APPENDIX B: HAZARDOUS WASTE LANDFILL COVER DESIGN CONSIDERATIONS

B-1. General.

a. Intended Use of Document. This document for landfill cover design was developed to aid in project planning, scheduling, and budgeting; pre-design investigations and A/E services; as a checklist for conducting landfill cover designs; for use in reviewing A/E products; and as a source for technical references. It should be noted that input from appropriate technical staff is necessary, as a document of this type may not address all site-specific issues associated with a particular project.

b. Purpose and Function of Cover System. Various types of landfill covers are used to close municipal solid waste landfills, hazardous waste landfills, and other types of hazardous waste sites. The primary purpose of a landfill cover is to isolate waste materials from the environment by minimizing the infiltration of surface water, preventing human and animal contact with the waste materials, and controlling landfill gases. A landfill cover will also control surface runoff to minimize erosion and adverse impacts on adjacent waterways and properties.

c. Alternative Cover Types. The components of a cover system depend its function, environment, applicable regulations, and site-specific conditions. The Environmental Protection Agency's (EPA) *Resource Conservation and Recovery Act* (RCRA) provides guidance on covers for both municipal solid waste and hazardous waste landfills. The Federal guidelines for closure of municipal solid waste landfills are set forth in 40 CFR Part 258. The Federal guidelines for closure of hazardous waste landfills are set forth in 40 CFR Part 264. State and local governmental agencies may have established their own criteria for cover systems that are more stringent than Federal guidelines. The most stringent regulations or guidelines usually govern the design. In some cases, cover systems that rely on natural processes to isolate waste materials are known as "Alternative Covers." These cover systems vary in configuration and are known as evapotranspiration (ET) caps, capillary barriers, dry barriers, or infiltration control caps. They have been primarily considered for landfills located in arid and semi-arid climates. Additional information regarding alternative cover systems can be found at http://www.rtdf.org/public/phyto/minutes/altcov/default.htm.

d. RCRA Hazardous Waste Landfill Covers. This document will focus on covers for RCRA Subtitle C hazardous waste landfills. In general, CERCLA (*Comprehensive Environmental Response, Compensation, and Liability Act*) hazardous waste landfill covers have been designed to RCRA standards. The components of a hazardous waste landfill cover consist of a protective cover layer, a drainage layer, a low-permeability layer, and random fill overlying the waste. Optional layers include a gas collection system and a biotic barrier. Biotic barriers are placed in the upper portions of a landfill cover to prevent plants and animals from damaging the cover. However, they are rarely used and will not be discussed in this document. Site-specific physical conditions such as topography, material availability, and cover stability affect the design and material selection of the cover components. A typical RCRA hazardous waste landfill cover design incorporating all the optional layers is presented in Figure B-1.

B-2. Pre-design Investigations.

a. General. Prior to preparing a design analysis or plans and specifications for a landfill cover, it is necessary to conduct pre-design surveys and investigations to fill data gaps. The existing database available from the remedial investigation (RI), feasibility study (FS), and any other documents must be reviewed before scoping a pre-design investigation. The following information is often required in the design of a final cover.

b. Field Surveys and Record Searches.

(1) *Aerial Photography*. Historical aerial photographs can be used to preliminarily define the nature and extent of a landfill. The principal sources of aerial photographs are the U.S. Department of Agriculture (USDA) Natural Resource Conservation Service (NRCS), the U.S. Geological Survey (USGS), and some military installations.

(2) *Design and Operational Data.* Design and operational information obtained from as-built drawings, specifications, design analyses, and interviews of people associated with the site may help in identifying the nature and extent of a landfill. Information obtained from these sources may not always be readily available for existing hazardous waste sites.

(3) *Map Database*. The USGS, USDA, and other government agencies produce topographic, soils, ground water, and other maps that may be useful in defining landfill boundaries and cover design.

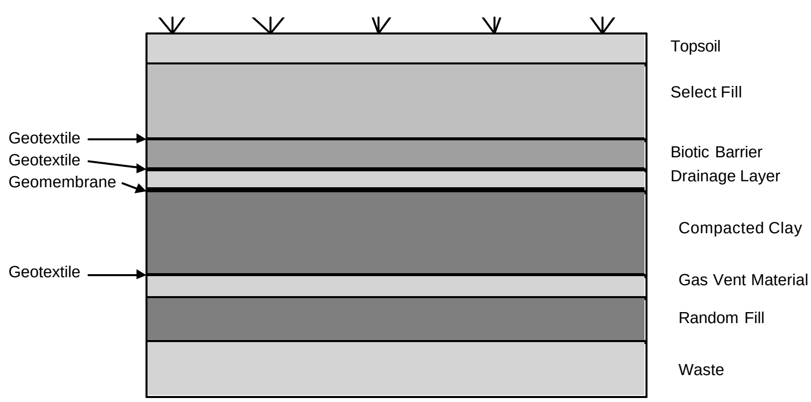


Figure B-1. Landfill cover with all optional layers.

(4) *Topographic Surveys*. Current topographic surveys of the project site are required. To allow for manipulation of data and to expedite the design process, the topographic survey should be mapped on a computer-aided design and drafting (CADD) system. Ideally, the topographic mapping will have 300-mm (1-ft) contour intervals. However, larger contour intervals may be acceptable,

depending on site-specific conditions (e.g., time, budget, topography, etc.). The topographic mapping should be referenced to the horizontal and vertical control used to perform the survey and should be accurate to within ± 30.0 mm (±0.1 ft) in ± the vertical and horizontal directions. Elevations of piezometers, monitoring wells, or other instrumentation should be accurate to ±3.0 mm (±0.01 ft) to allow for accurate interpretation of data. All surface features such as buildings, utilities, ponds, fences, trees, streams, ditches, and exploratory borings and trenches should be shown on the mapping.

(5) *Horizontal and Vertical Control*. At a minimum, three permanent control monuments need to be established. The monuments should be strategically located so that they are not damaged during construction and will not be affected by settlement of the landfill. All monuments should be assigned state plane coordinates. The vertical datum should be mean sea level.

(6) *Monitoring Baseline Data.* To monitor design concerns, it is often necessary to collect an initial set of data to establish a baseline for instrumentation such as settlement gauges, monitoring wells, piezometers, and slope movement markers.

(7) *Utilities*. All on-site above- and below-ground utilities need to be located. A utility search should consist of an on-site inspection, review of as-built drawings, and contacts with utility companies. The project drawings should show the location of on-site utilities, including horizontal and vertical alignment, type, and size.

(8) *Boundary Survey and Property Search*. The boundaries for all properties or parcels within project construction and access limits should be surveyed. The boundary survey should be tied to the site's horizontal control. A property search should also be conducted to identify property owners of all affected and adjacent parcels of land. Prior to any investigation or construction activity, it is essential to obtain construction easements and project rights-of-way. This may take 12 to 18 months; therefore, coordination with real estate elements should begin as soon as possible.

c. *Geological Investigations*. After the existing database has been reviewed, geological investigations can then be scoped. The following items need to be investigated in order to design a cover system.

(1) *Landfill Limits.* It is imperative that the depth of the waste materials and the limits of the landfill or contaminated area be determined. Depending on the composition of the waste material, the limits of the landfill can be tentatively defined by geophysical methods, such as electromagnetic conductivity surveys and ground penetrating radar. Surface depressions and stressed vegetation along with historical aerial photographs can also help in delineating approximate landfill boundaries. Intrusive methods, such as test pits or borings, should be used to verify landfill boundaries. All test pits and borings should be logged by a qualified geologist or geotechnical engineer. Surveys should also be made to determine the exact location of any geotechnical investigations used to define the landfill boundary.

(2) *Existing Cover*. Existing cover materials should be evaluated to determine cover thickness, material types, and overall conditions.

(3) *Landfill Gas*. Soil gas surveys or soil gas probes installed on the landfill surface can be used to determine if the landfill is emitting methane, hydrogen sulfide, or other gases. Empirical methods or estimates from soil gas surveys can also be used to estimate landfill gas emission rates.

(4) *Landfill Composition and Excavatability.* It is necessary to determine the composition of the waste materials for the design of any landfill cover system. The information is used to calculate potential cover settlement, determine landfill gas emission rates, and evaluate if excavation into the waste materials is feasible because of contaminant levels or potential health and safety concerns. When waste regrading or other intrusive work is necessary, the excavatability of the waste material should also be evaluated. Information required depends on site-specific conditions and could include material types, water table elevation, leachate levels, moisture content, and site stratigraphy.

(5) *Leachate.* In some situations, leachate may migrate laterally and exit at the surface of the existing landfill. The surface of the landfill should be inspected and leachate seepage exit areas surveyed and mapped. Drainage features to collect this seepage may need to be installed below the landfill cover before it is constructed. The leachate should be characterized, as its composition may affect the selection of leachate collection materials and subsequent leachate disposal.

(6) *Ground water*. It is necessary to define water levels, gradients, flow direction, and ground water chemistry in all water-bearing units in the vicinity of the landfill cover. Ground water investigations are usually done during the RI phase. Typically, one or more wells are placed up-gradient, and several wells are placed down-gradient of the site. The wells are used to determine if the site is contaminating the ground water. Monitoring well data should be reviewed during the pre-design phase to see if additional wells are needed.

(7) *Foundation Soils*. The foundation soils should be characterized by determining material types and extent, water content, density, depth to ground water, etc. In addition, disturbed and undisturbed soil samples should be collected to determine specific geotechnical engineering properties. The type of sample and amount of material required depends on the type of test that will be used.

d. Geotechnical Laboratory Tests. Geotechnical laboratory tests are required to assess the suitability of borrow sources and to establish soil properties for use in stability, settlement, and drainage analyses. Typical tests are described in the following paragraphs.

(1) *Classification Testing*. Classification tests consist of sieve and hydrometer analyses, Atterberg limits, and moisture content testing. These tests are used to select borrow sites for cover materials and to design filter and drainage layers. Classification tests are conducted along with consolidation and shear strength tests on the foundation soils beneath the landfill to determine if stability

and settlement will be a concern.

(2) *Standard or Modified Proctor*. Proctor tests are used to develop compaction criteria for all materials requiring compaction.

(3) *Hydraulic Conductivity.* Hydraulic conductivity tests are typically performed on all barrier and drainage layer soils when a borrow source is identified and available.

(4) *Density.* Density tests establish the existing condition of foundation and borrow soils. For borrow soils, this information can be used to estimate swell and shrinkage potential attributable to excavation and compaction.

(5) *Dispersive Clay*. This test, though not common, is used to determine the erodibility of a soil. In a cover system, dispersive soils can result in excessive surface erosion or clogging of drainage layers.

(6) *Consolidation*. Consolidation testing is sometimes performed on foundation soils to estimate settlement resulting from placement of the landfill cover.

