion.

Unless alternative provisions are made to control incident precipitation and resulting surface run-off, the impingement rate during the operating period of the MSWLF unit is usually at least an order of magnitude greater than the impingement rate after final closure. The critical design condition for meeting the 30 cm (12 in) criterion can therefore be expected during the operating life. The designer may evaluate the sensitivity of a design to meet the 30 cm (12 in) criterion as a result of changes in impingement rates, hydraulic conductivity, pipe spacing, and grades. Such sensitivity analysis may indicate which element of the design should be emphasized during construction quality monitoring or whether the design can be altered to comply with the 30 cm (12 in) criterion in a more cost-effective manner.

The soil material used for the drainage layer should be investigated at the borrow pit prior to use at the landfill. Typical borrow pit characterization testing would include laboratory hydraulic conductivity and grain size distribution. If grain size distribution information from the borrow pit characterization program can be correlated to the hydraulic conductivity data, then the grain size test, which can be conducted in a short time in the field, may be a useful construction quality control parameter. Compliance with this parameter would then be indicative that the hydraulic conductivity design criterion was achieved in the constructed drainage layer. This information could be incorporated into construction documents after the borrow pit has been characterized. If a correlation cannot be made between hydraulic conductivity and grain size distribution, then construction documents may rely on direct field or laboratory measurements to demonstrate that the hydraulic conductivity design criterion was met in the drainage layer.

Granular materials are generally placed using conventional earthmoving equipment, including trucks, scrapers, bulldozers, and front-end loaders. Vehicles should not be driven directly over the geosynthetic membrane when it is being covered. (U.S. EPA, 1988a).

Coarse granular drainage materials, unlike low-permeability soils, can be placed dry and do not need to be heavily compacted. Compacting granular soils tends to grind the soil particles together, which increases the fine material and reduces hydraulic conductivity. To minimize settlement following material placement, the granular material may be compacted with a vibratory roller. The final thickness of the drainage layer should be checked by optical survey measurements or by direct test pit measurements (U.S. EPA, 1988).

Geosynthetic Drainage Nets

Geosynthetic drainage nets (geonets) may be substituted for the granular layers of the LCRs on the bottom and sidewalls of the landfill cells. Geonets require less space than perforated pipe or gravel and also promote rapid transmission of liquids. They do, however, require geotextile filters above them and can experience problems with creep and intrusion. Long-term operating and performance experience of geonets is limited because the material and its application are relatively new (U.S. EPA, 1989).

If a geonet is used in place of a granular drainage layer, it must provide the same level of performance (maintaining less than 30 cm of leachate head above the liner). An explanation of the calculation used to compute the capacity of a geonet may be found in U.S. EPA (1987a). The transmissivity of a geonet can be reduced significantly by intrusion of the soil or a geotextile. A protective geotextile between the soil and geonet will help alleviate this concern. If laboratory transmissivity tests are performed, they should be done under conditions, loads, and configurations that closely replicate the actual field conditions. It is important that the transmissivity value used in the leachate collection system design calculations be selected based upon those loaded conditions (U.S. EPA, 1988). It is also important to ensure that appropriate factors of safety are used (Koerner, 1990).

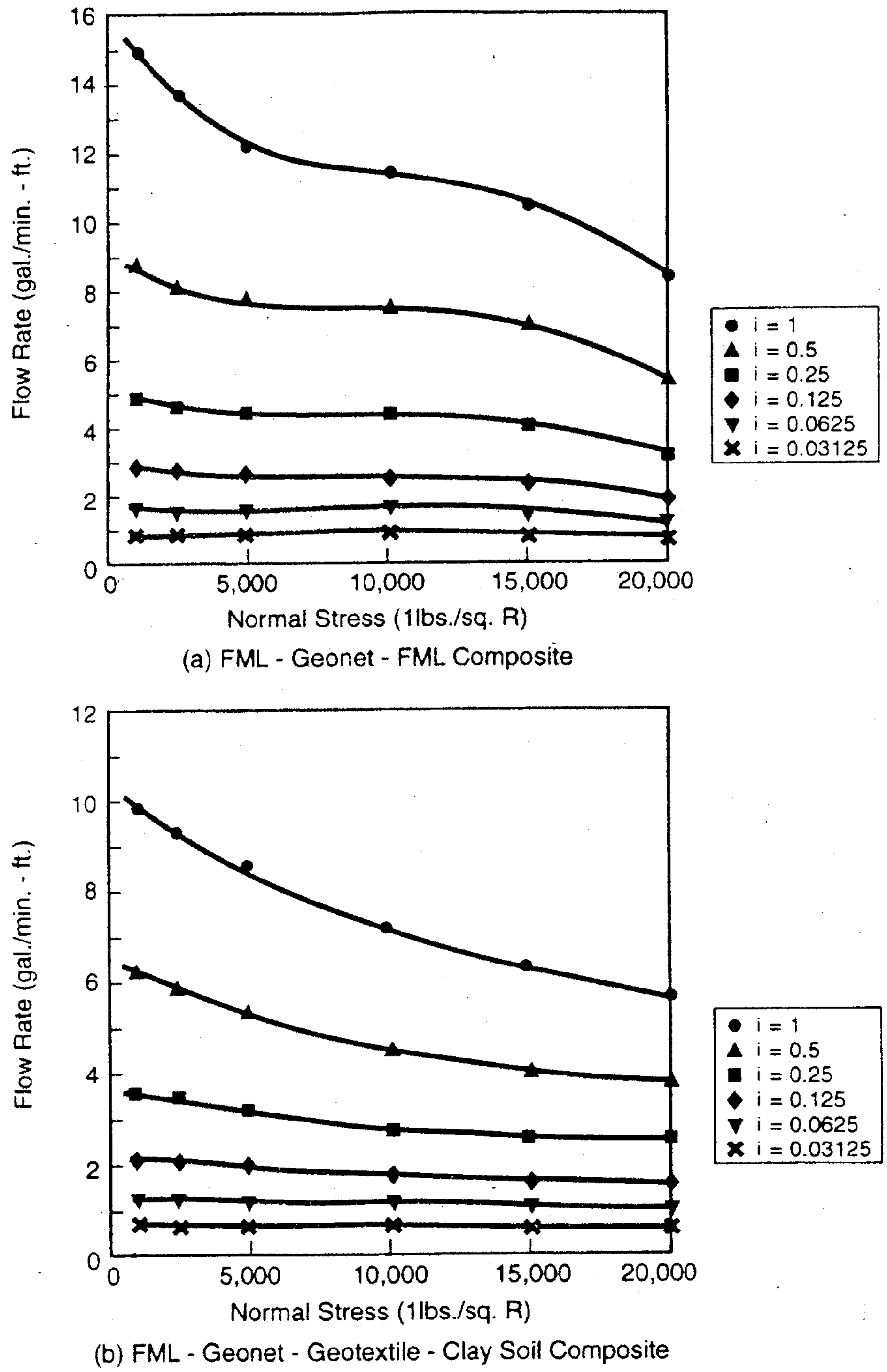
The flow rate or transmissivity of geonets may be evaluated by ASTM D-4716. This flow rate may then be compared to design-by-function equations presented in U.S. EPA (1989). In the ASTM D-4716 flow test, the proposed collector cross section should be modeled as closely as possible to actual field conditions (U.S. EPA, 1989).

Figure 4-7 shows the flow rate "signatures" of a geonet between two geomembranes (upper curves) and the same geonet between a layer of clay soil and a geomembrane (lower curves). The differences between the two sets of curves represent intrusion of the geotextile/clay into the apertures of the geonet. The curves are used to obtain a flow rate for the particular geonet being designed (U.S. EPA, 1989). Equations to determine the design flow rate or transmissivity are also presented in U.S. EPA (1989), Giroud (1982), Carroll (1987), Koerner (1990), and FHWA (1987).

Generally, geonets perform well and result in high factors of safety or performance design ratios, unless creep (elongation under constant stress) becomes a problem or adjacent materials intrude into apertures (U.S. EPA, 1989). For geonets, the most critical specification is the ability to transmit fluids under load. The specifications also should include a minimum transmissivity under expected landfill operating (dynamic) or completion (static) loads. The specifications for thickness and types of material should be identified on the drawings or in the materials section of the specifications, and should be consistent with the design calculations (U.S. EPA, 1988).

Geonets are often used on the sidewalls of landfills because of their ease of installation. They should be placed with the top ends in a secure anchor trench with the strongest longitudinal length extending down the slope. The geonets need not be seamed to each other on the slopes, only tied at the edges, butted, or overlapped. They should be placed in a loose condition, not stretched or placed in a configuration where they are bearing their own weight in tension. The construction specifications should contain appropriate installation requirements as described above or the requirements of the geonet manufacturer. All geonets need to be protected by a filter layer or geotextile to prevent clogging (U.S. EPA, 1988).

The friction factors against sliding for geotextiles, geonets, and geomembranes often can be estimated using manufacturers data because these materials do not exhibit the range of characteristics as seen in soil materials. However, it is important that the designer perform the actual tests using site materials and that the sliding stability calculations accurately represent the actual design configuration, site conditions, and the specified material characteristics (U.S. EPA, 1988).



Source: U.S. EPA. 1989.

Figure 4-7. Flow Rate Curves for Geonets in Two Composite Liner Configurations

Leachate Collection Pipes

All components of the leachate collection system must have sufficient strength to support the weight of the overlying waste, cover system, and post-closure loadings, as well as the stresses from operating equipment. The component that is most vulnerable to compressive strength failure is the drainage layer piping. Leachate collection system piping can fail by excessive deflection, which may lead to buckling or collapse (USEPA, 1988). Pipe strength calculations should include resistance to wall crushing, pipe deflection, and critical buckling pressure. Design equations and information for most pipe types can be obtained from the major pipe manufacturers. For more information regarding pipe structural strength, refer to U.S. EPA (1988).

Perforated drainage pipes can provide good long-term performance. These pipes have been shown to transmit fluids rapidly and to maintain good service lives. The depth of the drainage layer around the pipe should be deeper than the diameter of the pipe. The pipes can be placed in trenches to provide the extra depth. In addition, the trench serves as a sump (low point) for leachate collection. Pipes can be susceptible to particulate and biological clogging similar to the drainage layer material. Furthermore, pipes also can be susceptible to deflection. Proper maintenance and design of pipe systems can mitigate these effects and provide systems that function properly. Acceptable pipe deflections should be evaluated for the pipe material to be used (USEPA, 1989).

The design of perforated collection pipes should consider the following factors:

- The required flow using known percolation impingement rates and pipe spacing;
- Pipe size using required flow and maximum slope; and
- The structural strength of the pipe.

The pipe spacing may be determined by the Mound Model. In the Mound Model (see Figure 4-8), the maximum height of fluid between two parallel perforated drainage pipes is equal to (U.S. EPA, 1989):

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

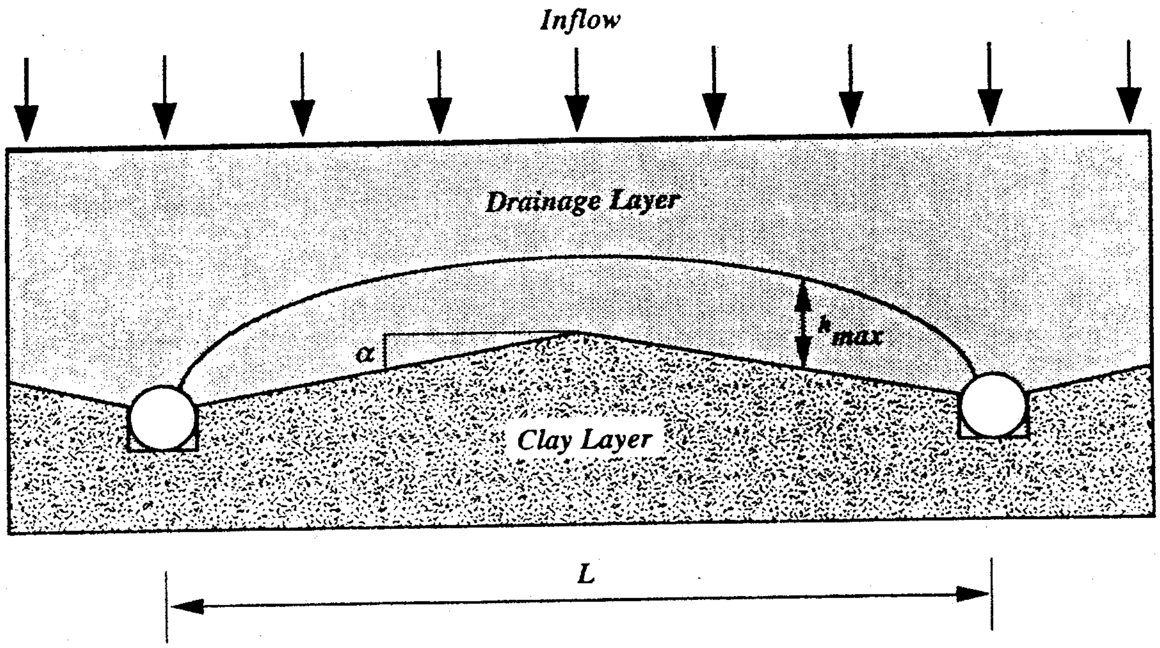
where c = q/k
k = permeability
q = inflow rate
α = slope.

The two unknowns in the equation are:

L = distance between the pipes; and
c = amount of leachate.

Using a maximum allowable head, h_{max}, of 30 cm (12 in), the equation is usually solved for "L" (U.S. EPA, 1989).

The amount of leachate, "c", can be estimated in a variety of ways including the Water Balance Method (U.S. EPA, 1989) and the computer model Hydrologic Evaluation of Landfill Performance (HELP). The HELP Model is a quasi-two-dimensional hydrologic model of water movement across, into, through, and out of landfills. The model uses climatologic, soil, and landfill design data and incorporates a solution technique that accounts for the effects of surface storage, run-off, infiltration, percolation, soil-moisture



Source: U.S. EPA, 1989

Figure 4-8. Definition of Terms for Mound Model Flow Rate Calculations

storage, evapotranspiration, and lateral drainage. The program estimates run-off drainage and leachate that are expected to result from a wide variety of landfill conditions, including open, partially open, and closed landfill cells. The model also may be used to estimate the depth of leachate above the bottom liner of the landfill unit. The results may be used to compare designs or to aid in the design of leachate collection systems (U.S. EPA, 1988).

Once the percolation and pipe spacing are known, the design flow rate can be obtained using the curve in Figure 4-9. The amount of leachate percolation at the particular site is located on the x-axis.

The required flow rate is the point at which this value intersects with the pipe spacing value determined from the Mound Model. Using this value of flow rate and the bottom slope of the site, the required diameter for the pipe can be determined (see Figure 4-10). Finally, the graphs in Figures 4-11 and 4-12 show two ways to determine whether the strength of the pipe is adequate for the landfill design. In Figure 4-11, the vertical soil pressure is located on the y-axis. The density of the backfill material around the pipe is not governed by strength, so it will deform under pressure rather than break. Ten percent is the absolute limiting deflection value for plastic pipe. Using Figure 4-11, the applied pressure on the pipe is located and traced to the trench geometry, and then the pipe deflection value is checked for its adequacy (U.S. EPA, 1989).

The LCS specifications should include (U.S. EPA, 1988):

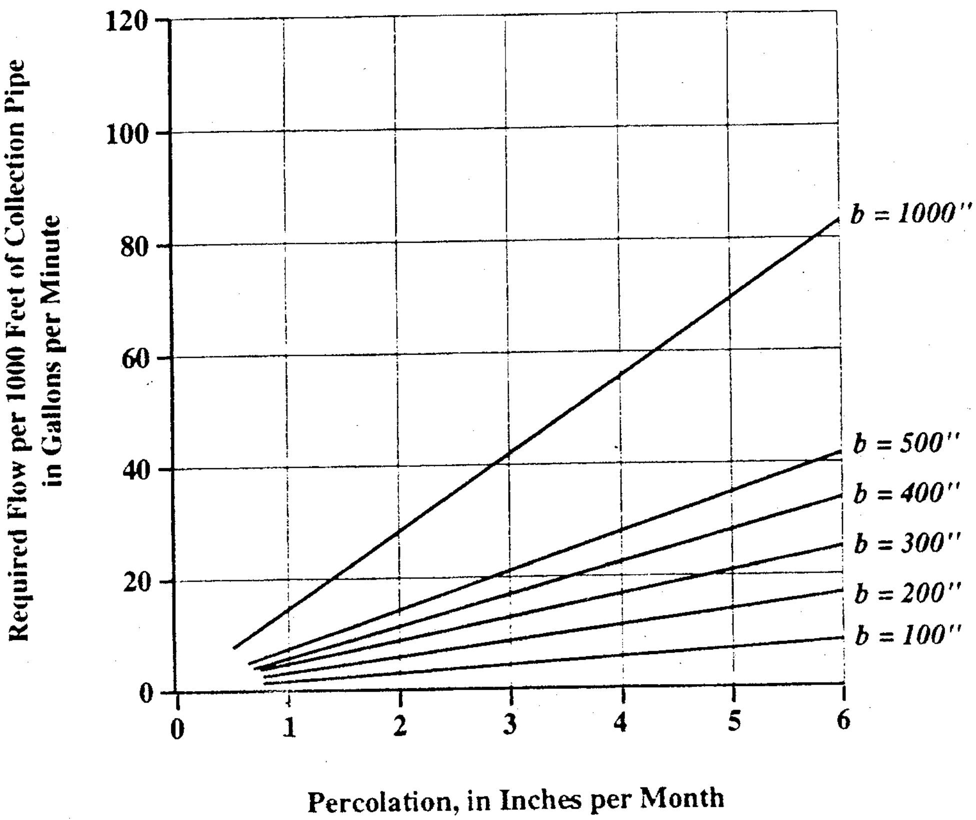
- Type of piping material;
- Diameter and wall thickness;
- Size and distribution of slots and perforations;
- Type of coatings (if any) used in the pipe manufacturing; and
- Type of pipe bedding material and required compaction used to support the pipes.

The construction drawings and specifications should clearly indicate the type of bedding to be used under the pipes and the dimensions of any trenches. The specifications should indicate how the pipe lengths are joined. The drawings should show how the pipes are placed with respect to the perforations. To maintain the lowest possible leachate head, there should be perforations near the pipe invert, but not directly at the invert. The pipe invert itself should be solid to allow for efficient pipe flow at low volumes (U.S. EPA, 1988).

When drainage pipe systems are embedded in filter and drainage layers, no unplugged ends should be allowed. The filter materials in contact with the pipes should be appropriately sized to prevent migration of the material into the pipe. The filter media, drainage layer, and pipe network should be compatible and should represent an integrated design.

