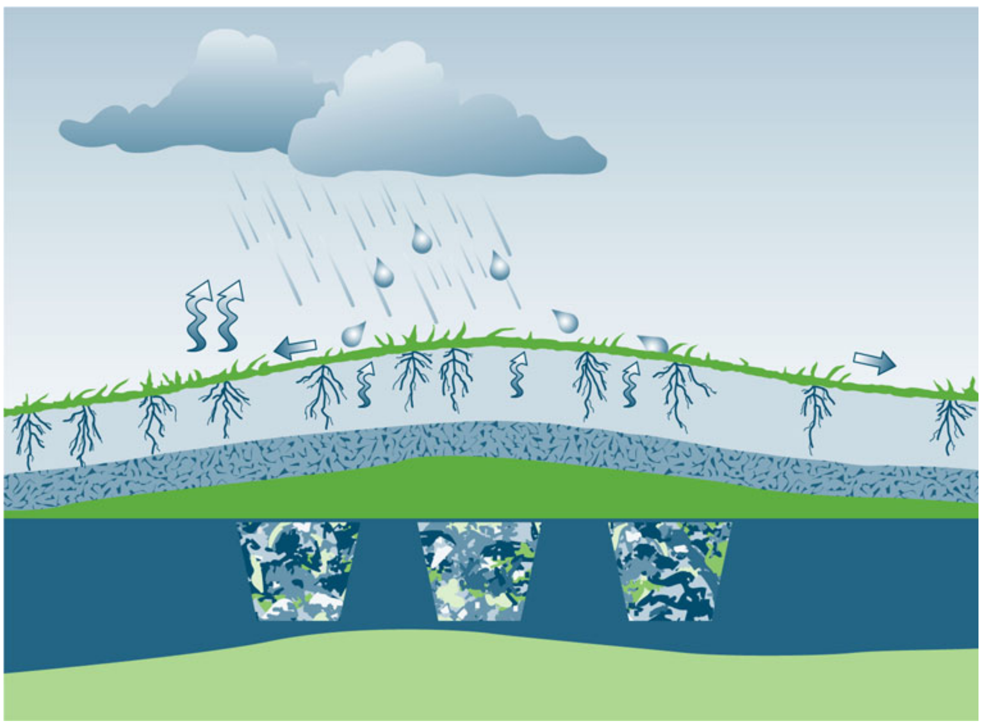
Technical and Regulatory Guidance

Technical and Regulatory Guidance for Design, Installation, and Monitoring of Alternative Final Landfill Covers



December 2003

Prepared by
The Interstate Technology & Regulatory Council
Alternative Landfill Technologies Team

ABOUT ITRC

Established in 1995, the Interstate Technology & Regulatory Council (ITRC) is a state-led, national coalition of personnel from the environmental regulatory agencies of some 40 states and the District of Columbia; three federal agencies; tribes; and public and industry stakeholders. The organization is devoted to reducing barriers to, and speeding interstate deployment of, better, more cost-effective, innovative environmental techniques. ITRC operates as a committee of the Environmental Research Institute of the States (ERIS), a Section 501(c)(3) public charity that supports the Environmental Council of the States (ECOS) through its educational and research activities aimed at improving the environment in the United States and providing a forum for state environmental policy makers. More information about ITRC and its available products and services can be found on the Internet at **www.itrcweb.org.**

DISCLAIMER

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We depend on input from all perspectives to give ITRC documents the broadest practical application in the industry. The team members have displayed that mix of perspectives and skills necessary to further our understanding of the Alternative Final Landfill Covers.

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EXECUTIVE SUMMARY

This Alternative Final Cover Technical/Regulatory Guidance Document is primarily written for decision makers associated with the plan development, review, and implementation of Alternative Final Covers (AFCs). The decision makers include, at a minimum, regulators, owners/operators, and consultants. This group is also referred as "practitioners" in this document. This document focuses on the decisions and facilitating the decision processes related to design, evaluation, construction, and post-closure care associated with AFCs. To facilitate the use of this document and understanding of the decision process, a decision tree is provided at the end of this Executive Summary. In the electronic version of this document, clicking on any process box or decision diamond in the decision tree accompanied by a section number will take you to that place in the document.

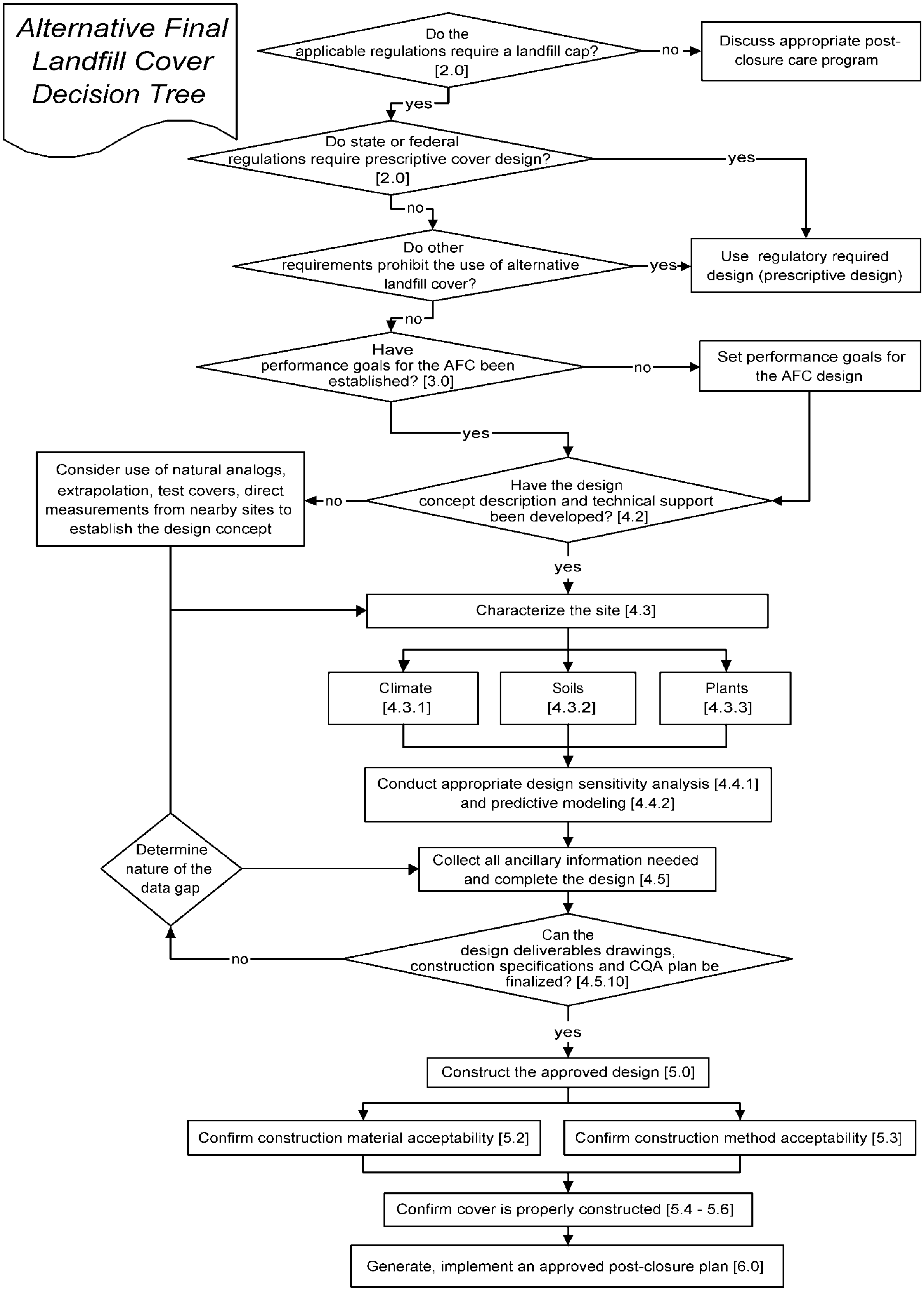
Modern engineered landfills are designed and constructed to minimize or eliminate the release of constituents into the environment. Solid and hazardous waste landfills are required by federal, state, and/or local regulations to cover waste materials prior to or as part of final closure. These final covers are only one element of landfill systems. Clearly the solid and hazardous waste regulations include language and provide mechanisms to support the permitting, design, construction, and maintenance of landfills with alternative covers. In fact, while the current federal regulations contain provisions for the construction of a regulation-prescribed landfill cover, there are no specific provisions requiring the use of a "conventional" cover or disallowing the use of an alternative landfill cover. There are several guidance documents available that provide specific construction techniques related to building landfills. Sometimes a more challenging aspect of AFC implementation is the decision related to the project. This document provides input related to key decision steps in the permitting, design, construction, and maintenance of AFCs.

The U.S. Environmental Protection Agency maintains a database tracking 64 alternative landfill cover demonstration projects and full-scale operating facilities in 18 different states. Annual rainfall associated with these alternative landfill cover projects ranges from a low of approximately 3.5 to a high of 56 inches per year. Twenty-four of the AFCs are demonstration projects, and 11 are full-scale covers at operating facilities. There are 20 solid waste/industrial waste/construction debris demonstration projects currently in the database. There are also two hazardous waste and three mixed waste demonstration projects. This database demonstrates the growing use of AFCs in a variety of settings and further supports the ability of regulators and owners/operators to negotiate, approve, and implement AFCs.

Alternative landfill covers are already in use in a variety of settings, or the designs are approved and field testing is being conducted at pre-Subtitle D unlined facilities, Subtitle D lined faculties, pre-Subtitle C unlined facilities, and Subtitle C lined facilities. There are Subtitle D alternative cover designs in place or approved at industrial, municipal, and debris landfills. Alternative final landfill covers have several potential benefits over the conventional landfill covers, while potentially being equally protective of human health and the environment. In addition, some researchers have documented via test plot studies that AFCs can equal the performance of composite covers in some locations and can outperform conventional compacted clay covers in certain settings. Some of the benefits include, but are not limited to, more readily available construction materials, ease of construction, less complex quality assurance/quality control programs, increased long-term cover integrity, and stability.

This document focuses on a class of landfill final covers ("alternative" covers) as integral parts of an overall landfill system that differs in both design and operational theory from those prescribed in Resource Conservation and Recovery Act regulations as minimum recommended designs. Several primary types of alternative landfill covers have been proposed by solid, hazardous, and mixed waste landfills. The AFC design process is flexible and creative and is predicated on sound scientific and engineering principles and practices. Alternative covers have been constructed and are fully operational at industrial waste, construction debris, municipal solid waste, and hazardous waste landfills. AFCs may be used on bioreactor, conventional, or other types of landfills. Types of AFCs may include, but are not limited to, asphalt covers, concrete covers, capillary barrier covers, and evapotranspiration (ET) covers. This document focuses on ET covers and the decisions associated with their successful design, construction, and long-term care. Therefore, the AFCs discussed in this document are assumed to be ET covers.

The following diagram is a decision tree leading the user through the general questions and decisions required during the earliest regulatory interpretations, cover conceptual design, site characterization, final design, construction quality control and post-closure care. Each point on this decision tree references the section within the document that provides important information on the topic.


Alternative Final Landfill Cover Decision Tree
Do the applicable regulations require a landfill cap? [2.0]
no
Discuss appropriate post-closure care program
yes
Do state or federal regulations require prescriptive cover design? [2.0]
yes
no
Do other requirements prohibit the use of alternative landfill cover?
yes
Use regulatory required design (prescriptive design)
no
Have performance goals for the AFC been established? [3.0]
no
Set performance goals for the AFC design
yes
Consider use of natural analogs, extrapolation, test covers, direct measurements from nearby sites to establish the design concept
no
Have the design concept description and technical support been developed? [4.2]
yes
Characterize the site [4.3]
Climate [4.3.1]
Soils [4.3.2]
Plants [4.3.3]
Conduct appropriate design sensitivity analysis [4.4.1] and predictive modeling [4.4.2]
Determine nature of the data gap
Collect all ancillary information needed and complete the design [4.5]
no
Can the design deliverables drawings, construction specifications and CQA plan be finalized? [4.5.10]
yes
Construct the approved design [5.0]
Confirm construction material acceptability [5.2]
Confirm construction method acceptability [5.3]
Confirm cover is properly constructed [5.4 - 5.6]
Generate, implement an approved post-closure plan [6.0]

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TECHNICAL AND REGULATORY GUIDANCE FOR DESIGN, INSTALLATION, AND MONITORING OF ALTERNATIVE FINAL LANDFILL COVERS

1. ALTERNATIVE FINAL COVERS

1.1 Introduction

This guidance document is written for decision makers associated with the plan development, review, and implementation of alternative final covers (AFCs), which may also be referred to in this text as alternative covers, alternative landfill covers, or ET (evapotranspiration covers). These decision makers—including, at a minimum, regulators, owners/operators, and consultants—are also referred as "practitioners" in this document. This is not a how-to document describing specific techniques and methodologies associated with the design and construction of AFCs. It focuses instead on the decisions and decision processes related to the design, evaluation, construction, and post-closure care associated with AFCs.

AFCs are well understood and accepted in some regions but are still considered an innovative technology. There appears to be a perception that many state regulations do not afford the opportunity to install alternative landfill covers at municipal solid waste landfills (MSWLFs). Some regulators perform many functions while discharging their job duties. They may or may not be well-versed in the various disciplines required to evaluate the flexibility imbued in the regulations they are implementing and interpreting. If regulators are applying regulations for which they do not have substantive background or training, then they may tend toward a conservative application of the regulations without fully appreciating the regulations' inherent options. Some agencies tend to be overly conservative in their approach to interpreting their regulations and the flexibility built into the regulations. This is demonstrated by a degree of unwillingness on the part of some regulators and/or agencies to deviate from the regulation-derived conventional covers. There are presently no written rules to follow when reviewing an AFC design.

Alternative landfill covers are still a new idea that has not been officially written into any policy or regulations in many states. It will probably take another few years for the "equivalent alternative" of a conventional cover to have the correlation of the field data, performance assessment, modeling, and written regulations. For regulators to be comfortable approving alternative final landfill covers, they will need an understanding of the engineering of landfills and the science behind a water balance cap, capillary barrier cap, or other alternative to evaluate them and to apply the flexibility in the regulations associated with alternative landfill covers.

Alternative landfill covers are already in use—or the designs are approved and field testing is being conducted—at pre-Subtitle D unlined facilities, Subtitle D lined faculties, pre-Subtitle C unlined facilities, and Subtitle C lined facilities. There are Subtitle D alternative cover designs in place or approved at industrial, municipal, and debris landfills. Alternative landfill covers have several potential benefits over the current regulatory prescribed landfill covers, while being equally protective of human health and the environment. Some of the benefits include, but are not limited to, more readily available construction materials, ease of construction, less complex quality assurance/quality control programs, greater cost-effectiveness, and increased long-term sustainability with decreased maintenance.

Alternative final covers may be combined with other remedy elements as part of an overall site solution. For example, AFCs may be linked with constructed wetlands to treat leachate generated by the landfill. AFCs may also be enhanced with phytoremediation, where the AFC isolates the waste to protect human health and environment and phytoremediation methods are used to treat an existing groundwater contamination plume. The Interstate Technology & Regulatory Council (ITRC) has technical/regulatory guidance documents on both constructed wetlands and phytoremediation, available through the ITRC Web site at www.itrcweb.org.

Modern engineered landfills are designed and constructed to minimize or eliminate the release of constituents into the environment. Solid and hazardous waste landfills are required by federal, state, and/or local regulations to cover waste materials prior to or as part of final closure. These final covers are only one element of landfill systems. The landfill system may include one or more liners, the actual waste material, a cover, run-on and runoff control features, security systems to reduce and/or eliminate human intrusion, groundwater monitoring networks, and settlement monitoring markers.

This document focuses on a class of landfill final covers (alternative covers) as integral parts of an overall landfill system that differ in both design and operational theory from the designs described in Resource Conservation and Recovery Act (RCRA) regulations as minimum recommended designs. Several primary types of alternative landfill covers have been proposed by solid, hazardous, and mixed waste landfills. Types of AFCs include, but are not limited to, asphalt, concrete, capillary barrier, and evapotranspiration (ET) covers. This document focuses on ET covers and the decisions associated with their successful design, construction, and long-term care. Unless specifically stated otherwise, AFCs discussed in this document are assumed to be ET covers including integrated vegetation cover systems.

An owner or regulator may decide to set a flux rate through the cover, with a specific value or range selected based on the nature of the contained waste, the hydrogeological vulnerability of the site, and other factors (as discussed in Section 3.2). If the U.S. Environmental Protection Agency (EPA) promulgates flux rates, those criteria should be considered in the design decision process. Different site-specific percolation rates may be acceptable for certain sites.

Some design criteria may be lower than the accuracy of the numerical models and field methods that are currently used to assess cover system hydraulic performance. Practitioners should recognize that measurements made without consideration of the accuracy of existing devices and used as model input will increase uncertainty in the model results.