(7) *Shear Strength.* The shear strength of soils may be determined for use in stability analysis of the cover and foundation soils. Shear strength of the waste material is normally estimated because of the difficulty in obtaining representative samples.

(8) *Direct Shear Tests.* Direct shear tests should be conducted on all potentially critical cover interfaces to determine interface friction values for use in stability analyses.

e. Chemical Data Requirements. Chemical testing for site contaminants is often required for the design of various landfill cover features. A chemist should be involved in the testing program for these aspects of the project.

(1) *Landfill Gas Composition*. Generally, the percentage of methane, carbon dioxide, oxygen, and other non-methanogenic gases should be determined. This information is used in the design of the landfill gas collection and treatment system.

(2) *Borrow Soil Testing*. In addition to the typical geotechnical tests, potential borrow sources are often tested for contamination to ensure that materials used to construct the cover system are clean. Quality assurance samples taken by the Government may also be prudent to verify the seller's claims by analyzing for target analytes. Backfill is commonly tested for the site-specific contaminants being cleaned up or the testing is based on suspicion of contamination at the site from which the backfill is originating. The specifications should describe what contaminants the soil should be tested for and how frequently the tests should be done. Backfill should not be used until borrow source test results have been submitted and approved.

(3) *Leachate.* To evaluate what disposal options are available for landfill leachate, it is necessary to determine the leachate characteristics. For preliminary design, the total organic loading (BOD/COD), nutrient loading, suspended solids, and hazardous constituents (e.g., heavy metals, VOCs, etc.) should be determined.

(4) *Ground Water*. Ground water characteristics, if unknown, must be analyzed both up-gradient and down-gradient of the landfill. Chemical analysis required may vary, depending on applicable regulatory requirements.

(5) *Determination of Landfill Limits.* Although the limits of the waste materials are often easily determined by visual observation during trenching activities, additional soil testing for site contaminants is sometimes required to better define the limits of the waste materials.

(6) *Contaminated Materials Handling and Disposal*. To evaluate the safest way to handle the waste material during construction (e.g., waste regrading), it is necessary to know what contaminants are present. Also, this information is required to properly dispose of contaminated materials removed from the site.

(7) *Decontamination Water*. Chemical analysis of the water used to decontaminate equipment at the site must be specified in the contract documents so that disposal options can be determined.

(8) *Air Monitoring*. Air monitoring may be required for some operations during the construction of the landfill cover and should be included in the contract documents. Site operations may need to be modified if off-site air emissions are above regulatory limits.

(9) *Contaminated Surface Water Runoff.* Provisions should be made in the contract documents for the collection of storm water runoff that has come into contact with contaminated materials. The collected water should be tested for contamination so that disposal options can be determined.

B-3. Cover System Components.

a. General. The following design guidance satisfies the requirements of 40 CFR 264 and 265. Other final cover designs may be acceptable, depending upon site-specific conditions and upon a determination by regulators that an alternative design adequately fulfills the regulatory requirements. The components of a hazardous waste landfill cover generally consist of an erosion control layer, a protective soil layer, a drainage layer, a barrier layer, and a random fill layer overlying the waste. A gas collection system can also be a component of a landfill cover, if landfill gas is found to be present.

b. Erosion Control Layer.

(1) *General*. The erosion control layer of a cover system is designed to protect underlying cap components from wind and water erosion. The erosion control layer is usually vegetated; however, an armored surface may be applicable in some situations.

(2) *Design Criteria—Vegetative Cover*. Vegetation on the protective layer can resist wind and water erosion, maximize evapotranspiration, and enhance aesthetics of the final cover system. The selection of appropriate plant species is critical in establishing a vegetative cover. Grasses and low-growing plants are most suitable and are available for most regions and climates. In contrast, trees, shrubs, and other woody vegetation are usually unsuitable because their deep root systems can damage the underlying layers, plug drainage layers, and inhibit visual inspection of the landfill surface. Planting during the appropriate season can also be critical to successfully establishing a vegetative cover. It is recommended that an expert in local vegetation be consulted for a specific seed mixture. In general, the vegetation used at a site should meet the following requirements.

(a) Locally adapted perennial plants.

(b) Resistant to drought and temperature extremes.

(c) Roots that will not disrupt the drainage and low-permeability layer.

(d) Capable of thriving in low-nutrient soil with minimum nutrient addition.

(e) Sufficient plant density to minimize soil erosion to no more than 0.45 kg/m^2 per year (2 tons/acre per year), calculated using the USDA Revised Universal Soil Loss Equation (RUSLE). A higher erosion rate may be acceptable during the construction and vegetation establishment period. Otherwise, temporary erosion protection should be provided until the final cover is well established. Additional discussion on erosion control is covered in Paragraph B-4*h*, *Cover Surface Runoff and Erosion Control Requirements*.

(f) Capable of surviving and functioning with little or no maintenance.

(3) *Design Criteria—Armored Cover Alternative*. An armored cover is used when a vegetative cover is inappropriate as the erosion control layer of the cover system. This would occur in climates that do not support vegetation or where other conditions, such as steep slopes, preclude the use of vegetation. An armored cover is typically constructed with very coarse materials, such as crushed rock or cobbles. However, concrete, asphaltic cement, or other recycled materials may also be used. The armored component should meet the following requirements:

(a) Capable of remaining in place and minimizing erosion of underlying material during extreme weather.

(b) Capable of accommodating settlement of the underlying material.

(c) Capable of maintaining the surface slope approximately the same as the underlying soil.

c. Protective Soil Layer. The composition of the protective soil layer depends on the type of erosion control layer that will be used. When a vegetative cover is used, the lower component should consist of topsoil overlying select fill. In the case of an armored cover, topsoil is not required and the protective soil layer will be entirely select fill. In either case, the EPA recommends that the protective soil layer be composed of at least 600 mm (24 in.) of soil. A layer thicker than 600 mm (24 in.) may be required to prevent freeze–thaw damage to underlying layers or to increase the water storage capacity available to plants. Guide Specification CEGS-02140 should be used in the contract documents to specify the topsoil and select fill for a landfill cover. General guidelines for the design of these alternatives are discussed in the following paragraphs.

(1) *Topsoil.*

(a) *General.* A relatively thin layer of topsoil is provided in the cover system to promote seed germination and plant root system development. Medium-textured soils such as loam soils have the best overall characteristics to help seeds germinate and plant roots develop. Sandy or coarse-grained soils are often a problem because of high erodibility, low water retention, and loss of nutrients by leaching.

(b) *Design Criteria.* Generally, the selected topsoil should have a pH value between 6.0 and 7.5 to ensure that it is not too acidic to sustain vegetation. In addition, topsoil should contain from 5 to 20% organic matter to promote and sustain plant growth through water retention and nutrient availability. Topsoil should be uniformly distributed and evenly spread over the select fill material to a minimum thickness of 150 mm (6 in.) with minimal compactive effort. The topsoil should also be free of contamination and representative of soils in the vicinity that produce heavy growths of vegetation.

(2) *Select Fill.*

(a) *General.* Below the topsoil layer or armored surfacing is the select fill layer. The purpose of the select fill is to provide a soil that can sustain the vegetative cover through dry periods and protect the underlying geosynthetics and clay barrier layer from human activities, animals, frost penetration, desiccation, and maintenance equipment. The select fill also provides water-holding capacity to attenuate rainfall infiltration to the underlying drainage layer. As with topsoil, select fill should consist of medium-textured soils, such as loams, for both function and constructibility. Cohesionless silts and sands are undesirable because these soils are highly erodible, do not retain water well, and nutrients are easily leached from them. Clayey soil types are more fertile than sandy soils. However, high-plasticity clays can be difficult to place and can damage underlying geosynthetics during placement. The best materials are cohesive but not highly plastic and include SC (clayey sand) and CL (lean clay) as classified by the Unified Soil Classification System (ASTM D 2487).

(b) *Design Criteria*. Material type and gradation requirements should be specified to prevent the use of highly plastic soils and to ensure compatibility with the underlying filter layer. In addition, a maximum particle size should be specified to protect against puncture or other damage to underlying geosynthetics. The maximum particle size specified will typically range from 9.5 mm (0.375 in.) to 25 mm (1 in.), depending on the type of geosynthetics present immediately beneath the select fill. The use of angular material should also be avoided because of increased potential for damaging geosynthetics. The ultimate choice of a select fill material will depend on the availability of economical borrow sources. The EPA recommends that the total thickness of the cover soils should be a minimum of 600 mm (24 in.) or equal to the maximum frost depth, whichever is greater. Constructibility issues are critical when placing select fill. Select fill should be placed starting at the toe and advancing up the slope. Placing fill in a top-down fashion can induce surface slope failures and tension in the underlying geosynthetics. The first layer of select fill should be placed in a loose lift 380 to 460 mm (15 to 18 in.) in thickness to protect underlyng geosynthetic materials. Select fill should be placed on geosynthetics by dropping from a height no greater than 900 mm (36 in.). To further protect geosynthetics from damage, low ground pressure (5–7 psi) equipment should be utilized on the first lift of select fill. After the initial lift, soils can be compacted to a specific density; however, the compaction from placement equipment is usually sufficient and will enhance the soil's ability to support vegetation. Where temporary haul roads are located over the geosynthetic components of the cover system, it is recommended that a minimum thickness of 760 to 920 mm (30 to 36 in.) should be maintained.

d. Filter Layer—Geotextile.

(1) *General*. A filter layer is normally required between the select fill and the underlying drainage layer. The filter layer ensures consistent drainage properties by preventing migration of fine-grained soil particles into the void spaces of the drainage layer below. For a landfill cover, the filter is normally a geotextile fabric; however, a series of graded granular materials could also be used. The majority of geotextiles used in cover systems are made from polypropylene or polyester polymers. The design of a geotextile filter depends on a number of factors, as discussed in the following paragraphs.

(2) *Design Criteria*. Guide Specification CEGS-2373 should be used in contract documents when specifying geotextiles for separation/filtration. AASHTO M 288-96 and Koerner (1998) provide detailed design information about the geotextile properties listed in the following paragraphs.

(a) *Soil Retention*. A geotextile filter must be designed to prevent the migration of soil particles from the select fill into the drainage layer. To accomplish this, the openings in the geotextile fabric must be small enough to retain the soil on the top side of the fabric. In the design of the geotextile filter, the coarser sized soil particles must be retained. Although some fines will initially pass through the filter, the coarse particles will eventually block further losses of finer particles if the soil is well graded. There are a number of methods available to evaluate the retention capability of a geotextile filter. All of these methods select an appropriate geotextile by comparing the particle size distribution of the soil to a fabric's opening sizes. Soil particle size is often represented by the percent passing a specific sieve size. For example, the term D_{85} refers to the sieve size that will allow 85% of a soil sample to pass. The opening size distribution of a geotextile is often represented by the percentage of a given particle size that will be retained by a geotextile. For example, O_{95} indicates that a geotextile will retain 95% of a given particle size. Geotextile design methods also differ depending on other criteria, such as whether the soils are cohesive or noncohesive, if the fabric is woven or nonwoven, soil gradation, etc. The designer should select a method that is well documented, has proven to be reliable, and is appropriate for site-specific conditions. Designers should refer to AASHTO-ABC-ARBTA Task Force Number 25 *Specification for Geotextiles*, which provides complete detailed design procedures regarding the following simplified guidance: For soils with 50% or fewer particles by weight passing U.S. No. 200 sieve, apparent opening size (AOS) should be less than 0.6 mm. For soils with more than 50% particles by weight passing U.S. No. 200 sieve, AOS should be less than 0.297 mm. AOS and O_{95} are equivalent terms.