Protection of Leachate Collection Pipes

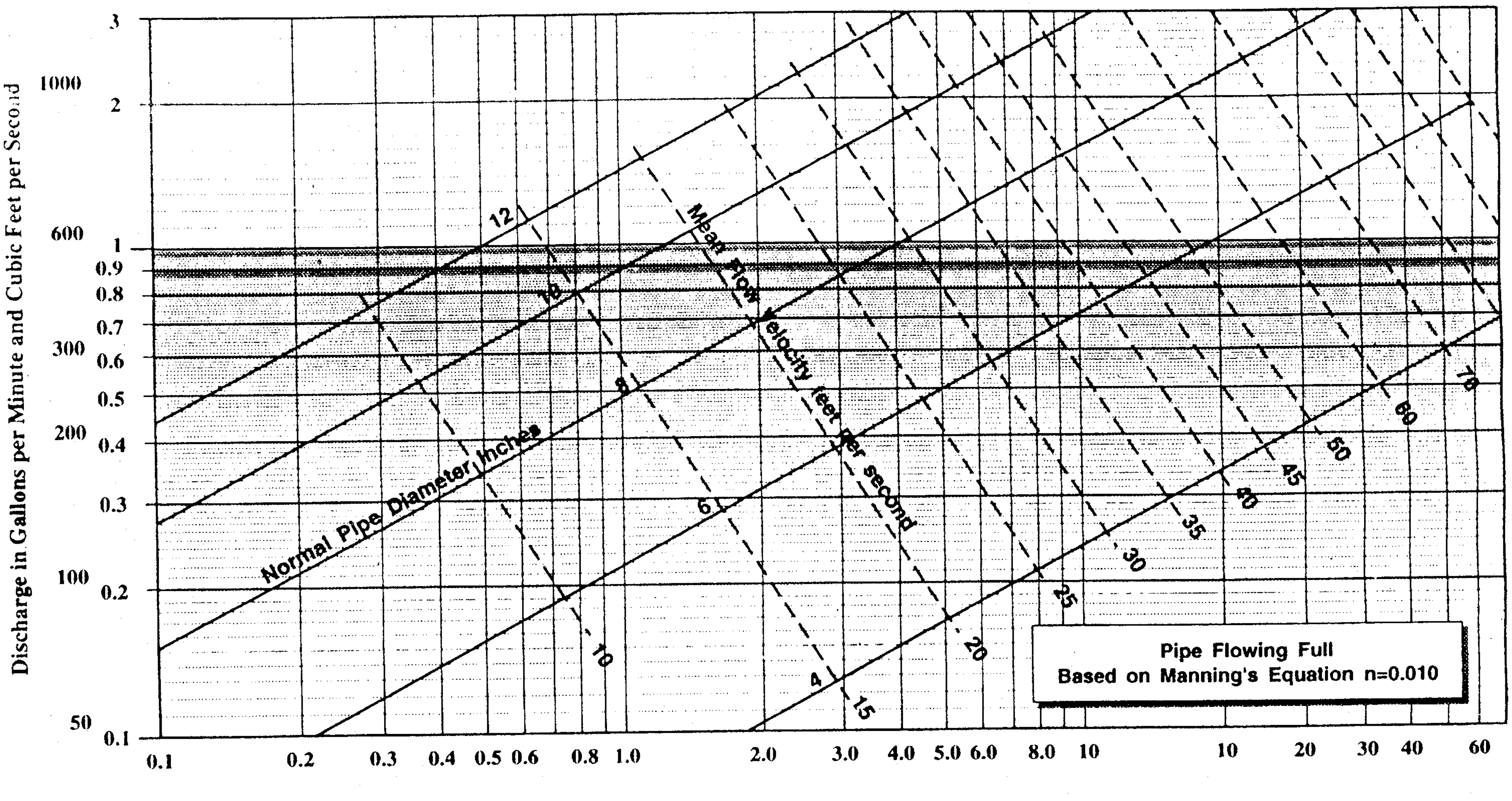
The long-term performance of the LCS depends on the design used to protect pipes from physical clogging (sedimentation) by the granular drainage materials. Use of a graded material around the pipes is most effective if accompanied by proper sizing of pipe perforations. The Army Corps of



*Where b = width of area contributing to leachate collection pipe

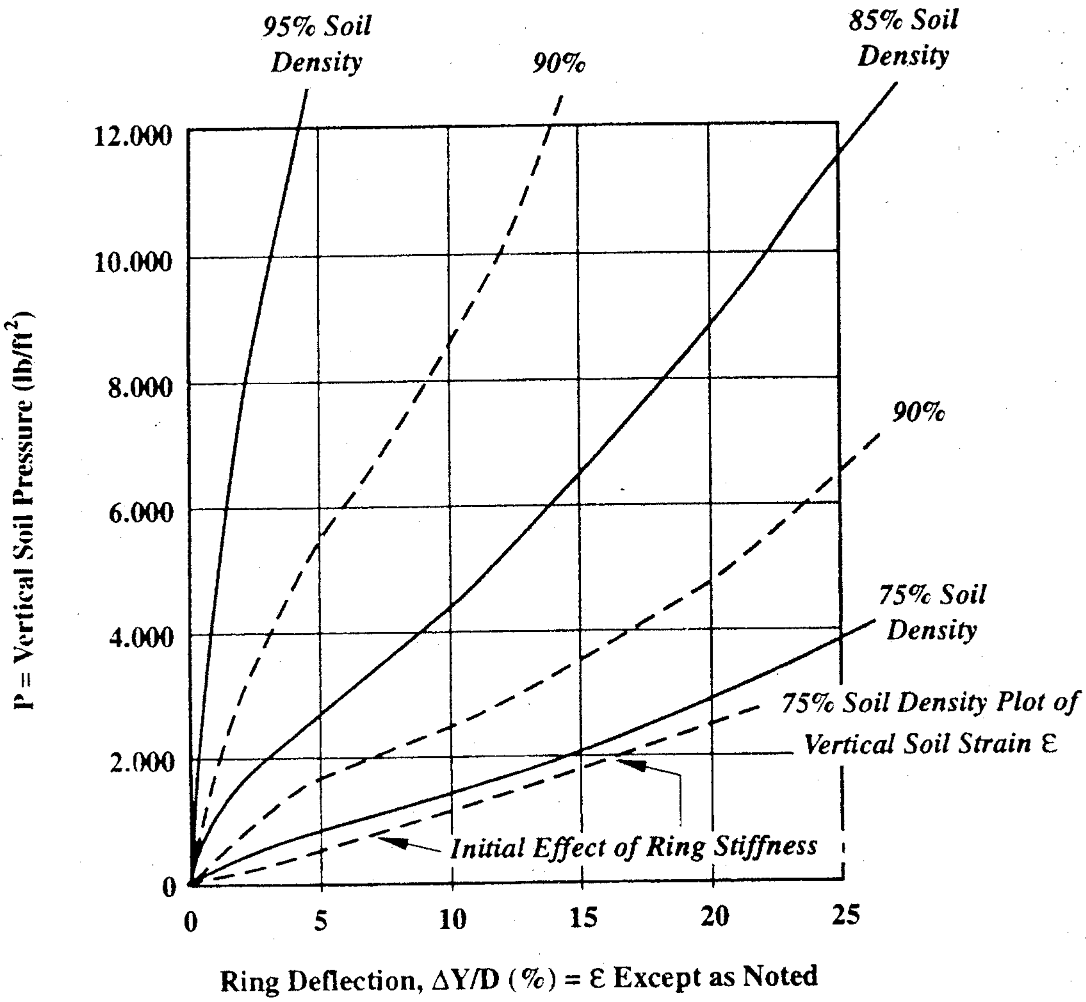
Source: U.S. EPA, 1989

Figure 4-9. Required Capacity of Leachate Collection Pipe



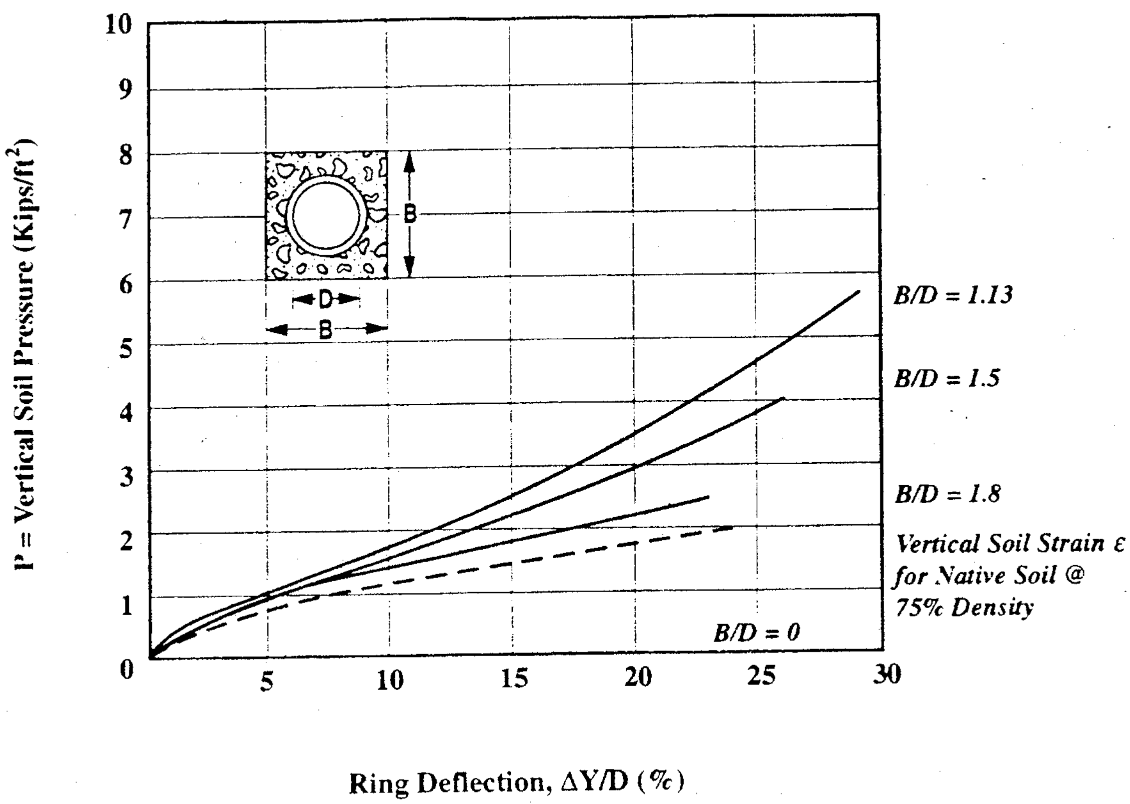
Source: U.S. EPA, 1989

Figure 4-10. Leachate Collection Pipe Sizing Chart



Source: U.S. EPA. 1989

Figure 4-11. Vertical Ring Deflection Versus Vertical Soil Pressure for 18-inch Corrugated Polyethylene in High Pressure Soil Cell



Source: U.S. EPA, 1989

Figure 4-12. Example of the Effect of Trench Geometry and Pipe Sizing on Ring Deflection

Engineers (GCA Corporation, 1983) has established design criteria using graded filters to prevent physical clogging of leachate drainage layers and piping by soil sediment deposits. When installing graded filters, caution should be taken to prevent segregation of the material (USEPA, 1991a).

Clogging of the pipes and drainage layers of the leachate collection system can occur through several other mechanisms, including chemical and biological fouling (USEPA, 1988). The LCS should be designed with a cleanout access capable of reaching all parts of the collection system with standard pipe cleaning equipment.

Chemical clogging can occur when dissolved species in the leachate precipitate in the piping. Clogging can be minimized by periodically flushing pipes or by providing a sufficiently steep slope in the system to allow for high flow velocities for self-cleansing. These velocities are dependent on the diameter of the precipitate particles and on their specific gravity. ASCE (1969) discusses these relationships. Generally, flow velocities should be in the range of one or two feet per second to allow for self-cleansing of the piping (U.S. EPA, 1988).

Biological clogging due to algae and bacterial growth can be a serious problem in MSWLF units. There are no universally effective methods of preventing such biological growth. Since organic materials will be present in the landfill unit, there will be a potential for biological clogging. The system design should include features that allow for pipe system cleanings. The components of the cleaning system should include (U.S. EPA, 1991b):

- A minimum of six-inch diameter pipes to facilitate cleaning;
- Access located at major pipe intersections or bends to allow for inspections and cleaning; and
- Valves, ports, or other appurtenances to introduce biocides and/or cleaning solutions.

In its discussion of drainage layer protection, the following section includes further information concerning protection of pipes using filter layers.

Protection of the High-Permeability Drainage Layer

The openings in drainage materials, whether holes in pipes, voids in gravel, or apertures in geonets, must be protected against clogging by accumulation of fine (silt-sized) materials. An intermediate material that has smaller openings than those of the drainage material can be used as a filter between the waste and drainage layer. Sand may be used as filter material, but has the disadvantage of taking up vertical space (USEPA, 1989). Geotextiles do not use up air space and can be used as filter materials.

Soil Filter Layers

There are three parts to an analysis of a sand filter that is placed above drainage material. The first determines whether or not the filter allows adequate flow of liquids. The second evaluates whether the void spaces are small enough to prevent solids from being lost from the upstream materials. The third estimates the long-term clogging behavior of the filter (U.S. EPA, 1989).

The particle-size distribution of the drainage system and the particle-size distribution of the invading (or upstream) soils are required in the design of granular soil (sand filter) materials. The filter material should have its large and small size particles intermediate between the two extremes. Equations for adequate flow and retention are:

- Adequate Flow:
  $d_{85f} > (3 \text{ to } 5) d_{15d.s.}$
- Adequate Retention:
  $d_{15f} < (3 \text{ to } 5) d_{85w.f.}$

Where f = required filter soil;
d.s. = drainage stone; and
w.f. = water fines.

There are no quantitative methods to assess soil filter clogging, although empirical guidelines are found in geotechnical engineering references.

The specifications for granular filter layers that surround perforated pipes and that protect the drainage layer from clogging are based on a well-defined particle size distribution. The orientation and configuration of filter layers relative to other LCS components should be shown on all drawings and should be described, with ranges of particle sizes, in the materials section of the specifications (U.S. EPA, 1988a).

Thickness is an important placement criterion for granular filter material. Generally, the granular filter materials will be placed around perforated pipes by hand, forming an "envelope." The dimensions of the envelope should be clearly stated on the drawings or in the specifications. This envelope can be placed at the same time as the granular drainage layer, but it is important that the filter envelope protect all areas of the pipe where the clogging potential exists. The plans and specifications should indicate the extent of the envelope. The construction quality control program should document that the envelope was installed according to the plans and specifications (U.S. EPA, 1988).

A granular filter layer is generally placed using the same earthmoving equipment as the granular drainage layer. The final thickness should be checked by optical survey or by direct test pit measurement (U.S. EPA, 1988).

This filter layer is the uppermost layer in the leachate collection system. A landfill design option includes a buffer layer, 12 inches thick (30 cm) or more, to protect the filter layer and drainage layer from damage due to traffic. This final layer can be general fill, as long as it is no finer than the soil used in the filter layer (U.S. EPA, 1988). However, if the layer has a low permeability, it will affect leachate recirculation attempts.

Geotextile Filter Layers

Geotextile filter fabrics are often used. The open spaces in the fabric allow liquid flow while simultaneously preventing upstream fine particles from fouling the drain. Geotextiles save vertical space, are easy to install, and have the added advantage of remaining stationary under load. Geotextiles also can be used as cushioning materials above geomembranes (USEPA, 1989). Because geotextile filters are susceptible to biological clogging, their use in areas inundated by leachate (e.g., sumps, around leachate collection pipes, and trenches) should be avoided.

Geotextile filter design parallels sand filter design with some modifications (U.S. EPA, 1989). Adequate flow is assessed by comparing the material (allowable) permittivity to the design imposed permittivity. Permittivity is measured by the ASTM D-4491 test method. The design permittivity utilizes an adapted form of Darcy's law. The resulting comparison yields a design ratio, or factor of safety, that is the focus of the design (U.S. EPA, 1989):

$DR = ø_{allow}/ø_{reqd}$

where:

$ø_{allow}$ = permittivity from ASTM D-4491

$ø_{reqd} = (q/a)\ (1/h_{max})$

q/a = inflow rate per unit area

h_{max} = 12 inches

The second part of the geotextile filter design is determining the opening size necessary for retaining the upstream soil or particulates in the leachate. It is well established that the 95 percent opening size is related to particles to be retained in the following type of relationship:

$O_{95} < \text{fct.}\ (d_{50}, CU, DR)$

where:

O_{95} = 95% opening size of geotextile;

d_{50} = 50% size of upstream particles;

CU = Uniformity of the upstream particle size; and

DR = Relative density of the upstream particles.

The O_{95} size of a geotextile in the equation is the opening size at which 5 percent of a given value should be less than the particle size characteristics of the invading materials. In the test for the O_{95} size of the geotextile, a sieve with a very coarse mesh in the bottom is used as a support. The geotextile is placed on top of the mesh and is bonded to the inside so that the glass beads used in the test cannot escape around the edges of the geotextile filter. The particle-size distribution of retained glass beads is compared to the allowable value using any of a number of existing formulas (U.S. EPA, 1989).

The third consideration in geotextile design is long-term clogging. A test method for this problem that may be adopted by ASTM is called the Gradient Ratio Test. In this test, the hydraulic gradient of 1 inch of soil plus the underlying geotextile is compared with the hydraulic gradient of 2 inches of soil. The higher the gradient ratio, the more likely that a clog will occur. The final ASTM gradient ratio test will include failure criteria. An alternative to this test method is a long-term flow test that also is performed in a laboratory. The test models a soil-to-fabric system at the anticipated hydraulic gradient. The flow rate through the system is monitored. A long-term flow rate will gradually decrease until it stops altogether (U.S. EPA, 1989).

The primary function of a geotextile is to prevent the migration of fines into the leachate pipes while allowing the passage of leachate. The most important specifications are those for hydraulic conductivity and retention. The hydraulic conductivity of the geotextile generally should be at least ten times the soil it is retaining. An evaluation of the retention ability for loose soils is based on the average particle size of the soil and the apparent opening size (AOS) of the geotextile. The maximum apparent opening size, sometimes called equivalent opening size, is determined by the size of the soil that will be retained; a geotextile is then selected to meet that specification. The material specifications should contain a range of AOS values for the geotextile, and these AOS values should match those used in the design calculations (U.S. EPA, 1988).

One of the advantages of geotextiles is their light weight and ease of placement. The geotextiles are brought to the site, unrolled, and held down with sandbags until they are covered with a protective layer. They are usually overlapped, not seamed; however, on slopes or in other configurations, they may be sewn (U.S. EPA, 1988).

As with granular filter layers, it is important that the design drawings be clear in their designation of geotextile placement so that no potential route of pipe or drainage layer clogging is left unprotected. If geotextiles are used on a slope, they should be secured in an anchor trench similar to those for geomembranes or geonets (U.S. EPA, 1988).

Leachate Removal System

Sumps, located in a recess at the low point(s) within the leachate collection drainage layer, provide one method for leachate removal from the MSWLF unit. In the past, low volume sumps have been constructed successfully from reinforced concrete pipe on a concrete footing, and supported above the geomembrane on a steel plate to protect the geomembrane from puncture. Recently, however, prefabricated polyethylene structures have become available. These structures may be suitable for replacing the concrete components of the sump and have the advantage of being lighter in weight.

These sumps typically house a submersible pump, which is positioned close to the sump floor to pump the leachate and to maintain a 30 cm (12 in) maximum leachate depth. Low-volume sumps, however, can present operational problems. Because they may run dry frequently, there is an increased probability of the submersible pumps burning out. For this reason, some landfill operators prefer to have sumps placed at depths between 1.0 and 1.5 meters. While head levels of 30 cm or less are to be maintained on the liner, higher levels are acceptable in sumps. Alternatively, the sump may be designed with level controls and with a backup pump to control initiation and shut-off of the pumping sequence and to have the capability of alternating between the two pumps. The second pump also may be used in conjunction with the primary pump during periods of high flow (e.g., following storm events) and as a backup if the primary pump fails to function. A visible alarm warning light to indicate pump failure to the operator also may be installed.

Pumps used to remove leachate from the sumps should be sized to ensure removal of leachate at the maximum rate of generation. These pumps also should have a sufficient operating head to lift the leachate to the required height from the sump to the access port. Portable vacuum pumps can be used if the required lift height is within the limit of the pump. They can be moved in sequence from one leachate sump to another. The type of pump specified and the leachate sump access pipes should be compatible and should consider performance needs under operating and closure conditions (U.S. EPA, 1988).

Alternative methods of leachate removal include internal standpipes and pipe penetrations through the geomembrane, both of which allow leachate removal by gravity flow to either a leachate pond or exterior pump station. If a leachate removal standpipe is used, it should be extended through the entire landfill from liner to

CHAPTER 5
SUBPART E
GROUND-WATER MONITORING AND CORRECTIVE ACTION

5.1 INTRODUCTION

The Criteria establish ground-water monitoring and corrective action requirements for all existing and new MSWLF units and lateral expansions of existing units except where the Director of an approved State suspends the requirements because there is no potential for migration of leachate constituents from the unit to the uppermost aquifer. The Criteria include requirements for the location, design, and installation of ground-water monitoring systems and set standards for ground-water sampling and analysis. They also provide specific statistical methods and decision criteria for identifying a significant change in ground-water quality. If a significant change in ground-water quality occurs, the Criteria require an assessment of the nature and extent of contamination followed by an evaluation and implementation of remedial measures.

Portions of this chapter are based on a draft technical document developed for EPA's hazardous waste program. This document, "RCRA Ground-Water Monitoring: Draft Technical Guidance" (EPA/530-R-93-001), is undergoing internal review, and may change. EPA chose to incorporate the information from the draft document into this chapter because the draft contained the most recent information available.

5.2 APPLICABILITY
40 CFR §258.50 (a) & (b)

5.2.1 Statement of Regulation

(a) The requirements in this Part apply to MSWLF units, except as provided in paragraph (b) of this section.