1.2 Alternative Cover Concepts

EPA has a database tracking AFC demonstration projects and full-scale operating facilities in locations representing the range of physical environmental across the country. Annual rainfall associated with these alternative landfill cover projects ranges from a low of approximately 3.5 to a high of 56 inches per year. Twenty-four of the AFCs are demonstration projects, and 11 are full-scale covers at operating facilities. Twenty solid waste/industrial waste/construction debris demonstration projects are currently in the database. There are also two hazardous waste and three mixed waste demonstration projects. ITRC recently published a case study document

(ITRC 2003) describing the installation and acceptance of several alternative landfill covers. The case studies contain details about construction properties and performance evaluations.

Final covers serve to isolate the waste materials from human and ecological receptors and vectors. In addition, landfill covers serve to reduce the amount of infiltration and minimize the generation of leachate. Minimizing the generation of leachate reduces the need to manage the liquids and reduce the potential of contaminants from the landfill to impact the environment whether soils, groundwater, or surface water.

Conventional covers are designed to use low-permeability materials (i.e., compacted clay or geomembranes) to reduce or eliminate the infiltration of precipitation into the waste layers, thereby reducing the head on the liner and potential for leaching contaminants into the surrounding environment. While the concept is sound, practice has demonstrated that some of the existing requirements may be detrimental to achieving the goal of waste isolation, which may lead to the problems identified below.

Often regulations and guidance require use of low-permeability compacted clay material (see Sections 2 and 3 regarding regulatory flexibility and cover goals) to isolate the waste layers. One problem may be that acceptable clay borrow materials for construction purposes may not be readily available. Clays have the potential to dry and fracture. Then water (precipitation) may migrate through the fractures, compromising the intended matrix flow of low-permeability compacted clay. Desiccation as well as freezing, intrusion by plant roots, or burrowing animals, can result in the development of preferential flow paths in clay barriers, thus compromising long-term performance.

Conceptually, the simplest type of alternative cover consists of a vegetated soil layer. Sometimes referred to as an "evapotranspiration cover," the single soil layer has the advantages of being simple and potentially economical to construct and maintain and, in the appropriate setting and with an appropriate design, can be very effective. The principle upon which an ET cover works is that the soil layer holds incoming precipitation until it is removed by evapotranspiration. If the soil layer has sufficient storage capacity to hold the water until it can be removed by evapotranspiration, then no deep percolation will penetrate past the cover (Hauser, Weand, and Gill 2001a; Chadwick et al. 1999; Somasundaram et al. 1999). Despite the apparent simplicity of the design, proper performance of an ET cover depends on careful and robust analysis of the site variables and a thorough design procedure. Proper design of an ET cover depends on a thorough understanding of three fundamental concepts, as follows.

1.2.1 Soil Water Storage

Soils vary in ability to absorb and retain moisture according to pore structure, which is largely a function of grain size (i.e., fine-grained soil can store more water than coarse, sandy soils). The soil column that composes an ET cover must be capable of storing the required quantity of water and supporting the vegetation community required to remove the water from the cover.

1.2.2 Evapotranspiration

The movement of water from the soil column to the atmosphere by bare-soil evaporation and transpiration by plants is crucial to ET cover function. While evaporation is a component of ET, in most environments the largest fraction of ET is provided by transpiration. Several things must be considered when evaluating a design plant community:

- the plants must be capable of rooting through the entire depth of the soil column;
- the plants should be capable of transpiring throughout the growing (warm) season;
- native species, though not required, may be best suited to the environmental factors at the site; and
- agronomic factors at the site should be carefully considered to ensure optimal rates of transpiration.

1.2.3 Climatic Factors and Critical Design Period

The most important factors are precipitation and the atmospheric parameters that influence evapotranspiration. Other factors (temperature, humidity, etc) influence the rate of transpiration, but the amount and timing of precipitation is most important to proper design. The design precipitation event or events to be considered in ET cover design is a site specific determination. In cold climates where transpiration is essentially nonexistent during the winter, a cover should be capable of storing all or most of the precipitation that occurs during that period. The decision to use average or extreme event precipitation data for that period may be a topic of discussion between design engineer and regulator. The timing of precipitation events is critical to ET cover design. For example, two sites with equal annual precipitation and annual potential ET may have very different cover requirements if one site receives the majority of precipitation during the winter (nontranspiring) season while the other experiences predominately summer precipitation. The critical design period may not be known prior to initiating cover design. Choice of critical design period is a difficult task and may be addressed through modeling or field tests.

1.2.4 The Physics of Soil Water Movement

The physics of water movement in an unsaturated soil column such as an AFC is complex and beyond the scope of this document. However, some understanding of the physics of water movement within the soil is important to an understanding of the principles that govern the performance of a vegetative landfill cover. The modern understanding of water movement in unsaturated soils has been under development for about 150 years, and the development of new concepts continues in the modern era. Henri Darcy (1856) provided the earliest known quantitative description of water flow in porous mediums. Darcy developed an equation for water flow in saturated sand, and modern equations for both saturated and unsaturated flow are based on his early work.

The two most important principles of soil physics for landfill cover design are saturated hydraulic conductivity and available water-storage capacity. Saturated hydraulic conductivity (commonly abbreviated as K_{sat} or K_s) is a parameter that describes the ability of a soil to transmit water while fully saturated. A sandy or gravelly soil will have a high value of K_s; a clay-rich soil will have a much lower value. Simply, a sandy soil will transmit much more water in response to a driving force, or head gradient, than will a clayey soil. K_s has been a primary criterion for design and approval of conventional cover designs that use low-permeability materials (i.e., compacted clay) to impede the movement of water through a cover.

AFC design, in contrast, tends to emphasize the ability of a soil profile to store and retain water during periods when precipitation exceeds ET. This function depends on the second topic in this discussion of soil physics, namely available water-holding capacity (AWC). The concept of AWC is based on the idea that all soils can absorb some water before significant drainage occurs. To use this concept in AFC design, two points must be defined. The first is how wet a soil can become before significant drainage occurs ("field capacity"); the second is how dry a soil column will become in the designed application ("wilting point"). At field capacity (when the stored water is under a tension of about 0.33 atmospheres or 33 kPa), the soil will have a low value of unsaturated hydraulic conductivity (typically less than about 10^{-7} cm/sec). The possible water movement downward in the soil is very small for such low values of K, and the K value decreases rapidly as the soil dries. Theoretically, and as measured in the field, soil water never stops moving; however, the rate of movement is very small at these low values of K. Wilting point, as the term suggests, describes the status of soil moisture when plants lose their ability to remove additional water from the soil. As in the case of field capacity, wilting point is typically defined as a tension at which the remaining water in the soil is held. From agricultural applications this value is commonly described as 15 atmospheres or 1500 kPa although plants in arid locations commonly maintain transpiration capability at soil water tensions of 60 atmospheres (6000 kPa). The difference between these two points—how wet the soil can become before significant drainage occurs and how dry the soil column will become under the influence of the design plant community—defines the AWC.

During landfill cover design, estimated values of hydraulic conductivity may be needed to model water flow in the finished landfill cover soil. Uncertainty about whether laboratory measurements represent the finished soil may make it necessary to estimate, rather than directly measure, the hydraulic conductivity. Numerous authors have developed methods for estimating the hydraulic conductivity functions from simpler and more easily measured soil parameters. For example, Savabi (2001) employed methods described by 12 different authors to estimate hydraulic conductivity in his model evaluation of the hydrology of a region in Florida. [V]an Genuchten, Leij, and Yates (1991); Zhang and van Genuchten (1994); and Othmer, Diekkruger, and Kutilek (1991) each developed computer code to estimate hydraulic functions for unsaturated soils.

1.2.5 Vegetative Cover Considerations

Some constructed vegetative covers have not met the requirements for an effective landfill cover. Therefore, it is worthwhile to examine the cause of poor performance so that it may be accounted for in the design and design evaluation process.

Anderson (1997) summarized several recent experiments: "Past failures of earthen barriers as final caps on landfills in arid or semiarid regions likely result from insufficient depths of soil to store precipitation and support healthy stands of perennial plants."

Warren, Hakonson, and Bostik (1996) reported the results of a four-year experiment with four landfill covers at Hill Air Force Base in northern Utah. Their experiment included a RCRA cover, a control plot with a vegetative cover, and two capillary barriers with vegetative covers. They measured leachate (potential infiltration into the waste) and collected the data for 46 months. Because the site is in a semiarid climate, all of the vegetative covers should have minimized leachate, but none of the covers performed adequately. In 1994 a capillary barrier, (called the "Hanford Barrier"), was constructed at the Hill Air Force Base site, using soil from the U.S. Department of Energy (DOE) Hanford Site near Richland, Washington. Since installation there has been no drainage. The performance of the Hanford Barrier compared to the failure of the other alternative covers is attributed to the large storage capacity (>500 mm) of the soil used in the Hanford Barrier (Gee, Ward, and Kirkham 1998).

Warren, Hakonson, and Bostik (1996) stated that most of the leachate was the result of snowmelt and early spring rains and that leachate amount was unrelated to ground cover or plant biomass. Their data suggest that the vegetative cover might have controlled leachate had the soil thickness been increased and/or had the whole soil profile dried adequately in the fall before the accumulation of snow. These results emphasize the need to evaluate the most critical event during design—in this case, snowmelt and early spring rain. A key factor is to conduct a comprehensive site analysis including not only precipitation quantities but also the timing of the precipitation relative to soil storage and plant transpiration capacity.

Plant transpiration removes the largest amount of moisture from AFC systems. Transpiration is greatest when the plant mass and plant activity are the greatest. The maximum rate of infiltration of water into the cover may or may not fall during the period of maximum transpiration. The cover should be evaluated during its maximum stress conditions (i.e., during the period of minimum evapotranspiration or a spring snowmelt event). The maximum stress event ("critical event") must be discussed with the regulators. The design may be based on estimated future extreme events predicted from models or extrapolated from available records. However, some regulators have chosen criteria other than the critical event as a design basis. As an example some regulators may wish to determine the impact of a long-duration, low-intensity storm where precipitation does not exceed the rate of infiltration. This scenario may not present a deleterious erosional impact on the cover but could place the maximum amount of stress on the cover by causing the greatest amount of water to percolate into the cover materials. This situation could create a significant potential for precipitation to percolate through the cover. A similar situation may be created by snowmelt. It is critical to note that the design event for any individual cover may be a period as long as a season and may be as short as a several-day storm or snowmelt.

Although not discussed by the authors, high soil density may have reduced root growth in these experimental plots and thereby reduced the amount of soil drying produced by the plant cover. Warren, Hakonson, and Bostik (1996) compacted the soil in all treatments, including the vegetative cover, to a bulk density of 1.86 Mg/m^3. Root growth can be reduced by soil bulk density above 1.5 Mg/m^3, and bulk densities above 1.7 Mg/m^3 may effectively prevent root growth in some soils. In addition to inhibiting root growth, soil compaction reduces soil water-holding capacity, thus further limiting the potential for success.

It has often been suggested that soil freezing and thawing will amend poor physical properties important to plant growth in compacted soils. However, recent evidence suggests that this may not be true. Any of the following factors could cause poor performance of vegetative covers: inadequate soil depth, reduction of water-holding capacity by soil compaction, or poor root growth resulting from soil compaction.

1.2.6 Types of Alternative Covers

Technology Overview Using Case Studies of Alternative Landfill Technologies and Associated Regulatory Topics (ITRC 2003) contains an evaluation of AFCs. As already stated, this current document focuses on ET-type AFCs and addresses decisions associated with their design, review, construction, and long-term care. This section contains a brief discussion of some other types of AFCs.

As noted above, AFCs may have advantages or disadvantages depending on specific site conditions. These are experimental systems with limited field use. Because of the water-holding properties of soils and the fact that most precipitation returns to the atmosphere via ET, it is possible to devise landfill covers that meet the requirements for remediation and yet contain no low-permeability barrier layer (Figure 1-1). These covers usually employ a layer of soil on top of the landfill where grass, shrubs, or trees grow for the purpose of controlling erosion and removing water from the soil.

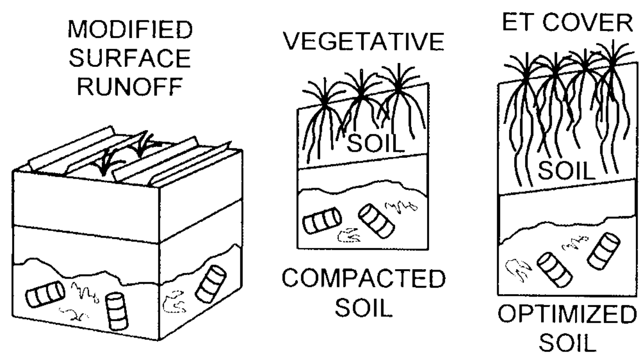

Figure 1-1. Alternative covers with no barrier.

O'Donnell, Ridky, and Schulz (1997) describe a cover that we label the "modified surface runoff" (MSR) cover. In their experiment, the amount of surface runoff was controlled by placing panels on the surface of the landfill cover to divert a portion of the precipitation. Between the panels, they planted Pfitzer junipers. This cover met the requirement for keeping the underlying waste dry at a Maryland site. To demonstrate the effectiveness of alternative landfill covers, the Naval Facilities Engineering Service Center teamed with the Los Alamos National Laboratory and Colorado State University to investigate the performance of a variety of ET covers with MSR. The demonstration study was performed at Marine Corps Base Hawaii Kaneohe Bay, where annual rainfall exceeds ~25 inches (63.5 cm). The results, based on 28 months of field monitoring data, support the concept of using runoff enhancement to manage the infiltration of water through a landfill cover (Hakonson, Karr, and Harre 1999).

The ET cover in Figure 1-1 is an optimized vegetative cover. The ET landfill cover is designed to work with the forces of nature rather than attempting to thwart them. It uses a layer of soil covered by plants, and it contains no low-permeability barrier layers. The ET cover uses two natural processes to control infiltration into the waste: the soil provides a water reservoir, and natural evaporation from the soil plus plant transpiration empty the soil water reservoir. It is an inexpensive, practical, and easily maintained biological system that will remain effective over extended periods of time, perhaps centuries, at low cost.

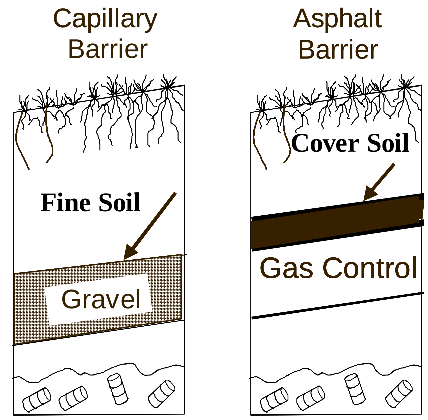

Figure 1-2. Alternative covers with barriers.

The capillary barrier (Figure 1-2) is formed by two layers—a layer of fine soil over a layer of coarser material (e.g., sand or gravel). The name is derived from the break in pore structure that results at the interface of the two soil types. The barrier is created in this type of cover by the large change in pore sizes between the layers of fine and coarse material (Ankeny et al. 1997, Stormont 1997, Gee and Ward 1997). Capillary force causes the layer of fine soil overlying the coarser material to hold more water than if there were no change in particle size between the layers. Soil water is held in the fine-grained layer by capillary forces and will not move into the coarse-grained layer until the fine-grained layer approaches saturation near the interface. (Stormont 1997; Jury, Gardner, and Gardner 1991). This barrier can fail if too much water accumulates in the fine-particle layer or if the desired large change in pore size is missing in spots. Quality control in constructing a capillary break layer may be particularly important to prevent mixing of the coarse-grained and fine-grained layers and to ensure that flaws in the capillary break do not cause failure (Morel-Seytoux 1996). The potential and consequences for lateral flow in the fine-grained soil above a capillary break should also be considered (Stormont 1997, Morel-Seytoux 1996). Stability of the capillary break function is dependent on maintaining a clear separation between the fine and coarse layers (Stormont 1997). This may require a layer of geotextile between the layers to prevent mixing of the fines into the coarse for the required time period. Laboratory and field-scale testing of covers incorporating capillary breaks have demonstrated their potential viability but included some failures (Stormont 1997, Dwyer 2001).

Ankeny et al. (1997) proposed a concept referred to as a "dry barrier," where a capillary break is constructed so that wind-driven air flow through the coarse layer removes any water that may infiltrate into the layer. Gee and Ward (1997) discuss the benefits, particularly in dry climates where clay barriers may fail because of desiccation, of using an asphalt barrier (Figure 1-2) rather than a conventional compacted clay barrier. Particularly in arid areas, gravel is sometimes incorporated into the uppermost part of the soil profile to allow development of a "desert pavement" that will reduce erosion and possibly help sustain vegetation through dry periods by reducing evaporation from the soil surface (Gee and Ward 1997). On occasion, it may be necessary to include nontraditional layers to the ET cover to handle special functions. At some sites it may be deemed necessary to include a layer to deter animals and roots from burrowing through the cover into the underlying waste.

The ET cover differs from those that are commonly called vegetative covers. It has the following minimum criteria:

- The soil should support rapid and prolific root growth in all parts of the soil cover.
- The soil should hold enough water to minimize water movement below the cover during extreme or critical design periods.