(b) *Cross-plane Permeability.* The design of the geotextile must allow an adequate flow of water from the select fill through the filter to the drainage layer. Consequently, the design must ensure that the cross-plane permeability of the geotextile is greater than the vertical permeability of the overlying select fill by some factor of safety. Depending on the method selected, the factor of safety can range from 1 to over 10. Because of the compressible nature of nonwoven geotextiles, the manufacturer often specifies a permittivity value for the geotextile. Permittivity is defined as the volumetric flow rate of water per unit area, per unit head, under laminar flow conditions.

(c) *Clogging (Long-term Compatibility).* In addition to meeting the soil retention and permeability requirements, the geotextile should continue to allow sufficient cross-plane flow even if a percentage of the pores become clogged during the life of the system. For filters used in covers, clogging is usually a result of soil particles embedding in the open spaces of the fabric. Although generally not a problem in landfill covers, chemical or biological clogging, or both, could also occur if the filter is exposed to leachate or high pH liquids. There have been a number of empirical methods developed to evaluate the clogging potential of a geotextile. If necessary, the long-term compatibility of the geotextile can be directly determined by evaluating the select fill and geotextile filter in the laboratory using the gradient ratio test as described in ASTM D 5101. Clogging potential can also be evaluated using ASTM D 1987.

(d) *Survivability.* Survivability refers to the ability of the fabric to withstand the construction and installation process. Items that should be considered include the type of construction equipment, construction technique, and subgrade material. The index tests commonly referred to as the survivability criteria for geotextiles are puncture (ASTM D 4833), grab tensile strength (ASTM D 4632), and trapezoidal tear strength (ASTM D 4533). The American Association of State Highway and Transportation Officials AASHTO-ABC-ARBTA Task Force No. 25 and other organizations have published recommended minimum values for these and other tests that are intended to minimize the potential for construction damage. It is also essential that proper construction techniques be specified and used to ensure that the filter will not be damaged during construction.

(e) *Sewn Seams.* Both sewn and overlapped seams are used for landfill cover geotextiles. A flat seam using a two-thread chain stitch is often used for filtration geotextiles. Heat bonding and overlapping are other potential methods of joining geotextiles. The contract documents should indicate which seams must be sewn. Field seam testing is rarely performed for geotextiles used for filtration and separation.

(f) *Overlapped Seams.* For overlapped seams, a 300-mm (12-in.) overlap should be the minimum requirement in all cases. Table 3 of AASHTO M 288-96 provides additional guidance on overlap requirements.

e. Filter Layer—Granular Materials.

(1) *General*. Design criteria for granular filters are largely empirical and are given in terms of characteristic particle sizes (D_{15}, D_{85}, etc.). Engineer Manual (EM) 1110-2-1913 specifies that a granular filter must meet three requirements: piping or stability, permeability, and sufficient discharge capacity if the filter is also used as a drain. In some cases, it may be necessary to design a multiple layered or graded filter to meet these requirements. For severely gap-graded soils, the design of a filter using standard empirical relationships may not be appropriate. In these cases, it may be necessary to do filtration tests.

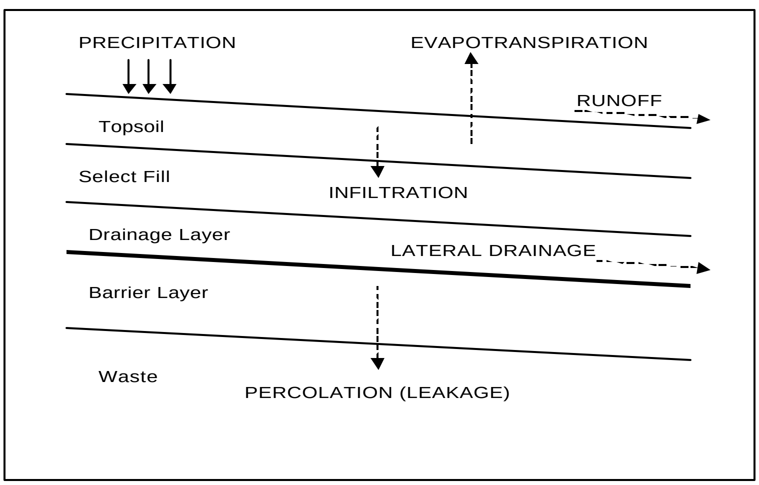
(2) *Design Criteria*.

(a) *Piping or Stability.* Filters allow seepage to move out of a protected soil more quickly than the seepage moves within the protected soil. Thus, the filter material must be more open and have a larger grain size than the protected soil. To prevent the movement of erodible soils and rocks through filters, the pore spaces between filter particles should be small enough to hold some of the larger particles of the protected material in place. These larger sized particles will eventually block finer soil particles from migrating through the filters if the soils are well graded. Appendix D of EM 1110-2-1913 provides tables and equations for designing filters to prevent piping.

(b) *Permeability.* The design of the filter must assure that the filter material is much more permeable than the material being drained. Appendix D of EM 1110-2-1913 provides the following guidance for the permeability criterion. The requirement that seepage move more quickly through the filter than through the protected soil is met by comparing the D_{15} size of the filter to the D_{15} size of the protected soil. If the D_{15} of the filter is at least 5 times greater than the D_{15} of the soil, the filter will be approximately 25 times more permeable than the protected soil. The criteria listed above define a wide range or band of gradations that will satisfy the design requirements. The gradation that is specified should fall within this band, be approximately parallel to the gradation curve or curves of the protected soil, and reflect materials that are locally available.

f. Drainage Layer.

(1) *General*. The primary function of a drainage layer in a landfill cover is to intercept water that percolates through the top layer of the cover and drain it laterally to a collection system and away from the cover. Adequate cover soil drainage is necessary to reduce hydraulic head on the underlying barrier layer and to reduce seepage induced slope failures. It is generally recognized that most cover system slides and failures are caused by inadequate drainage layer system design. The drainage layer in a landfill cap is usually constructed with either geosynthetic drainage products or granular materials. A complex drainage system might incorporate a series of collectors, laterals, and main lines to direct and discharge water from the drainage system.



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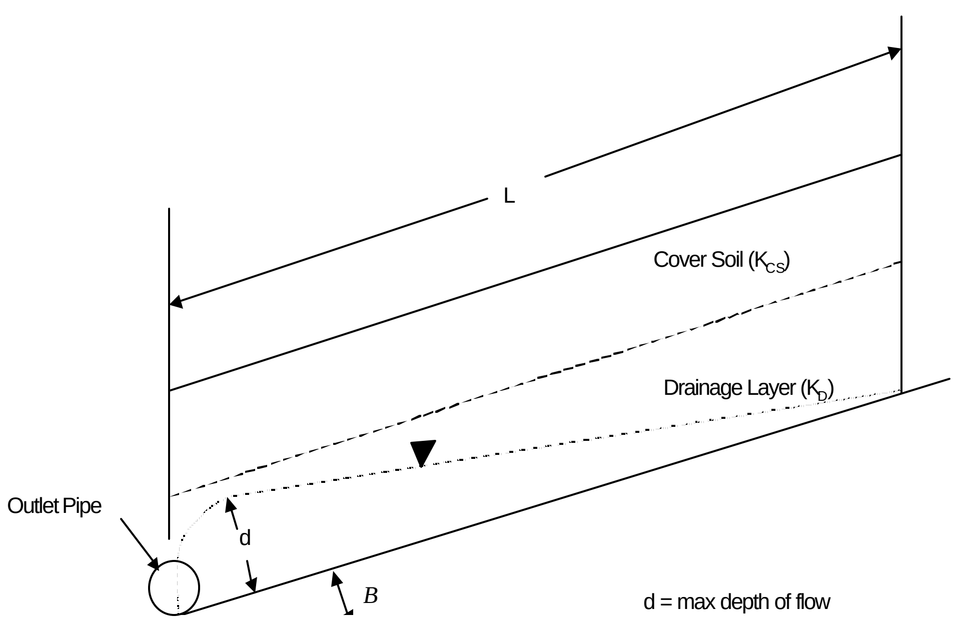

Figure B-3. Head build-up in drainage layer.

(a) *Manual Methods*. To calculate infiltration through the topsoil and select fill and into the drainage layer, one may assume that Darcy's formula applies for saturated systems under laminar flow. A worst-case scenario is assumed to determine Q_{IN}. The assumptions are as follows: 1) the cover soils are saturated prior to a storm event; 2) evapotranspiration effects are negligible; and 3) there is no percolation through the barrier layer. As precipitation falls onto the cover, water will flow into the drainage layer at a rate generally limited by the permeability of the cover soils. This method, depicted in Figure B-3 and summarized below, is further described by Thiel and Stewart (1993).

$$Q_{IN} = K_{CS} \times I \times A_1$$

where

Q_{IN}	=	flow into the drainage layer
K_{CS}	=	hydraulic conductivity of cover soils
I	=	gradient (1 for this case)
A_1	=	(unit width) $\times$ (slope length, L).

Similarly, for planar flow through the drainage layer:

$$Q_{OUT} = K_D \times I \times A_2$$

where:

Q_{OUT} = flow exiting the drainage layer
K_D = hydraulic conductivity of drainage layer
I = gradient (sin$B$)
A_2 = (unit width) $\times$ (depth of drainage layer).

This method is conservative; however, it is applicable for most cover drainage layer designs. As shown in Figure B-3, one may determine an appropriate spacing (slope length, L) between drainage collection pipes, or outlet drains, by having $Q_{IN} = Q_{OUT}$. If the cover system is constructed of high permeability soils (i.e., rate of infiltration > rate of precipitation), one should compare the infiltration of a storm event, such as a 6-hour, 25-year storm (or other event) to calculate drainage layer flows.