(b) Ground-water monitoring requirements under §258.51 through §258.55 of this Part may be suspended by the Director of an approved State for a MSWLF unit if the owner or operator can demonstrate that there is no potential for migration of hazardous constituents from that MSWLF unit to the uppermost aquifer (as defined in §258.2) during the active life of the unit and the post-closure care period. This demonstration must be certified by a qualified ground-water scientist and approved by the Director of an approved State, and must be based upon:

(1) Site-specific field collected measurements, sampling, and analysis of physical, chemical, and biological processes affecting contaminant fate and transport, and

(2) Contaminant fate and transport predictions that maximize contaminant migration and consider impacts on human health and environment.

5.2.2 Applicability

The ground-water monitoring requirements apply to all existing MSWLF units, lateral expansions of existing units, and new MSWLF units that receive waste after October 9, 1993. The requirements for ground-water monitoring may be suspended if the Director of an approved State finds that no potential exists for migration of hazardous constituents from the MSWLF unit to the uppermost aquifer during the active life of the unit, including closure or post-closure care periods.

The "no potential for migration" demonstration must be based upon site-specific information relevant to the fate and transport of any hazardous constituents that may be expected to be released from the unit. The predictions of fate and transport must identify the maximum anticipated concentrations of constituents migrating to the uppermost aquifer so that a protective assessment of the potential effects to human health and the environment can be made. A successful demonstration could exempt the MSWLF unit from requirements of §§258.51 through 258.55, which include installation of ground-water monitoring systems, and sampling and analysis for both detection and assessment monitoring constituents. *Preparing No-Migration Demonstrations for Municipal Solid Waste Disposal Facilities-Screening Tool* is a guidance document describing a process owners/ operators can use to prepare a no-migration demonstration (NMD) requesting suspension of the ground-water monitoring requirements.

5.2.3 Technical Considerations

All MSWLF units that receive waste after the effective date of Part 258 must comply with the ground-water monitoring requirements. The Director of an approved State may exempt an owner/operator from the ground-water monitoring requirements at §258.51 through §258.55 if the owner or operator demonstrates that there is no potential for hazardous constituent migration to the uppermost aquifer throughout the operating, closure, and post-closure care periods of the unit. Owners and operators of MSWLFs not located in approved States will not be eligible for this waiver and will be required to comply with all ground-water monitoring requirements. The "no-migration" demonstration must be certified by a qualified ground-water scientist and approved by the Director of an approved State. It must be based on site-specific field measurements and sampling and analyses to determine the physical, chemical, and biological processes affecting the fate and transport of hazardous constituents. The demonstration must be supported by site-specific data and predictions of the maximum contaminant migration. Site-specific information must include, at a minimum, the information necessary to evaluate or interpret the effects of the following properties or processes on contaminant fate and transport:

Physical Properties or Processes:

- <u>Aquifer Characteristics</u>, including hydraulic conductivity, hydraulic gradient, effective porosity, aquifer thickness, degree of saturation, stratigraphy, degree of fracturing and secondary porosity of soils and bedrock, aquifer heterogeneity, ground-water discharge, and ground-water recharge areas;

- <u>Waste Characteristics</u>, including quantity, type, and origin (e.g., commercial, industrial, or small quantity generators of unregulated hazardous wastes);

- Climatic Conditions, including annual precipitation, leachate generation estimates, and effects on leachate quality;

- Leachate Characteristics, including leachate composition, solubility, density, the presence of immiscible constituents, Eh, and pH; and

- Engineered Controls, including liners, cover systems, and aquifer controls (e.g., lowering the water table). These should be evaluated under design and failure conditions to estimate their long-term residual performance.

Chemical Properties or Processes:

- Attenuation of contaminants in the subsurface, including adsorption/ desorption reactions, ion exchange, organic content of soil, soil water pH, and consideration of possible reactions causing chemical transformation or chelation.

Biological Processes:

- Microbiological Degradation, which may attenuate target compounds or cause transformations of compounds, potentially forming more toxic chemical species.

The alternative design section of Chapter 5.0 discusses these and other processes that affect contaminant fate and solute transport.

When owners or operators prepare a no-migration demonstration, they must use predictions that are based on maximum contaminant migration both from the unit and through the subsurface media. Assumptions about variables affecting transport should be biased toward over-estimating transport and the anticipated concentrations. Assumptions and site specific data that are used in the fate and transport predictions should conform with transport principles and processes, including adherence to mass-balance and chemical equilibria limitations. Within these physicochemical limitations, assumptions should be biased toward the objective of assessing the maximum potential impact on human health and the environment. The evaluation of site-specific data and assumptions may include some of the following approaches:

- Use of the upper bound of known aquifer parameters and conditions that will maximize contaminant transport (e.g., hydraulic conductivity, effective porosity, horizontal and vertical gradients), rather than average values

- Use of the lower range of known aquifer conditions and parameters that tend to attenuate or retard contaminant transport (e.g., dispersivities, decay coefficients, cation exchange capacities, organic carbon contents, and recharge conditions), rather than average values

- Consideration of the cumulative impacts on water quality, including both existing water quality data and cumulative health risks posed by hazardous constituents likely to migrate from the MSWLF unit and other potential or known sources.

A discussion of mathematical approaches for evaluating contaminant or solute transport is provided in Chapter 5.

5.3 COMPLIANCE SCHEDULE 40 CFR § 258.50 (c)

5.3.1 Statement of Regulation*

***[NOTE: EPA finalized several revisions to 40 CFR Part 258 on October 1, 1993 (58 FR 51536), and these revisions delay the effective date for some categories of landfills. More detail on the content of the revisions is included in the introduction.]**

(c) Owners and operators of MSWLF units must comply with the ground-water monitoring requirements of this part according to the following schedule unless an alternative schedule is specified under paragraph (d):

(1) Existing MSWLF units and lateral expansions less than one mile from a drinking water intake (surface or subsurface) must be in compliance with the ground-water monitoring requirements specified in §§258.51 - 258.55 by October 9, 1994;

(2) Existing MSWLF units and lateral expansions greater than one mile but less than two miles from a drinking water intake (surface or subsurface) must be in compliance with the ground-water monitoring requirements specified in §§258.51 - 258.55 by October 9, 1995;

(3) Existing MSWLF units and lateral expansions greater than two miles from a drinking water intake (surface or subsurface) must be in compliance with the ground-water monitoring requirements specified in §§258.51 - 258.55 by October 9, 1996;

(4) New MSWLF units must be in compliance with the ground-water monitoring requirements specified in §§258.51 - 258.55 before waste can be placed in the unit.

5.3.2 Applicability

The rule establishes a self-implementing schedule for owners or operators in States with programs that are deemed inadequate or not yet approved. As indicated in the Statement of Regulation, this schedule depends on the distance of the MSWLF unit from drinking water sources. Approved States may specify an alternative schedule under §258.50 (d), which is discussed in Section 5.4.

Existing units and lateral expansions less than one mile from a drinking water intake must be in compliance with the ground-water monitoring requirements by October 9, 1994. If the units are greater than one mile but less than two miles from a drinking water intake, they must be in compliance by October 9, 1995. Those units located more than two miles from a drinking water intake must be in compliance by October 9, 1996 (see Table 5-1).

New MSWLF units, defined as units that have not received waste prior to October 9, 1993, must be in compliance with these requirements before receiving waste regardless of the proximity to a water supply intake.

5.3.3 Technical Considerations

For most facilities, these requirements will become applicable 3 to 5 years after the promulgation date of the rule. This period

Table 5-1. Compliance Schedule for Existing Units and Lateral Expansions in States with Unapproved Programs

Distance From Water Supply Intake	Time to Comply From October 9, 1991
One mile or less	3 Years
More than one mile but less than two miles	4 Years
More than two miles	5 Years

should provide sufficient time for the owner or operator to conduct site investigation and characterization studies to comply with the requirements of 40 CFR §258.51 through §258.55. For those facilities closest to drinking water intakes, the period provides 2 to 3 years to assess seasonal variability in ground-water quality. A drinking water intake includes water supplied to a user from either a surface water or ground-water source.

5.4 ALTERNATIVE COMPLIANCE SCHEDULES 40 CFR 258.50 (d)(e) & (g)

5.4.1 Statement of Regulation

(d) The Director of an approved State may specify an alternative schedule for the owners or operators of existing MSWLF units and lateral expansions to comply with the ground-water monitoring requirements specified in §§258.51 - 258.55. This schedule must ensure that 50 percent of all existing MSWLF units are in compliance by October 9, 1994 and all existing MSWLF units are in compliance by October 9, 1996. In setting the compliance schedule, the Director of an approved State must consider potential risks posed by the unit to human health and the environment. The following factors should be considered in determining potential risk:

(1) Proximity of human and environmental receptors;

(2) Design of the MSWLF unit;

(3) Age of the MSWLF unit;

(4) The size of the MSWLF unit;

(5) Types and quantities of wastes disposed, including sewage sludge; and

(6) Resource value of the underlying aquifer, including:

(i) Current and future uses;

(ii) Proximity and withdrawal rate of users; and

(iii) Ground-water quality and quantity.

(e) Once established at a MSWLF unit, ground-water monitoring shall be conducted throughout the active life and post-closure care period of that MSWLF unit as specified in §258.61.

(f) (See Section 5.5 for technical guidance on qualifications of a ground-water scientist.)

(g) The Director of an approved State may establish alternative schedules for demonstrating compliance with §258.51(d)(2), pertaining to notification of placement of certification in operating record; § 258.54(c)(1), pertaining to notification that statistically significant increase (SSI) notice is in operating record; § 258.54(c)(2) and (3), pertaining to an assessment monitoring program; § 258.55(b), pertaining to sampling and analyzing Appendix II constituents; §258.55(d)(1), pertaining to placement of notice (Appendix II constituents detected) in record and notification of notice in record; § 258.55(d)(2), pertaining to sampling for Appendix I and II; § 258.55(g), pertaining to notification (and placement of notice in record) of SSI above ground-water protection standard; § 258.55(g)(1)(iv) and § 258.56(a), pertaining to assessment of corrective measures; § 258.57(a), pertaining to selection of remedy and notification of placement in record; § 258.58(c)(4), pertaining to notification of placement in record (alternative corrective action measures); and § 258.58(f), pertaining to notification of placement in record (certification of remedy completed).

5.4.2 Applicability

The Director of an approved State may establish an alternative schedule for requiring owners/operators of existing units and lateral expansions to comply with the ground-water monitoring requirements. The alternative schedule is to ensure that at least fifty percent of all existing MSWLF units within a given State are in compliance by October 9, 1994 and that all units are in compliance by October 9, 1996.

In establishing the alternative schedule, the Director of an approved State may use site-specific information to assess the relative risks posed by different waste management units and will allow priorities to be developed at the State level. This site-specific information (e.g., proximity to receptors, proximity and withdrawal rate of ground-water users, waste quantity, type, containment design and age) should enable the Director to assess potential risk to the uppermost aquifer. The resource value of the aquifer to be monitored (e.g., ground-water quality and quantity, present and future uses, and withdrawal rate of ground-water users) also may be considered.

Once ground-water monitoring has been initiated, it must continue throughout the active life, closure, and post-closure care periods. The post-closure period may last up to 30 years or more after the MSWLF unit has received a final cover.

In addition to establishing alternative schedules for compliance with ground-water monitoring requirements, the Director of an approved State may establish alternative schedules for certain sampling and analysis requirements of §§258.54 and 258.55, as well as corrective action requirements of §§258.56, 258.57, and 258.58. See Table 5-2 for a summary of notification requirements for which approved States may establish alternative schedules.

5.4.3 Technical Considerations

The rule allows approved States flexibility in establishing alternate ground-water monitoring compliance schedules. In setting an alternative schedule, the State will consider potential impacts to human health and the environment. Approved States have the option to address MSWLF units that have environmental problems immediately. In establishing alternative schedules for installing ground-water monitoring systems at existing MSWLF units, the Director of an approved State may consider information including the age and design of existing facilities. Using this type of information, in conjunction with a knowledge of the wastes disposed, the Director should be able to qualitatively assess or rank facilities based on their risk to local ground-water resources.

5.5 QUALIFICATIONS 40 CFR 258.50 (f)

5.5.1 Statement of Regulation

(f) For the purposes of this Subpart, a qualified ground-water scientist is a scientist or engineer who has received a baccalaureate or post-graduate degree in

Table 5-2. Summary of Notification Requirements

Section	Description
§258.51(d)(2)	14 day notification period after well installation certification by a qualified ground-water scientist (GWS)
§258.54(c)(1)	14 day notification period after finding a statistical increase over background for detection parameter(s)
§258.55(d)(1)	14 day notification period after detection of Appendix II constituents
§258.57(a)	14 day notification period after selection of corrective measures
§258.58(c)(4)	14 day notification period prior to implementing alternative measures
§258.58(f)	14 day notification period after remedy has been completed and certified by GWS

the natural sciences or engineering and has sufficient training and experience in ground-water hydrology and related fields as may be demonstrated by State registration, professional certifications, or completion of accredited university programs that enable that individual to make sound professional judgements regarding ground-water monitoring, contaminant fate and transport, and corrective action.

5.5.2 Applicability

The qualifications of a ground-water scientist are defined to ensure that professionals of appropriate capability and judgement are consulted when required by the Criteria. The ground-water scientist must possess the fundamental education and experience necessary to evaluate ground-water flow, ground-water monitoring systems, and ground-water monitoring techniques and methods. A ground-water scientist must understand and be able to apply methods to solve solute transport problems and evaluate ground-water remedial technologies. His or her education may include undergraduate or graduate studies in hydrogeology, ground-water hydrology, engineering hydrology, water resource engineering, geotechnical engineering, geology, ground-water modeling/ground-water computer modeling, and other aspects of the natural sciences. The qualified ground-water scientist must have a college degree but need not have professional certification, unless required at the State or Tribal level. Some States/Tribes may have certification programs for ground-water scientists; however, there are no recognized Federal certification programs.

5.5.3 Technical Considerations

A qualified ground-water scientist must certify work performed pursuant to the following provisions of the ground-water monitoring and corrective action requirements:

- No potential for migration demonstration (§258.50(b))
- Specifications concerning the number, spacing, and depths of monitoring wells (§258.51(d))
- Determination that contamination was caused by another source or that a statistically significant increase resulted from an error in sampling, analysis, or evaluation (§§258.54 (c)(3) and 258.55 (g)(2))
- Determination that compliance with a remedy requirement is not technically practicable (§258.58(c)(1))
- Completion of remedy (§258.58(f)).

The owner or operator must determine that the professional qualifications of the ground-water specialist are in accordance with the regulatory definition. In general, a certification is a signed document that transmits some finding (e.g., that monitoring wells were installed according to acceptable practices and standards at locations and depths appropriate for a given facility). The certification must be placed in the operating record of the facility, and the State Director must be notified that the certification has been made. Specific details of these certifications will be addressed in the order in which they appear in this guidance document.

Many State environmental regulatory agencies have ground-water scientists on staff. The owner or operator of a MSWLF unit or facility is not necessarily required to obtain certification from an independent (e.g., consulting) ground-water scientist and may, if agreed to by the Director in an approved State, obtain approval by the Director in lieu of certification by an outside individual.

5.6 GROUND-WATER MONITORING SYSTEMS 40 CFR §258.51 (a)(b)(d)

5.6.1 Statement of Regulation

(a) A ground-water monitoring system must be installed that consists of a sufficient number of wells, installed at appropriate locations and depths, to yield ground-water samples from the uppermost aquifer (as defined in §258.2) that:

(1) Represent the quality of background ground water that has not been affected by leakage from a unit. A determination of background quality may include sampling of wells that are not hydraulically upgradient of the waste management area where:

(i) Hydrogeologic conditions do not allow the owner or operator to determine what wells are hydraulically upgradient; or

(ii) Sampling at other wells will provide an indication of background ground-water quality that is as representative or more representative than that provided by the upgradient wells; and

(2) Represent the quality of ground water passing the relevant point of compliance specified by the Director of an approved State under §258.40(d) or at the waste management unit boundary in unapproved States. The downgradient monitoring system must be installed at the relevant point of compliance specified by the Director of an approved State under §258.40(d) or at the waste management unit boundary in unapproved States that ensures detection of ground-water contamination in the uppermost aquifer. When physical obstacles preclude installation of ground-water monitoring wells at the relevant point of compliance at existing units, the down-gradient monitoring system may be installed at the closest practicable distance hydraulically down-gradient from the relevant point of compliance or specified by the Director of an approved State under §258.40 that ensures detection of ground-water contamination in the uppermost aquifer.

(b) The Director of an approved State may approve a multi-unit ground-water monitoring system instead of separate ground-water monitoring systems for each MSWLF unit when the facility has several units, provided the multi-unit ground-water monitoring system meets the requirement of §258.51(a) and will be as protective of human health and the environment as individual monitoring systems for each MSWLF unit, based on the following factors:

(1) Number, spacing, and orientation of the MSWLF units;

(2) Hydrogeologic setting;

(3) Site history;

(4) Engineering design of the MSWLF units; and

(5) Type of waste accepted at the MSWLF units.

(c) (See Section 5.7 for technical guidance on monitoring well design and construction.)

(d) The number, spacing, and depths of monitoring systems shall be:

(1) Determined based upon site-specific technical information that must include thorough characterization of:

(i) Aquifer thickness, ground-water flow rate, ground-water flow direction including seasonal and temporal fluctuations in ground-water flow; and

(ii) Saturated and unsaturated geologic units and fill materials overlying the uppermost aquifer, materials comprising the uppermost aquifer, and materials comprising the confining unit defining the lower boundary of the uppermost aquifer; including, but not limited to: thicknesses, stratigraphy, lithology, hydraulic conductivities, porosities and effective porosities.

(2) Certified by a qualified ground-water scientist or approved by the Director of an approved State. Within 14 days of this certification, the owner or operator must notify the State Director that the certification has been placed in the operating record.

5.6.2 Applicability

The requirements for establishing a ground-water monitoring system pursuant to §258.51 apply to all new units, existing units, and lateral expansions of existing units according to the schedules identified in 40 CFR §258.50. A ground-water monitoring system consists of both background wells and wells located at the point of compliance or waste management unit boundary (i.e., downgradient wells). The ground-water monitoring network must be capable of detecting a release from the MSWLF unit. A sufficient number of monitoring wells must be located downgradient of the unit and be screened at intervals in the uppermost aquifer to ensure contaminant detection. Generally, upgradient wells are used to determine background ground-water quality.

The downgradient wells must be located at the relevant point of compliance specified by the Director of an approved State, or at the waste management unit boundary in States that are not in compliance with regulations. If existing physical structures obstruct well placement, the downgradient monitoring system should be placed as close to the relevant point of compliance as possible. Wells located at the relevant point of compliance must be capable of detecting contaminant releases from the MSWLF unit to the uppermost aquifer. As discussed earlier in the section pertaining to the designation of a relevant point of compliance (Section 4.4), the point of compliance must be no greater than 150 meters from the unit boundary.

The Director of an approved State may allow the use of a multi-unit ground-water monitoring system. MSWLF units in

States that are deemed not in compliance with the regulations must have a monitoring system for each unit.

A qualified ground-water scientist must certify that the number, spacing, and depths of the monitoring wells are appropriate for the MSWLF unit. This certification must be placed in the operating records. The State Director must be notified within 14 days that the certification was placed in the operating record.

5.6.3 Technical Considerations

The objective of a ground-water monitoring system is to intercept ground water that has been contaminated by leachate from the MSWLF unit. Early contaminant detection is important to allow sufficient time for corrective measures to be developed and implemented before sensitive receptors are significantly affected. To accomplish this objective, the monitoring wells should be located to sample ground water from the uppermost aquifer at the closest practicable distance from the waste management unit boundary. An alternative distance that is protective of human health and the environment may be granted by the Director of an approved State. Since the monitoring program is intended to operate through the post-closure period, the location, design, and installation of monitoring wells should address both existing conditions and anticipated facility development, as well as expected changes in ground-water flow.

Uppermost Aquifer

Monitoring wells must be placed to provide representative ground-water samples from the uppermost aquifer. The uppermost aquifer is defined in §258.2 as "the geologic formation nearest to the natural ground surface that is an aquifer, as well as lower aquifers that are hydraulically interconnected with this aquifer within the facility property boundary." These lower aquifers may be separated physically from the uppermost aquifer by less permeable strata (having a lower hydraulic conductivity) that are often termed aquitards. An aquitard is a less permeable geologic unit or series of closely layered units (e.g., silt, clay, or shale) that in itself will not yield significant quantities of water but will transmit water through its thickness. Aquitards may include thicker stratigraphic sequences of clays, shales, and dense, unfractured crystalline rocks (Freeze and Cherry, 1979).