Because of these minimum criteria, design and construction methods for ET covers differ from those of conventional vegetative and barrier covers.

1.3 Advantages and Disadvantages

As with many technologies, AFCs are not a one-size-fits-all solution for landfills. They have advantages and disadvantages. Below are some potential advantages of proposing and using AFCs:

- Reduced construction costs associated with
  - locally available cover soils reduce soil hauling costs,
  - reduced soil engineering or required energy (mixing, wetting, compacting) to achieve low-permeability specifications,
  - reduced or eliminated cover elements such as geosynthetics,
  - reduced quality control/quality assurance (QC/QA) testing due to the elimination of some required cover elements or the use of indexing techniques, and
  - reduced construction time due to the reduced number of cover elements.

- Reduced long-term stewardship liabilities:
  - low maintenance related to reduced erosion related to established plant communities,
  - lower maintenance related to lack of potential geosynthetic failure,
  - increased stability reducing the potential for cover failure and releases that impact human health and the environment,
  - less energy placed into the cover construction, involving fewer items that have to hold more energy for a longer time (less dewatering of clays that are compacted wet of optimum to achieve the low-permeability specification), and
  - reduced long-term monitoring cost related to progressive monitoring plans based on continued stability of the covers.

While AFCs have many advantages, they are not appropriate for all situations:

- They may not be acceptable to authorized oversight regulatory agency.
- They may have increased cost associated with test pads.
- They may involve increased total (not construction) time related to proof-of-performance testing.
- They may not be applicable in settings where there is insufficient evapotranspiration to remove the precipitation from the soil column.
- They may not be applicable at facilities with insufficient available volume of desirable soils.

The goal of this guidance document is to present information useful for the successful design, construction, and maintenance of AFCs.

2. COVER GOALS AND REGULATORY FLEXIBILITY

2.1 Cover Goals and Objectives

EPA guidance for the design and construction of final covers (EPA 1991) emphasizes that proper closure is essential to complete a waste landfill. One question that should be asked is whether a cover is required either to satisfy the regulations or to protect human health or environment. EPA's basic approach to ensuring proper closure has been to prescribe generic design criteria for a final cover that meet the stringent closure regulations specified under RCRA. This approach applies on a national level and has generally been accepted by the public and regulatory community, regardless of whether it offers the best option considering site conditions.

The EPA does, however, acknowledge that the design of a final cover must consider site conditions and encourages alternative designs that are innovative and utilize site-specific information. These alternative designs are accepted as long as they demonstrate a level of performance that is at least equivalent to the EPA-recommended design or show that they adequately meet the intent of the regulatory requirements. The ability to satisfy the intent of the regulations creates the opportunity for alternative landfill cover designs. This section reviews regulations and guidance related to landfill cover design and operation. The regulatory flexibility is identified that can be incorporated into alternative landfill covers.

2.2 RCRA Regulations and Guidance

The key federal legislation governing the closure of landfills was written in the early 1980s, and the beginning of the remediation programs for the correction of past disposal practices followed shortly thereafter. The Resource Conservation and Recovery Act is the controlling federal law for both municipal solid waste and hazardous waste landfills; however, for the most part, the remediation of old landfills is not addressed directly under RCRA. It is regulated under Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) or other state regulations/requirements. Under CERCLA, RCRA is the source of potential "applicable or relevant and appropriate requirements" (ARARs) that govern cleanup (Gill et al. 1999) and may still have a critical impact.

2.2.1 Hazardous Waste Disposal Facilities

ITRC's survey of its member states (see Appendix B) indicated that of that six of the twelve responding states had adopted the federal hazardous waste and hazardous landfill regulations either with or without modification. Therefore, these states have regulations that allow implementation of alternative landfill covers for hazardous waste facilities. Six of the twelve responding states have approved or are in the process of testing or installation of alternative landfill covers at solid and hazardous waste facilities. The EPA database (http://cluin.org/products/altcovers) indicates there is a growing number of demonstration and full scale AFCs in use at solid and hazardous waste facilities. Installed alternative landfill covers span a variety of climatic zones with respect to temperature and precipitation and include Colorado and Arkansas.

The Code of Federal Regulations (CFR) Title 40 Subchapter I, Parts 260–279 contains regulations governing the management of hazardous waste facilities. At several points the regulations indicate that alternative regulatory requirements may be used to supplant the more specific prescriptive regulations. CFR Section 264.110 below affords the opportunity to use "alternative requirements," provided they are protective of human health and the environment:

> § 264.110 Applicability.
> (c) The Regional Administrator may replace all or part of the requirements of this subpart (and the unit-specific standards referenced in § 264.111(c) applying to a regulated unit), with alternative requirements set out in a permit or in an enforceable document (as defined in 40 CFR 270.1(c)(7)), where the Regional Administrator determines that:
> (1) The regulated unit is situated among solid waste management units (or areas of concern), a release has occurred, and both the regulated unit and one or more solid waste management unit(s) (or areas of concern) are likely to have contributed to the release; and
> (2) It is not necessary to apply the closure requirements of this subpart (and those referenced herein) because the alternative requirements will protect human health and the environment and will satisfy the closure performance standard of § 264.111 (a) and (b).

(51 Federal Register [FR] 16444, May 2, 1986, as amended at 51 FR 25472, July 14, 1986; 57 FR 37264, Aug. 18, 1992; 63 FR 56733, Oct. 22, 1998)

Clearly Section 264.110 does not specify prescriptive regulatory requirements but focuses on managing the potential risk associated with a hazardous waste or solid waste management unit. The alternative requirements that are protective of human health and the environment are left to negotiations between the facility owner/operator and the regulators. While Part 264 of the CFR pertains to permitted hazardous waste facilities, similar regulations are found in Part 256, which apply to interim status hazardous waste facilities.

Section 265.110(d) is of particular note because it affords the opportunity for the regional administrator to use "alternative requirements" protective of human health and the environment. Interestingly, these regulations do not contain specific performance requirements but identify the need to be protective or manage the risks associated with a given hazardous waste activity. Therefore, this section of the regulations clearly supports the design, construction, and operation of alternative landfill covers.

The RCRA regulations are very clear in establishing closure performance standards for hazardous waste disposal facilities. These standards are found in 40 CFR Sections 264.111 and 265.111 for permitted and interim hazardous waste disposal facilities, respectively, and apply to hazardous waste landfills and other RCRA-regulated units closed as landfills. The standards state the following:

> The owner or operator must close the facility in a manner that:
> a. Minimizes the need for further maintenance; and
> b. Controls, minimizes, or eliminates, to the extent necessary to protect human health and the environment, post-closure escape of hazardous waste, hazardous constituents, leachate, contaminated runoff, or hazardous waste decomposition products to the ground or surface waters or to the atmosphere....

The intent of these standards is reiterated along with other requirements under 40 CFR Section 264.310. These minimum technical requirements establish the primary goals for closure of permitted hazardous waste landfills. Analogous requirements for interim status hazardous waste landfills are contained in 40 CFR Section 265.310. The specific requirements of the regulations for permitted landfills are as follows:

Section 264.310 Closure and post-closure care.

(a) At final closure of the landfill or upon closure of any cell, the owner or operator must cover the landfill or cell with a final cover designed and constructed to:
   (1) Provide long-term minimization of migration of liquids through the closed landfill;
   (2) Function with minimum maintenance;
   (3) Promote drainage and minimize erosion or abrasion of the cover;
   (4) Accommodate settling and subsidence so that the cover's integrity is maintained; and
   (5) Have a permeability less than or equal to the permeability of any bottom liner system or natural subsoils present.

(b) After final closure, the owner or operator must comply with all post-closure requirements contained in §264.117 through 264.120, including maintenance and monitoring throughout the post-closure care period (specified in the permit under §264.117). The owner or operator must:
   (1) Maintain the integrity and effectiveness of the final cover, including making repairs to the cap as necessary to correct the effects of settling, subsidence, erosion, or other events;
   (2) Continue to operate the leachate collection and removal system until leachate is no longer detected;
   (3) Maintain and monitor the leak detection system in accordance with §264.301(c)(3)(iv) and (4) and 264.303(c), and comply with all other applicable leak detection system requirements of this part;
   (4) Maintain and monitor the ground-water monitoring system and comply with all other applicable requirements of subpart F of this part;
   (5) Prevent run-on and runoff from eroding or otherwise damaging the final cover; and
   (6) Protect and maintain surveyed benchmarks used in complying with § 264.309.

(47 FR 32365, July 26, 1982, as amended at 50 FR 28748, July 15, 1985; 57 FR 3491, Jan. 29, 1992)

These minimum technical requirements provide goals that allow a performance-based cover system design. To meet these regulatory performance-based goals, EPA issued minimum technology guidance for cover systems (EPA 1989a) that essentially prescribed material-based specifications. The cover system for hazardous waste landfills recommended in the 1989 EPA guidance consists of the following:

- a top layer consisting of two components: (1) either a vegetated or armored surface component, selected to minimize erosion and, to the extent possible, promote drainage off the cover, and (2) a soil component with a minimum thickness of 60 cm

(24 in.), comprised of topsoil and/or fill soil as appropriate, the surface of which slopes uniformly at least 3 percent but not more than 5 percent; a soil component of greater thickness may be required to assure that the underlying low-permeability layer is below the frost zone;

- either a soil drainage (and flexible membrane liner [FML] protective bedding) layer with minimum thickness of 30 cm (12 in.) and a minimum hydraulic conductivity of 1×10^{-2} cm/sec that will effectively minimize water infiltration into the low-permeability layer, and will have a final slope of at least 3 percent after settlement and subsidence; or a drainage layer consisting of geosynthetic materials with equivalent performance characteristics; and

- a two-component low-permeability layer, lying wholly below the frost zone, that provides long-term minimization of water infiltration into the underlying wastes, consisting of (1) a 20-mil (0.5-mm) minimum thickness FML component and (2) a compacted soil component with a minimum thickness of at least 60 cm (24 in.) and a maximum in-place saturated hydraulic conductivity of 1×10^{-7} cm/sec.

This material-based guidance is not much help for an alternative cover design since it is oriented to conventional hydraulic barrier–type cover designs. However, the previously mentioned goals established in the hazardous waste regulations will be reviewed later to determine how they relate to alternative cover designs. While the covers are important in their own right, the covers are an integral part of a designed landfill system.

2.2.2 Municipal Solid Waste Disposal Facilities

Minimum technical requirements are also provided for closure of MSWLFs regulated under RCRA Subtitle D. The requirements, contained in 40 CFR Section 258.60, allow either a prescriptive minimum criteria cover system or a performance-based cover system design. The specific requirements of the regulation are as follows:

Section 258.60 Closure Criteria.

(a) Owners or operators of all MSWLF units must install a final cover system that is designed to minimize infiltration and erosion. The final cover system must be designed and constructed to:

  (1) Have a permeability less than or equal to the permeability of any bottom liner system or natural subsoils present, or a permeability no greater than 1×10^{-5} cm/sec, whichever is less, and

  (2) Minimize infiltration through the closed MSWLF by the use of an infiltration layer that contains a minimum 18 inches of earthen material, and

  (3) Minimize erosion of the final cover by the use of an erosion layer that contains a minimum of 6 inches of earthen material that is capable of sustaining native plant growth.

(b) The Director of an approved State may approve an alternative final cover design that includes:

(1) An infiltration layer that achieves an equivalent reduction in infiltration as the infiltration layer specified in paragraphs (a)(1) and (a)(2) of this section, and
(2) An erosion layer that provides equivalent protection from wind and water erosion as the erosion layer specified in paragraph (a)(3) of this section.
(3) The Director of an approved State may establish alternative requirements for the infiltration barrier in a paragraph (b)(1) of this section, after public review and comment, for any owners or operators of MSWLFs that dispose of 20 tons of municipal solid waste per day or less, based on an annual average. Any alternative requirements established under this paragraph must:
    (i) Consider the unique characteristics of small communities;
    (ii) Take into account climatic and hydrogeologic conditions; and
    (iii) Be protective of human health and the environment.

(c) The owner or operator must prepare a written closure plan that describes the steps necessary to close all MSWLF units at any point during their active life in accordance with the cover design requirements in § 258.60(a) or (b), as applicable. The closure plan, at a minimum, must include the following information:
(1) A description of the final cover, designed in accordance with § 258.60(a) and the methods and procedures to be used to install the cover....

Although not as stringent, these requirements indicate cover system goals having the same theme (i.e., minimize erosion, minimize infiltration through the closed landfill) as the RCRA Subtitle C regulatory requirements.

2.3 Flexibility in State Solid Waste Regulations

2.3.1 Acceptance of Regulatory Flexibility

As stated above, the EPA database identified test plots in 17 states and full-scale alternative landfill covers being implemented in seven states. In addition, ITRC's survey indicated that 75% of the responding states were in the process of reviewing a solid waste landfill application incorporating an AFC design. The states implementing the installation of alternative landfill covers cover a variety of climatic zones with respect to temperature and precipitation and include states such as Maryland and New Jersey on the eastern seaboard, to Kansas, Nebraska, and Montana in the Midwest, and California on the west coast. Each of these states has at least one alternative landfill cover implemented, while some states such as Maryland indicated that they had too many alternative landfill covers to be able to list all of them on the survey. Therefore, regardless of the definition of the term "equivalent," either in the regulations or the public sector, state agencies across the United States have successfully implemented alternative landfill covers at municipal solid waste landfills. Examples of regulatory flexibility are located in Appendix C.

2.3.2 Conventional Requirements vs. Performance Requirements

The regulatory and guidance citations mentioned above identify conventional requirements that have long dictated not only the application of a landfill cover as a remedial alternative, but also its actual technical design primarily based on permeability design criteria. More recently, however, EPA has adopted policies that are meant to speed remediation and encourage the use of innovative designs (Gill et al. 1999). The 2002 EPA *Draft Technical Guidance for*

RCRA/CERCLA Final Covers (Bonaparte et al. 2002) focuses more on EPA's consideration of alternative cover designs on a case-by-case basis, and the flexibility that also exists in the regulations. This flexibility allows for innovation and alternative designs by limiting the use of specific minimum conventional requirements as much as possible, and by providing performance criteria in lieu of design specifications. The following will review the performance-based requirements that provide the goals for an alternative cover system design, as well as offer additional considerations for site-specific goals and objectives.

3. PERFORMANCE GOALS AND CRITERIA

3.1 Primary Goals for Alternative Landfill Cover System Designs

There is a hierarchy of goals when developing an alternative landfill cover system. These goal levels range from primary goals addressing regulatory compliance to secondary goals related to particular aspects of a site. Because goals sometimes present only the "big picture," specific objectives must also be developed to provide direction for accomplishing the goals. This section will review the primary goals and related objectives that should be addressed by an alternative cover design to comply with regulatory requirements.

3.1.1 Protect Human Health and the Environment

EPA guidance for the design and construction of final covers (EPA 1991) states that one of the goals of a cover system is to protect human health and the environment. This goal is based on RCRA's general performance standard to close facilities in a manner that "Controls, minimizes, or eliminates, to the extent necessary to protect human health and the environment, post-closure escape of hazardous waste, hazardous constituents, leachate, contaminated runoff, or hazardous waste decomposition products to the ground or surface waters or to the atmosphere...."

This goal provides flexibility in alternative cover designs, allowing for a risk-based approach to the landfill as a system. Conversely, it has also been used as a basis to include more stringent goals that control design features and may result in redundancy and higher costs. The first step in determining how to implement this goal is to assess site conditions, including the following:

- type, size, and location of site,
- site regulatory authority (RCRA Subtitle C, RCRA Subtitle D, CERCLA),
- access policies,
- climate,
- amount of fill required under cover for surface water control,
- future use of site,
- type of waste,
- institutional controls,
- monitoring systems (e.g., groundwater, leachate and/or cover monitoring), and
- seismic considerations.

Other conditions may be taken into account to support a design that is protective of human health and the environment. Often this goal is viewed as "protecting the waste," and only cover leakage is considered in assessing performance. This approach appears too restrictive for the intent of the goal and does not consider a holistic approach of evaluating landfills as complex systems with many interdependent and supporting parts. A holistic approach integrates the evaluation of the site conditions mentioned above but also considers other input to determine whether a design is protective of human health and the environment:

- the acceptable level of risk to human health and the environment,
- the ability of some wastes to store and consume water,

- presence and efficiency of bottom liners and leachate collection systems,
- the presence and efficiency of secondary liners systems to prevent the release of leachate into the environment,
- presence and efficiency of downgradient groundwater treatment systems,
- results of modeling,
- results of test plots, and
- natural analog observations.

Site owners and the regulatory community typically reach agreement on how to evaluate the protectiveness of alternative covers and landfill systems as part of the design process. In some cases, risk assessment evaluation may be needed to evaluate the risk associated to the specific landfill. This agreement is a consideration regarding how the other goals are established, integrated, and interpreted.