(b) *Computer Models*. Several water balance models have been developed for estimating water movement in and through soil. Some are simplified spreadsheets that account for water balances each month or day. The Hydrologic Evaluation of Landfill Performance (HELP) model is the one most commonly used to evaluate the overall performance of a cover system and its individual components. HELP models the daily hydrologic processes in a landfill system, including surface runoff, infiltration, evapotranspiration, soil moisture storage, lateral drainage, and leachate production. The HELP model is used to estimate long-term landfill cover effectiveness, drainage layer flow, head build-up in select fill, leachate collection system flow, and available water storage for a vegetative cover (wilting point). The version of HELP currently being used is Version 3. EPA/600/R-94/168a and b provide detailed guidance on the use of the HELP model. Designers are cautioned that HELP may significantly underestimate lateral drainage flow rates that are appropriate for drainage layer design (Richardson and Garrett 2000). This underestimation is most often the result of inappropriate input parameters or using long-term HELP model results to design short-term, high flow storm events. Lateral drainage flow values obtained from HELP should always be compared to flow rates calculated by manual methods.

(3) *Geosynthetic Drains*. Geosynthetic drainage systems have often replaced granular materials for drainage media, as they require less space and are easier to construct. Geosynthetic drainage systems typically consist of a three-dimensional drainage core with a geotextile fabric attached to one or both of its sides. The core, which transmits the flow, must be protected by a fabric that acts as a filter/separator from the overlying soil. Water passes through the geotextile and into the drainage core. The geosynthetics industry has developed many drainage core configurations. Some of the drainage cores that are available include: biaxial extruded geonets, triplanar geonets, and many other configurations as well. Currently, the most common geosynthetic drainage system used for landfill cover systems are those that use geonets with attached geotextile filters, commonly called geocomposite drainage layers. Most commercially available resins used for geonets are made of polyethylene. The final compound is approximately 97% polyethylene, with 2–3% carbon black added for ultra-violet (UV) resistance. An additional 0.5–1% is additives, such as antioxidants and processing aids. Geonets typically range from 5.0 to 8.0 mm (0.20 to 0.30 in.) in thickness but can be considerably thicker.

(a) *Design Criteria*. To design a geocomposite or geonet drainage layer, a required flow rate

($q_{req'd}$) can be developed from the following realationship:

$$FS = (q_{allow})/(q_{req'd})$$

where

FS	=	factor of safety
q_{allow}	=	allowable flow rate obtained from laboratory testing
$q_{req'd}$	=	required flow rate for design.

The planar flow rate, or transmissivity, of geonet and geocomposite drainage layers is determined using ASTM D 4716. Laboratory tests should reflect the worst-case normal load and hydraulic gradient expected in the field. The type of material in contact with the geonet or geocomposite drainage layer can affect the flow properties of the drainage layer and must be considered when evaluating transmissivity test data. The transmissivity determined in the laboratory should reflect expected field conditions as much as possible. Other adjustments, in the form of factors of safety, may account for:

- Elastic deformation or intrusion of the adjacent geosynthetics into the geonet's core space.

- Creep deformation of the geonet and adjacent geosynthetics into the geonet's core space.

- Physical clogging of the geonet's core space with fine soil particles.

- Chemical clogging or precipitation of chemicals in the geonet's core space, or both.

- Biological clogging and root intrusion of the geonet's core space.

A typical total factor of safety may range from 2.0 to 8.0. Details of the design and guidelines for the various adjustments and reduction factors are given in Koerner (1998) and Richardson and Zhao (1999). Guide Specification CEGS-02374 should be used in the contract documents when specifying geonet or geocomposite drainage layers.

(b) *Compatibility.* Chemical compatibility between infiltrating surface water and the geonet is generally not critical and does not require compatibility testing. However, if a geonet or geocomposite drainage layer is used to intercept leachate exiting the landfill side slopes, the chemical resistance or susceptibility to biological clogging of the drainage layer to the leachate may need to be evaluated.

(c) *Compressive Strength.* The flow capability of a geonet or geocomposite drainage layer is reduced as it deforms under compressive loads. For landfill covers, the normal stresses imposed from overlying fill material and live loads from construction equipment should be checked, but are usually small and do not appreciably reduce flow capacity.

(d) *Overlaps*. Because of the great variation among geosynthetic drainage materials, manufacturer's recommendations regarding overlap requirements should be followed. In general, geonets and geocomposite drainage layers should be placed parallel to the line of slope and not across it. Care should be taken to ensure that all flow remains in the drainage layer and that head does not build-up in the overlying cover soils. For this reason, the flow capacity of any end seams on drainage slopes should be considered. Geonet to geonet contact should be ensured at all geocomposite end seam connections. End seams are not recommended on slopes steeper than 4 horizontal on 1 vertical.

(4) *Granular Drains*. Granular materials can also be used to construct the drainage layer. The design requires choosing an appropriate drainage material, layer thickness, and location of lateral drains. A designer should consider the following guidelines when designing a granular drainage layer.

(a) *Thickness*. A minimum thickness of 300 mm (12 in.) and minimum slope of 3% at the bottom of the layer should be used. A greater thickness or slope, or both, may be necessary to provide ample drainage flow.

(b) *Gradation*. Granular material should have a minimum of fines that can migrate and collect in downslope areas, thus clogging the outlet. The hydraulic conductivity of drainage material should be no less than 1×10^{-2} cm/s; however, higher hydraulic conductivities may be required to provide adequate flow capacity. If large (> 9.5 mm [0.375 in.]) or angular materials are used for a drainage layer, the underlying geosynthetics should be protected with cushion layer materials. Details regarding cushion layer design are given in *Design Methodology for the Puncture Protection of Geomembranes* (Wilson-Fahmy et al. 1996).

g. Drainage Collection and Removal System.

(1) *General*. Once the drainage layer has been designed, the next step is to design a drainage collection and removal system to allow collected water to exit the cover. It is essential that the collection and removal system be adequately sized so that water does not “build up” in the drainage layer of the landfill cover. Water collected from the drainage layer may be released through a variety of methods; however, perimeter toe drains, perforated pipe collectors, or a combination of the two are most commonly used.

(2) *Design Criteria*. The outlet drainage system must be capable of removing the maximum flow from the cover drainage layer. Often, the lateral drainage layer simply drains freely at the toe of the cover into a perimeter ditch or swale. However, if the landfill cover is relatively large with long drainage slopes, it may be necessary to install additional drainage collection pipes at some regular spacing (typically every 150 to 200 ft) to prevent exceeding the capacity of the drainage layer (see Figure B-3). These pipes are then routed via gravity flow to the perimeter of the landfill cover and discharged to drain out and away from the landfill. Manning's formula for open channel flow can be used for sizing these pipes. A 150-mm (6-in.) diameter pipe is typically the minimum size used for drainage systems to allow for easy maintenance. In addition, cleanout risers are recommended at a spacing not to exceed

100 m (300 ft).

(3) *Bedding Materials and Pipe Perforations*. The design of bedding materials and drainage media must include an evaluation of the criteria outlined in Paragraph B-3*e*, *Filter Layer— Granular Materials*. EM 1110-2-1901 provides guidance on sizing perforations for preventing infiltration of material into the perforated pipe:

$$\frac{\text{50\% size of filter material}}{\text{hole diameter or slot width}} \geq 1.0 \text{ (holes) or } \geq 1.2 \text{ (slots)}$$

(4) *Pipe Considerations*. Perforated polyvinyl chloride (PVC) pipe, smooth-walled high-density polyethylene (HDPE) pipe, or corrugated HDPE pipe may be used to construct a drainage collection system. The most common are corrugated HDPE pipe systems. These materials are easy to install in the field, flexible enough to withstand minor settlements, and are relatively inexpensive.

(a) *PVC Pipe*. PVC pipes are often supplied in 6.1-m (20-ft) lengths and are joined via couplings or with bell and spigot ends. The basic resin should be as defined in ASTM D-1755. For PVC specified as Schedule 40, 80, and 120, reference ASTM D-1785. For pipe specified by the standard dimension ratio (SDR), the appropriate specification is ASTM D-2241.

(b) *HDPE Smooth-wall Pipe*. HDPE smooth-wall pipes are generally supplied in 6.1-m (20-ft) lengths and are joined using butt-end fusion. Other joining methods are also available. The HDPE material consists of 97–98% resin, with approximately 2% carbon black and minor other additives.

(c) *HDPE Corrugated Pipe*. This pipe is available in several forms, each design being supplier-specific. The pipe may be perforated or slotted, the inside may be smooth lined or not, and various connections and fittings are available as well. HDPE corrugated pipe is the one most commonly used for cover drains. AASHTO M 252 and M 294 provide detailed design information for corrugated HDPE pipes.

h. Barrier Layer—Geomembrane.

(1) *General*. The objective of the barrier layer is to minimize percolation of precipitation into underlying waste materials. Geomembranes are thin sheets of flexible, relatively impervious polymeric materials, whose primary function is to act as a barrier to liquids and vapors. The polymeric materials are manufactured into sheets and transported to the job site, where they are placed and seamed.

(2) *Design Criteria*. Common types of geomembranes currently being used for landfill covers are PVC and polyethylene, with polyethylene being the most frequently used geomembrane on Corps of Engineers projects. A minimum thickness of 1.0 mm (40 mils) is recommended for cover

geomembranes. Geomembranes can be manufactured with textured surfaces, which improve the frictional resistance at adjacent interfaces. Textured geomembranes should only be considered for slopes greater than about 10°. In general, textured geomembranes are more expensive, have diminished physical properties, have potentially more manufacturing defects, and are more difficult to inspect than non-textured geomembranes. Guide Specification CEGS-02372 should be used in contract documents when specifying geomembranes. *Designing with Geosynthetics* (Koerner 1998) provides a detailed summary of geomembrane design considerations.

i. Barrier Layer—Clay.

(1) *General*. The purpose of the clay barrier layer in a composite cover is to inhibit the movement of water that may pass through any holes in the geomembrane. Soils used for the clay barrier layer are selected to meet a specific hydraulic conductivity requirement (typically 1×10^{-7} cm/s). The designer needs to ensure that a sufficient amount of suitable soil is available for the clay barrier layer and specifications are written so that the soil is properly placed, compacted, and protected. If soils found in the vicinity of the project do not contain a sufficient amount of suitable clay, a common practice is to blend available natural soils with bentonite (typically 2 to 10% by weight) to achieve required properties. Clay barrier layers are normally a minimum of 600 mm (24 in.) in thickness. Clay barriers are vulnerable to increases in permeablility from dessication cracking because of drying, especially during construction. Procedures outlined in CEGS-02377 should be followed to ensure that the clay barrier does not dry out. Freeze–thaw cycles can also increase the permeability of a clay layer. Therefore, the cover should be designed so that the clay layer is located below frost depth.

(2) *Design Criteria*. Guide Specification CEGS-02377 should be used in contract documents when specifying clay barrier layers. A clay borrow source can be located during the design process, or it can be left up to the contractor. If locating and testing a borrow source is left up to the contractor, the designer should verify that acceptable borrow sources exist in the area during the design phase. In general, the testing and quality control steps required for construction of a clay barrier layer are as follows:

- A potential borrow source is located and explored to determine its vertical and lateral extent and to obtain representative samples for testing.

- Once construction begins, quality control (QC) and quality assurance (QA) tests are performed to confirm the suitability of materials being used.