To be considered part of the uppermost aquifer, a lower zone of saturation must be hydraulically connected to the uppermost aquifer within the facility property boundary. Generally, the degree of communication between aquifers is evaluated by ground-water pumping tests. Methods have been devised for use in analyzing aquifer test data. A summary is presented in *Handbook: Ground Water,* Vol. II (USEPA, 1991). The following discussions under this section (5.6.3) should assist the owner or operator in characterizing the uppermost aquifer and the hydrogeology of the site.

Determination of Background Ground-Water Quality

The goal of monitoring-well placement is to detect changes in the quality of ground water resulting from a release from the MSWLF unit. The natural chemical composition of ground water is controlled primarily by the mineral composition of the geologic unit comprising the aquifer. As ground water moves from one geologic unit to another, its chemical composition may change. To reduce the probability of detecting naturally occurring differences in ground-water quality between background and downgradient locations, only ground-water samples collected from the same geologic unit should be compared.

Ground-water quality in areas where the geology is complex can be difficult to characterize. As a result, the rule allows the owner or operator flexibility in determining where to locate wells that will be used to establish background water quality.

If the facility is new, ground-water samples collected from both upgradient and downgradient locations prior to waste disposal can be used to establish background water quality. The sampling should be conducted to account for both seasonal and spatial variability in ground-water quality.

Determining background ground-water quality by sampling wells that are not hydraulically upgradient may be necessary where hydrogeologic conditions do not allow the owner or operator to determine which wells are hydraulically upgradient. Additionally, background ground-water quality may be determined by sampling wells that provide ground-water samples as representative or more representative than those provided by upgradient wells. These conditions include the following:

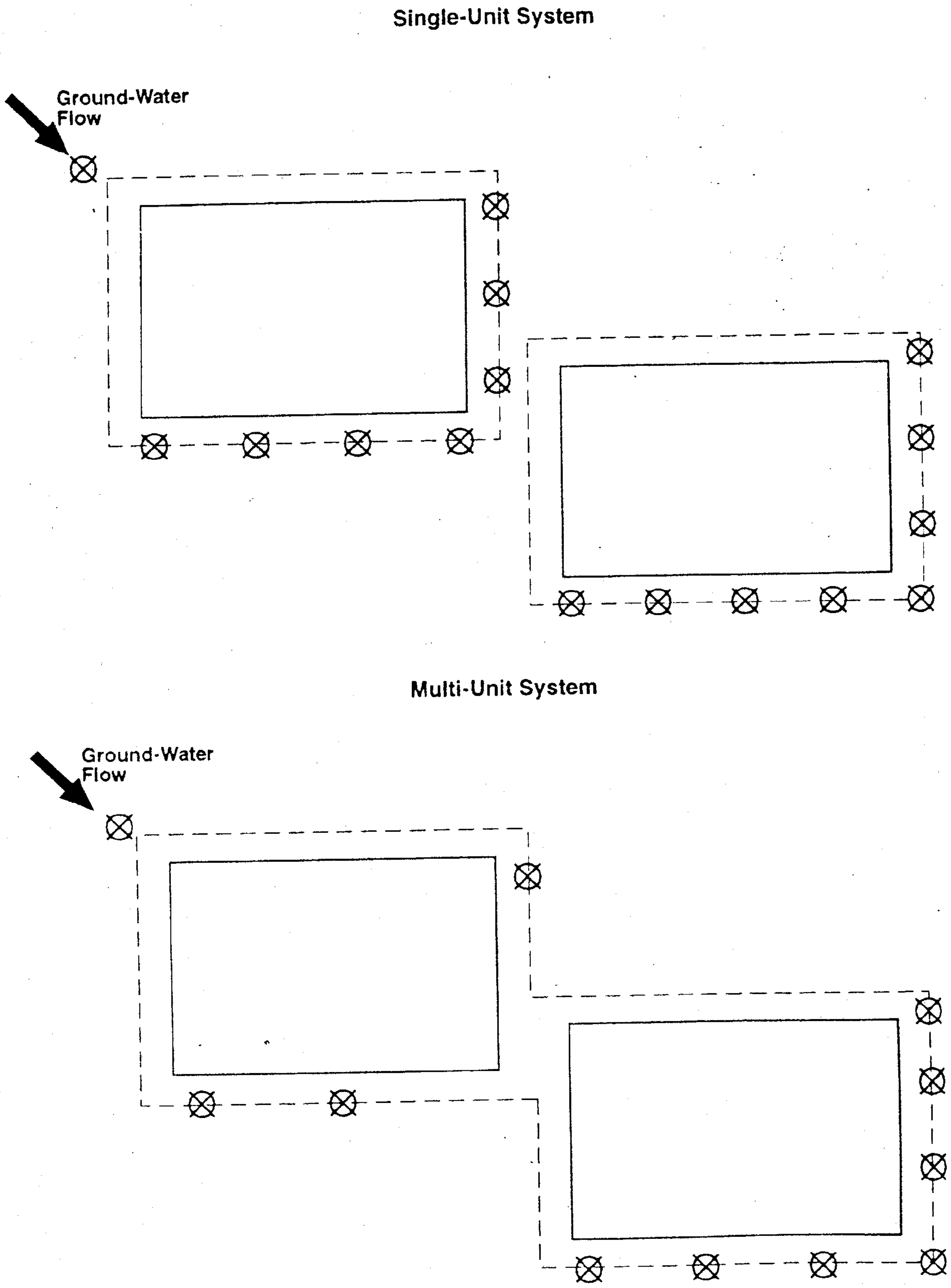
- The facility is located above an aquifer in which ground-water flow directions change seasonally.
- The facility is located near production wells that influence the direction of ground-water flow.
- Upgradient ground-water quality is affected by a source of contamination other than the MSWLF unit.
- The proposed or existing landfill overlies a ground-water divide or local source of recharge.
- Geologic units present at downgradient locations are absent at upgradient locations.
- Karst terrain or fault zones modify flow.
- Nearby surface water influences ground-water flow directions.
- Waste management areas are located close to a property boundary that is upgradient of the facility.

Multi-Unit Monitoring Systems

A multi-unit ground-water monitoring system does not have wells at individual MSWLF unit boundaries. Instead, an imaginary line is drawn around all of the units at the facility. (See Figure 5-1 for a comparison of single unit and multi-unit systems.) This line constitutes the relevant point of compliance. The option to establish a multi-unit monitoring system is restricted to facilities located in approved States. A multi-unit system must be approved by the Director of an approved State after consideration has been given to the:

- Number, spacing, and orientation of the MSWLF units

Figure 5-1. Comparison of Single Unit and Multi-Unit Monitoring System



- Hydrogeologic setting
- Site history
- Engineering design of the MSWLF units
- Type of wastes accepted at the facility.

The purpose of a multi-unit system is to reduce the number of monitoring wells that can provide the same information. The conceptual design of the multi-unit system should consider the use and management of the facility with respect to anticipated unit locations. In some cases, it may be possible to justify a reduction in the number of wells if the waste management units are aligned along the same flow path in the ground-water system.

The multi-unit monitoring system must provide a level of protection to human health and the environment that is comparable to monitoring individual units. The multi-unit system should allow adequate time after detection of contamination to develop and implement corrective measures before sensitive receptors are adversely affected.

Hydrogeological Characterization

Adequate monitoring-well placement depends on collecting and evaluating hydrogeological information that can be used to form a conceptual model of the site. The goal of a hydrogeological investigation is to acquire site-specific data concerning:

- The lateral and vertical extent of the uppermost aquifer
- The lateral and vertical extent of the upper and lower confining units/layers
- The geology at the owner's/operator's facility (e.g, stratigraphy, lithology, and structural setting)
- The chemical properties of the uppermost aquifer and its confining layers relative to local ground-water chemistry and wastes managed at the facility
- Ground-water flow, including:
  - The vertical and horizontal directions of ground-water flow in the uppermost aquifer
  - The vertical and horizontal components of the hydraulic gradient in the uppermost and any hydraulically connected aquifer
  - The hydraulic conductivities of the materials that comprise the upper-most aquifer and its confining units/layers
  - The average linear horizontal velocity of ground-water flow in the uppermost aquifer.

The elements of a program to characterize the hydrogeology of a site are discussed briefly in the sections that follow and are addressed in more detail in "RCRA Ground-Water Monitoring: Draft Technical Guidance" (USEPA, 1992a).

Prior to initiating a field investigation, the owner or operator should perform a preliminary investigation. The preliminary investigation will involve reviewing all available information about the site, which may consist of:

- Information on the waste management history of the site, including:
  - A chronological history of the site, including descriptions of wastes managed on-site
  - A summary of documented releases
  - Details on the structural integrity of the MSWLF unit and physical controls on waste migration
- A literature review, including:
  - Reports of research performed in the area of the site
  - Journal articles
  - Studies and reports available from local, regional, and State offices (e.g., geologic surveys, water boards, and environmental agencies)
  - Studies available from Federal offices, such as USGS or USEPA
- Information from file searches, including:
  - Reports of previous investigations at the site
  - Geological and environmental assessment data from State and Federal reports.

The documentation itemized above is by no means a complete listing of information available for a preliminary investigation. Many other sources of hydrogeological information may be available for review during the preliminary investigation.

Characterizing Site Geology

After the preliminary investigation is complete, the owner/operator will have information that he/she can use to develop a plan to characterize site hydrogeology further.

Nearly all hydrogeological investigations include a subsurface boring program. A boring program is necessary to define site hydrogeology and the small-scale geology of the area beneath the site. The program usually requires more than one iteration. The objective of the initial boreholes is to refine the conceptual model of the site derived from the preliminary investigation.

The subsurface boring program should be designed as follows:

- The initial number of boreholes and their spacing is based on the information obtained during the preliminary investigation.
- Additional boreholes should be installed as needed to provide more information about the site.
- Samples should be collected from the borings at changes in lithology. For boreholes that will be completed as monitoring wells, at least one sample should be collected from the interval that will be the screened interval. Boreholes that will not be completed as monitoring wells must be properly decommissioned.

Geophysical techniques, cone penetrometer surveys, mapping programs, and laboratory analyses of borehole samples can be used to plan and supplement the subsurface boring program. Downhole geophysical techniques include electric, sonic, and nuclear logging. Surface geophysical techniques include seismic reflection and refraction, as well as electromagnetic induction and resistivity.

The data obtained from the subsurface boring program should enable the owner or operator to identify:

- Lithology, soil types, and stratigraphy
- Zones of potentially high hydraulic conductivity
- The presence of confining formations or layers
- Unpredicted geologic features, such as fault zones, cross-cutting structures, and pinch-out zones
- Continuity of petrographic features, such as sorting, grain size distribution, and cementation
- The potentiometric surface or water table.

Characterizing Ground-Water Flow Beneath the Site

In addition to characterizing site geology, the owner/operator should characterize the hydrology of the uppermost aquifer and its confining layer(s) at the site. The owner or operator should install wells and/or piezometers to assist in characterizing site hydrology. The owner/operator should determine and assess:

- The direction(s) and rate(s) of ground-water flow (including both horizontal and vertical components of flow)
- Seasonal/temporal, natural, and artificially induced (e.g., off-site production well-pumping, agricultural use) short-term and long-term variations in ground-water elevations and flow patterns
- The hydraulic conductivities of the stratigraphic units at the site, including vertical hydraulic conductivity of the confining layer(s).

Determining Ground-Water Flow Direction and Hydraulic Gradient

Installing monitoring wells that will provide representative background and downgradient water samples requires a thorough understanding of how ground water flows beneath a site. Developing such an understanding requires obtaining information regarding both ground-water flow direction(s) and hydraulic gradient. Ground-water flow direction can be thought of as the idealized path that ground-water follows as it passes through the subsurface. Hydraulic gradient (i) is the change in static head per unit of distance in a given direction. The static head is defined as the height above a standard datum of the surface of a column of water (or other liquid) that can be supported by the static pressure at a given point (i.e., the sum of the elevation head and pressure head).

To determine ground-water flow directions and hydraulic gradient, owners and operators should develop and implement a water level-monitoring program. This program should be structured to provide precise water level measurements in a sufficient number of piezometers or wells at a sufficient frequency to gauge both seasonal average flow directions and temporal fluctuations in ground-water flow directions. Ground-water flow direction(s) should be determined from water levels measured in wells screened in the same hydro-stratigraphic position. In heterogeneous geologic settings (i.e., settings in which the hydraulic conductivities of the subsurface materials vary with location in the subsurface), long well screens can intercept stratigraphic horizons with different (e.g., contrasting) ground-water flow directions and different heads. In this situation, the resulting water levels will not provide the depth-discrete head measurements required for accurate determination of the ground-water flow direction.

In addition to evaluating the component of ground-water flow in the horizontal direction, a program should be undertaken to assess the vertical component of ground-water flow. Vertical ground-water flow information should be based, at least in part, on field data from wells and piezometers, such as multi-level wells, piezometer clusters, or multi-level sampling devices, where appropriate. The following sections provide acceptable methods for assessing the vertical and horizontal components of flow at a site.

Ground-Water Level Measurements

To determine ground-water flow directions and ground-water flow rates, accurate water level measurements (measured to the nearest 0.01 foot) should be obtained. Section 5.8 delineates procedures for obtaining water level measurements. At facilities where it is known or plausible that immiscible contaminants (i.e., non-aqueous phase liquids (NAPLs)) occur (or are determined to be potentially present after considering the waste types managed at the facility) in the subsurface at the facility, both the depth(s) to the immiscible layer(s) and the thickness(es) of the immiscible layer(s) in the well should be recorded.

For the purpose of measuring total head, piezometers and wells should have as short a screened interval as possible. Specifically, the screens in piezometers or wells that are used to measure head should generally be less than 10 feet long. In circumstances including the following, well screens longer than 10 feet may be warranted:

- Natural water level fluctuations necessitate a longer screen length.
- The interval monitored is slightly greater than the appropriate screen length (e.g., the interval monitored is 12 feet thick).
- The aquifer monitored is homogeneous and extremely thick (e.g., greater than 300 feet); thus, a longer screen (e.g., a 20-foot screen) represents a fairly discrete interval.

The head measured in a well with a long screened interval is a function of all of the different heads over the entire length of the screened interval. Care should be taken when interpreting water levels collected from wells that have long screened intervals (e.g., greater than 10 feet).

The water-level monitoring program should be structured to provide precise water level measurements in a sufficient number of piezometers or wells at a sufficient frequency to gauge both seasonal average flow directions and temporal fluctuations in ground-water flow directions. The owner/operator should determine and assess seasonal/temporal, natural, and artificially induced (e.g., off-site production well-pumping, agricultural use) short-term and long-term variations in ground-water elevations, ground-water flow patterns, and ground-water quality.

Establishing Horizontal Flow Direction and the Horizontal Component of Hydraulic Gradient

After the water level data and measurement procedures are reviewed to determine that they are accurate, the data should be used to:

- Construct potentiometric surface maps and water table maps based on the distribution of total head. The data used to develop water table maps should be from piezometers or wells screened across the water table. The data used to develop potentiometric surface maps should be from piezometers or wells screened at approximately the same elevation in the same hydrostratigraphic unit;

- Determine the horizontal direction(s) of ground-water flow by drawing flow lines on the potentiometric surface map or water table map (i.e., construct a flow net);

- Calculate value(s) for the horizontal and vertical components of hydraulic gradient.

Methods for constructing potentiometric surface and water table maps, constructing flow nets, and determining the direction(s) of ground-water flow are provided by USEPA (1989c) and Freeze and Cherry (1979). Methods for calculating hydraulic gradient are provided by Heath (1982) and USEPA (1989c).

A potentiometric surface or water table map will give an approximate idea of general ground-water flow directions. However, to locate monitoring wells properly, ground-water flow direction(s) and hydraulic gradient(s) should be established in both the horizontal and vertical directions and over time at regular intervals (e.g., over a 1-year period at 3-month intervals).

Establishing Vertical Flow Direction and the Vertical Component of Hydraulic Gradient

To make an adequate determination of the ground-water flow directions, the vertical component of ground-water flow should be evaluated directly. This generally requires the installation of multiple piezometers or wells in clusters or nests, or the installation of multi-level wells or sampling devices. A piezometer or well nest is a closely spaced group of piezometers or wells screened at different depths, whereas a multi-level well is a single device. Both piezometer/well nests and multi-level wells allow for the measurement of vertical variations in hydraulic head.

When reviewing data obtained from multiple placement of piezometers or wells in single boreholes, the construction details of the well should be carefully evaluated. Not only is it extremely difficult to seal several piezometers/wells at discrete depths within a single borehole, but sealant materials may migrate from the seal of one piezometer/well to the screened interval of another piezometer/well. Therefore, the design of a piezometer/well nest should be considered carefully. Placement of piezometers/wells in closely spaced boreholes, where piezometers/wells have been screened at different, discrete depth intervals, is likely to produce more accurate information. The primary concerns with the installation of piezometers/wells in closely spaced, separate boreholes are: 1) the disturbance of geologic and soil materials that occurs when one piezometer is installed may be reflected in the data obtained from another piezometer located nearby, and 2) the analysis of water levels measured in piezometers that are closely spaced, but separated horizontally, may produce imprecise information regarding the vertical component of ground-water flow. The limitations of installing multiple piezometers either in single or separate boreholes may be overcome by the installation of single multi-level monitoring wells or sampling devices in single boreholes. The advantages and disadvantages of these types of devices are discussed by USEPA (1989f).

The owner or operator should determine the vertical direction(s) of ground-water flow using the water levels measured in multi-level wells or piezometer/well nests to construct flow nets. Flow nets should depict the piezometer/well depth and length of the screened interval. It is important to portray the screened interval accurately on the flow net to ensure that the piezometer/well is actually monitoring the desired water-bearing unit. A flow net should be developed from information obtained from piezometer/ well clusters or nests screened at different, discrete depths. Detailed guidance for the construction and evaluation of flow nets in cross section (vertical flow nets) is provided by USEPA (1989c).

Further information can be obtained from Freeze and Cherry (1979).

Determining Hydraulic Conductivity

Hydraulic conductivity is a measure of a material's ability to transmit water. Generally, poorly sorted silty or clayey materials have low hydraulic conductivities, whereas well-sorted sands and gravels have high hydraulic conductivities. An aquifer may be classified as either homogeneous or heterogeneous and either isotropic or anisotropic according to the way its hydraulic conductivity varies in space. An aquifer is <u>homogeneous</u> if the hydraulic conductivity is independent of location within the aquifer; it is <u>heterogeneous</u> if hydraulic conductivities are dependent on location within the aquifer. If the hydraulic conductivity is independent of the direction of measurement at a point in a geologic formation, the formation is <u>isotropic</u> at that point. If the hydraulic conductivity varies with the direction of measurement at a point, the formation is <u>anisotropic</u> at that point.

Determining Hydraulic Conductivity Using Field Methods

Sufficient aquifer testing (i.e., field methods) should be performed to provide representative estimates of hydraulic conductivity. Acceptable field methods include conducting aquifer tests with single wells, conducting aquifer tests with multiple wells, and using flowmeters. This section provides brief overviews of these methods, including two methods for obtaining vertically discrete measurements of hydraulic conductivity. The identified references provide detailed descriptions of the methods summarized in this section.

A commonly used test for determining horizontal hydraulic conductivity with a single well is the slug test. A slug test is performed by suddenly adding, removing, or displacing a known volume of water from a well and observing the time that it takes for the water level to recover to its original level (Freeze and Cherry, 1979). Similar results can be achieved by pressurizing the well casing, depressing the water level, and suddenly releasing the pressure to simulate the removal of water from the well. In most cases, EPA recommends that water not be introduced into wells during aquifer tests to avoid altering ground-water chemistry. Single-well tests are limited in scope to the area directly adjacent to the well screen. The vertical extent of the well screen generally defines the part of the geologic formation that is being tested.

A modified version of the slug test, known as the multilevel slug test, is capable of providing depth-discrete measurements of hydraulic conductivity. The drawback of the multilevel slug test is that the test relies on the ability of the investigator to isolate a portion of the aquifer using a packer. Nevertheless, multilevel slug tests, when performed properly, can produce reliable measurements of hydraulic conductivity.