3.1.2 Minimize Infiltration through the Closed Landfill

The interpretation of this goal is dependent on the decisions made regarding the previously mentioned evaluation of "protecting human health and the environment." The goal is a critical aspect of the design and identified in RCRA and EPA guidance as follows:

- As a minimum technical requirement under RCRA Subtitle C with the statement, "Provide long-term minimization of migration of liquids through the closed landfill."
- As a minimum technical requirement under RCRA Subtitle D with the statement, "Minimize infiltration through the closed MSWLF by the use of an infiltration layer that contains a minimum 18 inches of earthen material." (The regulations provide for an alternative infiltration layer if it achieves an equivalent reduction in infiltration.)
- As an objective of a cover system design in EPA guidance (EPA 1991) with the statement, "Limit the infiltration of water to the waste so as to minimize creation of leachate that could possibly escape to groundwater sources."

Water that infiltrates into a cover is not necessarily a problem. Alternative cover designs manage the water by retaining it in the soil layer and then primarily by transpiration through the vegetation. Water that percolates through the cover system and into the waste may dissolve contaminants and form leachate, which can pollute both soil and groundwater as it travels from the site (Gill et al. 1999). However, not all leachate is released into the environment. EPA policies and regulations have evolved within a framework originally described by the agency as a "liquids management strategy." A prime aspect of the strategy is to minimize leachate generation by keeping liquids out of the landfill (EPA 1989b). The terms "minimize" and "through the landfill cover" provide appropriate goals but do not provide specific performance criteria. The decision that must be made is how much percolation/leachate is allowable (how much risk is there to human health and the environment), how to manage the leachate (if the landfill has a leachate monitoring/recovery system), and where to measure compliance to demonstrate an equivalent design.

A site's owner/operator and regulator must determine whether to approach the landfill as a "dry tomb" (minimal leakage), a "moist" landfill (some incidental leakage allowed), or a "bioreactor" landfill (leakage into waste desired). The evaluation conducted to protect human health and the environment will assist in this process. The performance goals that are then established may indicate an allowable leakage or flux rate past a certain compliance point (e.g., bottom of cover, bottom of waste, accumulated in the leachate collection system), or they may indicate a risk-based goal evaluated downgradient of the cover or at the site's boundary via a groundwater monitoring network.

If a performance-based (allowable leakage/flux) goal is used, there are several options to consider when evaluating the cover's potential performance. Please recognize that these are options as listed below:

- determine allowable flux through the cover based on a performance comparison to a conventional cover (established by computer modeling in most situations),
- determine allowable flux through the cover based on a set of criteria,
- determine an allowable flux rate through the cover and waste or at some other point of compliance,
- combine the two preceding options evaluating the landfill system in an holistic approach,
- test the conventional and alternative covers in a side-by-side demonstration, and/or
- use performance data, via test covers at this or other sites or models, for similar conventional and alternative cover studies.

If an owner or regulator decides to set a flux rate through the cover, the hydrogeological vulnerability of the site and other factors should be considered. If EPA promulgates regulations or publishes guidance regarding flux rates, those criteria should be considered in the design decision process. Practitioners should consider that some design criteria may be lower than the accuracy of the numerical models and field methods that are currently used to assess cover system hydraulic performance and recognize that different site-specific percolation rates may be acceptable for certain sites. In addition, measurements made below the accuracy of existing devices and used a model input values will decrease the precision of the model results.

3.1.3 Have a Permeability Less Than or Equal to the Permeability of Any Bottom Liner System or Natural Subsoils Present

This goal is stated in RCRA as a minimum technical requirement under both Subtitles C and D regulations. The Subtitle D requirement also states that the hydraulic conductivity must be no greater than 1×10^{-5} cm/sec. The intent of this regulation is to reduce amount of water migrating through the cover through the use of low-permeability materials resulting in a decrease or elimination of leachate migrating through the waste. Alternative landfill covers perform differently than conventional covers. Since AFCs are designed to reduce percolation into the waste through storage of infiltration and subsequent transpiration and not through the use of low-permeability materials, this goal is not achieved in the strictest sense by AFC designs. Properly designed and constructed AFCs can adequately reduce the flux of water through the cover. Essentially, the evaluations conducted under Sections 3.1.1 and 3.1.2 should result in compliance with this goal.

3.1.4 Function with Minimum Maintenance

Another cover system goal identified in the EPA guidance for the design and construction of final covers (EPA 1991) is the need to minimize further maintenance. This goal is also included as one of the RCRA Subtitle C minimum technical requirements ("Function with minimum maintenance"). This goal is appropriate for all landfill covers and can be achieved by establishing related goals (e.g., for erosion control, surface water control, and vegetation establishment) and by proper planning for long-term care.

3.1.5 Promote Drainage and Minimize Erosion or Abrasion of the Cover

This goal is a minimum technical requirement under RCRA Subtitle C, but has a similar concept also presented as a requirement under RCRA Subtitle D. The Subtitle D version states, "Minimize erosion of the final cover by the use of an erosion layer that contains a minimum 6 inches of earthen material that is capable of sustaining native plant growth." The Subtitle D version allows for an alternative erosion layer that provides equivalent protection from wind and water erosion as that specified.

This goal will likely lead to the development of related objectives as the issues are somewhat contradictory. To promote drainage generally means to increase slopes. Contrarily, to minimize erosion generally means to reduce slopes. In the *Draft Technical Guidance for RCRA/CERCLA Final Covers* (Bonaparte et al. 2002), EPA states that most landfill cover system top decks are designed to have a minimum inclination of 2% to 5%, after accounting for settlement, to promote runoff of surface water. However, EPA states that in some cases involving the closure or remediation of existing landfills, waste piles, or source areas, flatter slopes may already exist and that the cost to increase the slope inclination by fill placement or waste excavation may be significant. In these cases, slightly flatter inclinations can be considered if the future settlement potential can be demonstrated to be small, if concerns about localized subsidence can be adequately addressed, and if monitoring and maintenance provisions exist to repair areas of grade reversal or subsidence.

The objective of this goal, therefore, is to balance drainage and erosion in conjunction with site conditions. The goals should also address controlling surface runoff, while preventing surface run-on. The design basis section of this document will provide related discussion on evaluating these issues and determining appropriate criteria to achieve the goal.

3.1.6 Accommodate Settling and Subsidence so that the Cover's Integrity Is Maintained

This goal is listed as a minimum technical requirement under RCRA Subtitle C. Because cover soil densities would typically be lower for an alternative cover than a conventional cover, the design must incorporate appropriate materials and methods to meet this goal. Maintaining the integrity of the cover is also related to proper planning for long-term maintenance and ecological diversity/density goals.

3.1.7 Design Cover Performance for the Long Term

The regulations address design life both directly and indirectly. The minimum technical requirements mention that covers should provide long-term minimization of migration of liquids and that the integrity of the cover should be maintained. RCRA regulations require a minimum post-closure care period of 30 years; however, the design life of the cover system may be much longer and is primarily defined by the service life characteristics of the material used to construct the cover system. EPA (2002) states that the design life goal for RCRA and CERCLA cover systems is to minimize infiltration into the waste for "as long as possible." Owners, operators, and regulatory agencies must again consider the risk to human health and the environment but may consider a design life of several hundreds of years since alternative cover systems are typically a more natural system. Goals associated with design life may relate more to the anticipated level and frequency of maintenance and monitoring procedures.

3.2 Secondary Goals

The following goals may be just as critical to the overall performance of an alternative cover design, but are listed as secondary goals due to their lack of regulatory basis.

3.2.1 Prevent the Migration or Release of Significant Quantities of Gases Produced at Landfills

An alternative cover design may have a different approach to managing gases than a conventional cover. Goals should be established to control odors and gases. In addition, gas releases from landfill systems should be in compliance with applicable air quality regulations.

3.2.2 Habitat Goals

Goals should be established for managing wildlife and ensuring isolation of the waste. Goals can be determined after considering related issues, such as the following:

- What types of wildlife are present at the site?
- Are these wildlife desirable or undesirable in the cover area?
- Are habitat goals compatible with cover maintenance goals?
- Is a biota barrier necessary to isolate the waste materials?
- How can biotic intrusion be minimized?
- Should the design incorporate surface aesthetics?

3.2.3 Ecological Diversity and Density

Goals should be established for the vegetation to promote successful performance, provide a seed mix to optimize the growing season, and highlight any early concerns with establishment or continued growth. Ecological enhancements may become an aspect of the final cover design. The final cover design may be a function of the known or potential future land use as noted below. Therefore, the concepts ecological enhancements may be integrated into the design using future land use as a design goals or objectives.

3.2.4 Future Land Use

Future land use should be incorporated into the design to the extent possible. Consideration of future use as a commercial, industrial, recreational, or other parcel may impact all aspects of the design criteria (access, storm water management, landfill configuration, vegetation, etc.), specifications, and post-closure care. Certainly it appears beneficial to integrate potential future use scenarios at the beginning of the design process. This may facilitate cost savings and a return of the parcel to beneficial use.

3.3 Types of Hazards Related to Risks Associated with Landfill Systems

There are a variety of risks associated with the design, construction, and maintenance of landfill systems. Because the risks can impact the landfill goals, they may be addressed by the design and post-closure care of the landfill. Therefore, evaluating and appreciating these risks facilitates how they in turn may affect the landfill design. One place to begin when assessing the risk associated with landfill systems is to understand the types of material insolated within the landfill and its impacts o the landfill systems. Table 3-1 summarizes types of hazardous materials.

Table 3-1. Types of hazardous materials

Type	Typically found in nature?	Importance of chemical form to toxicity	Does hazard decay naturally?	Do we know how to destroy hazard?
Radio-active isotopes	Yes[a]	• Can affect the level of exposure to the hazard by altering the ingestion or inhalation uptake of isotopes	Natural decay is fixed for each isotope	• Nil prospects for in situ destruction or treatment • Ex situ treatment may be practical to separate long-lived isotopes from short-lived isotopes
Toxic organic compounds[b]	No	• Affects ingestion and inhalation uptake • Determines toxicity level	Decay generally slow (years, decades) and often dependent on specific chemical environment, e.g., trichloroethylene	• In situ decay may be deliberately enhanced by microbes • Ex situ destruction generally possible but with associated risks and costs during transportation and destruction
Toxic metals	Yes, although sometimes not in the more hazardous chemical forms	• Can affect ingestion or inhalation uptake • Generally affects toxicity	Metals won't decay, but the chemical form may naturally change into less toxic forms	• Destruction (changing one element into something else) is not practical • In situ alteration of chemical form can sometimes be enhanced by microorganisms • Ex situ destruction generally possible, but with associated risks and costs during transportation and destruction

[a] However, the specific radioactive isotopes are typically are not the specific isotopes found in nature.
[b] There are also some toxic compounds that are neither organic nor metals, e.g., asbestos (in this case found in nature). *Source:* Piet et al. 2003.

Many sites have more than one type of hazardous material, complicating design and assessment challenges. Hazard characteristics that influence the barrier design and associated performance assessment approaches include the following:

- Is it (or something like it) found in nature? If so, we may be able to learn from nature how the hazardous material behaves over long periods of time. Also, the risk perception literature shows that people view as less hazardous materials that are considered "natural."
- Is the chemical form important? If so, can we reduce its hazard or transportability? Do we have to monitor the chemical form of the hazards?
- What physical forms (solids, powder, sludge, liquids, gases) are involved? Can they change with time? If so, do we have to monitor such changes?
- How long will the hazard last if left alone?
- Do we know how to destroy the hazard or risk associated with the disposal facility?

Table 3-1 is presented as information regarding the potential risks associated with landfill systems. The risks may affect the goals associated with the design and long-term stewardship associated with landfill systems. While this document does not provide a tool to quantify the impact of the listed items on landfill design and post-closure care, it does list the information of consideration in the design process. Table 3-2 illustrates that, as the hazard time frame increases, associated engineering experience and the range of long-term solutions decrease.

In addition, the landfill goals relate the qualitative aspects of the regulations that discuss risk attributes of the system, protection of human health and the environment, and the design:

- Allocate performance criteria and goals to individual parts of the design as illustrated in Figure 3-1. Then, identify method(s) to validate the functions assigned to individual parts of the system.
- Identify which processes may degrade the alternative cap (e.g., Table 3-3). Perform a failure modes, effects, and criticality analysis (Table 3-4). Then, identify methods to be used to address the identified failure modes.

Figure 3-1 is a system developed by some AFC practitioners and is provided as a potential tool only, illustrating the concept of explicitly allocating functions to different parts of the system. If, for example, a part of the alternative cap must prevent animal intrusion, that function would be explicitly identified. For each allocated function, there must then be an explanation of why that portion of the system will successfully provide that function. Possible methods include natural analogs, experience from existing covers at similar sites, test covers, computer modeling, and technical literature.

It may also be helpful for the designer to list those stressors that may affect the cover and correlate those stressors to the landfill system goals. That assessment should be specific for the cover design and location and can be used to identify key aspects of the cover to monitor during post-closure care. Table 3-3 provides an example. Such an explicit list shows the regulator that the designer has been complete in considering what could degrade the cover. The next step is to identify potential failure modes, the effects that may result from those stressors, and how the design and/or post-closure management criteria will provide protection. Table 3-4 provides an example.

Table 3-2. Time scales

Hazard type	Institutional	Intermediate term	Geological
Decay to insignificant levels within....[a]	~100 years (e.g., 10 half-lives of radioisotopes)	Several hundred years	Tens of thousands of years, or longer
Radioisotopes	^{3}H (12.3 years), ^{60}Co (5.3 years), etc., with half-lives less than say 15 years	^{90}Sr (29 years), ^{137}Cs (30 years), etc., with intermediate half-lives	^{99}Tc (21,000 years), ^{239}Pu (24,000 years), etc., with very long half-lives
Hazardous metals[b]	Metals whose hazardous form is unstable in the environment in question	Metals whose hazardous form is moderately stable in the environment in question	Metals whose hazardous form(s) is very stable (lead, beryllium/beryllium oxide)
Hazardous organic compounds	Readily biodegradable organic compounds such as fuel hydrocarbons	Recalcitrant organic compounds such as chlorinated solvents	Little or no data
Relevant engineering experience on that time scale....	Many structures of many types have lasted this long, especially if designed for long life	Several structures have lasted this long (e.g., Roman aqueducts still used to supply water)	None
Effective strategies include....[c]	Wait them out—monitor hazard and prevent human exposure by institutional controls (e.g., keeping people away)	"Temporary" sequestration—temporary manipulation of the biogeochemical environment to fix contamination in place or engineered barriers to prevent further movement	Temporary but adaptable sequestration or "permanent" sequestration—rely on the long-term biogeochemical environmental stability of the site

[a] What constitutes "insignificant" is open to debate. The values in this table are only provided to clarify different time scales of interest and to point out that different control strategies can be appropriate depending on the time scale

[b] For metals, it is often the chemical form that matters.

[c] One can always use a strategy for a longer-duration hazard for a shorter-duration hazard.

Source: Adapted from the text in Piet et al. 2003.

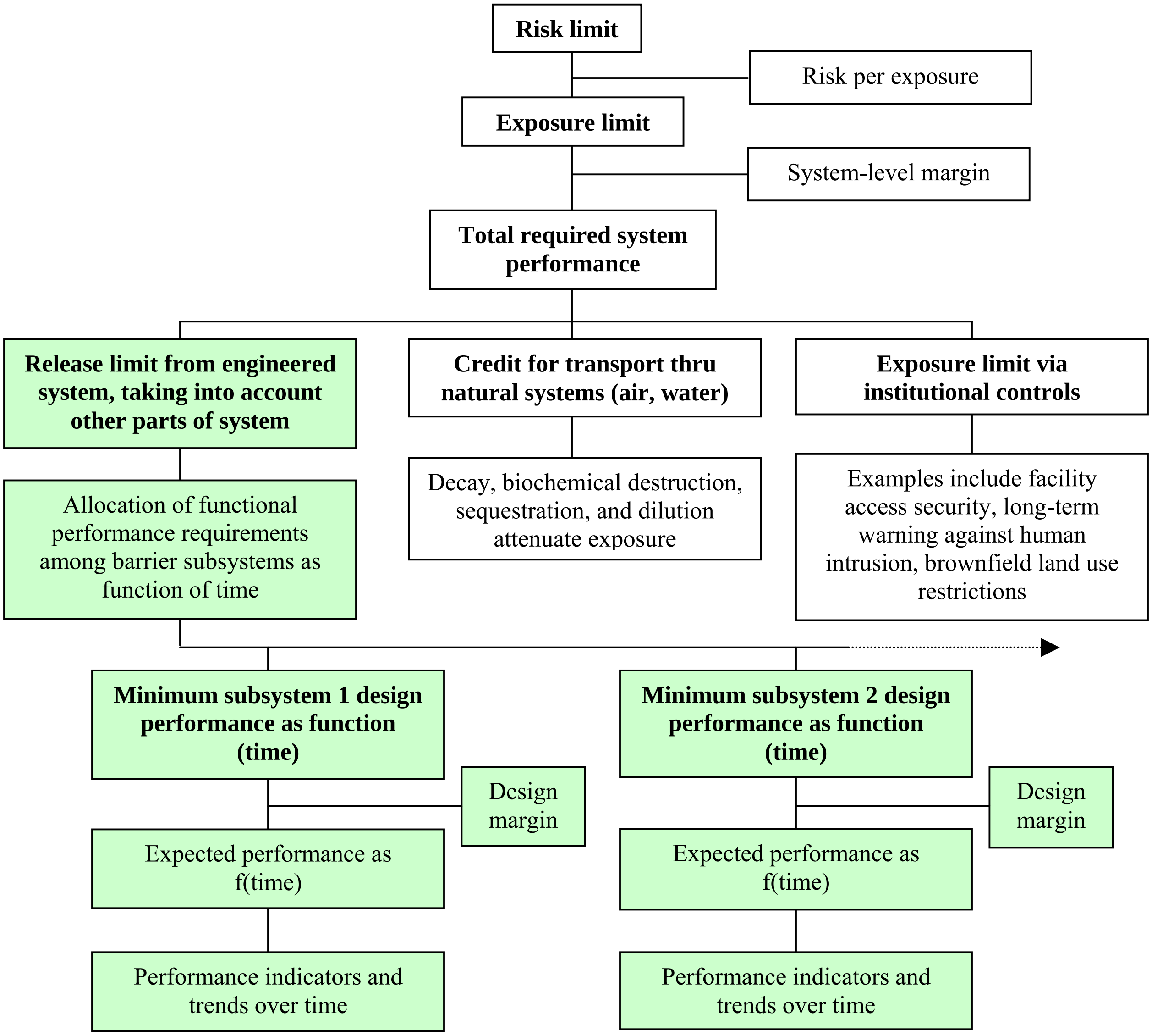

Figure 3-1. Success tree showing how subsystem performances combine to meet total system performance requirements.