- After a lift of soil has been placed, additional tests are performed to verify the soils are being placed and compacted properly.

(3) *Borrow Assessment Testing*. EPA/600/R-93/182 describes the required properties of a clay barrier borrow soil. Tests should be conducted on each principal type or combination of proposed materials to assure compliance with specified physical properties and to develop compaction

requirements for placement. At a minimum, one set of borrow assessment tests should be done for each borrow source proposed. A set should consist of classification, moisture–density (compaction), and hydraulic conductivity testing.

(a) *Classification Testing*. Test pits or borings should be made in a grid pattern to characterize each proposed borrow source. Small samples obtained from borings are excellent for index property testing but often do not provide a very good indication of subtle stratigraphic changes in the borrow area. Test pits excavated into the borrow soil with a backhoe or other excavation equipment can expose a large cross section, providing a much better idea of the variability of soil than viewing small soil samples obtained from borings. Soils should be grouped into “principal types” based on visual classification by a qualified geologist or geotechnical engineer. Classification testing should be performed on representative samples of each principal type or combination of materials. At a minimum, one set of classification tests should be performed per 5000 m^3 (6500 yd^3) of proposed borrow. Classification testing should consist of moisture content, liquid and plastic limits, and particle size analysis.

(b) *Compaction Testing*. One of the most important aspects of constructing a clay barrier layer is proper remolding and compaction of the soil. The traditional method of specifying the “acceptable zone” of moisture contents and densities has been based on achieving adequate strength and limiting compressibility. This method is not ideal for clay layers designed to achieve low hydraulic conductivities. EPA/600/R-93/182 provides detailed guidance on a satisfactory approach to developing moisture–density criteria for a clay barrier layer. The same general procedure may also be used for soil–bentonite mixtures. The procedure is outlined below:

- For each soil type to be used in the clay barrier layer, prepare and compact samples with modified (ASTM D 1557) and standard (ASTM D 698) compaction procedures to develop compaction curves.

- Based on compaction test results, specimens should be compacted to various densities and permeated using the test procedure described in ASTM D 5084. Confining pressures and hydraulic gradients used to perform this testing should be representative of landfill cover conditions.

- An acceptable zone should be developed that encompasses the moisture contents and densities that achieve the required permeability.

- The acceptable zone should be modified on the basis of shear strength considerations, if applicable.

j. Barrier Layer—Geosynthetic Clay Liner.

(1) *General*. Geosynthetic clay liners (GCLs) are factory manufactured hydraulic barriers

consisting of bentonite clay materials supported by geotextiles or geomembranes. GCLs are used to augment or replace compacted clay layers or geomembranes. All of the GCL products available in North America use sodium bentonite clay powder or granules, with a mass per unit area in the range of 3.2 to 6.0 kg/m^2 (0.66 to 1.2 lb/ft^2). The clay thickness of the products varies between 4.0 to 8.0 mm (160 to 320 mils). GCLs are available in widths of 2.2 to 5.2 m (7 to 17 ft) and lengths of 30 to 60 m (100 to 200 ft). GCLs are most often considered for use where there is a limited supply of natural clay, limited landfill space, or where differential settlements could cause unacceptable tension cracking in a compacted clay liner. GCLs are also less susceptible to the effects of desiccation and freeze–thaw than compacted clay layers. One limitation to consider is that hydrated, GCLs have extremely low in-plane shear strength. Because of this, geotextile-backed GCLs should be reinforced with stitch bonding or needle punching if the GCL is to be used on slopes that are steeper than 3 to 5°. If a geomembrane backed GCL is used on slopes, the bentonite component of the GCL should be fully encased with geomembrane to prevent it from hydrating.

(2) *Design Criteria*. EPA/600/R-93/171, *Report of Workshop on Geosynthetic Clay Liners* summarizes information on GCLs. Guide Specification CEGS-02376 should be used in contract documents to specify material and installation requirements for geosynthetic clay liners.

k. Cover Penetrations.

(1) *General*. Penetrations through the landfill cover are required for gas vents, monitoring wells, and other purposes. However, the number of penetrations should be minimized. Geomembranes should be attached to the penetrating object in a way that ensures a watertight seal but still allows for movement from settlement or horizontal displacement.

(2) *Design Criteria*. Most geomembrane manufacturers, fabricators, or installers have their own typical penetration details. Therefore, in many cases, it is only necessary to show locations of the penetrations on the drawings and note that penetration details must be in accordance with approved geomembrane manufacturer, fabricator, or installer details. GCL penetration details should also be as recommended by the GCL manufacturer. Pipes that penetrate deeply into the waste material are likely to settle at a different rate and to a smaller magnitude than the adjoining landfill cover. The differential settlement between the pipe and the cover system creates stress concentrations at the boot connection that can tear the geomembrane away from the pipe. Slip couplings are typically used in this situation to allow differential movement while maintaining a watertight seal.

l. Gas Collection and Removal System.

(1) *General*. Landfill gas production results from vaporization, chemical reactions, and biological decomposition. Biological and chemical degradation of organic waste materials is the predominant source of landfill gas. Degradation of organic materials results in the production of carbon dioxide (CO_2) and methane (CH_4). Other gases may also be generated, depending on the composition of the waste. Gases migrate by two processes: convection and diffusion. Convection is gas flow induced by

pressure gradients. Gas flow by diffusion is induced by concentration gradients resulting from gas production. Vertical or lateral migration paths for gas movement out of the landfill are influenced by the presence of migration corridors or barriers, or both. Migration corridors include sand and gravel lenses, void spaces, cracks, fissures, utility conduits, and drainage culverts. Barriers to gas migration include clay layers, geomembranes, GCLs, geological formations, and high or perched water tables. The potential impacts of landfill gas are as follows:

- *Explosion Hazard*. Methane can migrate through the subsurface and collect in adjacent structures creating a potential explosion hazard.

- *Vegetation Distress*. Landfill gases can distress the vegetation on a landfill cover.

- *Odor*. Odor control becomes a design parameter if the landfill is located adjacent to existing or potential developments.

- *Physical Disruption of Cover Components.* Gas pressure build-up beneath the geomembrane can force the geomembrane to protrude or "bubble out" from the cover.

- *Toxic Gases*. Gases produced by landfills can be toxic or may not comply with regulatory requirements.

(2) *Design of Gas Control Systems.* Gas control systems consist of collection, conveyance, and outlet components and are designed to be either passive or active. A passive system allows the landfill gas to exit the collection system without mechanical assistance, whereas an active system does the opposite, using mechanical assistance, such as blowers, to extract gases. Depending on the potential impacts of the landfill gas and local regulatory criteria, gases are either dispersed into the atmosphere or collected and treated. Options for gas control systems are described below.

(a) *Continuous Blanket Systems.* The EPA recommends that a continuous blanket system to collect gas have a minimum of 300 mm (12 in.) of granular fill or an equivalent geosynthetic material located below the impermeable barrier layer and above the random fill. A continuous blanket system - will allow free movement of gases to either collection or outlet pipes. Vertical outlet pipes transport the collected gases from beneath the landfill cover to the atmosphere. The number of vent pipes should be minimized and are normally spaced about 60 m (200 ft) apart. This provides approximately one vent per 4000 m^2 (one per acre). Perforated horizontal collection pipes can also be incorporated into the design of either passive or active blanket systems. A geotextile filter layer may also be required to prevent clogging of the gas collection blanket material.

(b) *Shallow Trench Systems.* For landfills where the waste materials are relatively shallow (less than 12 m [40 ft] in depth), collection trenches may be used. The trenches are usually excavated about 0.5 to 1 m (2 to 3 ft) into the waste, are lined with a geotextile, have a perforated pipe installed, and then are filled with coarse rock. The trenches should be spaced approximately 60 m (200 ft) apart and should not be interconnected. This will allow for individual lines to be valved independently for future active system control and balancing.

(c) *Well Systems*. Well systems consist of a series of gas extraction wells (perforated or slotted vertical collection pipes) that penetrate to near the bottom of the refuse. Well systems are recommended for landfills or portions of landfills that exceed 12 m (40 ft) in depth. The vent borehole diameter may range from 0.3 to 1 m (1 to 3 ft). The components of extraction wells are usually similar to those of standard ground water monitoring wells (i.e., riser, screen, gravel pack). A well system, either active or passive, is useful for layered landfills where vertical gas migration is impeded. The design of a well system requires estimates of the rate of gas production and the radius of influence of the wells. Because of the variability of landfill refuse, design procedures are difficult to apply to gas collection systems. Gas collection wells are typically spaced at a frequency of one per acre.

(d) *Wellheads and Header Piping*. Wellheads for passive gas vents are typically configured to prevent precipitation and wildlife from entering the well. Wellheads for active well systems may include sampling ports, pressure gauges, control valves, and flexible connections. Header piping is used for active systems to transport gas from the collection system to a flare. The header piping is typically made of PVC or HDPE and should be sized to provide for minimal head losses and additional capacity, should supplementary extraction wells be required at a later date. The piping can be placed on the landfill surface or be buried. The advantage of placing the header pipe on the landfill surface is ease of pipe maintenance. However, this type of installation will expose the piping to UV radiation and increase the possibility for damage from maintenance equipment and vandalism, potentially blocking surface runoff. The potential for blockage by condensate freezing in the pipes is also increased if the header pipe is placed on the landfill surface. If the header pipe is buried within the landfill cover, it is typically located above the geomembrane cover system but below frost depth. A minimum of 150 mm (6 in.) of bedding material should be placed over the geomembrane prior to placement of the header pipe. Condensate collection points should be located at low points in the header pipe system to prevent blocking of the pipe with condensate. Depending on local regulations, condensate is sometimes allowed to drip back into the waste either through the wellheads or a separate percolation drain.

(e) *Monitoring Probes*. Gas monitoring probes are used in conjunction with both active and passive systems to detect landfill gases that may migrate off-site. Usually, the regulatory compliance point is the property boundary, and the maximum concentration allowed is usually 10% of the LEL (Lower Explosive Limit) for methane. Probes are typically placed around the perimeter of the landfill at a minimum spacing of 150–300 m (500–1000 ft), although they may be closer, depending on site conditions. At some sites, probes may be closely spaced (every 30–60 m [100–200 ft]) if there are buildings near the landfill. A typical monitoring probe consists of a small-diameter slotted pipe in a borehole that extends to an elevation corresponding with the bottom of the waste or to the water table, whichever is shallower. Specific monitoring probe designs are given in EM 1110-1-4001, *Soil Vapor Extraction and Bioventing*.

m. Random Fill and Regraded Waste.