Multiple-well tests involve withdrawing water from, or injecting water into, one well, and obtaining water level measurements over time in observation wells. Multiple-well tests are often performed as pumping tests in which water is pumped from one well and drawdown is observed in nearby wells. A step-drawdown test should precede most pumping tests to determine an appropriate discharge rate. Aquifer tests conducted with wells screened in the same water-bearing zone can be used to provide hydraulic conductivity data for that zone. Multiple-well tests for hydraulic conductivity characterize a greater proportion of the subsurface than single-well tests and, thus, provide average values of hydraulic conductivity. Multiple-well tests require measurement of parameters similar to those required for single-well tests (e.g., time, drawdown). When using aquifer test data to determine aquifer parameters, it is important that the solution assumptions can be applied to site conditions. Aquifer test solutions are available for a wide variety of hydrogeologic settings, but are often applied incorrectly by inexperienced persons. Incorrect assumptions regarding hydrogeology (e.g., aquifer boundaries, aquifer lithology, and aquifer thickness) may translate into incorrect estimations of hydraulic conductivity. A qualified ground-water scientist with experience in designing and interpreting aquifer tests should be consulted to ensure that aquifer test solution methods fit the hydrogeologic setting. Kruseman and deRidder (1989) provide a comprehensive discussion of aquifer tests.

Multiple-well tests conducted with wells screened in different water-bearing zones furnish information concerning hydraulic communication among the zones. Water levels in these zones should be monitored during the aquifer test to determine the type of aquifer system (e.g., confined, unconfined, semi-confined, or semi-unconfined) beneath the site, and their leakance (coefficient of leakage) and drainage factors (Kruseman and deRidder, 1989). A multiple-well aquifer test should be considered at every site as a method to establish the vertical extent of the uppermost aquifer and to evaluate hydraulic connection between aquifers.

Certain aquifer tests are inappropriate for use in karst terrains characterized by a well-developed conduit flow system, and they also may be inappropriate in fractured bedrock. When a well located in a karst conduit or a large fracture is pumped, the water level in the conduit is lowered. This lowering produces a drawdown that is not radial (as in a granular aquifer) but is instead a trough-like depression parallel to the pumped conduit or fracture. Radial flow equations do not apply to drawdown data collected during such a pump test. This means that a conventional semi-log plot of drawdown versus time is inappropriate for the purpose of determining the aquifer's transmissivity and storativity. Aquifer tests in karst aquifers can be useful, but valid determinations of hydraulic conductivity, storativity, and transmissivity may be impossible. However, an aquifer test can provide information on the presence of conduits, on storage characteristics, and on the percentage of Darcian flow. McGlew and Thomas (1984) provide a more detailed discussion of the appropriate use of aquifer tests in fractured bedrock and on the suitable interpretation of test data. Dye tracing also is used to determine the rate and direction of ground-water flow in karst settings (Section 5.2.4).

Several additional factors should be considered when planning an aquifer test:

- Owners and operators should provide for the proper storage and disposal of potentially contaminated ground water pumped from the well system.

- Owners and operators should consider the potential effects of pumping on existing plumes of contaminated ground water.

- In designing aquifer tests and interpreting aquifer test data, owners/operators should account and correct for seasonal, temporal, and anthropogenic effects on the potentiometric surface or water table. This is usually done by installing piezometers outside the influence of the stressed aquifer. These piezometers should be continuously monitored during the aquifer test.

- Owners and operators should be aware that, in a very high hydraulic conductivity aquifer, the screen size and/or filter pack used in the test well can affect an aquifer test. If a very small screen size is used, and the pack is improperly graded, the test may reflect the characteristics of the filter pack, rather than the aquifer.

- EPA recommends the use of a step-drawdown test to provide a basis for selecting discharge rates prior to conducting a full-scale pumping test. This will ensure that the pumping rate chosen for the subsequent pumping test(s) can be sustained without exceeding the available drawdown of the pumped wells. In addition, this test will produce a measurable drawdown in the observation wells.

Certain flowmeters recently have been recognized for their ability to provide accurate and vertically discrete measurements of hydraulic conductivity. One of these, the impeller flowmeter, is available commercially. More sensitive types of flowmeters (i.e., the heat-pulse flowmeter and electromagnetic flowmeter) should be available in the near future. Use of the impeller flowmeter requires running a caliper log to measure the uniformity of the diameter of the well screen. The well is then pumped with a small pump operated at a constant flow rate. The flowmeter is lowered into the well, and the discharge rate is measured every few feet by raising the flowmeter in the well. Hydraulic conductivity values can be calculated from the recorded data using the Cooper-Jacob (1946) formula for horizontal flow to a well. Use of the impeller flowmeter is limited at sites where the presence of low permeability materials does not allow pumping of the wells at rates sufficient to operate the flowmeter. The application of flowmeters in the measure of hydraulic conductivity is described by Molz et al. (1990) and Molz et al. (1989).

Determining Hydraulic Conductivity Using Laboratory Methods

It may be beneficial to use laboratory measurements of hydraulic conductivity to augment the results of field tests. However, field methods provide the best estimates of hydraulic conductivity in most cases. Because of the limited sample size, laboratory tests can fail to account for secondary porosity features, such as fractures and joints, and hence, can greatly underestimate overall aquifer hydraulic conductivities. Laboratory tests may provide valuable information about the vertical component of hydraulic conductivity of aquifer materials. However, laboratory test results always should be confirmed by field measurements, which sample a much larger portion of the aquifer. In addition, laboratory test results can be profoundly affected by the test method selected and by the manner in which the tests are carried out (e.g., the extent to which sample collection and preparation have changed the in situ hydraulic properties of the tested material). Special attention should be given to the selection of the appropriate test method and test conditions and to quality control of laboratory results. McWhorter and Sunada (1977), Freeze and Cherry (1979), and Sevee (1991) discuss determining hydraulic conductivity in the laboratory. Laboratory tests may provide the best estimates of hydraulic conductivity for materials in the unsaturated zone, but they are likely to be less accurate than field methods for materials in the saturated zone (Cantor et al., 1987).

Determining Ground-Water Flow Rate

The calculation of the average ground-water flow rate (average linear velocity of ground-water flow), or seepage velocity, is discussed in detail in USEPA (1989c), in Freeze and Cherry (1979), and in Kruseman and deRidder (1989). The average linear velocity of ground-water flow ($\bar{v}$) is a function of hydraulic conductivity (K), hydraulic gradient (i), and effective porosity (n_e):

$$\bar{v} = -\frac{Ki}{n_e}$$

Methods for determining hydraulic gradient and hydraulic conductivity have been presented previously. Effective porosity, the percentage of the total volume of a given mass of soil, unconsolidated material, or rock that consists of interconnected pores through which water can flow, should be estimated from laboratory tests or from values cited in the literature. (Fetter (1980) provides a good discussion of effective porosity. Barari and Hedges (1985) provide default values for effective porosity.) USEPA (1989c) provides methods for determining flow rates in heterogeneous and/or anisotropic systems and should be consulted prior to calculating flow rates.

Interpreting and Presenting Data

The following sections offer guidance on interpreting and presenting hydrogeologic data collected during the site characterization process. Graphical representations of data, such as cross sections and maps, are typically extremely helpful both when evaluating data and when presenting data to interested individuals.

Interpreting Hydrogeologic Data

Once the site characterization data have been collected, the following tasks should be undertaken to support and develop the interpretation of these data:

- Review borehole and well logs to identify major rock, unconsolidated material, and soil types and establish their horizontal and vertical extent and distribution.
- From borehole and well log (and outcrop, where available) data, construct representative cross-sections for each MSWLF unit, one in the direction of ground-water flow and one orthogonal to ground-water flow.
- Identify zones of suspected high hydraulic conductivity, or structures likely to influence contaminant migration through the unsaturated and saturated zones.
- Compare findings with other studies and information collected during the preliminary investigation to verify the collected information.
- Determine whether laboratory and field data corroborate and are sufficient to define petrology, effective porosity, hydraulic conductivity, lateral and vertical stratigraphic relationships, and ground-water flow directions and rates.

After the hydrogeologic data are interpreted, the findings should be reviewed to:

- Identify information gaps
- Determine whether the collection of additional data or reassessment of existing data is required to fill in the gaps
- Identify how information gaps are likely to affect the ability to design a RCRA monitoring system.

Generally, lithologic data should correlate with hydraulic properties (e.g., clean, well-sorted, unconsolidated sands should exhibit high hydraulic conductivity). Additional boreholes should be drilled and additional samples should be collected to describe the hydrogeology of the site if the investigator is unable to 1) correlate stratigraphic units between borings, 2) identify zones of potentially high hydraulic conductivity and the thickness and lateral extent of these zones, or 3) identify confining formations/layers and the thickness and lateral extent of these formation layers.

When establishing the locations of wells that will be used to monitor ground water in hydrogeologic settings characterized by ground-water flow in porous media, the following should be documented:

- The ground-water flow rate should be based on accurate measurements of hydraulic conductivity and hydraulic gradient and accurate measurements or estimates of effective porosity

- The horizontal and vertical components of flow should be accurately depicted in flow nets and based on valid data

- Any seasonal or temporal variations in the water table or potentiometric surface, and in vertical flow components, should be determined.

Once an understanding of horizontal and vertical ground-water flow has been established, it is possible to estimate where monitoring wells will most likely intercept contaminant flow.

Presenting Hydrogeologic Data

Subsequent to the generation and interpretation of site-specific geologic data, the data should be presented in geologic cross-sections, topographic maps, geologic maps, and soil maps. The Agency suggests that owners/operators obtain or prepare and review topographic, geologic, and soil maps of the facility, in addition to site maps of the facility and MSWLF units. In cases where suitable maps are not available, or where the information contained on available maps is not complete or accurate, detailed mapping of the site should be performed by qualified and experienced individuals. An aerial photograph and a topographic map of the site should be included as part of the presentation of hydrogeologic data. The topographic map should be constructed under the supervision of a qualified surveyor and should provide contours at a maximum of 2-foot intervals.

Geologic and soil maps should be based on rock, unconsolidated material, and soil identifications gathered from borings and outcrops. The maps should use colors or symbols to represent each soil, unconsolidated material, and rock type that outcrops on the surface. The maps also should show the locations of outcrops and all borings placed during the site characterization. Geologic and soil maps are important because they can provide information describing how site geology fits into the local and regional geologic setting.

Structure contour maps and isopach maps should be prepared for each water-bearing zone that comprises the uppermost aquifer and for each significant confining layer, especially the one underlying the uppermost aquifer. A structure contour map depicts the configuration (i.e., elevations) of the upper or lower surface or boundary of a particular geologic or soil formation, unit, or zone. Structure contour maps are especially important in understanding dense non-aqueous phase liquid (DNAPL) movement because DNAPLs (e.g., tetrachloroethylene) may migrate in the direction of the dip of lower permeability units. Separate structure contour maps should be constructed for the upper and lower surfaces (or contacts) of each zone of interest. Isopach maps should depict contours that indicate the thickness of each zone. These maps are generated from borings and geologic logs and from geophysical measurements. In conjunction with cross-sections, isopach maps may be used to help determine monitoring well locations, depths, and screen lengths during the design of the detection monitoring system.

A potentiometric surface map or water table map should be prepared for each water-bearing zone that comprises the uppermost aquifer. Potentiometric surface and water table maps should show both the direction and rate of ground-water flow and the locations of all piezometers and wells on which they are based. The water level measurements for all piezometers and wells on which the potentiometric surface map or water table map is based should be shown on the potentiometric surface or water table map. If seasonal or temporal variations in ground-water flow occur at the site, a sufficient number of potentiometric surface or water table maps should be prepared to show these variations. Potentiometric surface and water table maps can be combined with structure contour maps for a particular formation or unit. An adequate number of cross sections should be prepared to depict significant stratigraphic and structural trends and to reflect stratigraphic and structural features in relation to local and regional ground-water flow.

Hydrogeological Report

The hydrogeological report should contain, at a minimum:

- A description of field activities
- Drilling and/or well construction logs
- Analytical data
- A discussion and interpretation of the data
- Recommendations to address data gaps.

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

Monitoring Well Placement

This section separately addresses the lateral placement and the vertical sampling intervals of point of compliance wells. However, these two aspects of well placement should be evaluated together in the design of the monitoring system. Site-specific hydrogeologic data obtained during the site characterization should be used to determine the lateral placement of detection monitoring wells and to select the length and vertical position of monitoring well intakes. Potential pathways for contaminant migration are three-dimensional. Consequently, the design of a detection monitoring network that intercepts these potential pathways requires a three-dimensional approach.

Lateral Placement of Point of Compliance Monitoring Wells

Point of compliance monitoring wells should be as close as physically possible to the edge of the MSWLF unit(s) and should be screened in all transmissive zones that may act as contaminant transport pathways. The lateral placement of monitoring wells should be based on the number and spatial distribution of potential contaminant migration pathways and on the depths and thicknesses of stratigraphic horizons that can serve as contaminant migration pathways.

Point of compliance monitoring wells should be placed laterally along the downgradient edge of the MSWLF unit to intercept potential pathways for contaminant migration. The local ground-water flow direction and gradient are the major factors in determining the lateral placement of point of compliance wells. In a homogeneous, isotropic hydrogeologic setting, well placement can be based on general aquifer characteristics (e.g., direction and rate of ground-water flow), and potential contaminant fate and transport characteristics (e.g., advection, dispersion). More commonly, however, geology is variable and preferential pathways exist that control the migration of contaminants. These types of heterogeneous, anisotropic geologic settings can have numerous, discrete zones within which contaminants may migrate.

Potential migration pathways include zones of relatively high intrinsic (matrix) hydraulic conductivities, fractured/faulted zones, and subsurface material that may increase in hydraulic conductivity if the material is exposed to waste(s) managed at the site (e.g., a limestone layer that underlies an acidic waste). In addition to natural hydrogeologic features, human-made features may influence the ground-water flow direction and, thus, the lateral placement of point of compliance wells. Such human-made features include ditches, areas where fill material has been placed, buried piping, buildings, leachate collection systems, and adjacent disposal units. The lateral placement of monitoring wells should be based on the number and spatial distribution of potential contaminant migration pathways and on the depths and thicknesses of stratigraphic horizons that can serve as contaminant migration pathways.

In some settings, the ground-water flow direction may reverse seasonally (depending on precipitation), change as a result of tidal influences or river and lake stage fluctuations, or change temporally as a result of well-pumping or changing land use patterns. In other settings, ground water may flow away from the waste management area in all directions. In such cases, EPA recommends that monitoring wells be installed on all sides (or in a circular pattern) around the waste management area to allow for the detection of contamination. In these cases, certain wells may be downgradient only part of the time, but such a configuration should ensure that releases from the unit will be detected.

The lateral placement of monitoring wells also should be based on the physical/chemical characteristics of the contaminants of concern. While the restriction of liquids in MSWLFs may limit the introduction of hazardous constituents into landfills, it is important to consider the physical/chemical characteristics of contaminants when designing the well system. These characteristics include solubility, Henry's Law constant, partition coefficients, specific gravity, contaminant reaction or degradation products, and the potential for contaminants to degrade confining layers. For example, contaminants with low solubilities and high specific gravities that occur as DNAPLs may migrate in the subsurface in directions different from the direction of ground-water flow. Therefore, in situations where the release of DNAPLs is a concern, the lateral placement of compliance point ground-water monitoring wells should not necessarily only be along the downgradient edge of the MSWLF unit. Considering both contaminant characteristics and hydrogeologic properties is important when determining the lateral placement of monitoring wells.

Vertical Placement and Screen Lengths

Proper selection of the vertical sampling interval is necessary to ensure that the monitoring system is capable of detecting a release from the MSWLF unit. The vertical position and lengths of well intakes are functions of (1) hydro-geologic factors that determine the distribution of, and fluid/vapor phase transport within, potential pathways of contaminant migration to and within the uppermost aquifer, and (2) the chemical and physical characteristics of contaminants that control their transport and distribution in the subsurface. Well intake length also is determined by the need to obtain vertically discrete ground-water samples. Owners and operators should determine the probable location, size, and geometry of potential contaminant plumes when selecting well intake positions and lengths.

Site-specific hydrogeologic data obtained during the site characterization should be used to select the length and vertical position of monitoring well intakes. The vertical positions and lengths of monitoring well intakes should be based on the number and spatial distribution of potential contaminant migration pathways and on the depths and thicknesses of stratigraphic horizons that can serve as contaminant migration pathways. Figure 5-2 illustrates examples of complex stratigraphy that would require multiple vertical monitoring intervals.

The depth and thickness of a potential contaminant migration pathway can be determined from soil, unconsolidated material, and rock samples collected during the boring program, and from samples collected while drilling the monitoring well. Direct physical data can be supplemented by geophysical data, available regional/local hydrogeological data, and other data that provide the vertical distribution of hydraulic conductivity. The vertical sampling interval is not necessarily synonymous with aquifer thickness. Monitoring wells are often screened at intervals that represent a portion of the thickness of the aquifer. When monitoring an unconfined aquifer, the well screen typically should be positioned so that a portion of the well screen is in the saturated zone and a portion of the well screen is in the unsaturated zone (i.e., the well screen straddles the water table). While the restriction of liquids in MSWLFs may limit the introduction of hazardous constituents into landfills, it is important to consider the physical/chemical characteristics of contaminants when designing the well system.

The vertical positions and lengths of monitoring well intakes should be based on the same physical/chemical characteristics of the contaminants of concern that influence the lateral placement of monitoring wells. Considering both contaminant characteristics and hydrogeologic properties is important when choosing the vertical position and length of the well intake. Some contaminants may migrate within very narrow zones. Of course, for well placement at a new site, it is unlikely that the owner or operator will be able to assess contaminant characteristics.

Different transport processes control contaminant migration depending on whether the contaminant dissolves or is immiscible in water. Immiscible

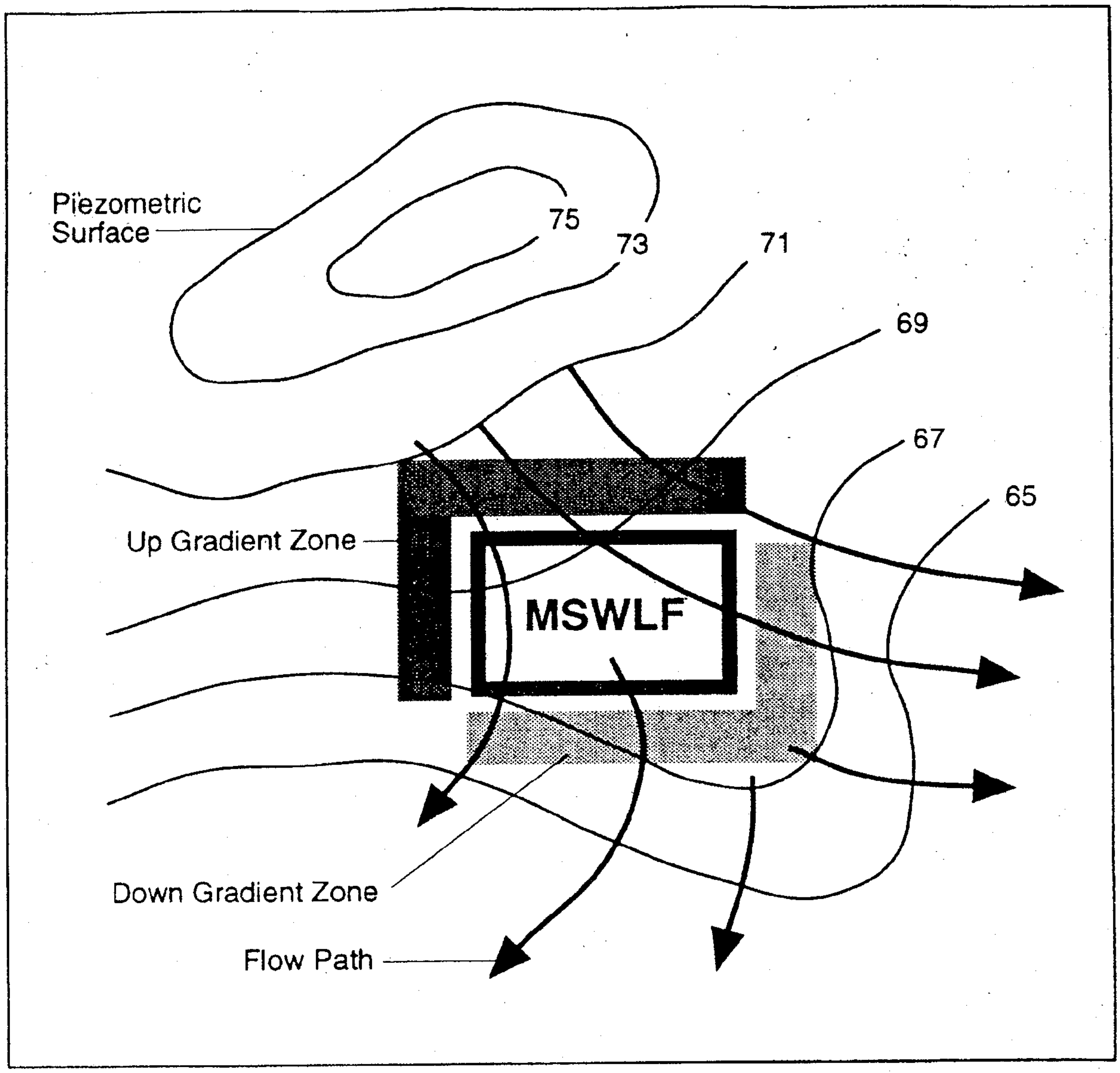


Figure 5-2
Upgradient and Downgradient Designations for Idealized MSWLF

contaminants may occur as light non aqueous phase liquids (LNAPLs), which are lighter than water, and DNAPLs, which are denser than water. LNAPLs migrate in the capillary zone just above the water table. Wells installed to monitor LNAPLs should be screened at the water table/capillary zone interface, and the screened interval should intercept the water table at its minimum and maximum elevation. LNAPLs may become trapped in residual form in the vadose zone and become periodically remobilized and contribute further to aquifer contamination, either as free phase or dissolved phase contaminants, as the water table fluctuates and precipitation infiltrates the subsurface.