Table 3-3. Examples of stressors that may degrade alternative covers

Stressor	Mechanical Effects	Biochemical Effects
Water (rainfall/ snowfall, surface water)	• Hydrostatic head • Erosion (runoff, surface water, movement of materials within barriers, localized depressions pooling water) • Ice expansion/contraction	• Wet/dry cycles • Corrosion • Leaching • Water influences plant, animal, microbial behavior • Water transports contaminants • Surface water brings seeds → plant ecology • Water brings microbes → microbial ecology
Temperature changes	• Differential thermal expansion • Freeze/thaw • Ice expansion/contraction	• Influences biochemical reaction rates • Climate changes impact biota
Wind	• Mechanical load • Wind-blown objects • Erosion • Delayering (lifting layers)	• Bring seeds → plant ecology • Bring microbes → microbial ecology • Add soil → change plant growing conditions → change/hurt/help vegetation
Mechanical loads (seismic, vibration, subsidence, impacting objects)	• Punctures • Mechanical loads • Settling of fines into coarse layers	N/A
Plants	• Macro open porosity • Surface level (run-on)	• Uptake contaminated material and bring to surface • Impact animal ecology (food supply) • Impact microbial ecology (e.g., nutrient profiles) • Evapotranspiration
Animals	• Macro open porosity • Surface level (run-on) • Erosion (of excavated material) • Excavate contaminated material and bring to surface	• Impact plant community/species • Impact microbial ecology (e.g., nutrient profiles)
Microbes	Plug capillaries	• Biocorrosion • Bioleaching • Change surface tension (e.g., in pores and capillaries) • Change PRB biochemistry • Soil formation → change plant biota → change animal biota
Radiation (UV, ionizing)	N/A	Material property degradation

Table 3-4. Illustration of failure modes, effects, and critical analysis

Failure mode	Effect	Criticality (Importance)	How design provides protection	How observable?	How management of cover provides protection if found needed
Erosion of top soil	Soil quality degrades, leading to reduction in plant cover	High—evapotranspiration degrades; water removal may be inadequate	Possibilities include soil erosion protection, soil depth margin, design for degraded ET performance, etc.	Possibilities include visual monitoring of plant cover health, direct ET measurements, direct soil quality measurements, etc.	Possibilities include soil amendments, restore topsoil, etc.
Invasion of plant species with poorer ET performance	Design plant cover is reduced	High—evapotranspiration degrades; water removal may be inadequate	Possibilities include starting with a biodiverse plant cover that resists invading plants, design for degraded ET performance, etc.	Possibilities include visual monitoring of plant mix, direct ET measurements, etc.	Possibilities include mechanical plant removal, biochemical attack of invading species, etc.

4. DESIGN

AFC design is an imprecise science combining traditional engineering design principles, unsaturated zone hydrology, plant physiology, agricultural science, and an ability to meld these disciplines into a site-specific design. In contrast, the design of conventional covers relies on the use of low-permeability materials (i.e., geomembranes or compacted clay) and the assumption that these materials will impede the downward flow of water over large areas and for extended periods of time. The net result of this assumption inherent in conventional design is that the question of performance is largely avoided through specification of material parameter values. Design of conventional covers is typically a three-step process: (1) borrow source or material characterization, (2) development of a set of engineering specifications for placement of the material, and (3) development of a construction quality control plan. AFC design depends on combining soil layers, plant species, and atmospheric conditions to form sustainable, functioning ecosystems that tend to maintain the desired water balance. AFC design must focus on performance by evaluating each component of a design individually and with respect to its interaction with the other components. It is readily apparent that there exists variability in each of the three AFC system components and even more uncertainty in the interaction among them. Variability and uncertainty can be problematic in processes governed by regulations and can lead to insistence on conservative approaches.

The ITRC Alternative Landfill Technologies Team realizes that the diversity in climatic conditions, available soils, and plant communities in addition to differences in performance criteria preclude the establishment of a rigid design process that is essentially prescriptive. A flexible and creative design process suggests there will be variation in both the process and in the selection of design tools used by different design engineers and required by different regulators. In the interest of cost and efficiency, and in some instances regulatory requirements, the ITRC team recommends that certain aspects of the design process be discussed, and if possible agreement obtained between the design engineer and regulator as design progresses. Appropriate topics for discussion may include but are not limited to:

- performance criteria (see Section 3);
- choice of conceptual design;
- choice of site characterization and methodologies;
- choice of design sensitivity analysis methods;
- choice of model, computer or otherwise;
- choice of input data sets, parameters, and supporting data;
- choice of design sensitivity analysis methods; and
- choice of design product format and content.

4.1 Introduction

Based on the ITRC team’s experience, design of an AFC typically proceeds with a five-step process: (1) selection of performance criteria (discussed in the preceding section), (2) preliminary/conceptual design, (3) site characterization, (4) design sensitivity analysis/computer modeling, and (5) final design. Inclusion of all these steps is not required. For example, facility owners, operators, consultants, and regulators should determine the need for modeling early in the design process. In some situations, a risk-based approach may be more appropriate than a landfill cover percolation approach. Existing site data or data from similar sites, may make modeling unnecessary.

For practical reasons of cost or timing, the initial preliminary design can be achieved without extensive site characterization. With knowledge of the water-storage capacity of the available borrow soils understanding of how much water storage will be required; a design engineer can readily calculate a preliminary estimate of the depth of soil that will be required. If economic concerns allow further consideration of an AFC and/or the initial assessment indicates probable success, then the design personnel should proceed with extensive site characterization. The design should be refined through numerical simulation using characterization data to evaluate changes in performance related to both changes in the cover design elements and environmental factors (e.g., rainfall duration and intensity, antecedent moisture conditions, temperature, relative humidity, etc.).

4.2 Preliminary/Conceptual Design

AFC proponents provide the basis as part of the design submittal to regulators for review and approval. When using a conventional cover design, the "basis" is an exercise of following the stated conventional cover regulations. This may or may not be adequate or appropriate for a given site, and indeed many conventional covers have failed and not provided desired performance. When using an AFC, the burden is on the owner/operator/designer to provide a package that includes the design basis. There are many ways to provide and organize a design basis. In broad terms, one can focus on allocation of functions to be successfully allocated to parts of the system, on identification and resolution of failure modes, or both. The design basis should provide the link between the design goals and the design objectives as stated in the example below.

4.2.1 Design Concept

Some practitioners support the use of screening processes as part of an initial site assessment to determine whether an AFC would have probability of success at a given location. The authoring ITRC team did not agree on a particular screening technique, however, the majority of the team did agree that, depending on the required performance criteria, AFCs could be successfully constructed and maintained in many locations. Some climatic settings may require innovative design, additional engineering effort, and different material resources than others, but no site should be automatically eliminated for use of an AFC based solely on any specific screening criteria.

Selection of a conceptual design for an AFC should include some indication of expected performance. This indication may rely on data or information from diverse sources:

- *Natural analogs.* In some locations recharge to the groundwater system may be naturally limited to levels appropriate to waste containment. The published literature, especially from agricultural studies, will likely have data relevant to the movement of water in nearby soils. Some care is required for use of such data; quantities of water deemed insignificant in other applications may be critical for waste containment. In addition, the engineered soils used in

AFCs may not be similar in composition to native soils or borrow source soils. If the final placed engineered soils do not replicate the native or borrow source soils, then water migration through the native soils will not be exact representation of the AFC. An expanded discussion of natural analogs can be found in Section 4.5.9.

- *Test section data.* Performance data from nearby (on-site or regional) lysimeter studies will provide an excellent indication of expected performance at a site. Validity of the data depends on proximity of the field test and similarities of soil, plants, and climatic factors. The Alternative Cover Assessment Program (ACAP) has conducted lysimeter tests of various cover designs in ten locations across the country. Those data can provide an indication of the likelihood of success of a cover design. Test sections are discussed in greater detail in Section 4.5.8.

- *Full-scale data.* The performance of alternative covers at nearby sites should be considered as well. Data from full-scale covers or test sections can provide an important first validation of a design concept. The extrapolation of data from nearby facilities with AFCs may save significant time and money.

Preliminary indications of performance from these other sources of information can prompt a design engineer to either proceed with a relatively simple design (a monofill, for example) or add features such as a capillary break or additional soil layers to improve performance. Preliminary modeling and information can be used to refine the design concept. In all cases, a thorough site investigation should be performed, and any further predictive modeling should be performed using site-specific data.

4.2.2 Preliminary Design

For practical reasons of cost, a preliminary design can be achieved without extensive site characterization. Within the context of this guidance document "preliminary design" is to be used as a cursory decision point. With knowledge of the approximate water-storage capacity of the available borrow soils and how much water storage will be required, a design engineer can easily calculate a preliminary estimate of the depth of soil that will be required. This process is briefly outlined below. If economic reasons allow further consideration of an AFC, design personnel should proceed with extensive site characterization. The preliminary design evaluates the suitability of an AFC for a particular site and may be relatively simple. The following three steps may be used in conducting this evaluation:

1. Determine the soil water-storage capacity of the available soils (see Section 1.2.4). This quantity represents the difference in volumetric water content between wilting point and field capacity of the soil. Wilting point is the water content at which transpiration ceases and thus represents the driest state of the proposed cover. Field capacity is the water content at which no additional water can be added to the soil profile without significant drainage. The difference between these two points represents the storage capacity of the soil. Soil water storage is reported in units of depth of water-storage capacity per unit depth of soil (i.e., meters of soil storage capacity per meter of soil).

2. Determine the quantity (depth) of water for which storage in the cover will be required during periods when precipitation rate exceeds evapotranspiration rate. In cold climates where transpiration is essentially nonexistent for several months each year, this may be fairly simple to determine. In such locations one might conservatively expect the cover to store all precipitation between onset of freezing temperatures in the fall and the time of active transpiration during the spring. Locations where significant precipitation occurs during a season when some transpiration occurs can require a more detailed analysis. There are a variety of procedures for estimating the storage requirements for a cover. These procedures may be refined as part of the design process and design sensitivity analysis.

3. Determine the depth of soil required to store the quantity of water that represents the difference between precipitation and evapotranspiration. This is done by dividing the quantity of water storage required (depth of water) by the soil water-storage capacity (depth of water per unit depth of soil). The result of this procedure will be a calculated depth of soil and will represent an acceptable starting point for further evaluation of an AFC.

The simple procedure described here does not account for many of the environmental stresses that may be placed on a cover, nor does it address agronomic issues important to maintenance of a viable plant community. The procedure does, however, enable a design engineer to make a valid preliminary decision to proceed with design of an AFC. Agronomic considerations and other site characterization data should be given careful consideration and are discussed in subsequent sections.

4.3 Site Characterization

This section discusses several of the key aspect of site characterization, including climate, soils, and vegetation. Part of site characterization should include an assessment of the research conducted by facilities in the same or similar setting in the same locale or region.

4.3.1 Climate

Precipitation and the atmospheric factors that influence evapotranspiration are of primary importance to alternative cover design. Climate is one factor that cannot be controlled or engineered by the designers of alternative landfill covers. An analysis of regional climate should be the first consideration when evaluating the suitability of, or level of design effort required for, an alternative landfill cover for a site. If the regional climate appears to be compatible with the requirements of the alternative cover and the regulatory requirements, then site characteristics should be examined to determine whether there are important differences between the site climate and the regional climate. The site climate will be similar to that at nearby stations for most of the country. However, site and regional climate data may differ substantially for sites near mountains, in valleys, in the rain shadow of coastal mountains, or near the coast.

Climate data should represent the conditions at the site to the maximum extent possible, and the longer the record, the better. In practice, however, the data may not be at the exact landfill location or for an extended period of time. While an extended period of climatic data is preferred—some think that as much as 20 years should be minimal record—designers do the best they can with the available data. As discussed above, this is a design uncertainty that is addressed in the design process and accounted for through the assumptions used to predict the amount of precipitation that will impact the cover, the soil moisture holding capacity, and the estimated actual evapotranspiration of the site.

Site-specific climatic factors that are important to the performance of alternative landfill covers include daily precipitation values, maximum and minimum temperature, relative humidity, total solar radiation, and daily wind run. Of particular interest to AFCs is the relative timing of precipitation and transpiration. At locations where significant precipitation occurs during seasons when transpiration is limited or nonexistent, cover design should account for the required water storage. If the performance of the cover is to be evaluated with the use of a computer model it will be necessary to determine the data input requirements of the particular model. Since the results of numerical prediction are greatly influenced by the selection of input data sets such as precipitation data, a design engineer may choose to discuss the choice of climate data for modeling purposes with the appropriate regulatory agency prior to running the model. Conservative estimates of climate data should be used in the design process. This approach will form a bounding limit on worst-case conditions that the cover may be expected to endure.

The cover should be evaluated during its critical conditions (for example, during the period of minimum evapotranspiration or a spring snowmelt event). The design may be based on events predicted from models or extrapolated from available records. Some regulators may wish to determine the impact of a long-duration, low-intensity storm where precipitation does not exceed the rate of infiltration. This scenario may not present a deleterious erosional impact on the cover but could place the maximum amount of stress on the cover by causing the greatest amount of water to percolate into the cover materials. This situation could create a significant potential for precipitation to percolate through the cover. A similar situation may be created by snowmelt. It is critical to note that the design event for any individual cover may be a period as long as a season or as short as a several-day storm or snowmelt event.

4.3.2 Soil Characterization

AFC design and construction should optimize two factors: soil water storage and water use by plants. The soils provide the capacity to trap and store the water, while transpiration from plants and evaporation from atmospheric conditions provide the mechanisms to remove the water from the soil. AFCs control the precipitation falling on the surface by providing adequate water-storage capacity in the soil to contain the infiltrating precipitation and reduce or eliminate the flux of water through the waste. Total, potential soil water-storage capacity is controlled by soil properties and should be optimized by selecting the most beneficial soil properties during the design and specification development process. The storage capacity available at any instant in time is controlled primarily by the balance between infiltration from precipitation and rate of water removal from the soil by ET.

The soil must have desirable water-retention characteristics and meet the necessary agronomic requirements to support an active plant community. A number of additional soil properties are of interest to design and construction engineers, such as compaction characteristics, Atterberg limits, clay content by mineralogy, and grain size. These properties can be used to delineate acceptable borrow sources, evaluate the potential for shrink/swell problems, and assist in construction QA.

Soils can be classified by either the Unified Soils Classification System (USCS) system in common use by civil and geotechnical engineers or by the U.S. Department of Agriculture (USDA) soil textural classification system, which was developed for use in describing soils in which plants grow (Sparks et al. 1996, Hillel 1998). Definitions of terms used in the USDA system are readily available in the glossary of terms published by the Soil Science Society of America (SSSA 1997) and in textbooks such as those written by Hillel (1980, 1998). There are benefits to using each of these classification systems; both have strengths in designing a successful AFC, and integration of the two during the design process may yield the best result. As previously stated, AFCs depend on engineered covers with geotechnical characteristics optimizing water retention and plant growth promoting characteristics. These may be better defined using traditional geotechnical practices. In addition, the soil characteristics should be determined that optimize plant growth, favoring the USDA classification system.

By its very nature, construction of an AFC modifies the soil used to create the cover. Hence, the construction process offers the opportunity to either place the soil so that it will perform better than before it was moved or damage the soil and greatly reduce the opportunity for success in meeting the requirements for the cover. It is important to understand soil properties that control success and how they can be optimized during cover construction.