(1) *General*. Random fill is used as the foundation layer for overlying cover materials and to establish slopes for drainage. In some situations, wastes can be graded to help establish slopes for drainage. The thickness of random fill will be dictated by settlement, stability, and drainage requirements. Most soils are suitable for use as random fill. Therefore, the ultimate selection of a random fill is usually based on the availability of local materials. Materials that may be unsuitable for use as random fill include debris, roots, brush, sod, organic or frozen materials, and soils classified (ASTM D 2487) as PT, OH, or OL. In some locations, it may be feasible to place fly ash as random fill. Fly ash is often available at little or no cost as local utilities are looking to either dispose of or use it. Fly ash sources should be evaluated prior to use, as some fly ash materials may have elevated metals and radionuclides present. As another option, site debris and other materials can sometimes be used as fill in the random fill zone if they will not create settlement problems. Generally, these materials are placed as low as possible in the random fill zone.

(2) *Placement Criteria*. The random fill layer should be a minimum of 300 mm (12 in.) thick to provide a foundation to allow adequate compaction of the low-permeability clay layer. Typically, random fill is placed in loose lift thicknesses of 200 mm (8 in.) for cohesive materials and 300 mm (12 in.) for cohesionless materials. Specific compaction requirements (density) are often not used for the bottom lifts of the random fill because of the soft, compressible nature of the underlying refuse. For these lower layers, a procedure specification should be used that identifies the minimum number of passes of a specific type of compaction equipment. Compaction requirements for the upper layers of random fill are typically based on the standard proctor test (ASTM D 698). Random fill is typically compacted to a minimum of 90% of maximum density, at a test frequency of one test per acre per lift.

(3) *Waste Excavation*. In certain circumstances, limited excavation and reshaping of the landfill surface can minimize the volume of random fill required and flatten steep slopes. If waste excavation is required, the excavated waste material should be regraded and located under the random fill layer. The waste should be recompacted in 300–600 mm (12–24 in.) layers with a minimum of five passes of a standard municipal landfill trash compactor. When municipal refuse is regraded, 150 mm (6 in.) of daily cover is normally required to control vectors and odors. Surface runoff control measures are also needed to ensure that receiving streams are not contaminated should rain fall during regrading operations. Excavation into waste materials may expose unknown landfill contents, such as buried drums, medical waste, unexploded ordnance, nuclear waste, or bulky debris. Consequently, excavation into the landfill may require specific safety and health considerations, such as air monitoring and personnel protective equipment (PPE). The level of PPE should be determined for each.

n. Clearing and Grubbing. Clearing and grubbing is performed prior to placement of the random fill layer. Grubbing is often not done on hazardous waste landfills or is minimized because of the added costs for disposal of hazardous materials and health and safety concerns. The limits of clearing and grubbing should be identified on the drawings. Guide Specification CEGS-02110 should be edited and included in the contract documents. The method of disposal for cleared and grubbed materials should be clearly stated in the specification. Cleared and grubbed material is often placed beneath the landfill cover in the lower regions of the random fill layer.

B-4. Geotechnical Design.

a. Settlement.

(1) *General.* Settlement of the cover system is the result of consolidation of both the waste material and the foundation soils. Settlement is attributable to relocation of soil particles and landfill debris, physical–chemical changes from corrosion and oxidation, and bio-chemical decomposition. The magnitude of settlement depends on a number of factors, including the following:

- Thickness of waste or refuse.
- Type of waste (e.g., construction debris and municipal refuse).
- Density or void ratio of wastes.
- Amount of decomposable materials.
- Leachate levels and ground water conditions.
- Weight of final cover.
- Type of foundation soils.
- Stress history (landfill operational history).

It is important to note that many sites require a combination of remedial technologies. For example, ground water pump and treat systems are often used in conjunction with final covers. If pump and treat systems are part of the remedial action, the effect of lowering the water table needs to be considered in the settlement analysis. Lowering the water table will create higher effective stresses in the previously saturated strata, which may result in a greater degree of consolidation of these soils and larger settlement of the landfill cover.

(2) *Results of Settlement.* Excessive total or differential settlement of the cover system can have the following effects:

- Increased permeability of the clay layer because of cracking.
- Slope instability because of steepened side slopes.

- Geomembrane or other geosynthetic failure because of tensile stresses.
- Cover penetration connection (e.g., gas vent pipe boots) failures because of the development of stress concentrations.
- Internal drainage layer and surface drainage disruption because of changes in design slopes.
- Leachate or gas collection system disruptions because of changes in design slopes.
- Surface water ponding.

(3) *Design Criteria*.

(a) *Waste Settlement Analysis*. Mechanical settlement, caused by the placement of the landfill cover, occurs rapidly and is typically complete in several weeks. Mechanical settlement is a function of the compressibility of the waste and is related to its void ratio. The combination of mechanical secondary compression, physical–chemical action, and biochemical decay causes settlement to continue with time. The method of settlement analysis typically used for landfills is presented by Sowers (1973). EPA/600/52-87/025 and EPA/600/2-85/035 provide additional technical information on the settlement of landfill covers. Settlement of a landfill should be determined across several sections that are considered representative of it to determine if adverse impacts are expected as a result of settlement.

A method for determining the stresses in geosynthetic fabrics resulting from differential settlement is presented in EPA/625/4-91/025, *Design and Construction of RCRA/CERCLA Final Covers*.

(b) *Foundation Settlement Analysis*. If the foundation material under the waste fill is composed of fine-grained soils, such as soft clays, foundation consolidation will contribute to the overall settlement of the final cover. Traditional settlement analyses, based upon site-specific soil characteristics and loading conditions, should be used to estimate foundation settlement. EM 1110-1-1904 provides detailed information on how to do settlement analyses.

(c) *Settlement Design Considerations*. Prior to the placement of random fill material, the landfill surface must be cleared of vegetation and can be proof-rolled to reduce settlement. Compaction equipment weighing 18,000 to 45,000 kg (40,000 to 100,000 lb) is often used for proof rolling. The initial 8 to 12 passes of this equipment has the greatest effect. It should be noted that this compaction effort will affect only the upper few feet of waste, and resilient materials, such as old tires, will not densify under any amount of rolling. When settlement of either the waste fill or the foundation is expected to be excessive, preloading (or dewatering) can be used to minimize post-construction settlement. After preloading is complete, the surcharge fill can be reshaped as the random fill layer.

b. Stability Analysis.

(1) *General*. Potential stability problems for a landfill cover could result from the foundation soil, or the waste, or at cover material interfaces. The stability of a landfill is controlled in broad terms by the following factors:

- Properties of the foundation soil.
- Strength characteristics and weight of refuse.
- Inclination of slopes.
- Leachate levels and movements within the landfill.
- Frictional resistance of cover material interfaces.
- Ability of the cover to freely drain infiltration.

Quantification of the geotechnical properties of waste materials is very difficult; therefore, geotechnical investigations of these materials are rarely undertaken. The following stability issues should be addressed during design.

(2) *Design Criteria*.

(a) *Cover Component Interfaces*. The stability of geosynthetic interfaces normally controls the design of side slopes of a cover rather than the stability of the waste fill or foundation. Cover component stability is assessed by analyzing the frictional resistance between each adjacent layer. EPA/625/4-91/025 describes procedures for analyzing the stability of cover systems and determining strength requirements for reinforcement materials. Typical interface friction angles between adjacent geosynthetics or between the geosynthetics and adjacent soils range from 8 to 25°. Because of this large variation in friction angles, it is important to have a requirement in the specifications that the contractor conduct interface friction tests on the actual project materials and submit the results to the designer for approval. Interface friction values should be determined on samples of the materials to be used for construction. Placement, loading, and wetting conditions used during testing should also be representative of field conditions. ASTM D 5321 describes the procedure used to perform interface friction tests. Reinforcement layers can be incorporated into the design to prevent tensile forces from developing in the geosynthetic components of the cover. Typically, geotextiles or geogrids are used for this purpose. When reinforcement layers are utilized, the material must have sufficient tensile strength and must be properly anchored. Benches on the landfill cover can also be used to provide additional stability for the cover system.

(b) *Factor of Safety for Cover Interfaces*. Typically, a minimum factor of safety of 1.5

should be used for static conditions. This value may need to be increased in seismically active areas. If possible, friction testing should be conducted during design using site-specific materials and anticipated field conditions. Where this is not possible, frictional resistance values should be selected for design calculations on the basis of tests performed by others under conditions that are similar to those anticipated in the field.

(c) *Waste Fill Mass and Foundation Stability.* After the slopes are preliminarily selected, the overall stability of the waste fill mass and foundation needs to be analyzed. As noted previously, the geotechnical characteristics of waste materials are extremely difficult to determine. The mechanical behavior of municipal refuse is typically expressed in terms of an apparent friction angle and a cohesion intercept. These parameters are back-calculated from actual cases of failure or cases where large deformations in refuse have occurred. They can also be conservatively estimated by observing existing refuse slopes and then back-calculating to determine the strength parameters, assuming a factor of safety of 1.0. It should be noted that waste mass materials could be highly variable. The text entitled *Geotechnical Practice for Waste Disposal* (Daniel 1993) provides estimates of waste strength parameters. Additional information on properties of waste fill materials can be found in ASTM STP 1070 (Morris and Woods 1994). Strength parameters used for the foundation soils are usually determined through field sampling and laboratory testing. Seismic considerations should also be addressed where applicable. The computer program UTEXAS (current version) may be used to perform stability analyses for landfills. Edris and Wright (1992) provide information on the use of UTEXAS.

(d) *Waste Fill Mass and Foundation Factor of Safety.* Recommendations for minimum factors of safety for slope stability analyses can be found in the document entitled *Guide to Technical Resources for the Design of Land Disposal Facilities* (EPA/625/6-88/018). If the designer is confident of strength parameters, a safety factor of 1.25 is recommended where there is no imminent danger to human life or to the environment if the slope fails. The safety factor should be increased to 1.5 when strength values are uncertain. When there is imminent danger to human life or if there would be a major environmental impact if the slope failed, the minimum factor of safety should be 1.5 or greater.

(e) *Other Stability Issues*. In addition to the items presented above, there are a number of other factors that may need to be considered during design. These include the effects of surface water, leachate seepage forces, desiccation cracking, seismic conditions, freeze–thaw effects, construction equipment loadings, and long-term stress relaxation of reinforcement geosynthetics.

c. Test Fills.

(1) *General*. A test fill is sometimes constructed before the full-scale landfill cover for the following reasons:

- To evaluate cover stability.

- To ensure the as-built cover meets the performance objectives.
- To verify that geosynthetics are not damaged during construction.
- To conduct large-scale permeability tests using sealed double ring infiltrometers.
- To determine material placement criteria.

(2) *Design Criteria*. Test fills are often constructed on the steepest slope of the landfill cover, which provides a worst-case scenario for slope stability and placement techniques. A test fill should be a minimum of three times the width of the compaction vehicles. Widths are typically 10–15 m (30–50 ft). Lengths should be sufficient to allow equipment to reach proper operating speed for a minimum of 8 m (25 ft). Test fills are typically 20–30 m (65–100 ft) long. The materials, construction procedures, and test procedures should be as specified for full-scale construction of the landfill cover. Before beginning construction, the contractor should be required to construct drainage controls to divert surface runoff around the test fill. Guide Specification 02318 should be used as part of the contract documents for the test fill design.