The migration of free-phase DNAPLs may be influenced primarily by the geology, rather than the hydrogeology, of the site. That is, DNAPLs migrate downward through the saturated zone due to density and then migrate by gravity along less permeable geologic units (e.g., the slope of confining units, the slope of clay lenses in more permeable strata, bedrock troughs), even in aquifers with primarily horizontal ground-water flow. Consequently, if wastes disposed at the site are anticipated to exist in the subsurface as a DNAPL, the potential DNAPL should be monitored:

- At the base of the aquifer (immediately above the confining layer)
- In structural depressions (e.g., bedrock troughs) in lower hydraulic conductivity geologic units that act as confining layers
- Along lower hydraulic conductivity lenses and units within units of higher hydraulic conductivity
- "Down-the-dip" of lower hydraulic conductivity units that act as confining layers, both upgradient and downgradient of the waste management area.

Because of the nature of DNAPL migration (i.e., along structural, rather than hydraulic, gradients), wells installed to monitor DNAPLs may need to be installed both upgradient and downgradient of the waste management area. It may be useful to construct a structure contour map of lower permeability strata and identify lower permeability lenses upgradient and downgradient of the unit along which DNAPLs may migrate. The wells can then be located accordingly.

The lengths of well screens used in ground-water monitoring wells can significantly affect their ability to intercept releases of contaminants. The complexity of the hydrogeology of a site is an important consideration when selecting the lengths of well screens. Most hydrogeologic settings are complex (heterogeneous and anisotropic) to a certain degree. Highly heterogeneous formations require shorter well screens to allow sampling of discrete portions of the formation that can serve as contaminant migration pathways. Well screens that span more than a single saturated zone or a single contaminant migration pathway may cause cross-contamination of transmissive units, thereby increasing the extent of contamination. Well intakes should be installed in a single saturated zone. Well intakes (e.g., screens) and filter pack materials should not interconnect, or promote the interconnection of, zones that are separated by a confining layer.

Even in hydrologically simple formations, or within a single potential pathway for contaminant migration, the use of shorter well screens may be necessary to detect contaminants concentrated at particular depths. A contaminant may be concentrated at a particular depth because of its physical/chemical properties and/or because of hydrogeologic properties. In homogeneous formations, a long well screen can permit excessive amounts of uncontaminated formation water to dilute the contaminated ground water entering the well. At best, dilution can make contaminant detection difficult; at worst, contaminant detection is impossible if the concentrations of contaminants are diluted to levels below the detection limits for the prescribed analytical methods. The use of shorter well screens allows for contaminant detection by reducing excessive dilution. When placed at depths of predicted preferential flow, shorter well screens are effective in monitoring the aquifer or the portion of the aquifer of concern.

Generally, screen lengths should not exceed 10 feet. However, certain hydrogeologic settings may warrant or necessitate the use of longer well screens for adequate detection monitoring. Unconfined aquifers with widely fluctuating water tables may require longer screens to intercept the water table surface at both its maximum and minimum elevations and to provide monitoring for the presence of contaminants that are less dense than water. Saturated zones that are slightly greater in thickness than the appropriate screen length (e.g., 12 feet thick) may warrant monitoring with longer screen lengths. Extremely thick homogeneous aquifers (e.g., greater than 300 feet) may be monitored with a longer screen (e.g., a 20-foot screen) because a slightly longer screen would represent a fairly discrete interval in a very thick formation. Formations with very low hydraulic conductivities also may require the use of longer well screens to allow sufficient amounts of formation water to enter the well for sampling. The importance of accurately identifying such conditions highlights the need for a complete hydrogeologic site investigation prior to the design and placement of detection wells.

Multiple monitoring wells (well clusters or multilevel sampling devices) should be installed at a single location when (1) a single well cannot adequately intercept and monitor the vertical extent of a potential pathway of contaminant migration, or (2) there is more than one potential pathway of contaminant migration in the subsurface at a single location, or (3) there is a thick saturated zone and immiscible contaminants are present, or are determined to be potentially present after considering waste types managed at the facility. Conversely, at sites where ground water may be contaminated by a single contaminant, where there is a thin saturated zone, and where the site is hydrogeologically homogeneous, the need for multiple wells at each sampling location is reduced. The number of wells that should be installed at each sampling location increases with site complexity.

The following sources provided additional information on monitoring well placement: USEPA (1992a), USEPA (1990), USEPA (1991), and USEPA (1986a).

Contaminated Groundwater at Superfund Sites, (USEPA, 1988).

5.14 ASSESSMENT OF CORRECTIVE MEASURES 40 CFR §258.56

5.14.1 Statement of Regulation

(a) Within 90 days of finding that any of the constituents listed in Appendix II have been detected at a statistically significant level exceeding the ground-water protection standards defined under §258.55(h) and (i) of this part, the owner or operator must initiate an assessment of corrective measures. Such an assessment must be completed within a reasonable period of time.

(b) The owner or operator must continue to monitor in accordance with the assessment monitoring program as specified in §258.55.

(c) The assessment shall include an analysis of the effectiveness of potential corrective measures in meeting all of the requirements and objectives of the remedy as described under §258.57, addressing at least the following:

(1) The performance, reliability, ease of implementation, and potential impacts of appropriate potential remedies, including safety impacts, cross-media impacts, and control of exposure to any residual contamination;

(2) The time required to begin and complete the remedy;

(3) The costs of remedy implementation; and

(4) The institutional requirements such as State or local permit requirements or other environmental or public health requirements that may substantially affect implementation of the remedy(s).

(d) The owner or operator must discuss the results of the corrective measures assessment, prior to the selection of remedy, in a public meeting with interested and affected parties.

5.14.2 Applicability

An assessment of corrective measures must be conducted whenever any Appendix II constituents are detected at statistically significant levels exceeding the GWPS. The assessment of corrective measures must be initiated within 90 days of the finding. During the initiation of an assessment of corrective measures, assessment monitoring must be continued. The assessment of corrective measures must consider performance (including potential impacts), time, and cost aspects of the remedies. If implementation requires additional State or local permits, such requirements should be identified. Finally, the results of the corrective measures assessment must be discussed in a public meeting with interested and affected parties.

5.14.3 Technical Considerations

An assessment of corrective measures is site-specific and will vary significantly depending on the design and age of the facility, the completeness of the facility's historical records, the nature and concentration of the contaminants found in the ground water, the complexity of the site hydrogeology, and the facility's proximity to sensitive receptors. Corrective measures are generally approached from two directions: 1) identify and remediate the source of contamination and 2) identify and remediate the known contamination. Because each case will be site-specific, the owner or operator should be prepared to document that, to the best of his or her technical and financial abilities, a diligent effort has been made to complete the assessment in the shortest time practicable.

The factors listed in §258.56(c)(1) must be considered in assessing corrective measures. These general factors are discussed below in terms of source evaluation, plume delineation, ground-water assessment, and corrective measures assessment.

Source Evaluation

As part of the assessment of corrective measures, the owner or operator will need to identify the nature of the source of the release. The first step in this identification is a review of all available site information regarding facility design, wastes received, and onsite management practices. For newer facilities, this may be a relatively simple task. However, at some older facilities, detailed records of the facility's history may not be as well documented, making source definition more difficult. Design, climatological, and waste-type information should be used to evaluate the duration of the release, potential seasonal effects due to precipitation (increased infiltration and leachate generation), and possible constituent concentrations. If source evaluation is able to identify a repairable engineering condition that likely contributed to the cause of contamination (e.g., unlined leachate storage ponds, failed cover system, leaky leachate transport pipes, past conditions of contaminated storm overflow), such information should be considered as part of the assessment of corrective measures.

Existing site geology and hydrogeology information, ground-water monitoring results, and topographic and cultural information must be documented clearly and accurately. This information may include soil boring logs, test pit and monitoring well logs, geophysical data, water level elevation data, and other information collected during facility design or operation. The information should be expressed in a manner that will aid interpretation of data. Such data may include isopach maps of the thickness of the upper aquifer and important strata, isoconcentration maps of contaminants, flow nets, cross-sections, and contour maps. Additional guidance on data interpretation that may be useful in a source evaluation is presented in *RCRA Facility Investigation Guidance: Volume I - Development of an RFI Work Plan and General Considerations for RCRA Facility Investigations,* (USEPA 1989a), *RCRA Facility Investigation Guidance: Volume IV - Case Study Examples,* (USEPA 1989d), and *Practical Guide For Assessing and Remediating Contaminated Sites* (USEPA 1989e).

Plume Delineation

To effectively assess corrective measures, the lateral and vertical extent of contamination must be known. When it is determined that a GWPS is exceeded during the assessment monitoring program, it may be necessary to install additional wells to characterize the contaminant plume(s). At least one additional well must be added at the property boundary in the direction of contaminant migration to allow timely notification to potentially affected parties if contamination migrates offsite.

The following circumstances may require additional monitoring wells:

- Facilities that have not determined the horizontal and vertical extent of the contaminant plume

- Locations where the subsurface is heterogeneous or where ground-water flow patterns are difficult to establish

- Mounding associated with MSWLF units.

Because the requirements for additional monitoring are site-specific, the regulation does not specifically establish cases where additional wells are necessary or establish the number of additional wells that must be installed.

During the plume delineation process, the owner or operator is not relieved from continuing the assessment monitoring program.

The rate of plume migration and the change in contaminant concentrations with time must be monitored to allow prediction of the extent and timing of impact to sensitive receptors. The receptors may include users of both ground-water and surface water bodies where contaminated ground water may be discharged. In some cases, transfer of volatile compounds from ground water to the soil and to the air may provide an additional migration pathway. Information regarding the aquifer characteristics (e.g., hydraulic conductivity, storage coefficients, and effective porosity) should be developed for modeling contaminant transport if sufficient data are not available. Anisotropy and heterogeneity of the aquifer must be evaluated, as well as magnitude and duration of source inputs, to help explain present and predicted plume configuration.

Currently, most treatment options for ground-water contamination at MSWLF units involve pump and treat or in-situ biological technologies (bio-remediation). The cost and duration of treatment depends on the size of the plume, the pumping characteristics of the aquifer, and the chemical transport phenomena. Source control and ground-water flow control measures to reduce the rate of contaminant migration should be included in the costs of any remedial activity undertaken. Ground-water modeling of the plume may be initiated to establish the following:

- The locations and pumping rates of withdrawal and/or injection wells

- Predictions of contaminant concentrations at exposure points

- Locations of additional monitoring wells

- The effect that source control options may have on ground-water remediation

- The effects of advection and dispersion, retardation, adsorption, and other attenuation processes on the plume dimensions and contaminant concentrations.

Any modeling effort must consider that simulations of remedial response measures and contaminant transport are based on many necessary simplifying assumptions, which affect the accuracy of the model. These assumptions include boundary conditions, the degree and spatial variability of anisotropy, dispersivity, effective porosity, stratigraphy, and the algorithms used to solve contaminant transport equations. Model selection should be appropriate for the amount of data available, and the technical uncertainty of the model results must be documented by a sensitivity analysis on the input parameters. A sensitivity analysis is generally done after model calibration by varying one input parameter at a time over a realistic range and then evaluating changes in model output. For additional information on modeling, refer to the Further Information Section of Chapter 5.0 and the *RCRA Facility Investigation Guidance: Volume II - Soil, Groundwater and Subsurface Gas Releases* (USEPA, 1989b).

Ground-Water Assessment

To assess the potential effectiveness of corrective measures for ground-water contamination, the following information is needed:

- Plume definition (includes the types, concentration, and spatial distribution of the contaminants)
- The amenability of the contaminants to specific treatment and potential for contaminants to interfere with treatability
- Fate of the contaminants (whether chemical transformations have, are, or may be occurring, and the degree to which the species are sorbed to the geologic matrix)
- Stratigraphy and hydraulic properties of the aquifer
- Treatment concentration goals and objectives.

The owner or operator should consider whether immediate measures to limit further plume migration (e.g., containment options) or measures to minimize further introduction of contaminants to ground water are necessary.

The process by which a remedial action is undertaken will generally include the following activities:

- Hydrogeologic investigation, which may include additional well installations, detailed vertical and lateral sampling to characterize the plume, and core sampling to determine the degree of sorption of constituents on the geologic matrix
- Risk assessment, to determine the impact on sensitive receptors, which may include identification of the need to develop treatment goals other than GWPSs
- Literature and technical review of treatment technologies considered for further study or implementation
- Evaluation of costs of different treatment options
- Estimation of the time required for completion of remediation under the different treatment options

- Bench-scale treatability studies conducted to assess potential effectiveness of options
- Selection of technology(ies) and proposal preparation for regulatory and public review and comment
- Full-scale pilot study for verification of treatability and optimization of the selected technology
- Initiation of full-scale treatment technology with adjustments, as necessary
- Continuation of remedial action until treatment goals are achieved.

Corrective Measures Assessment

To compare different treatment options, substantial amounts of technical information must be assembled and assessed. The objective of this information-gathering task is to identify the following items for each treatment technology:

- The expected performance of individual approaches
- The time frame when individual approaches can realistically be implemented
- The technical feasibility of the remediation, including new and innovative technologies, performance, reliability and ease of implementation, safety and cross media impacts
- The anticipated time frame when remediation should be complete
- The anticipated cost of the remediation, including capital expenditures, design, ongoing engineering, and monitoring of results
- Technical and financial capability of the owner or operator to successfully complete the remediation
- Disposal requirements for treatment residuals
- Other regulatory or institutional requirements, including State and local permits, prohibitions, or environmental restrictions that may affect the implementation of the proposed remedial activity.

The performance objectives of the corrective measures should be considered in terms of source reduction, cleanup goals, and cleanup time frame. Source reduction would include measures to reduce or stop further releases and may include the repair of existing facility components (liner systems, leachate storage pond liners, piping systems, cover systems), upgrading of components (liners and cover systems), or premature closure in extreme cases. The technology proposed as a cleanup measure should be the best available technology, given the practicable capability of the owner or operator.

The technologies identified should be reliable, based on their previous performance; however, new innovative technologies are not discouraged if they can be shown, with a reasonable degree of confidence, to be reliable.

Because most treatment processes, including biorestoration, potentially produce byproducts or release contaminants to different media (e.g., air stripping of volatile compounds), the impacts of such potential releases must be evaluated. Releases to air may constitute a worker health and safety concern and must be addressed as part of the alternatives assessment process. Other cross media impacts, including transfer of contaminants from soils to ground water, surface water, or air, should be assessed and addressed in the assessment of corrective actions. Guidance for addressing air and soil transport and contamination is provided in USEPA (1989b) and USEPA (1989c).

Analyses should be conducted on treatment options to determine whether or not they are protective of human health and the environment. Environmental monitoring of exposure routes (air and water) may necessitate health monitoring for personnel involved in treatment activities if unacceptable levels of exposure are possible. On a case-by-case basis, implementation plans may require both forms of monitoring.

The development and screening of individual corrective measures requires an understanding of the physio-chemical relationships and interferences between the constituents and the sequence of treatment measures that must be implemented. Proper sequencing of treatment methods to produce a feasible remedial program must be evaluated to avoid interference between the presence of some constituents and the effective removal of the targeted compound. In addition, screening and design parameters of potential treatment options should be evaluated in the early stages of conceptual development and planning to eliminate technically unsuitable treatment methods. In general, selection of an appropriate treatment method will require the experience of a qualified professional and will necessitate a literature review of the best available treatment technologies.

Numerous case studies and published papers from scientific and engineering technical journals exist on treatability of specific compounds and groups of related compounds. Development of new technologies and refinements of technologies have been rapid. A compendium of available literature that includes treatment technologies for organic and inorganic contaminants, technology selection, and other sources of information (e.g., literature search data bases pertinent to ground-water extraction, treatment, and responses) is included in *Practical Guide for Assessing and Remediating Contaminated Sites* (USEPA, 1989e).

The general approach to remediation typically includes active restoration, plume containment, and source control as discussed below. The selection of a particular approach or combination of approaches must be based on the corrective action objectives. These general approaches are outlined in Table 5-3. It should be emphasized that the objective of a treatment program should be to restore ground water to pre-existing conditions or to levels below applicable ground-water protection standards while simultaneously restricting further releases of contaminants to ground water. Once treatment objectives are met, the chance of further contamination should be mitigated to the extent practicable.

Active Restoration

Active restoration generally includes ground-water extraction, followed by onsite or offsite wastewater treatment. Offsite wastewater treatment may include sending the contaminated water to a local publicly owned treatment works (POTW) or to a facility designed to treat the contaminants of concern. Treated ground water may be re-injected, sent to a local POTW, or discharged to a local body of surface water, depending on local, State, and Federal requirements. Typical treatment practices that may be implemented include coagulation and precipitation of metals, chemical oxidation of a number of organic compounds, air stripping to remove volatile organic compounds, and biological degradation of other organics.

The rate of contaminant removal from ground water will depend on the rate of ground-water removal, the cation exchange capacity of the soil, and partition coefficients of the constituents sorbed to the soil (USEPA, 1988). As the concentration of contaminants in the ground water is reduced, the rate at which constituents become partitioned from the soil to the aqueous phase may also be reduced. The amount of flushing of the aquifer material required to remove the contaminants to an acceptable level will generally determine the time frame required for restoration. This time frame is site-specific and may last indefinitely.

In-situ methods may be appropriate for some sites, particularly where pump and treat technologies create serious adverse effects or where it may be financially prohibitive. In-situ methods may include biological restoration requiring pH control, addition of specific micro-organisms, and/or addition of nutrients and substrate to augment and encourage degradation by indigenous microbial populations. Bioremediation requires laboratory treatability studies and pilot field studies to determine the feasibility and the reliability of full-scale treatment. It must be demonstrated that the treatment techniques will not cause degradation of a target chemical to another compound that has unacceptable health risks and that is subject to further degradation. Alternative in-situ methods may also be designed to increase the effectiveness of desorption or removal of contaminants from the aquifer matrix. Such methodologies may include steam stripping, soil flushing, vapor extraction, thermal desorption, and solvent washing, and extraction for removal of strongly sorbed organic compounds. These methods also may be used in unsaturated zones where residual contaminants may be sorbed to the geologic matrix during periodic fluctuations of the water table. Details of in-situ methods may be found in several sources: USEPA (1988); USEPA (1985); and Eckenfelder (1989).

Plume Containment

The purpose of plume containment is to limit the spread of the contaminants. Methods to contain plume movement include passive hydraulic barriers, such as grout curtains and slurry walls, and active gradient control systems involving pumping wells and french drains. The types of aquifer characteristics that favor plume containment include:

- Water naturally unsuited for human consumption
- Contaminants present in low concentration with low mobility
- Low potential for exposure to contaminants and low risk associated with exposure

- Low transmissivity and low future user demand.

Often, it may be advantageous for the owner or operator to consider implementing ground-water controls to inhibit further contamination or the spread of contamination. If ground-water pumping is considered for capturing the leading edge of the contaminant plume, the contaminated water must be managed in conformance with all applicable Federal and State requirements. Under most conditions, it is necessary to consult with the regulatory agencies prior to initiating an interim remedial action.