4.3.2.1 Soil Properties

Engineering and hydrologic parameters:

- Atterberg limits
- bulk density
- compaction
- particle size distribution
- percentage of clay mineral
- saturated hydraulic conductivity
- total porosity
- type of clay mineral
- unsaturated flow parameters
- water-holding capacity: field capacity/wilting point

Agronomic soil conditions/factors affecting plant growth:

- aeration properties/connection between pores
- ammonia
- anions/salinity
- available nutrients
- bacteria
- CO_2 from decaying organic matter
- fertility
- fungi
- humus content
- oxygen in soil air
- pH
- sodium content
- soil strength
- temperature
- tilth
- toxic substances
- water content

4.3.2.2 Parameter Descriptions

The glossary at the end of this document contains more detailed discussion of these parameters and how they relate to AFCs.

Soil humus content: Humus is composed of organic compounds in soil exclusive of undecayed organic matter. Humus is resistant to decay, provides significant cation exchange capacity (CEC) in addition to that of clay minerals, and improves soil structure. The addition of organic material to soil to improve its properties usually improves soil tilth and fertility temporarily, but it may not be worth the expense in a landfill cover because most of the added material oxidizes and disappears in a few months or years, after which soil properties revert to those of the original soil material.

Harmful constituents in soil: Landfill cover soils should be free of harmful amounts of manmade chemicals. Oil, natural salts, and sodium can cause deflocculation (i.e., dispersion) of clay particles, thereby causing poor soil tilth.

Atterberg limits: The use of high-plasticity materials may result in soil volumetric changes (shrinkage) induced by moisture fluctuations. The result may be the development of preferential flow paths that can lead to undesirable increases in percolation through the cover. The upper limit of plasticity index to be specified for a given project can be defined from shrinkage tests on cover soils. Zornberg reports limiting the soil plasticity index to a range between 8% and 30% at the Operating Industries, Inc. Superfund landfill and using a liquid limit of less than 50% to limit desiccation cracking (ITRC 2003). Desiccation cracking is of more concern in clayey soils with a high liquid limit than in silty or loamy soils with a lower liquid limit. Chadwick et al. (1999) also discuss the use of plasticity properties cross-referenced to unsaturated hydraulic properties as a method of identifying acceptable borrow soils. They report the use of soil with a plasticity index between 7% and 30% and a liquid limit less than 40% (see Section 4.4.5).

Grain size distribution: The gradation of the soil particle sizes has a significant impact on the saturated hydraulic conductivity, moisture retention properties, and unsaturated hydraulic conductivity of the cover soils. Determination of the entire particle size curve (i.e., using both sieve analysis and hydrometer tests) can be beneficial. Zornberg reports the use of fines content (passing through the #200 sieve) greater than 35% to prevent excessive erosion and to ensure proper moisture storage capacity and infiltration control (ITRC 2003). Similarly, Chadwick et al. (1999) report the testing and use of soils with a fines content ranging from 35% to 50% and greater than 50%. Additional post-demonstration testing identified soil textures that should be acceptable for AFCs. Practitioners should account for limits on clay and silt content with respect to vegetation growth considerations.

Saturated hydraulic conductivity: A low saturated hydraulic conductivity is required for situations in which the cover is under saturated conditions, such as when there is ponding on the cover or excessive snowmelt. Most regulatory agencies require a soil with a saturated hydraulic conductivity equivalent to or lower than that required for conventional compacted clay liner covers (i.e., 10^{-5} m/s). A compacted silty or loamy soil has the advantage of having a reasonably low saturated hydraulic conductivity but a very low unsaturated hydraulic conductivity. The saturated hydraulic conductivity is typically measured using a constant or falling head permeameter. The saturated hydraulic conductivity represents the point on the unsaturated hydraulic conductivity versus suction head curve at which the suction is zero. The unsaturated hydraulic conductivity is governed by several (typically five) parameters, only one of which is the saturated hydraulic conductivity. However, for a given set of moisture retention properties, the unsaturated hydraulic conductivity decreases with decreasing saturated hydraulic conductivity values.

Unsaturated hydraulic conductivity: Determination of unsaturated hydraulic conductivity is needed for numerical modeling of unsaturated flow through the cover system using Richards' equation. The unsaturated hydraulic conductivity of cover soil is defined by the soil saturated hydraulic conductivity and soil water characteristic curve. The soil water characteristic curve is defined by the relationship between soil suction and soil moisture content.

Water pressure within an unsaturated soil is negative and referred to as "soil suction." A saturated soil (a soil with a degree of saturation equal to 100% or a volumetric moisture content equal to the porosity) has a suction of zero. The relationship between suction and water content is not unique and may exhibit hysteretic behavior (i.e., different drying and wetting paths). Flow of water takes place under unsaturated conditions, but the hydraulic conductivity is significantly lower in an unsaturated soil than in a saturated soil. Hydraulic conductivity relationships (also known as "K functions") differ greatly among soils. The relationship is sensitive to the soil density, particle size distribution, soil structure, and the wetting history of the soil. In the unsaturated soils of an ET cover, hydraulic conductivity may vary over several orders of magnitude. Some studies have developed methods for estimating the hydraulic conductivity functions from more easily measured soil parameters. For example, Savabi (2001) employed methods described by 12 different authors to estimate hydraulic conductivity in his model evaluation of the hydrology of a region in Florida. [V]an Genuchten, Leij, and Yates (1991); Zhang and van Genuchten (1994); and Othmer, Diekkruger, and Kutilek (1991) each developed computer code to estimate hydraulic functions for unsaturated soils. While the estimation of hydraulic properties of soils (e.g., soil water characteristic curve) from their index properties (e.g., particle size distribution) is useful for quality control programs, estimation of the soil water characteristic curve from measured moisture retention data should be more accurate.

Soil shear strength: The shear strength of the soil should be defined for soil cover systems where stability is an important design aspect. The soil shear strength envelope can be defined using direct shear or triaxial testing programs, conducted using specimens prepared at the target soil density. The stability analysis of cover systems and the laboratory methods used for determination of soil shear strength are no different than in the analyses and laboratory methods used for conventional geotechnical structures (e.g., soil embankments). Geotechnical practice is well established for characterization of soil shear strength. Typically, the design engineer characterizes the soil shear strength using an effective shear strength linear envelope (i.e., Mohr-Coulomb shear strength envelope characterized by a cohesion c' and a soil friction angle ϕ'). The stability analysis of landfills is a topic of significant relevance but not specific to the case of ET covers.

Soil water-holding properties: Soils that hold much water will achieve the desired water control with a thinner layer of soil than those with low water-holding capacity. Important water-holding properties include the permanent wilting point, field capacity, and plant-available water content, defined as follows (SSSA 1996):

- Permanent wilting point: "The largest water content of a soil at which indicator plants, growing in that soil, wilt and fail to recover when placed in a humid chamber."
- Field capacity: "The content of water on a mass or volume basis, remaining in a soil 2 or 3 days after having been wetted with water and after free drainage is negligible."
- Available water: "The amount of water released between in situ field capacity and the permanent wilting point."

Soil tilth: "The physical condition of soil as related to its ease of tillage, fitness as a seedbed, and its impedance to seedling emergence and root penetration."

Soil bulk density: The road and building construction industry expresses soil compaction as "percent of standard Proctor." The "standard Proctor density" evaluates the potential soil strength and other structural properties that may be achieved with given soil materials. The Science Society of America defines bulk density as, "The mass of dry soil per unit bulk volume" (Sparks et al. 1996). The soil must be weak for a successful AFC. Densities should be low enough to encourage active root development throughout the cover profile but high enough to prevent differential settlement, which can cause surface ponding. Growth-limiting bulk density is a concept whereby a mix of soil properties is used to determine an appropriate range of condition conducive to root growth.

Soil strength properties: Soil strength is an important physical factor in soils supporting plant growth because excessive strength can reduce or stop root growth (Rendig and Taylor 1989). Soil strength is controlled by several factors, including bulk density, particle size distribution, and water content. It is possible to control soil bulk density in an AFC during construction, and if it is controlled within a desirable range, the resulting soil strength is usually satisfactory.

Soil aeration properties: This property is discussed further in Appendix D.

4.3.2.3 Preliminary Soil Volume

A designer may want to use available data from a soil survey to make a preliminary decision about the suitability of local soil types and the economic viability of an AFC design without conducting a field effort. The procedure is typically not detailed or quantitative enough to be used for design purposes; rather it is intended to give only a general evaluation of the feasibility of an AFC design.

After the decision is made to design an AFC, the first step should be careful inventory of soils available for use in the cover to determine their properties, volume available, distance from the site to the soil resource and to estimate cost for acquisition and hauling to the site. At this stage the designer should make a preliminary estimate of the performance of a cover utilizing available soil and determine whether it is appropriate to continue with design of an AFC for the site. After determining that an AFC is appropriate, followed by complete soil evaluation, it is then possible to design an effective AFC.

Descriptions that are suitable for initial survey of soils found near the site are available from official soil surveys of the USDA Natural Resource Conservation Service (NRCS) available at county or state offices. The land grant universities are also a source of soil data for their respective states. The USDA/NRCS soil surveys include aerial photos of each county with individual soil units marked for reference to the data contained in tables. The user should collect information on the soils that are available within a reasonable (economically viable for the project) haul distance of the landfill site. After the initial evaluation, the user should sample and evaluate the soil in the proposed borrow source. The literature contains examples of how to use the USDA soil data during the AFC planning stage.

It is important to realize, however, that landfill covers are engineered systems and that cover soil will typically be placed to a specified value of density. Engineered soils are subject to the natural processes of wetting and drying cycles and freezing and over a long period tend to some limiting value of density. Soils placed at densities significantly less than long-term equilibrium values may experience considerable differential settlement and localized ponding. The potential for ponding should be monitored during the post-closure long-term care program. If ponding develops, then corrective action should be taken to promote the appropriate slopes and drainage. Measurement of the natural in situ values of soil density should provide an acceptable starting point for evaluation of desired density. While this is a starting point for the soil density, the soil density should be optimized and placed to promote plant growth and water retention.

4.3.2.4 Assessment of Borrow Sources

The assessment and evaluation of potential borrow sources is an essential phase of the design and construction of an AFC. The purpose of this assessment is to determine the actual engineering and agronomic soil characteristics of the soils available to construct an AFC. Evaluation of available soils consists of preliminary investigations, soil sampling, and laboratory testing. In addition to determining soil characteristics, it is important to determine the volume of soils available for use and the total costs to have a suitable soil available on site. The soil source costs may include the cost for transportation and/or costs to process/blend soil(s) to produce a suitable material. It is recommended that a borrow source assessment report be prepared to document the investigation.

Preliminary Investigations

Accessibility and proximity are often controlling factors in selecting borrow sources. Borrow materials, which may be available at the site, should be investigated for potential use for construction of all or part of an AFC. However, in many cases, suitable borrow materials may be found only off site. A general survey of soils that are locally available can be determined as described previous sections. Other commercial sources of borrow can be determined by contacting local quarries, contractors, or engineers.

The preliminary investigation typically requires a field or visual description of soils within the borrow area to determine the location and extent of potentially suitable soils for later verification through laboratory analysis of selected soil samples. The field investigation may be conducted by excavating soil pits or collection of soil cores using either drilling or geoprobe technology depending on depth of samples and site conditions. The visual descriptions of soils are needed to define soil variability and the extent of both suitable and unsuitable soils and to develop a soil sampling plan to verify field descriptions and characterize the soil types through laboratory analysis. The description of soil profiles based on soil pit excavations is most useful when the borrow area consists of undisturbed natural soils with distinct soil horizons (layers of soil that have different physical, chemical, and/or biological properties). The descriptions of developed soil horizons provide a means to define the thickness and extent of the most productive soil horizons (A and B horizons) that have developed over many years and often have properties such as soil organic matter and favorable soil structure that promote plant productivity and sustainability. The soil horizon descriptions provide a means to select those horizons that may not be suitable and to determine if there is an opportunity to segregate the most productive soil for use as an ET cover topsoil. Methods for describing soils in the field are provided in the following:

- American Society for Testing and Materials. 2000. *Method D 2488-00, Standard Practice for Description and Identification of Soils (Visual-Manual Procedure).*
- U.S. Department of Agriculture, Natural Resources Conservation Service. 2002. *Field Book for Describing and Sampling Soils*, Version 2.0, available on the Internet.
- U.S. Department of Agriculture, Natural Resources Conservation Service. *National Engineering Field Handbook*, available on the Internet.

In general, it is recommended that the borrow sources, whether from on-site or commercial sources, contain a volume of material well in excess of that anticipated for use. This is necessary so that if unsuitable soils are discovered during borrow source excavation, an ample supply of suitable soils is present to fulfill the needs of the project. In some cases, easements, permits, or an evaluation of natural or cultural resources may be required prior to obtaining access to certain borrow sources. These considerations should be established and addressed early in the process, after a potential borrow source has been identified.

Borrow Source Sampling

To determine the actual engineering and agronomic properties of the borrow soil, soil samples should be obtained and subsequently tested. Soil samples may be obtained from borings, test trenches, or pits. Classification of the deposits can be done by the USCS and/or USDA soil textural classification system. All exploration activities should be supervised by a qualified engineer, geologist, or soil scientist. Test trenches excavated into the borrow soil with a backhoe can expose a large cross section of the borrow soil. Variability of soil in the borrow area can be easily seen by examining exposed cuts rather than by viewing small soil samples obtained from borings. In general, it is recommended that soil borings or test trenches extend 2–4 feet below the anticipated final depth of the borrow area. The number of borings or trenches required for a borrow assessment will vary from site to site, depending on the uniformity of borrow materials available.

The design of the soil sampling program should be determined following evaluation of the information obtained from the preliminary field investigation to assess the soil variability, location, and extent of both suitable and unsuitable soil types. The soil sampling methods and locations should be based on the variability, location, and depth of soil types. Specific soil horizons can be sampled in those situations where the borrow source includes undisturbed near surface soils with developed horizons. The sampling and characterization of the soil horizons of the soil types provides a means to define the range of soil conditions. If the borrow source includes complex variable soils, such as those that developed from a fluvial depositional process, then a statistical approach may be required. The statistical approach to sampling may require random selection of sample locations and composite sampling to characterize the range of soil conditions.

Soil Testing

Soil tests should be performed on the soil samples obtained to determine the suitability of the borrow soil for use in an AFC. It should be noted that large bulk samples of soils are required to perform some of the soil tests. In addition, it is recommended that all borrow materials be tested to ensure they are not chemically contaminated before use on the site. The Table 4-1 shows some of the recommended tests for characterizing soils. The following list of field or visual soil descriptions may be used to provide an initial assessment of the suitability of a soil:

- percentage plant cover
- percentage rock fragment (volume)
- plant root distribution and depth
- soil color (Munsell soil color charts)
- soil consistence or resistance to deformation
- soil moisture
- soil reaction to hydrochloric acid to assess presence of carbonates (salinity)
- soil structure or the arrangement of primary soil particles into units
- soil texture (feel method or D422)
- surface slope

4.3.2.5 Indexing

Some facilities have used an indexing methodology to make correlations between different site characterization parameters following characterization. The concept is to develop a relationship between two, or possibly more, parameters. This relationship may then be used during construction to add additional information to the QA/QC program, save time, save money, or all of these. One such example might include a correlation between soil hydraulic properties and grain size. The evaluation of soil hydraulic properties can be both time-consuming and expensive. Timing can be critical during the construction phase of the project. If a lift of material is covered only to find out that it failed the required hydraulic performance parameters, then it could be costly in time and money to exhume and rebuild. Similarly, parameters such as Atterberg limits may be correlated with other parameters that can be determined in real time in the field during the construction phase. Simpler, more time-efficient tests, such as grain size analysis, may be conducted quickly and inexpensively to evaluate the quality of the constructed materials.

The range of soil parameter values described in a characterization and indexing exercise may also be useful to design sensitivity analysis (see Section 4.4.1).

Table 4-1. Potential borrow assessment soil tests

Test type	Test method	
	ASTM	Other
Soil classification and taxonomy	D 2487	SSSA-4
Particle size analysis	D 422	SSSA-4
Fines content	D 1140	
Atterberg limits	D 4318	
Moisture content	D 2216	SSSA-4
pH	D 4972	SSSA-3
Compaction	D 698 and D 1557	
Hydraulic conductivity	D 5084	SSSA-1
Soil bulk density	D 2167, D 2922, and D 2937	SSSA-4
Direct shear strength	D 3080	
Triaxial shear strength	D 2850	
Capillary-moisture relationships for fine-textured soils	D 3152	
Capillary-moisture relationships for coarse- and medium-textured soils	D 2325	
Moisture retention characteristics (various methods)	D 6836	SSSA-1
Moisture retention characteristics via hanging column		SSSA-1
Phosphorus		SSSA-3, pp. 869–919
Potassium		SSSA-3
Inorganic soil nitrogen		SSSA-3, pp. 1123–84
Organic soil nitrogen		SSSA-3, pp. 1185–1200
Electrical conductance		SSSA 1996, SSSA-3
Sulfur		SSSA-3, pp. 921–60
Total salt content		SSSA-3, pp. 417–35
Cation exchange capacity		SSSA-3
Organic matter		SSSA-3
Sodium adsorption ratio		SSSA-3

4.3.2.6 *Data Extrapolation*

Data collected by facilities with the same characteristics may be useful and could possibly be extrapolated to another facility. Using extrapolated data may translate to project cost and time savings. If data is going to be extrapolated from one site to another, the practitioner should be prepared to explain the following:

- the differences between the two sites,
- the impact on the data extrapolated from one site to another,
- the potential error introduced in the data due to extrapolation, and
- what additional data, if any, should be collected to support the extrapolated data.