(a) *Testing*. Density, moisture content, classification, and permeability tests should be performed on each lift of the test fill clay layer. Shelby tube samples collected for permeability testing should also be examined to determine if there has been good interface bonding between lifts of clay. Geomembrane seams can be destructively tested for strength and non-destructively tested for leaks. Seams for geotextiles and geogrids should be tested if they will be required to carry tensile loads. Tests should be required on other components of the test fill, as needed, using test procedures outlined in the construction specifications. Survey control points are often placed along the sides of the test fill and consist of pins set back from both sides of the edge of the test fill at approximately 6-m (20-ft) intervals. Markings are placed on the outside edges of the geosynthetics in the test fill so that the relative movement between the geosynthetics can be monitored. Control points are typically surveyed immediately after construction and every 5 days thereafter for the life of the test fill. After the test fill is built, a 6- by 6-m (20- by 20-ft) section should be carefully dismantled to inspect for damage to the geosynthetics.

(b) *Work Plan*. The contractor should be required to submit a detailed work plan describing all aspects of the proposed test fill section construction and monitoring. This plan should include scale drawings, survey procedures, test procedures, and equipment to be used. The contractor should also submit a post-construction report that includes as-built drawings, test results, survey data, and conclusions. The contractor should be required to videotape construction and dismantling of the test fill.

d. Borrow Areas.

(1) *General*. Borrow sites may be investigated during either the pre-design or design phases. The investigations should determine if adequate borrow material is available for the various layers of the cover. It is important to ensure that an excess of each borrow type is available in case some of the material at a borrow site later proves to be unacceptable or investigations indicate the landfill cover is larger than anticipated. Borrow sources are required for topsoil, select fill, random fill, clay, and granular materials. Granular materials are required for drainage layers, gas collection layers, and road surfacing. Larger diameter materials may also be required for ditch linings, gabion structures, and stilling basins. The availability of both on-site and off-site borrow should be evaluated. On-site borrow will normally result in substantial cost savings over off-site materials. Off-site materials must be purchased by the contractor and hauled to the project. If on-site borrow is available, investigations are required to define the nature and extent of the borrow source. On-site borrow areas can be used for wetland mitigation if needed. A borrow area grading plan is sometimes required along with profiles showing excavation limits and subsurface features. Access and haul roads from a borrow source to the landfill location must also be assessed. Hauling activities may damage access roads and may be a concern to the public owing to increased traffic volume.

(2) *Design Criteria*. Potential borrow sites should be characterized by determining material types and their extent, natural water content, and depth to ground water. In addition, soil samples should be collected from all materials that will be used in construction. These samples will be used to determine specific geotechnical engineering properties of the soils. The type of sample and amount of material required depends on the type of testing that will be done. Samples should also be taken from each borrow site to verify that the soils are not contaminated. The chemical testing required should be as outlined in Paragraph B-2*e*(2) *Borrow Soil Testing*.

e. Ground Water Monitoring.

(1) *General*. Closure requirements mandate that the upper aquifer beneath the landfill be monitored to determine if it is causing degradation of ground water quality. Ground water monitoring wells are placed both up- and down-gradient from the landfill and are sometimes located within the landfill footprint. Before the cover is constructed, all existing monitoring wells should be evaluated to see if they would be useful for long-term monitoring. If any monitoring wells are located within the limits of construction, it will be necessary to protect, raise, abandon, or relocate the wells. If wells are to be abandoned, well abandonment procedures required by the state or other government agencies should be described in the specifications.

(2) *Design Criteria*. The requirements for monitoring ground water at solid waste management units, such as hazardous waste landfills, are described in 40 CFR 264 Subpart F—*Releases from Solid Waste Management Units.* Ground water monitoring well design criteria are described in EM 1110-1-4000. Guide Specification CEGS-02522 should be used in contract documents to specify construction requirements for monitoring wells.

f. Cover Grading Requirements. Development of the grading plans for the various layers is an iterative process. Grading plans are normally developed for the random fill, clay barrier, and topsoil layers. The grading plans should be well defined by horizontal and vertical control such that the cover grades can be easily staked in the field. The final slopes must reflect minimum grade requirements after settlement and must accommodate both internal and surface drainage requirements. The final slopes must also reflect stability considerations. In general, minimum slopes after settlement should be greater than 3% to maintain surface drainage and maximum slopes should not exceed 4H:1V to assure cover stability and safe operation of maintenance equipment. To ensure that the various layers meet the design grades, each layer must be surveyed after construction.

g. Leachate Control. Leachate seeps exiting from the landfill surface need to be identified and located during pre-design and construction regrading activities. A leachate collection blanket, consisting of either granular fill or a geonet coupled with a conveyance pipe and outlet, is sometimes required to control these seeps. Uncontrolled leachate seeps can cause a build-up of hydrostatic pressure behind the low-permeability layer, resulting in decreased stability of the cover system. After the leachate is collected, it must be stored and ultimately treated, either on or off the site.

h. Cover Surface Runoff and Erosion Control Requirements.

(1) *General.* Soil erosion is a natural process when soil particles are displaced and carried away by water, wind, or physical disturbance. The rate at which erosion occurs depends on the properties of soil, terrain, climate, rainfall intensity and duration, and the volume and characteristics of the water flow. Erosion is likely to occur at any area where flows are concentrated. Erosion commonly occurs on slopes greater than 50-m (150-ft) or less depending on the percent slope and soil type, the outer banks of curved channels, at culvert outlets or inlets and other areas of high flow concentration. Erosion control features should be designed that are simple to construct and are effective in their operation. After drainage is directed off of the cover, perimeter drainage features, such as ditches, gabions, or storm sewers, are required to carry the water away from the toe of the landfill.

(2) *Design Criteria.*

(a) *Revised Universal Soil Loss Equation.* The USDA Natural Resource Conservation Service developed the Revised Universal Soil Loss Equation for use in determining terrace requirements for cropland on slopes. The equation has also been used for landfills to determine the maximum vertical spacing between terraces and to estimate sediment transport into ditches and detention ponds. Terraces and other permanent erosion control measures for landfill covers should be designed such that soil erosion is no greater than 0.45 kg/m^2 (2 tons/acre) per year. Some states have developed their own criteria for terrace sizes and spacing. More information on the Revised Universal Soil Loss Equation can be obtained at http://www.sedlab.olemiss.edu/rusle/, and detailed information is given in *Predicting Soil Erosion by Water: A Guide to Conservation Planning With the Revised Universal Soil Loss Equation (RUSLE)* (USDA 1997).

(b) *Terraces.* Terraces are used to reduce erosion, reduce sediment content in runoff water, and conduct surface runoff to a stable outlet or drop structure. Terraces are normally trapezoidal in shape and have a minimum depth of 300–600 mm (1–2 ft). Terraces should have enough capacity to control the design runoff event, which is typically the result of a 25-year, 24-hour rainfall event. Flow velocity depends on channel slope, friction, discharge depth, and flow volume. The flow velocity must be analyzed for all terraces, ditches, and drop structures to ensure that erosion will not occur. If grass-lined channels are not adequate, riprap, grout bags, geosynthetic erosion control materials, or gabions can be used to armor the side slopes and bottoms of terraces. The length of drainage terraces is controlled by flow capacity and non-erosive velocity requirements. Drainage terraces can also function as both an anchor for geosynthetics and a buttress for cover soils to improve cover stability.

(c) *Drop Structures*. Terraces normally discharge into collection ditches or drop structures that descend down the steep slopes of a cover. Depending on the slope, a drop structure may be constructed of vegetation, erosion control mats, riprap, or gabions. As with the terraces, the drop structures are usually trapezoidal in shape and must be hydraulically sized. A stilling basin at the toe of the cover is sometimes required to dissipate flow velocities prior to discharging the water off-site.

(d) *Perimeter Drainage Control*. Surface runoff from the cover should be controlled to prevent adverse impacts to adjoining properties and receiving waterways. Collecting the water in lined or unlined perimeter channels or storm sewers should control surface runoff.

(e) *Off-site Discharge Control*. Depending on the final cover's design, there may be an increase in both the total volume and the peak discharge of surface runoff leaving the site. The effect on the receiving stream from this increased runoff volume should be a design consideration. In addition, the potential downstream impacts of increased sedimentation both during construction and during normal project operations should be assessed. Off-site discharge can be regulated with detention ponds, which store water and trap sediments. State and local regulations must be assessed when discharge patterns are changed. National Pollution Discharge Elimination System (NPDES) requirements for storm water discharges must also be assessed.

(f) *Temporary Erosion Control Measures*. During construction, waste and soil will be exposed to the elements. Temporary erosion control measures such as mulches, hay bales, erosion control mats, and silt fences may be used until permanent measures are established. Temporary vegetative covers, using appropriate rapidly growing annual plants, can be applied to finish grades as a project progresses. It may be necessary for some temporary measures to be applied on the same site several times over the course of the project. Requirements for temporary erosion control should be specified in the contract documents.

(g) *Permanent Erosion Control Measures*. The selection of permanent erosion control measures is based on the location of the site, agronomic principles, availability of construction materials, and future maintenance requirements. Permanent erosion control methods include seeding of native and other grasses, turf reinforcement mats, and rock armor. Other design considerations are described in Paragraph B-3*b Erosion Control Layer*.

(h) *Floodplain Considerations*. Construction of the cover near a waterway may require placement of material within a floodplain. This may increase river stages and could result in greater flood damage to surrounding properties. Consequently, it may be necessary to design diversion channels, levees, or provide other flood protection measures to minimize impacts to surrounding properties. Erosion control materials may also need to be placed on potentially submerged areas of the landfill cover system.

(i) *Storm Water Runoff Calculations*. Selection of an appropriate method of calculating runoff is based on the size of the drainage area and the required output. Typically a 25-year 24-hour storm event is used to design landfill cover drainage systems. Other storm events may be used, depending on site specific regulatory requirements. Commonly used methods to determine runoff include: the Rational Method; the Peak Discharge Method; the Tabular Method (TR-55); and the Unit Hydrograph Method. Additional information for each of these methods can be found in the text *Hydrologic Analysis and Design* (McCuen 1989). The TR-55 program can be obtained at http://www.wcc.nrcs.usda.gov/water/quality/wst.html. Precipitation data can be obtained from the National Weather Service (NWS) Technical Paper No. 40 entitled *Rainfall Frequency Atlas of the United States*.