Source Control

Source control measures should be evaluated to limit the migration of the plume. The regulation does not limit the definition of source control to exclude any specific type of remediation. Remedies must control the source to reduce or eliminate further releases by identifying and locating the cause of the release (e.g., torn geomembrane, excessive head due to blocked leachate collection system, leaking leachate collection well or pipe). Source control measures may include the following:

- Modifying the operational procedures (e.g., banning specific wastes or lowering the head over the leachate collection system through more frequent leachate removal)

- Undertaking more extensive and effective maintenance activities (e.g., excavate waste to repair a liner failure or a clogged leachate collection system)

- Preventing additional leachate generation that may reach a liner failure (e.g., using a portable or temporary rain shelter during operations or capping landfill areas that contribute to leachate migrating from identified failure areas).

In extreme cases, excavation of deposited wastes for treatment and/or offsite disposal may be considered.

Public Participation

The owner or operator is required to hold a public meeting to discuss the results of the corrective action assessment and to identify proposed remedies. Notifications, such as contacting local public agencies, town governments, and State/Tribal governments, posting a notice in prominent local newspapers, and making radio announcements are effective. The public meeting should provide a detailed discussion of how the owner or operator has addressed the factors at §258.56(c)(1)-(4).

5.15 SELECTION OF REMEDY 40 CFR §258.57 (a)-(b)

5.15.1 Statement of Regulation

(a) Based on the results of the corrective measure assessment conducted under §258.56, the owner or operator must select a remedy that, at a minimum, meets the standards listed in paragraph (b) below. The owner or operator must notify the State Director, within 14 days of selecting a remedy, that a report describing the selected remedy has been placed in the operating record and how it meets the standards in paragraph (b) of this section.

(b) Remedies must:

(1) Be protective of human health and the environment;

(2) Attain the ground-water protection standard as specified pursuant to §§258.55(h) or (i);

(3) Control the source(s) of releases so as to reduce or eliminate, to the maximum extent practicable, further releases of Appendix II constituents into the environment that may pose a threat to human health or the environment; and

(4) Comply with standards for management of wastes as specified in §258.58(d).

5.15.2 Applicability

These provisions apply to facilities that have been required to perform corrective measures. The selection of a remedy is closely related to the assessment process and cannot be accomplished unless a sufficiently thorough evaluation of alternatives has been completed. The process of documenting the rationale for selecting a remedy requires that a report be placed in the facility operating record that clearly defines the corrective action objectives and demonstrates why the selected remedy is anticipated to meet those objectives. The State Director must be notified within 14 days of the placement of the report in the operating records of the facility. The study must identify how the remedy will be protective of human health and the environment, attain the GWPS (either background, MCLs, or, in approved States, health-based standards, if applicable), attain source control objectives, and comply with waste management standards.

5.15.3 Technical Considerations

The final method selected for implementation must satisfy the criteria in §258.57(b)(1)-(4). The report documenting the capability of the selected method to meet these four criteria should include such information as:

- Theoretical calculations
- Comparison to existing studies and results of similar treatment case histories
- Bench-scale or pilot-scale treatability test results
- Waste management practices.

The demonstration presented in the report must document the alternative option selection process.

5.16 SELECTION OF REMEDY 40 CFR §258.57 (c)

5.16.1 Statement of Regulation

(c) In selecting a remedy that meets the standards of §258.57(b), the owner or operator shall consider the following evaluation factors:

(1) The long- and short-term effectiveness and protectiveness of the potential remedy(s), along with the degree of certainty that the remedy will prove successful based on consideration of the following:

(i) Magnitude of reduction of existing risks;

(ii) Magnitude of residual risks in terms of likelihood of further releases due to waste remaining following implementation of a remedy;

(iii) The type and degree of long-term management required, including monitoring, operation, and maintenance;

(iv) Short-term risks that might be posed to the community, workers, or the environment during implementation of such a remedy, including potential threats to human health and the environment associated with excavation, transportation, and redisposal or containment;

(v) Time until full protection is achieved;

(vi) Potential for exposure of humans and environmental receptors to remaining wastes, considering the potential threat to human health and the environment associated with excavation, transportation, redisposal, or containment;

(vii) Long-term reliability of the engineering and institutional controls; and

(viii) Potential need for replacement of the remedy.

(2) The effectiveness of the remedy in controlling the source to reduce further releases based on consideration of the following factors:

(i) The extent to which containment practices will reduce further releases;

(ii) The extent to which treatment technologies may be used.

(3) The ease or difficulty of implementing a potential remedy(s) based on consideration of the following types of factors:

(i) Degree of difficulty associated with constructing the technology;

(ii) Expected operational reliability of the technologies;

(iii) Need to coordinate with and obtain necessary approvals and permits from other agencies;

(iv) Availability of necessary equipment and specialists; and

(v) Available capacity and location of needed treatment, storage, and disposal services.

(4) Practicable capability of the owner or operator, including a consideration of the technical and economic capability.

(5) The degree to which community concerns are addressed by a potential remedy(s).

<u>5.16.2 Applicability</u>

These provisions apply to facilities that are selecting a remedy for corrective action. The rule presents the considerations and factors that the owner or operator must evaluate when selecting the appropriate corrective measure.

5.16.3 Technical Considerations

The owner or operator must consider specific topics to satisfy the performance criteria under selection of the final corrective measure. These topics must be addressed in the report documenting the selection of a particular corrective action. The general topic areas that must be considered include the following:

- The anticipated long- and short-term effectiveness of the corrective action
- The anticipated effectiveness of source reduction efforts
- The ease or difficulty of implementing the corrective measure
- The technical and economic practicable capability of the owner or operator
- The degree to which the selected remedy will address concerns raised by the community.

Effectiveness of Corrective Action

In selecting the remedial action, the anticipated long-term and short-term effectiveness should be evaluated. Long-term effectiveness focuses on the risks remaining after corrective measures have been taken. Short-term effectiveness addresses the risks during construction and implementation of the corrective measure. Review of case studies where similar technologies have been applied provide the best measures to judge technical uncertainty, especially when relatively new technologies are applied. The long-term, post-cleanup effectiveness may be judged on the ability of the proposed remedy to mitigate further releases of contaminants to the environment, as well as on the feasibility of the proposed remedy to meet or exceed the GWPSs. The owner or operator must make a reasonable effort to estimate and quantify risks, based on exposure pathways and estimates of exposure levels and durations. These estimates include risks for both ground-water and cross-media contamination.

The source control measures that will be implemented, including excavation, transportation, re-disposal, and containment, should be evaluated with respect to potential exposure and risk to human health and the environment. The source control measures should be viewed as an integral component of the overall corrective action. Health considerations must address monitoring risks to workers and the general public and provide contingency plans should an unanticipated exposure occur. Potential exposure should consider both long- and short-term cases before, during, and after implementation of corrective actions.

The time to complete the remedial activity must be estimated, because it will have direct financial impacts on the project management needs and financial capability of the owner or operator to meet the remedial objectives. The long-term costs of the remedial alternatives and the long-term financial condition of the owner or operator should be reviewed carefully. The implementation schedule should indicate quality control measures to assess the progress of the corrective measure.

The operational reliability of the corrective measures should be considered. In addition, the institutional controls and management practices developed to assess the reliability should be identified.

Effectiveness of Source Reduction

Source control measures identified in previous sections should be discussed in terms of their expected effectiveness. If source control consists of the removal and re-disposal of wastes, the residual materials, such as contaminated soils above the water table, should be quantified and their potential to cause further contamination evaluated. Engineering controls intended to upgrade or repair deficient conditions in landfill component systems, including cover systems, should be quantified in terms of anticipated effectiveness according to current and future conditions. This assessment may indicate to what extent it is technically and financially practicable to make use of existing technologies. The decision against using a certain technology may be based on health considerations and the potential for unacceptable exposure(s) to both workers and the public.

Implementation of Remedial Action

The ease of implementing the proposed remedial action will affect the schedule and startup success of the remedial action. The following key factors need to be assessed:

- The availability of technical expertise
- Construction of equipment or technology
- The ability to properly manage and dispose of wastes generated by treatment
- The likelihood of obtaining local permits and public support for the proposed project.

Technical considerations, including pH control, ground-water extraction feasibility, or the ability to inject nutrients, may need to be considered, depending on the proposed treatment method. Potential impacts, such as potential cross-media contamination, need to be reviewed as part of the overall feasibility of the project.

The schedule of remedial activities should identify the start and end points of the following periods:

- Permitting phase
- Construction and startup period, during which initial implementation success will be evaluated, including time to correct any unexpected problems
- Time when full-scale treatment will be initiated and duration of treatment period
- Implementation and completion of source control measures, including the timeframe for solving problems associated with interim management and disposal of waste materials or treatment residuals.

Items that require long lead times should be identified early in the process and those tasks should be initiated early to ensure that implementation occurs in the shortest practicable period.

Practical Capability

The owner or operator must be technically and financially capable of implementing the chosen remedial alternative and ensuring project completion, including provisions for future changes to the remedial plan after progress is reviewed. If either technical or financial capability is inadequate for a particular alternative, then other alternatives with similar levels of protectiveness should be considered for implementation.

Community Concerns

The public meetings held during assessment of alternative measures are intended to elicit public comment and response. The owner or operator must, by means of meeting minutes and a record of written comments, identify which public concerns have been expressed and addressed by corrective measure options. In reality, the final remedy selected and implemented will be one that the State regulatory agency, the public, and the owner or operator agree to.

5.17 SELECTION OF REMEDY 40 CFR §258.57 (d)

5.17.1 Statement of Regulation

(d) The owner or operator shall specify as part of the selected remedy a schedule(s) for initiating and completing remedial activities. Such a schedule must require the initiation of remedial activities within a reasonable period of time taking into consideration the factors set forth in paragraphs (d) (1-8). The owner or operator must consider the following factors in determining the schedule of remedial activities:

(1) Extent and nature of contamination;

(2) Practical capabilities of remedial technologies in achieving compliance with ground-water protection standards established under §§258.55(g) or (h) and other objectives of the remedy;

(3) Availability of treatment or disposal capacity for wastes managed during implementation of the remedy;

(4) Desirability of utilizing technologies that are not currently available, but which may offer significant advantages over already available technologies in terms of effectiveness, reliability, safety, or ability to achieve remedial objectives;

(5) Potential risks to human health and the environment from exposure to contamination prior to completion of the remedy;

(6) Resource value of the aquifer including:

(i) Current and future uses;

(ii) Proximity and withdrawal rate of users;

(iii) Ground-water quantity and quality;

(iv) The potential damage to wildlife, crops, vegetation, and physical structures caused by exposure to waste constituent;

(v) The hydrogeologic characteristic of the facility and surrounding land;

(vi) Ground-water removal and treatment costs; and

(vii) The cost and availability of alternative water supplies.

(7) Practicable capability of the owner or operator.

(8) Other relevant factors.

5.17.2 Applicability

The requirements of §258.57(d) apply to owners or operators of all new units, existing units, and laterally expanded units at all facilities required to implement corrective actions. The requirements must be complied with prior to implementing corrective measures. The owner or operator must specify the schedule for remedial activities based on the following considerations:

- The size and nature of the contaminated area at the time the corrective measure is to be implemented
- The practicable capabilities of the remedial technology selected
- Available treatment and disposal capacity
- Potential use of alternative innovative technologies not currently available
- Potential risks to human health and the environment existing prior to completion of the remedy
- Resource value of the aquifer
- The practicable capability of the owner/operator
- Other relevant factors.

5.17.3 Technical Considerations

The time schedule for implementing and completing the remedial activity is influenced by many factors that should be considered by the owner or operator. The most critical factor is the nature and extent of the contamination, which significantly affects the ultimate treatment rate. The size of the treatment facility and the ground-water extraction and injection rates must be balanced for system optimization, capital resources, and remedial timeframe objectives. The nature of the contamination will influence the degree to which the aquifer must be flushed to remove adsorbed species. These factors, which in part define the practicable capability of the alternative (treatment efficiency, treatment rate, and replenishment of contaminants by natural processes), should be considered when selecting the remedy.

In addition, the rate at which treatment may occur may be restricted by the availability or capacity to handle treatment residues and the normal flow of wastes during remediation. Alternative residue treatment or disposal capacity must be identified as part of the implementation plan schedule.

If contaminant migration is slow due to low transport properties of the aquifer, additional time may be available to evaluate the value of emerging and promising innovative technologies. The use of such technologies is not excluded as part of the requirement to implement a remedial action as soon as practicable. Delaying implementation to increase the availability of new technologies must be evaluated in terms of achievable cleanup levels, ultimate cost, additional environmental impact, and potential for increased risk to sensitive receptors. If a new technology clearly is superior to existing options in attaining remediation objectives, it may be appropriate to delay implementation. This may require that existing risks be controlled through interim measures.

In setting the implementation schedule, the owner or operator should assess the risk to human health and the environment within the timeframe of reaching treatment objectives. If the risk is unacceptable, considering health-based assessments of exposure paths and exposure limits, the implementation time schedule must be accelerated or the selected remedy altered to provide an acceptable risk level in a timely manner.

Establishment of the schedule also may include consideration of the resource value of the aquifer, as it pertains to current and future use, proximity to users, quality and quantity of ground water, agricultural value and uses (irrigation water source or impact on adjacent agricultural lands), and the availability of alternative supplies of water of similar quantity and quality. Based on these factors, a relative assessment of the aquifer's resource value to the local community can be established. Impacts to the resource and the degree of financial or health-related distress by users should be considered. The implementation timeframe should attempt to minimize the loss of value of the resource to users. The possibility that alternative water supplies will have to be developed as part of the remedial activities may need to be considered.

Because owners or operators may not be knowledgeable in remediation activities, reliance on the owner or operator to devise the schedule for remediation may be impracticable. In these instances, use of an outside firm to coordinate remediation scheduling may be necessary. Similarly, development of a schedule for which the owner or operator cannot finance, when other options exist that do allow for owner or operator financing, should be prevented.

5.18 SELECTION OF REMEDY 40 CFR §258.57 (e)-(f)

5.18.1 Statement of Regulation

(e) The Director of an approved State may determine that remediation of a release of an Appendix II constituent from a MSWLF unit is not necessary if the owner or operator demonstrates to the satisfaction of the Director of an approved State that:

(1) The ground water is additionally contaminated by substances that have originated from a source other than a MSWLF unit and those substances are present in concentrations such that cleanup of the release from the MSWLF unit would provide no significant reduction in risk to actual or potential receptors; or

(2) The constituent(s) is present in ground water that:

(i) Is not currently or reasonably expected to be a potential source of drinking water; and

(ii) Is not hydraulically connected with waters to which the hazardous constituents are migrating or are likely to migrate in a concentration(s) that would exceed the ground-water protection standards established under §258.55(h) or (i); or

(3) Remediation of the release(s) is technically impracticable; or

(4) Remediation results in unacceptable cross-media impacts.

(f) A determination by the Director of an approved State pursuant to paragraph (e) above shall not affect the authority of the State to require the owner or operator to undertake source control measures or other measures that may be necessary to eliminate or minimize further releases to the ground water, to prevent exposure to the ground water, or to remediate the ground water to concentrations that are technically practicable and significantly reduce threats to human health or the environment.

5.18.2 Applicability

The criteria under §258.57(e) and (f) apply in approved States only. Remediation of the release of an Appendix II constituent may not be necessary if 1) a source other than the MSWLF unit is partly responsible for the ground-water contamination, 2) the resource value of the aquifer is extremely limited, 3) remediation is not technically feasible, or 4) remediation will result in unacceptable cross-media impacts. The Director may determine that while total remediation is not required, source control measures or partial remediation of ground water to concentrations that are technically practicable and significantly reduce risks is required.

5.18.3 Technical Considerations

There are four situations where an approved State may not require cleanup of hazardous constituents released to ground water from a MSWLF unit. If sufficient evidence exists to document that the ground water is contaminated by a source other than the MSWLF unit, the Director of an approved State may grant a waiver from implementing some or all of the corrective measure requirements. The owner or operator must demonstrate that cleanup of a release from its MSWLF unit would provide no significant reduction in risk to receptors due to concentrations of constituents from the other source.

A waiver from corrective measures also may be granted if the contaminated ground water is not a current or reasonably expected potential future drinking water source, and it is unlikely that the hazardous constituents would migrate to waters causing an exceedance of GWPS. The owner or operator must demonstrate that the uppermost aquifer is not hydraulically connected with a lower aquifer. The owner or operator may seek an exemption if it can be demonstrated that attenuation, advection/dispersion or other natural processes can remove the threat to interconnected aquifers. The owner or operator may seek the latter exemption if the contaminated zone is not a drinking water resource.

The Director of an approved State may waive cleanup requirements if remediation is not technically feasible. In addition, the Director may wave requirements if remediation results in unacceptable cross-media impacts. A successful demonstration that remediation is not technically feasible must document specific facts that attribute to this demonstration. Technical impracticabilities may be related to the accessibility of the ground water to treatment, as well as the treatability of the ground water using practicable treatment technologies. If the owner or operator can demonstrate that unacceptable cross-media impacts are uncontrollable under a given remedial option (e.g., movement in response to ground-water pumping or release of volatile organics to the atmosphere) and that the no action option is a less risky alternative, then the Director of an approved State may determine that remediation is not necessary.

A waiver of remedial obligation does not necessarily release the owner or operator from the responsibility of conducting source control measures or minimal ground-water remediation. The State may require that source control be implemented to the maximum extent practicable to minimize future risk of releases of contaminants to ground water or that ground water be treated to the extent technically feasible.

5.19 IMPLEMENTATION OF THE CORRECTIVE ACTION PROGRAM 40 CFR §258.58 (a)

5.19.1 Statement of Regulation

(a) Based on the schedule established under §258.57(d) for initiation and completion of remedial activities the owner/operator must:

(1) Establish and implement a corrective action ground-water monitoring program that:

(i) At a minimum, meets the requirements of an assessment monitoring program under §258.55;

(ii) Indicates the effectiveness of the corrective action remedy; and

(iii) Demonstrates compliance with ground-water protection standard pursuant to paragraph (e) of this section.

(2) Implement the corrective action remedy selected under §258.57; and

(3) Take any interim measures necessary to ensure the protection of human health and the environment. Interim measures should, to the greatest extent practicable, be consistent with the objectives of and contribute to the performance of any remedy that may be required pursuant to §258.57. The following factors must be considered by an owner or operator in determining whether interim measures are necessary:

(i) Time required to develop and implement a final remedy;

(ii) Actual or potential exposure of nearby populations or environmental receptors to hazardous constituents;

(iii) Actual or potential contamination of drinking water supplies or sensitive ecosystems;

(iv) Further degradation of the ground water that may occur if remedial action is not initiated expeditiously;

(v) Weather conditions that may cause hazardous constituents to migrate or be released;

(vi) Risks of fire or explosion, or potential for exposure to hazardous constituents as a result of an accident or failure of a container or handling system; and

(vii) Other situations that may pose threats to human health and the environment.

5.19.2 Applicability

These provisions apply to facilities that are required to initiate and complete corrective actions.

The owner or operator is required to continue to implement its ground water assessment monitoring program to evaluate the effectiveness of remedial actions and to demonstrate that the remedial objectives have been attained at the completion of remedial activities.

Additionally, the owner or operator must take any interim actions to protect human health and the environment. The interim measures must serve to mitigate actual threats and prevent potential threats from being realized while a long-term comprehensive response is being developed.

5.19.3 Technical Considerations

Implementation of the corrective measures encompass all activities necessary to initiate and continue remediation. The owner or operator must continue assessment monitoring to anticipate whether interim measures are necessary, and to determine whether the corrective action is meeting stated objectives.

Monitoring Activities

During the implementation period, ground-water monitoring must be conducted to demonstrate the effectiveness of the corrective action remedy. If the remedial action is not effectively curtailing further ground water degradation or the spread of the contaminant plume, replacement of the system with an alternative measure may be warranted. The improvement rate of the condition of the aquifer must be monitored and compared to the cleanup objectives. It may be necessary to install additional monitoring wells to more clearly evaluate remediation progress. Also, if it becomes apparent that the GWPS will not be achievable technically, in a realistic time-frame, the performance objectives of the corrective measure must be reviewed and amended as necessary.

Interim Measures

If unacceptable potential risks to human health and the environment exist prior to or during implementation of the corrective action, the owner or operator is required to take interim measures to protect receptors. These interim measures are typically short-term solutions to address immediate concerns and do not necessarily address long-term remediation objectives. Interim measures may include activities such as control of ground-water migration through high-volume withdrawal of ground water or response to equipment failures that occur during remediation (e.g., leaking drums). If contamination migrates offsite, interim measures may include providing an alternative water supply for human, livestock, or irrigation needs. Interim measures also pertain to source control activities that may be implemented as part of the overall corrective action. This may include activities such as excavation of the source material or in-situ treatment of the contaminated source. Interim measures should be developed with consideration given to maintaining conformity with the objectives of the final corrective action.