4.3.3 Vegetation Characteristics

As stated earlier, plant transpiration is the primary mechanism in removing water from an AFC. Without plants, AFCs would depend on only evaporation to remove the water from the cover system. While evaporation will remove some water from AFCs, plant transpiration affords the opportunity to design a successful cover that will reduce or eliminate water from migrating through the cover and into the waste. The following section discusses key parameters associated with vegetation used with AFCs. Several terms are discussed and defined for general use. See Appendix D for discussion of the concepts of wilting point and suction head as they relate to the AFC design process.

4.3.3.1 Plant Species

Plants play a key role in the success of an AFC design. Through transpiration, plants move water from the root zone to the atmosphere. Plant species selection can vary depending on climate, long-term land use, waste type, cover design limitations, etc. A mix of plant species may be appropriate to maximize the number of days, as well as the total amount, of transpiration by plants.

The goal of the plants, in concert with the post-closure goals, is to require little maintenance and have long-term sustainability. While some researches argue for only native plants, test plots with a mix of native and nonnative plants have proved very effective in reducing or eliminating water from the cover system. There are several good sources of information regarding which plants to select for cover systems including, but not limited to, agricultural universities and local agricultural agents. A variety of plant species should be growing both in the cool and warm seasons. A succession of species may be planted to enable early-start plants to begin the ET process while the later succession of plant population, which may provide higher transpiration rates, gets established. ET is effective soon after plants initiate growth and development, but for success criteria, a more mature plant community should be allowed to establish. A mature plant community can take 3–5 years or more to develop.

A diverse seed mixture ensures that a plant community mosaic of small-scale variation will develop and achieve the goal for vegetation on alternative landfill covers. The following considerations should be addressed when developing a seed mix for use on alternative landfill cover systems.

- Native vegetation can be classified through mapping or by listing local dominant species. Relict or other undisturbed areas can be most useful for determining common native species adapted to the area. Also, an inventory of plant species in less disturbed areas can provide an initial list of species for consideration in seed mixes for the alternative cover site.

- Improved varieties of many species, especially grasses, are commercially available; however, the cultivars appropriate for the specific project location should be selected considering their potential survival and whether they are considered a weed by the state or locality. It is desirable to use seed developed from local sources, if possible. Whatever the seed source, only high-quality, weed-free seed should be used. Autecological and synecological characteristics of the different plant species should also be considered for determining the rates of seeding for each individual species. Species easily established and very competitive with other species would be included in the mix at a lesser percentage than less easily established types. Seeding rates for each species should be based on recommendations by the local NRCS personnel or the land grant university.

- A concurrent soils mapping program should also be considered. Once soil types are known, NRCS manuals, other revegetation documents, and local experts can be consulted to determine appropriate plant species for each soil type. Matching plant species to the soil type(s) to be used for cover construction may refine the original list of species for consideration.

- Seed mixes could also be modified based on the topographic location being seeded. Seed mixes for dryer upland areas may be somewhat different than those for drainage swales with higher soil moisture. Root anatomy and rooting depth of species may also be of consideration. For alternative covers, plant species producing large, deep tap roots may not be as desirable as species that produce fibrous root systems concentrated in the upper portion of the cover.

- Species' potential leaf area index may be a consideration. Tall, leafy species may be desirable to promote transpiration. The list should include both cool- and warm-season species so that transpiration is active during most of the year.

- A mixture of bunch grasses and rhizomatous species may be desirable for optimum soil stabilization, particularly where water erosion is a problem.

- Ultimate land-use considerations could also influence species selection. Species may vary dependant upon whether the land will be grazed, managed open space, or habitat for specific wildlife. Other plant species may be selected for wildlife deterrence.

- Finally, availability of seed or plant materials needs to be considered. Seed mixes composed of species in limited supply might not be useful.

For some AFC applications (such as covers for active landfills that will be constructed sequentially over several years), a baseline seed mix can be used to conduct a "seeding trial." The test area can be monitored for species success in ease of establishment, persistence, competitiveness, etc. on site-specific and species-specific bases. Seed mixes can then be modified, additional seeding trials conducted and monitored, and final seed mixes formulated.

Table 4-2 is an example mix for an alternative landfill cover project at a semiarid site near Denver.

Table 4-2. Native grass species for alternative cover at the Rocky Mountain Arsenal

Scientific name	Common name	Variety	Pounds pure live seed per acre	% of mix
Poa compressa	Canada bluegrass	Reubens	0.1	10
Bouteloua gracilis	Blue grama	Hachita	0.6	30
Bouteloua curtipendula	Side-oats grama	Vaughn	1.2	15
Schizachyrium scoparium	Little bluestem	Pastura	0.9	15
Pascopyron smithii	Western wheatgrass	Arriba	2.1	15
Oryzopsis hymenoides	Indian ricegrass	Nezpar	0.5	5
Subtotal			5.5	90
Native forbs or semishrubs				
Penstemon angustifolia	Narrow-leaf penstemon		0.02	
Liatris punctata	Blazing-star		0.1	
Linum lewisii	Blue flax		0.03	
Helianthus annuus	Annual sunflower		0.1	
Achillea lanulosa	Yarrow		0.003	
Artemisia ludoviciana	Louisiana sagewort		0.002	
Sphaeralcea coccinea	Scarlet globemallow		0.02	
Artemisia frigida	Fringed sage		0.002	
Gutierrezia sarothrae	Broom snakeweed		0.01	
Opuntia polyacantha	Prickly-pear cactus		0.1	
Subtotal			0.387	
Native shrubs				
Ceratoides lanata	Winter fat		0.3	
Chrysothamnus nauseosus	Rubber rabbitbrush		0.04	
Atriplex canescens	Fourwing saltbush		0.3	
Rhus trilobata	Skunkbrush sumac		0.8	
Yucca glauca	Yucca		0.7	
Subtotal			2.14	10
Total			7.927	100

4.3.3.2 Growing season

Plants and transpiration are active only during the growing season of the established plant community. However, evaporation from the soil continues year-round. Changes in transpiration potential occur at the seasonal scale and are associated with precipitation, wind, atmospheric pressure, and temperature fluctuation. Within a growing season different species initiate and achieve peak growth at different times. Plants can also respond to alternating times of favorable and unfavorable conditions within a growing season.

For practical applications, it is generally important to establish a plant community that has the capability to respond to all favorable growing conditions during a growing season and thus maximize the amount of transpiration. Therefore, a mix of species including plants active in both cool and warm seasons should be specified so that transpiration by the plants is active at all times of the growing season. It may even be important to include annual, tree, and shrub species.

In some locations, the transpiration season may be year-round. At most sites, however, the growing season begins when air and soil temperatures are high enough to allow plant growth and ends when day length and temperatures decrease below a metabolic threshold for vegetation. Models should start and end plant growth based on air and soil temperature experienced or estimated for each day of each year. For modeling, exact dates are not necessary, and in fact dates will vary with yearly weather patterns. It may be prudent to estimate a conservative start and completion date that would apply in most years. For example, in the Denver, Colorado region, growth of the earliest cool-season species is significant in early March and declines to near zero in late October. For modeling metrics, a reasonable growing season for this area might be March 15 to October 15, even though growth and transpiration can certainly occur outside of these boundaries in many years.

4.3.3.3 Percentage Ground Cover

Ground cover can be composed of live plant material, mosses, lichen, standing dead plant material, litter, rock, and even miscellaneous debris. Total percentage of ground cover summed with percentage of bare ground should equal 100%. Estimates for percentage cover can be obtained through many approaches. An average number with a low standard deviation should be determined.

4.3.3.4 Percentage Bare Ground

Percentage bare ground is the inverse of percentage total ground cover. If there is a high degree of confidence associated with the leaf area index (LAI) values that are used, or if very conservative values are used, then the value for bare ground should be zero, regardless of the actual amount of bare ground measured or expected. Other models address ground cover and bare soil by the definition of plant density in combination with descriptions of plant characteristics.

4.3.3.5 Root Structure and Depth

Site specific data for root structure, density, and depth may be difficult to obtain. Actual rooting depth is usually controlled by soil properties and not by potential for the plant; therefore, it may be appropriate to use a model that accounts for actual root growth as limited by soil properties. EPA’s Alternative Cover Assessment Program is gathering data from sites being monitored and may be a source for root density profile information. In general, grass species have the majority of roots in a dense network of fibrous roots in the top ½ meter of soil. Grasses also send a lower proportion of roots 2–3 meters or more into the soil profile. Some species may be more or less adaptable to impacts of landfill gas production. Sensitive species may need to be avoided in favor of more tolerant species.

4.3.3.6 Leaf Area Index

The leaf area index is the total green leaf area (one-sided area for broad leaves) in the plant canopy per unit ground area; it is a major controller of transpiration. Leaf area plays a key role in the absorption of radiation, the deposition of photosynthates during the diurnal and seasonal cycles, and the pathways and rates of biogeochemical cycling within the canopy-soil system. Globally, it varies from less than 1 to above 10 but also exhibits significant variation within biomes at regional, landscape, and local levels.

Mean LAI (± standard deviation), distributed between 15 biome/land cover classes, ranges from 1.31 ± 0.85 for deserts to 8.72 ± 4.32 for tree plantations, with evergreen forests (needleleaf and broadleaf) displaying the highest LAI among the natural terrestrial vegetation classes. LAI also changes during the growing season, especially in grassland and deciduous systems. LAI may start and end the growing season with a value of zero. During the growing season, LAI rises and falls from a peak level of production. The LAI curve is also important in many model approaches because it controls plant transpiration.

Total leaf area has significant effects on plant water loss. Leaf production or shedding is an important way plant species ensure survival by adjusting their demand for and use of water to current availability. As plants grow, they increase their leaf area and consequently their water use. In general, species that have higher growth rates in terms of biomass have a higher allocation to leaves and their leaves are thinner (high specific leaf area), resulting in even higher rates of leaf area increase. Extreme examples are annual crops and desert shrubs. Under optimum growth conditions a wheat plant in its early ontogenic stage allocates 65% of photosynthates to new leaves that have a specific leaf area of 30 m^2/kg. Under the same optimum conditions seedlings of a desert plant like *Atriplex sp.* allocate to new leaves only 30% of their carbon uptake with specific leaf areas around 7 m^2/kg. After a net uptake of 1 kg of carbon, wheat plants will produce 20 m^2 of leaf area while *Atriplex* plants will produce only 2 m^2.

4.3.3.7 Potential Evapotranspiration and Evapotranspiration

Two different aspects of evapotranspiration are recognized: potential evapotranspiration (PET) and actual evapotranspiration. PET is a measure of the ability of the atmosphere to remove water from the surface through the processes of evaporation and transpiration assuming no control on water supply. Actual ET is the quantity of water actually removed from a soil due to the processes of evaporation and transpiration. Both types of evapotranspiration are considered for the practical purpose of water resource management. The following factors are considered when estimating PET:

- PET requires energy from the sun for evaporation. The amount of energy received from the sun accounts for 80% of the variation in PET.
- Wind is the second most important factor influencing PET. Wind enables water molecules to be removed from the ground and plant tissue surface by a process known as "eddy diffusion."
- The rate of evapotranspiration is associated with the gradient of vapor pressure between the ground and plant tissue surface and the layer of atmosphere receiving the evaporated water.

PET is measure of the amount of evapotranspiration that can be achieved if the process is not limited by the amount of available water. PET can establish how much water is required for optimum plant development but does not measure how much water will actually be removed via ET at a site. In fact PET may overestimate, because it is not later limited, the amount of water that can actually be removed from an AFC. AFCs may or may not be permitted to be irrigated for plant germination purposes. Regulators do not typically allow irrigation of AFCs following the initial plant germination stage. Therefore, the only water available for ET is the precipitation that falls at a site. Since the PET is an estimate of the maximum amount of water that can be removed from the AFC via ET if there is a limitless supply of water and ET is a measure of the actual amount of water available at a site that can be removed from the AFC, an estimation of ET is a better representation of the amount of water that can be removed from an AFC. Using ET instead of PET is also consistent with the cover goals discussed in Section 3 with regard to long-term stability and minimizing the required maintenance. Again, if the AFC is stable and requires a minimal amount of maintenance, then the risks to human health and the environment are reduced because there will be less chance of a release from the landfill system.

4.3.3.8 Soil Amendments

Soil amendments can be used to temporarily improve the physical and chemical properties of surface soils during plant establishment. Soil amendments may in some cases improve soil fertility to enable plant establishment; however, their use increases the cost for cover construction, and the beneficial properties of many amendments are temporary and will disappear in a relatively short time. If the amendments are not effective for decades, the owner may be saddled with a long-term cost for plant nutrient management. Generally, if true topsoil is available and is applied as the final 6- to 12-inch layer, amending the soil will not be necessary. However, the soil material should be characterized by appropriate agronomic analysis to determine whether nutrients are available in sufficient quantity to support vegetative growth or the material has nutrient deficiencies that would inhibit plant growth.

Phosphorus and potassium can be supplemented by conventional fertilization and often adequately amend an otherwise unsuitable subsoil. Fertilizer, especially phosphorus, should be incorporated deep into the rooting zone since some elements are not very mobile in the soil column. Supplemental nitrogen is highly mobile and can be applied at the surface or incorporated into shallow soil layers. However, supplemental nitrogen should be applied with caution, especially at sites where natural or introduced weed species are expected to be present. Amendment of soil deficient in micronutrients is less likely to produce long-term benefits. Most soils, including many subsoils, contain adequate micronutrients. If a borrow site investigated is deficient in one or more micronutrients, it is recommended that additional soils be investigated. Many micronutrient deficiencies are the result of high soil pH, which can cause micronutrients to be held in soil in forms that are unavailable to plants. The addition of high-quality compost or manure may alleviate micronutrient deficiencies; however, a single treatment may remain effective for only a few years. Micronutrients amendments must be carefully evaluated for long-term effectiveness.

A variety of materials can be effective for improvement of nitrogen-deficient soil:

- brewing byproducts
- composted biosolids (e.g., municipal sludge)
- composted manure
- grass hay
- ground bark
- humic substances
- oil seed meal
- other organic materials approved for use
- other wood waste material
- poultry waste
- sawdust

Composted organic material can provide the best results. Regardless of the type, weed-free organic material with a carbon to nitrogen ratio in the range of 20:1 to 30:1 is appropriate. An application rate of 40 dry tons of composted organic material per acre is generally considered the economic break point that will result in establishment of a sustainable plant community. The composting process can eliminate many weed seed problems while enhancing populations of soil microorganisms. All amendments must be free of stones, sticks, and soil or toxic substances harmful to plants. A suggested gradation for the material is that at least 95% of the amendment shall pass a No. 4 sieve and at least 80% shall pass a No. 8 sieve.

Soil amendments can be used to improve the seedbed, particularly where fertile subsoils are used on the surface of the landfill cover. However, it is usually better to employ standing crop residue to enhance plant establishment.

4.4 Design Sensitivity Analysis and Predictive Hydrologic Modeling

This section discusses the use of models to support AFC designs. The focus of this section is to identify criteria to be cognizant of and consider when using models and the type of decisions that can be made using models to support and AFC design. This section discusses some of the types of available models and their capabilities without advocating one model over another.

It must be understood that models are exactly that—models, not reality. They are imperfect at best, but they are still very useful tools to assist with the design of AFCs. They are not computer-generated, precise, and accurate representations of AFCs. In fact, some of the foremost researchers in the field of alternative landfill covers have indicated that, in some situations, it is difficult to predict in which direction a model will fail (either too much or too little water will migrate through the cover). Once a given model's capabilities and limitations are understood, it can be a useful tool in assisting with AFC design.

At this time not all states require the use of computer-generated models to support AFC design. At least one state uses an application process with a series of assumptions and equations to determine whether an alternative design will satisfy its regulatory requirements and can be approved. Many practitioners support the use of models to facilitate the AFC design process. Practitioners should use care when modeling AFCs to represent to the greatest degree practical the landfill site, its associated conditions, and the proposed AFC. Not only do the limitations of the given model need to be understood, but also the limitations of the measurement instruments. If measurements are made below the accuracy of the measurement device, then this data will introduce a given amount of error into the model results. Care should be taken to appreciate the amount of error associated with a given model and its results. All that being said, models are generally to preferred tool of the day when it comes to predicting the behavior of an AFC configuration prior to test pad or full-scale construction.

There are currently two broad categories of models available for use in landfill cover simulation, reflecting the origins and intended applications of the models: those used by practitioners of the physical sciences (geologists, hydrologists, soil physicists) to predict the movement of water under saturated conditions and those used by agronomists in agricultural applications (including crop yield, fertilizer requirements, soil leaching). Within these two categories, some models use the water balance approach to determining the flux through the AFC and others use the Richard's equation approach. There are strong advocates for each approach, but no current model adequately predicts performance of all cover designs in all environments.