B-5. Civil Design. There are many other features that must be addressed during design that are integral components of a landfill cover construction project. These features are discussed in the following paragraphs.

a. Site Access Routes. Both public and private access routes to the site need to be investigated to ensure that they can handle anticipated construction traffic. The contractor should be required to maintain any access routes including post-construction rehabilitation, if necessary. Aggregate surfaced roads may need to be built to allow access of vehicles or for operation and maintenance of the landfill. Access roads are often located around the landfill cover perimeter and may also be located on the cover system as well.

b. Staging Areas and Phasing Requirements. The contract documents should identify acceptable locations for support facilities, storage areas, and parking. Construction phasing requirements should also be identified in the contract documents to prevent the uncontrolled migration of contaminants, surface runoff, and dust.

c. Decontamination Facility.

(1) *General*. The contractor must decontaminate all vehicles and equipment that enter the exclusion zone or contamination reduction zone. The contract documents should address the requirements for a decontamination facility and for the treatment and disposal of rinsate water. The final

disposition of the decontamination facility should also be addressed. The contractor should be required to submit a plan as part of the *Site Health and Safety Plan*, which describes vehicle, equipment, and personnel decontamination procedures.

(2) *Design Criteria*. The decontamination facility typically has 150–300 mm (6–12 in.) of granular material underlain by a protective geotextile and a geomembrane 1.0 mm (40 mils) in thickness. More elaborate designs may be used if the decontamination facility will be operated for a significant period of time. To minimize the volume of decontamination water, a temporary cover should be used to shed rainfall when the facility is not in use. Rinsate water is collected by gravity into a polyethylene or precast concrete storage tank, which is typically about 3 m^3 (100 ft^3) in volume. Treatment and disposal of the rinsate water and sediments should be in accordance with all state and Federal regulations. See EP 200-1-2 for more detailed information on this subject.

d. Security Fencing. Chainlink security fencing is often used at the landfill boundary. The fence normally has a standard single outrigger holding three strands of barbed wire. The fence fabric should be a minimum of 1.8 m (6 ft) in height.

e. Demolition. Structures that will be demolished and debris that will be removed should be identified on the contract documents. Transportation and disposal regulations must be considered if demolition materials or debris contain hazardous waste. It may be possible to place the debris under the landfill cover.

B-6. Health and Safety.

a. General. An industrial hygienist is responsible for the health and safety issues of a final cover design. Elements to be addressed include the following: site description and contamination characterization; hazard/risk analysis; staff organization, qualifications, and responsibilities; training; personal protective equipment; medical surveillance; exposure monitoring/air sampling; standard operating safety procedures; site control measures; personal hygiene and decontamination; equipment decontamination; emergency response and contingency procedures; and record-keeping.

b. Design Criteria. Detailed safety and health requirements are described in ER 385-1-92. A *Health and Safety Design Analysis* should be included as a chapter of the project design analysis to describe the decision logic for safety and health requirements, which will be specified. Guide Specification CEGS-01351 should be edited based on the design analysis and included in the contract documents.

B-7. Chemistry.

a. General. Requirements for chemical sampling and analysis conducted during the construction or maintenance phase of the project, such as general air quality, off-gas testing, leachate, borrow soil, ground water, and miscellaneous testing for potential hazardous waste, should be prepared by the project chemist.

b. Design Criteria. Detailed requirements for chemical analyses are described in ER 1110-1-263. Guide Specification CEGS-01450 should be edited and included in the contract documents.

B-8. Operation and Maintenance Requirements.

a. General. The construction contractor is normally responsible for site operation and maintenance on the project for 1 year after completion. The contractor should also monitor parameters such as ground water, leachate generation, air quality, underground gas migration, and cover effectiveness. Baseline conditions must be measured either prior to or immediately after construction, depending upon the parameter. Consistent and accurate record-keeping during the post-closure period is essential.

b. Ground Water. Up- and down-gradient monitoring wells must be sampled after closure. Federal or state regulatory authorities will specify the frequency of monitoring and contaminants tested for. Samples are typically collected from ground water monitoring wells at a frequency of once every 1 to 3 months during the first year after construction; however, this frequency should be a function of the database available for the site. During each round of sampling, the ground water elevation should also be determined and changes in ground water flow conditions evaluated. Periodic maintenance of the monitoring wells may be necessary to assure proper operation.

c. Leachate. Leachate should be monitored at discharge outlets for flow rate as well as chemical composition. Leachate discharge should decrease with time once the cover is constructed.

d. Landfill Gas. The contractor should operate and maintain the landfill gas control system during the 1-year post-closure period. Landfill gas concentrations should be monitored at compliance points as determined by the EPA Regional Administrator or state regulatory authorities. Compliance points may include gas-monitoring probes, boundary monitoring stations, wellheads for passive systems, or flares for active systems. Monitoring at the compliance points is typically done once every 2 to 4 weeks for the first year after construction.

e. Settlement. When settlement is anticipated to be a problem, settlement markers should be installed on the final cover above the geomembrane. The contractor should place additional select fill and topsoil in areas where settlement has occurred. It is recommended that settlement be monitored visually each month and that settlement monuments be surveyed annually over time to determine long-term trends.

f. Slope Stability. Slope stability is monitored by visual inspection. Movement markers can also be placed on the steepest slopes of the cover and surveyed annually or more often if required.

g. Landfill cover. The contractor will be required to maintain the effectiveness of the final cover, including maintaining the cap subdrainage system, establishing the vegetative cover, and repairing erosion damage. Areas that have poor vegetative cover should be reseeded. The landfill cover should be mowed once the vegetative cover has been established to keep it healthy and keep trees or brush from establishing. The cover surface should also be inspected for rodent holes. Irrigation requirements may be considered for covers located in arid climates.

h. Runoff Controls. Drainage terraces, ditches, and drop structures should be inspected to assure that erosion is not occurring and that the erosion control features are performing as designed. The detention pond should be inspected to assure that there is sufficient storage available for sediment. Periodic dredging of sediment may be required from ditches or detention ponds.

i. Other Features. The contractor should also maintain other features such as fences and perimeter access roads during the 1-year maintenance period.

j. Inspections. The contractor is typically required to inspect the site once to twice each month. The inspection should monitor the condition of the cover, outlets to the cover subdrainage system, settlement, slope stability, runoff control structures, monitoring wells, gas extraction system, fences, and access roads. The contractor should furnish a report after each inspection is completed. Inspection reports should include a written summary of deficiencies noted, repairs undertaken, and other significant operational events. The report should also include instrumentation readings taken.

k. Maintenance. The contractor should notify the contracting officer in writing in advance of conducting any major maintenance activities. A representative of the contracting office should be present during all major maintenance activities. The contractor should prepare a maintenance completion report after any major maintenance has been performed.

B-9. Environmental and Regulatory Compliance. Table B-1 lists potentially applicable or relevant and appropriate Federal standards, requirements, and criteria. The purpose of this table is to provide a brief description of the Federal regulations that may be applicable to the design of a landfill cover. It should be noted that state regulations might override Federal regulations in some instances.

Table B-1
Potentially Applicable or Relevant and Appropriate Federal Standards, Requirements and Criteria

Standard Requirement, Criteria, or Limitation	Citation	Description
National Pollution Discharge Elimination (NPDES)	40 CFR 122 & 124	Establishes permit requirements.
Clean Air Act	42 USC 7401-7642	Establishes a regulatory system for air pollution from stationary and mobile sources.
Solid Waste Disposal Act (SWDA)	42 USC 6901-6987	
Resource Conservation and Recovery Act (RCRA)	PL 94-580 90 Stat. 2795	Enacted as an amendment to the SWDA.
Guidelines for the Land Disposal of Solid Wastes	40 CFR 241	Establishes requirements and procedures for land disposal of solid wastes.
Criteria for Classification of Solid Waste Disposal Facilities	40 CFR Part 257	Establishes criteria for use in determining which solid waste disposal facilities and practices pose a reasonable probability of adverse effects on health or the environment.
Solid Waste Disposal Facilities Criteria	40 CFR 258	Establishes minimum criteria for municipal solid waste landfills.
Hazardous Waste Management System: General	40 CFR Part 260	Establishes definitions as well as procedures and criteria for modification or revocation of any provision in 40 CFR Parts 260-265.
Identification and Listing of Hazardous Waste	40 CFR Part 261	Defines those solid wastes that are subject to regulations as hazardous wastes under 40 CFR Parts 262-265.
Standards Applicable to Generators of Hazardous Wastes	40 CFR Part 262	Establishes standard for generators of hazardous waste.
Standards Applicable to Transporters of Hazardous Wastes	40 CFR Part 263	Standards that apply to transporting hazardous waste if the transportation requires a manifest under 40 CFR Part 262.
Standards for Owners and Operators of Hazardous Waste Treatment, Storage and Disposal (TSD) Facilities	40 CFR Part 264	Standards which define acceptable management of hazardous waste for owners and operators of TSDs.
Interim Status Standards for Owners and Operators of Hazardous Waste TSDs	40 CFR Part 265	Standards for management of hazardous waste during the period of interim status and final closure or until post-closure responsibilities are fulfilled.
Interim Standards for Owners and Operators of New Hazardous Waste Land Disposal Facilities	40 CFR Part 267	Standards that define acceptable management of hazardous waste for new land disposal facilities.
Land Disposal Restrictions	40 CFR 268	Identifies hazardous wastes that are

Table B-1
Potentially Applicable or Relevant and Appropriate Federal Standards, Requirements and Criteria

Standard Requirement, Criteria, or Limitation	Citation	Description
National Pollution Discharge Elimination (NPDES)	40 CFR 122 & 124	Establishes permit requirements.
		restricted from land disposal.

B-10. Potential List of Drawings. Provided below is a list of key drawings that should be included in the contract documents. Not all drawings will be applicable to every project.

- Existing site conditions (including utilities).
- Test pit and boring location plan.
- Initial grading plan.
- Random fill grading plan.
- Clay barrier layer grading plan.
- Final grading plan.
- Erosion control features.
- Cap cross sections.
- Cap detail drawings: anchor trench, collection pipes and toe drains.
- Cover drainage layer collection system plan.
- Gas vent well details.
- Gas monitoring probe details.
- Gas collection header pipe details.
- Gas blower flare and piping details.
- Settlement monument, benchmark, and penetration details.
- Fence location and details.
- Monitoring well locations and details.

B-11. Potential List of Specifications. Provided below is a list of specifications that may be part of the contract documents. Not all specifications will be applicable to every project.

a. Division 1—General Requirements.

01351 *Safety, Health, and Emergency Response.*
01450 *Chemical Data Quality Control.*

b. Division 2—Site Work.

02111	*Excavation and Handling of Contaminated Material.*
02140	*Select Fill and Topsoil for Landfill Cover*.
02318	*Test Fill*.
02372	*Waste Containment Geomembrane*.
02373	*Separation/Filtration Geotextile.*
02374	*Geosynthetic Drainage Layer.*
02375	*Geogrid Soil Reinforcement.*
02376	*Geosynthetic Clay Liner.*
02377	*Clay Barrier Layer.*
02522	*Ground Water Monitoring Wells.*