5.20 IMPLEMENTATION OF THE CORRECTIVE ACTION PROGRAM 40 CFR §258.58 (b)-(d)

5.20.1 Statement of Regulation

(b) An owner or operator may determine, based on information developed after implementation of the remedy has begun or other information, that compliance with requirements of §258.57(b) are not being achieved through the remedy selected. In such cases, the owner or operator must implement other methods or techniques that could practicably achieve compliance with the requirements, unless the owner or operator makes the determination under §258.58(c).

(c) If the owner or operator determines that compliance with requirements under §258.57(b) cannot be practically achieved with any currently available methods, the owner or operator must:

(1) Obtain certification of a qualified ground-water specialist or approval by the Director of an approved State that compliance with requirements under §258.57(b) cannot be practically achieved with any currently available methods;

(2) Implement alternate measures to control exposure of humans or the environment to residual contamination, as necessary to protect human health and the environment; and

(3) Implement alternate measures for control of the sources of contamination, or for removal or decontamination of equipment, units, devices, or structures that are:

(i) Technically practicable; and

(ii) Consistent with the overall objective of the remedy.

(4) Notify the State Director within 14 days that a report justifying the alternative measures prior to implementing the alternative measures has been placed in the operating record.

(d) All solid wastes that are managed pursuant to a remedy required under §258.57, or an interim measure required under §258.58(a)(3), shall be managed in a manner:

(1) That is protective of human health and the environment; and

(2) That complies with applicable RCRA requirements.

5.20.2 Applicability

The requirements of the alternative measures are applicable when it becomes apparent that the remedy selected will not achieve the GWPSs or other significant objectives of the remedial program (e.g., protection of sensitive receptors). In determining that the selected corrective action approach will not achieve desired results, the owner or operator must implement alternate corrective measures to achieve the GWPSs. If it becomes evident that the cleanup goals are not technically obtainable by existing practicable technology, the owner or operator must implement actions to control exposure of humans or the environment from residual contamination and to control the sources of contamination. Prior to implementing alternative measures, the owner or operator must notify the Director of an approved State within 14 days that a report justifying the alternative measures has been placed in the operating record.

All wastes that are managed by the MSWLF unit during corrective action, including interim and alternative measures, must be managed according to applicable RCRA requirements in a manner that is protective of human health and the environment.

5.20.3 Technical Considerations

An owner or operator is required to continue the assessment monitoring program during the remedial action. Through monitoring, the short and long term success of the remedial action can be gauged against expected progress. During the remedial action, it may be necessary to install additional ground-water monitoring wells or pumping or injection wells to adjust to conditions that vary from initial assessments of the ground-water flow system. As remediation progresses and data are compiled, it may become evident that the remediation activities will not protect human health and the environment, meet GWPSs, control sources of contamination, or comply with waste management standards. The reasons for unsatisfactory results may include:

- Refractory compounds that are not amenable to removal or destruction (detoxification)
- The presence of compounds that interfere with treatment methods identified for target compounds
- Inappropriately applied technology
- Failure of source control measures to achieve desired results
- Failure of ground-water control systems to achieve adequate containment or removal of contaminated ground water
- Residual concentrations above GWPSs that cannot be effectively reduced further because treatment efficiencies are too low
- Transformation or degradation of target compounds to different forms that are not amenable to further treatment by present or alternative technologies.

The owner or operator should compare treatment assumptions with existing conditions to determine if assumptions adequately depict site conditions. If implementation occurred as designed, the owner or operator should attempt to modify or upgrade existing remedial technology to optimize performance and to improve treatment effectiveness. If the existing technology is found to be unable to meet remediation objectives, alternative approaches must be evaluated that could meet these objectives while the present remediation is continued. During this re-evaluation period, the owner or operator may suspend treatment only if continuation of remedial activities clearly increases the threat to human health and the environment.

5.21 IMPLEMENTATION OF THE CORRECTIVE ACTION PROGRAM 40 CFR §258.58 (e)-(g)

5.21.1 Statement of Regulation

(e) Remedies selected pursuant to §258.57 shall be considered complete when:

(1) The owner or operator complies with the ground-water protection standards established under §§258.55(h) or (i) at all points within the plume of contamination that lie beyond the ground-water monitoring well system established under §258.51(a).

(2) Compliance with the ground-water protection standards established under §§258.55(h) or (i) has been achieved by demonstrating that concentrations of Appendix II constituents have not exceeded the ground-water protection standard(s) for a period of three consecutive years using the statistical procedures and performance standards in §258.53(g) and (h). The Director of an approved State may specify an alternative length of time during which the owner or operator must demonstrate that concentrations of Appendix II constituents have not exceeded the ground-water protection standard(s) taking into consideration:

(i) Extent and concentration of the release(s);

(ii) Behavior characteristics of the hazardous constituents in the ground water;

(iii) Accuracy of monitoring or modeling techniques, including any seasonal, meteorological, or other environmental variabilities that may affect the accuracy; and

(iv) Characteristics of the ground water.

(3) All actions required to complete the remedy have been satisfied.

(f) Upon completion of the remedy, the owner or operator must notify the State Director within 14 days that a certification that the remedy has been completed in compliance with the requirements of §258.58(e) has been placed in the operating record. The certification must be signed by the owner or operator and by a qualified ground-water specialist or approved by the Director of an approved State.

(g) When, upon completion of the certification, the owner or operator determines that the corrective action remedy has been completed in accordance with the requirements under paragraph (e) of this section, the owner or operator shall be released from the requirements for financial assurance for corrective action under §258.73.

§258.59 [Reserved].

5.21.2 Applicability

These criteria apply to facilities conducting corrective action. Remedies are considered complete when, after 3 consecutive years of monitoring (or an alternative length of time as identified by the Director), the results show significant statistical evidence that

Appendix II constituent concentrations are below the GWPSs. Upon completion of all remedial actions, the owner or operator must certify to such, at which point the owner or operator is released from financial assurance requirements.

5.21.3 Technical Considerations

The regulatory period of compliance is 3 consecutive years at all points within the contaminant plume that lie beyond the ground-water monitoring system unless the Director of an approved State specifies an alternative length of time. Compliance is achieved when the concentrations of Appendix II constituents do not exceed the GWPSs for a predetermined length of time. Statistical procedures in §258.53 must be used to demonstrate compliance with the GWPSs.

The preferred statistical method for comparison is to construct a 99 percent confidence interval around the mean of the last 3 years of data and compare the upper limit of the confidence interval to the GWPS. An upper limit less than the GWPS is considered significant evidence that the standard is no longer being exceeded. The confidence interval must be based on the appropriate model describing the distribution of the data.

Upon completion of the remedy, including meeting the GWPS at all points within the contaminant plume, the owner or operator must notify the State Director within fourteen days that a certification that the remedy has been completed has been placed in the operating record. The certification must be signed by the owner or operator and a qualified ground-water scientist or approved by the Director of an approved State. Upon completion of the remedial action, in accordance with §258.58(e), the owner or operator is released from the financial assurance requirements pertaining to corrective actions.

The Director of an approved State may require an alternate time period (other than 3 years) to demonstrate compliance. In determining an alternate period the Director must consider the following:

- The extent and concentration of the release(s)
- The behavior characteristics (fate and transport) of the hazardous constituents in the ground water (e.g., mobility, persistence, toxicity, etc.)
- Accuracy of monitoring or modeling techniques, including any seasonal, meteorological or other environmental variabilities that may affect accuracy
- The characteristics of the ground water (e.g., flow rate, pH, etc.).

Consideration of these factors may result in an extension or shortening of the time required to show compliance with remediation objectives.

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the minimum design specified in §258.60(a). This provides an opportunity to incorporate different technologies or improvements into cover designs, and to address site-specific conditions.

6.3.3 Technical Considerations

An alternative material and/or an alternative thickness may be used for an infiltration layer as long as the infiltration layer requirements specified in §258.60(a)(1) and (a)(2) are met.

For example, an armored surface (e.g., one composed of cobble-rich soils or soils rich in weathered rock fragments) could be used as an alternative to the six-inch erosion layer. An armored surface, or hardened cap, is generally used in arid regions or on steep slopes where the establishment and maintenance of vegetation may be hindered by lack of soil or excessive run-off.

The materials used for an armored surface typically are (U.S. EPA, 1989b):

- Capable of protecting the underlying infiltration layer during extreme weather events of rainfall and/or wind;
- Capable of accommodating settlement of the underlying material without compromising the component;
- Designed with a surface slope that is approximately the same as the underlying soil (at least 2 percent slope); and
- Capable of controlling the rate of soil erosion.

The erosion layer may be made of asphalt or concrete. These materials promote run-off with negligible erosion. However, asphalt and concrete deteriorate due to thermal expansion and due to deformation caused by subsidence. Crushed rock may be spread over the landfill cover in areas where weather conditions such as wind, heavy rain, or temperature extremes commonly cause deterioration of vegetative covers (U.S. EPA, 1989b).

Other Considerations

Additional Cover System Components

To reduce the generation of post-closure leachate to the greatest extent possible, owners and operators can install a composite cover made of a geomembrane and a soil component with low hydraulic conductivity. The hydraulic properties of these components are discussed in Chapter 4 (Subpart D).

Other components that may be used in the final cover system include a drainage layer, a gas vent layer, and a biotic barrier layer. These components are discussed in the following sections and are shown in Figure 6-6.

Drainage Layer

A permeable drainage layer, constructed of soil or geosynthetic drainage material, may be constructed between the erosion layer and the underlying infiltration layer. The drainage layer in a final cover system removes percolating water that has infiltrated through the erosion layer after surface run-off and evapotranspiration losses. By removing water in contact with the low-permeability layer, the potential for

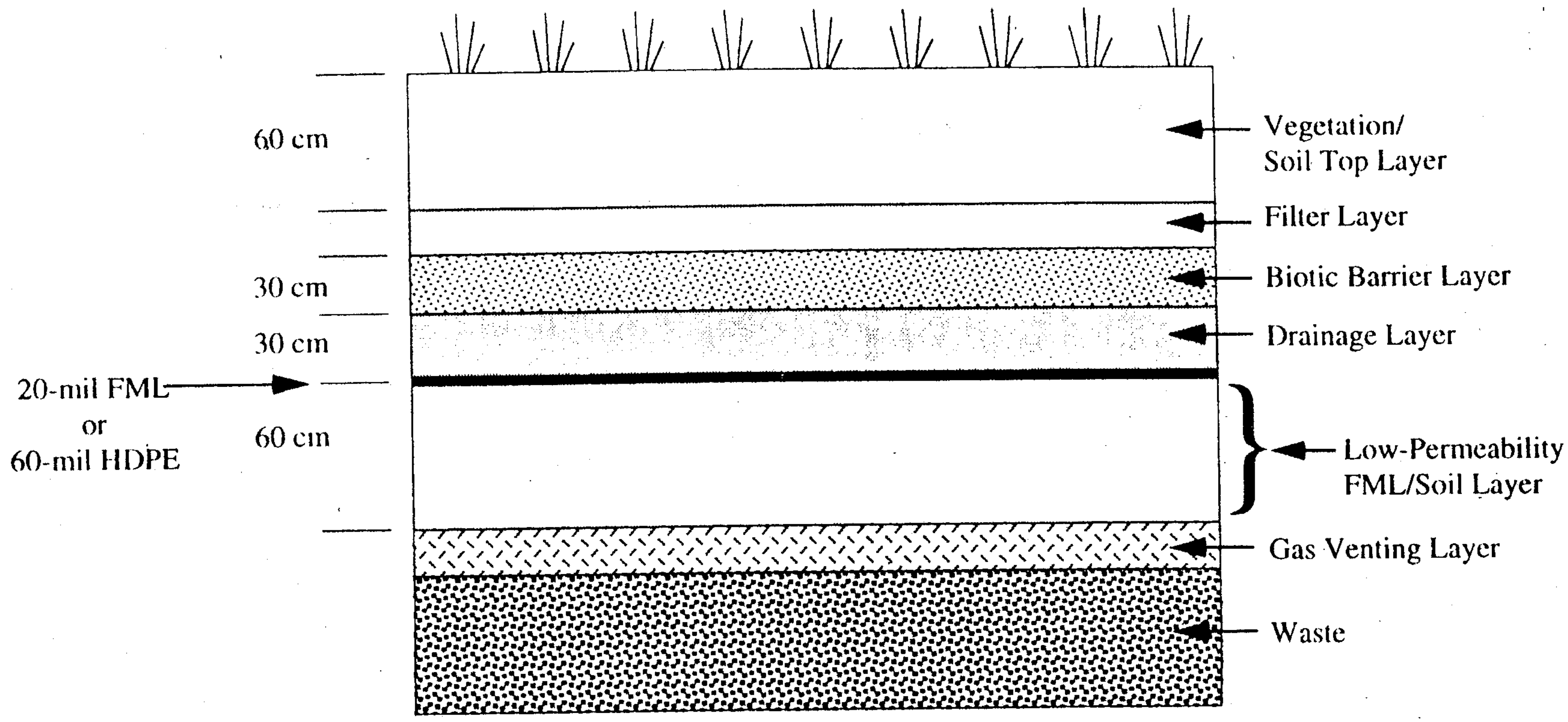

Figure 6-6
Example of an Alternative Final Cover Design

leachate generation is diminished. Caution should be taken when using a drainage layer because this layer may prematurely draw moisture from the erosion layer that is needed to sustain vegetation.

If a drainage layer is used, owners or operators should consider methods to minimize physical clogging of the drainage layer by root systems or soil particles. A filter layer, composed of either a low nutrient soil or geosynthetic material, may be placed between the drainage layer and the cover soil to help minimize clogging.

If granular drainage layer material is used, the filter layer should be at least 12 in. (30 cm) thick with a hydraulic conductivity in the range of 1 x 10^{-2} cm/sec to 1 x 10^{-3} cm/sec. The layer should be sloped at least 3 percent at the bottom of the layer. Greater thickness and/or slope may be necessary to provide sufficient drainage flow as determined by site-specific modeling (U.S. EPA, 1989b). Granular drainage material will vary from site to site depending on the type of material that is locally available and economical to use. Typically, the material should be no coarser than 3/8 inch (0.95 cm), classified according to the Universal Soil Classification System (USCS) as type SP, smooth and rounded, and free of debris that could damage an underlying geomembrane (U.S. EPA, 1989b).

Crushed stone generally is not appropriate because of the sharpness of the particles. If the available drainage material is of poor quality, it may be necessary to increase the thickness and/or slope of the drainage layer to maintain adequate drainage. The HELP model can be used as an analytical tool to evaluate the relative expected performance of alternative final cover designs.

If geosynthetic materials are used as a drainage layer, the fully saturated effective transmissivity should be the equivalent of 12 inches of soil (30 cm) with a hydraulic conductivity range of 1 x 10^{-2} cm/sec to 1 x 10^{-3} cm/sec. Transmissivity can be calculated as the hydraulic conductivity multiplied by the drainage layer thickness. A filter layer (preferably a non-woven needle punch fabric) should be placed above the geosynthetic material to minimize intrusion and clogging by roots or by soil material from the top layer.

Gas Vent Layer

Landfill gas collection systems serve to inhibit gas migration. The gas collection systems typically are installed directly beneath the infiltration layer. The function of a gas vent layer is to collect combustible gases (methane) and other potentially harmful gases (hydrogen sulfide) generated by micro-organisms during biological decay of organic wastes, and to divert these gases via a pipe system through the infiltration layer. A more detailed discussion concerning landfill gas, including the use of active and passive collection systems, is provided in Chapter 3 (Subpart C).

The gas vent layer is usually 12 in. (30 cm) thick and should be located between the infiltration layer and the waste layer. Materials used in construction of the gas vent layer should be medium to coarse-grained porous materials such as those used in the drainage layer. Geosynthetic materials may be substituted for granular materials in the vent layer if equivalent performance can be demonstrated. Venting to an exterior collection point can be provided by means such as horizontal pipes patterned laterally throughout the gas vent layer, which channel gases to vertical risers or lateral headers. If vertical risers are used, their number should be minimized (as they are frequently vandalized) and located at high points in the cross-section (U.S. EPA, 1989b). Condensates will form within the gas collection pipes; therefore, the design should address drainage of condensate to prevent blockage by its accumulation in low points.

The most obvious potential problem with gas collection systems is the possibility of gas vent pipe penetrations through the cover system. Settlement within the landfill may cause concentrated stresses at the penetrations, which could result in infiltration layer or pipe failure. If a geomembrane is used in the infiltration layer, pipe sleeves, adequate flexibility and slack material should be provided at these connections when appropriate. Alternatively, if an active gas control system is planned, penetrations may be carried out through the sides of the cover directly above the liner anchor trenches where effects of settlement are less pronounced. The gas collection system also may be connected to the leachate collection system, both to vent gases that may form inside the leachate collection pipes and to remove gas condensates that form within the gas collection pipes. This method generally is not preferred because if the leachate collection pipe is full, gas will not be able to move through the system. Landfill gas systems are also discussed in Chapter 3 (Subpart C).

Biotic Layer

Deep plant roots or burrowing animals (collectively called biointruders) may disrupt the drainage and the low hydraulic conductivity layers, thereby interfering with the drainage capability of the layers. A 30-cm (12-inch) biotic barrier of cobbles directly beneath the erosion layer may stop the penetration of some deep-rooted plants and the invasion of burrowing animals. Most research on biotic barriers has been done in, and is applicable to arid areas. Geosynthetic products that incorporate a time-released herbicide into the matrix or on the surface of the polymer also may be used to retard plant roots. The longevity of these products requires evaluation if the cover system is to serve for longer than 30 to 50 years (USEPA, 1991).

Settlement and Subsidence

Excessive settlement and subsidence, caused by decomposition and consolidation of the wastes, can impair the integrity of the final cover system. Specifically, settlement can contribute to:

- Ponding of surface water on the cap;
- Disruption of gas collection pipe systems;
- Fracturing of low permeability infiltration layers; and
- Failure of geomembranes.

The degree and rate of waste settlement are difficult to estimate. Good records regarding the type, quantity, and location of waste materials disposed will improve the estimate. Settlement due to consolidation may be minimized by compacting the waste during daily operation of the landfill unit or by landfilling baled waste. Organic wastes will continue to degrade and deteriorate after closure of the landfill unit.

Several models have been developed to analyze the process of differential settlement. Most models equate the layered cover to a beam or column undergoing deflection due to various loading conditions. While these models are useful to designers in understanding the qualitative relationship between the various land disposal unit characteristics and in identifying the constraining factors, accurate quantitative analytical methods have not been developed (U.S. EPA, 1988).

If the amount of total settlement can be estimated, either from an analytical approach or from empirical relationships from data collected during the operating life of the facility, the designer should attempt to estimate the potential strain imposed on the cover system components. Due to the uncertainties inherent in the settlement analysis, a biaxial strain calculation should be sufficient to estimate the stresses that may be imposed on the cover system. The amount of strain that a liner is capable of enduring may be as low as several percent; for geomembranes, it may be 5 to 12 percent (U.S. EPA, 1990). Geomembrane testing may be included as part of the design process to estimate safety factors against cover system failure.

The cover system may be designed with a greater thickness and/or slope to compensate for settlement after closure. However, even if settlement and subsidence are considered in the design of the final cover, ponding may still occur after closure and can be corrected during post-closure maintenance. The cost estimate for post-closure maintenance should include earthwork required to regrade the final cover due to total and differential settlements. Based on the estimates of total and differential settlements from the modeling methods described earlier, it may be appropriate to assume that a certain percentage of the total area needs regrading and then incorporate the costs into the overall post-closure maintenance cost estimate.

Sliding Instability

The slope angle, slope length, and overlying soil load limit the stability of component interfaces (geomembrane with soil, geotextile, and geotextile/soil). Soil water pore pressures developed along interfaces also can dramatically reduce stability. If the design slope is steeper than the effective friction angles between the material, sliding instability generally will occur. Sudden sliding has the potential to cause tears in geomembranes, which require considerable time and expense to repair. Unstable slopes may require remedial measures to improve stability as a means of offsetting potential long-term maintenance costs.

The friction angles between various media are best determined by laboratory direct shear tests that represent the design loading conditions. Methods to improve stability include using designs with flatter slopes, using textured material, constructing benches in the cover system, or reinforcing the cover soil above the membrane with geogrid or geotextile to minimize the driving force on the interface of concern. Methods for applying these design features can be found in (U.S. EPA 1989), (U.S.EPA 1991), and (Richardson and Koerner 1987).