Each model has its own equations, assumptions, input, and data requirements. Each type of data has its own associated collection cost and error, so practitioners must understand the strengths and weaknesses of the models they use, the limitations of input data (i.e., the error and bias associated with the measurements and data), and do the best they can with the tools at hand. It is important to remember that the intent of modeling is to support, not dominate, the design effort.

Since the early 1980s predictive hydrologic models have been used for landfill applications, primarily to predict the following values:

- percolation (flux) through covers/caps,
- percolation through bottom liners,
- leachate volume collected by a drainage/collection system,
- concentration of leachate-related contaminants in groundwater, and
- runoff volume produced by precipitation events.

A number of models have been used over the last 20 years. The Hydrologic Simulation on Solid Waste Disposal Sites (HSSWDS) program (Perrier and Gibson 1980, Schroeder and Gibson 1982) was replaced by the Hydrologic Evaluation of Landfill Performance (HELP) Version 1 Model (Schroeder, Gibson, and Smolen 1984; Schroeder et al. 1984). The HELP model has been updated twice, most recently to HELP Version 3.07 (EPA 1994). Other models are available to help predict landfill performance and assist in landfill design. Several of these models are discussed below and include the Unsaturated Water and Heat Flow (UNSAT-H) Model (Version 2.04) (Fayer and Jones 1990), the Erosion-Productivity Impact Calculator (EPIC) (Williams, Jones, and Dyke 1984a, 1984b), and HYDRUS-2D (Simunek, Sejna, and van Genuchten 1996).

This modeling section focuses only on predictive modeling for AFCs. Although percolation through covers remains an important factor for landfill design, as stated in Sections 2 and 3, it constitutes only one of the eight factors specified by Subtitle D. This document does not delve into a number of very real (and very complex) factors, including the following:

- water-holding capacity of waste,
- consumption of water during waste degradation/stabilization,
- movement of water through waste,
- leachate collection system effectiveness,

- percolation through bottom liners,
- addition of water to cover materials by methane oxidation, and
- leachate-derived contaminant transport by groundwater.

This document provides only a brief review of prior studies and validation tests that provide guidance and recommendations for the design and construction of AFCs. The *Alternative Cover Assessment Project Phase 1 Report* (Albright et al. 2002) and *Field Hydrology and Model Predictions for Final Covers in the Alternative Cover Assessment Program* (Roesler, Benson, and Albright 2002) provide exhaustive reviews of ACAP field study results, non-ACAP field study results, lysimeter construction methods, model attributes, and model validation results. Both of the references are available online at www.acap.dri.edu.

This guidance is based on the information available at the time of printing for predictive hydrologic model performance. It does not have the benefit of the significant lysimeter data and model evaluation work expected over the next five years.

4.4.1 Design Sensitivity Analysis

Most models simulate long-term seasonal processes reasonably well for design decision purposes and are able to predict general trends in water balance. None, however, simulate important short-term events with enough accuracy for design engineers and regulators to rely solely on modeled predictions for permitting activities.

Considering this limitation, it is appropriate to question the role of models in the process of landfill cover design. One use of carefully constructed models is to indicate relative change in predicted cover performance resulting from changes in design features and changes in environmental stresses. This process of evaluating changes in model outcome as a result of changes in input features is referred to as "design sensitivity analysis" (DSA) (i.e., finding how sensitive the model output is to incremental changes in a single model input) (Young et al. 2003). The results of a DSA can provide design engineers and regulatory analysts with significantly more information than simulation of a single cover design performed within the bounds of a single set of input parameters.

Varying the value of a single model input parameter over a predetermined range typically constitutes a DSA. The result of such an analysis can be a graph of model output (dependent variable) as a function of the chosen parameter (independent variable). The range over which the parameter is varied and the magnitude of the incremental changes are dependent on an expected range of values of the parameter of interest and the sensitivity of the model to changes in the parameter.

An example of a simple DSA follows: Consider a model of a monolithic landfill cover that has been assembled with reasonable and conservative values for all input data sets and parameters. This "reasonable" set of inputs includes measured values for soil hydrologic parameters, agreed-upon climate characteristics, and acceptable values for plant community activities. One factor in the design of the cover that is of primary interest is the required thickness of the soil profile and its effect upon the percolation below the cover. A DSA performed with thickness as the variable simply consists of several simulations performed with varied soil layer thickness. Thickness of the soil layer should range from a value that results in clearly unacceptable performance to a value that shows little or no increase in performance (see Figure 4-1).

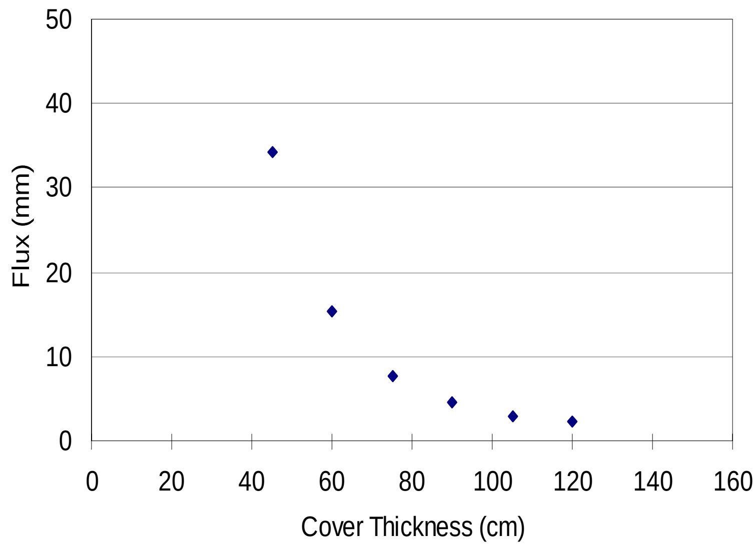

Figure 4-1. Sensitivity of simulated cover design performance to incremental changes in soil thickness.

To design for erosion protection, many designers traditionally based design on relatively high-intensity (long-frequency), short-duration storms (e.g., 24-hour, 100-year storm event). For purposes of water balance modeling, this type of storm may not represent a critical event in that infiltration may not be maximized by a high-intensity event. Some regulatory agencies now predicate the approved AFC design on longer-duration, low-intensity storms ("slow soakers"). The justification is that a low-intensity storm will provide a high stress on the AFC design if the event does not or minimally exceeds the designed infiltration rate. Since less water is extracted from the cover via runoff, then more of the precipitation will be managed by the cover soil. As more of the water infiltrates the cover, there is a greater chance of moisture breakthrough into the waste material. Snowmelt events may also produce a stress condition on an AFC as a long-duration, low-intensity storm. The type of analysis performed to estimate runoff might differ depending on the type of stress event that is agreed upon with the approving regulatory agency. In the absence of field data on the topic, choosing the critical precipitation event for design may be best addressed through careful modeling.

DSA can be performed on variations in soil thickness, soil hydrologic properties, climate characteristics (e.g., annual precipitation), plant community variables (rooting depth, phenology), or other variable parameters that the model will accommodate. In addition, DSA may provide a means to identify key design parameters that lend themselves to indexing as discussed in Section 4.3.2.

An important note on the use of DSA as a tool for design and regulatory approval concerns the type of computer code used. As previously noted, there is no one perfect model code that simulates all aspects of an AFC with complete accuracy and precision. Therefore, only those codes that most accurately simulate the physical processes relevant to calculating water balance in near-surface systems including soil, plants, and water are suitable for this use. Codes that do not calculate the movement of soil moisture according to Richards' equation can produce DSA results that do not accurately reflect the effect of incremental changes in design on the predicted performance of the cover, and may cause detrimental design decisions.

4.4.2 Determine the Need for Modeling

Before initiating modeling work for an AFC design, the need for modeling should be addressed. Predicting AFC performance using models may be necessary for many “new” landfill sites (closed after 1993, as required for municipal waste landfills in RCRA Subtitle D or, for hazardous waste landfills, after the most recent update of Subtitle C on 29 January 1992) but may not be required or applicable for some “old” landfills. While not all states require modeling as part of the landfill design approval process, 70% of those responding to this ITRC team’s survey indicated that models were required to support AFC designs. A risk-based approach that determines the need for cover installation (or cover improvement) based on factors such as groundwater quality may be more acceptable to regulators or appropriate in certain situations. To determine the need for modeling of cover performance, the following issues should be considered:

- Do existing regulations mandate the modeling of cover performance?
- Does the level of risk warrant modeling of cover performance?
- Would monitoring and/or modeling contaminant transport by groundwater better assess risk or regulatory noncompliance than modeling of cover performance?
- Can existing performance data for this site or other sites be used to approve a cover design without performing modeling?

4.4.3 Current Status of Modeling

The predictive accuracy of hydrologic models for landfill applications is still being debated, with special emphasis given to percolation through covers. A number of lysimeter studies performed over the last 10 years provided data required to compare actual results (within the confines of the measurement capabilities) with modeled results. These studies were performed on a variety of cover types/configurations and climate regions. Although models have performed well in some instances, in general they have been unable to accurately predict percolation rates through landfill covers with accuracy sufficient for regulatory application associated with AFCs (see Section 4.7.8). The adequacy of any prediction is dependent on the application and the need to contain uncertainty in the results. Most of the practitioners involved with this document and several external practitioners/reviewers indicate that no single current model predicts landfill cover performance in all environments with accuracy adequate to meet regulatory requirements for uncertainty.

Despite the current limitations of models, they can still provide great benefit for landfill design decision making. Model predictions of performance using conservative input parameters and careful selection of environmental/input data give designers and regulators a good indication of the theoretical performance of a proposed design. Additional design efforts, including careful consideration of factor-of-safety concerns, can form the basis for decisions. Models can also predict the relative impact of adding or changing a design feature (e.g., adding a capillary barrier layer beneath an ET cover) or of changes in environmental stresses (e.g. using extreme climatic data). They can also evaluate the sensitivity of predicted performance to long-term change in design features (e.g., the relative increase in predicted percolation if desiccation cracking increases a clay barrier permeability from 10^{-7} to 10^{-5} cm/s).

4.4.4 Establish the Modeling Approach

A design engineer may choose to consult with the regulator in regards to an acceptable modeling approach before initiating modeling. This effort should be guided by and integrated with the cover goals and objectives identified in Sections 2 and 3. The goals or outcomes of the modeling may be established before performing the modeling. This collaborative "think first, act second" approach is recommended for the following reasons:

- Limited guidance currently exists for modeling landfill covers, thus making modeling a relatively subjective process.
- Good planning minimizes the need for costly, time-consuming modeling iterations.
- A number of uncertainties (data gaps) exist that can greatly impact modeling results, including runoff, evapotranspiration rates, rooting depth, and the impact of frozen soils.
- Prior consensus establishes the criteria for failure or success before obtaining results.

Following is a list of issues a design engineer may choose to discuss with a regulator prior to modeling:

- how to fill in the data gaps—what values to use for uncertain items such as runoff (with or without snowmelt), ET rates, rooting depth, and the impact of frozen soils on hydraulic properties;
- how to perform sensitivity analysis (see Section 4.7.9);
- what climatic periods to use—average climatic conditions, worst-case climatic conditions, a weighted average of average and worst-case conditions, etc. (see Section 4.4.1);
- which model(s) to use;
- which cover cross sections will be modeled—soil layers, soil types, and soil thickness;
- where to set the "point of percolation" to account for the potential capillary barrier impact of waste—it may be appropriate in some situations to evaluate percolation past the cover <u>and</u> the top 1 foot of waste;
- how to characterize soil and amendment properties—literature values versus laboratory measurements (see sections on soil and amendment characterization);
- how much weight to give the modeling results (the degree of importance);
- how much "leeway" to give the modeling results (if any)—establish whether alternative cover percolation results must exactly equal (or better) conventional cover results or whether alternative cover results must achieve within a certain percentage of conventional cover results; and
- how the modeling results will be used to make permitting/closure/corrective action decisions—establish whether the modeled percolation results are the only criteria for regulatory decision making or other factors apply (and to what degree they apply).

Even though there is uncertainty in the predicted percolation values that represent performance of a proposed AFC, the use of numerical simulations can contribute greatly to both understanding of the important processes at a site and to regulatory review and permitting. The three most important uses of numerical or analytical simulations are (a) to give a theoretical evaluation of expected results given conservative choices of model input, (b) to allow creativity in design (i.e., the code must give physically realistic response to the addition of design features), and (c) design sensitivity analysis (i.e., the code must give realistic responses to systematic changes in design features). Ultimately modeling results should help an owner and a regulator to establish an appropriate design (i.e., establish soil thickness, degree of compaction, vegetation type).

This guidance document addresses flux through only covers, but in some situations the objective or interest may be in predicting flux through a certain thickness of waste, flux through the bottom of waste, flux through a bottom liner, and/or contaminant transport to a downgradient "point of relevant compliance." One should take into account the existing regulations and the inherent complexities/uncertainties with obtaining these modeling results.

The use of preliminary modeling should be limited to considerations of economic feasibility. These approaches may employ a simple water balance approach, a precipitation/ET ratio, or other methods to obtain a "quick and dirty" answer for potential alternative cover suitability. These preliminary approaches can provide vastly different results than those obtained by more rigorous modeling, either supporting or discouraging the use of an alternative cover.

4.4.5 Factors that Influence Modeling Results and Should Be Considered during the Design Process

A myriad of factors influence modeling results, as discussed throughout this guidance document. Roesler, Benson, and Albright (2002) evaluated the water balance of 17 landfill cover test sections under evaluation by ACAP. Surface runoff, frozen ground conditions, preferential flow, and uncertainty in vegetation characteristics were considered the primary factors that caused the discrepancy between field conditions and model predictions.

The factors that influence model results depend on the type of cover, the climatic conditions, and the model selected. However, factors that typically influence modeling results include the following:

- surface runoff from rainfall (selected runoff curve number, saturated hydraulic conductivity, desiccation and freeze-thaw cracks, root holes, worm holes);
- snow pack and snowmelt (timing and volume of snowmelt water influence runoff and infiltration rates);
- ET rates (as influenced by factors such as the reference PET equation, climatic conditions, plant growth, rooting depth, growing season length, leaf area index, and crop coefficient);
- saturated hydraulic conductivity (impacts runoff and infiltration rates);
- preferential flow conditions (desiccation and freeze-thaw cracks, root holes, worm holes);
- frozen ground conditions—affects runoff and infiltration rates;
- soil crusts that may reduce the amount of infiltration while increasing runoff;
- evaporative depth;
- soil-water retention functions;
- geosynthetic properties; and
- hysteresis.

4.4.6 Types of Models

The following is a general discussion regarding the major types of models. Three primary groups or levels of models exist to choose from for landfill cover design:

- "simplified" water balance models,
- "enhanced" water balance models, and
- Richards' equation–based models.

A number of models exist within each primary group to choose from, each with its own set of attributes and limitations. Albright et al. (2002) provide detailed descriptions of each of the models discussed, including background, processes, input parameters, verification, validation, sensitivity analysis, and application.

4.4.6.1 Simplified Water Balance Models

"Simplified" water balance models are the simplest approach to water balance modeling. These models typically use accounting procedures (e.g., Excel spreadsheets) to predict percolation and soil moisture changes based on the following water balance equations:

- inputs – outputs = change in storage
- precipitation + irrigation – evapotranspiration – runoff – drainage = change in storage
- drainage = change in storage + evapotranspiration + runoff – precipitation – irrigation

Soil parameters input into simplified water balance models are typically limited to field capacity and wilt point (with available water-holding capacity = field capacity – wilt point). These models usually assume that drainage (percolation) occurs only when soil moisture reaches field capacity and additional water enters the system. They do not account for upwards water movement, drainage under moisture conditions of less than field capacity, or the capillary impacts of variable soil layers. Runoff predictions are often made with simplifying assumptions (e.g., 20% of winter precipitation becomes runoff).

4.4.6.2 Enhanced Water Balance Models

"Enhanced" water balance models use the same premise and equations as simplified water balance models. They have the same primary limitations in that they also do not account for upwards water movement, drainage under moisture conditions of less than field capacity, or the capillary impacts of variable soil layers. However, enhanced water balance models have additional complexities and attributes beyond those of a simplified water balance model, including runoff prediction calculations, random weather generators, and ET calculations. Albright et al. (2002) identify three mass balance–based codes that can be considered enhanced water balance models:

- CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems) (Foster et al. 1980) and its extension GLEAMS (Groundwater Loading Effects of Agricultural Management Systems) (Knisel and Davis, 2000)

- EPIC (Erosion-Productivity Impact Calculator) (Williams, Jones, and Dyke 1984a, 1984b)
- HELP Version 3.07 (Hydrologic Evaluation of Landfill Performance) (EPA 1994)

CREAMS and its extension GLEAMS were developed by USDA. CREAMS was as one of the first numerical codes used for performance assessment of landfill covers (Devaurs and Springer 1988). CREAMS/GLEAMS have been widely used for agricultural scenarios and are regarded as two of the most rigorous codes for modeling runoff and erosion. Although not specifically designed for landfill cover evaluation purposes, CREAMS/GLEAMS have been used as such as either alone or in conjunction with HELP (aspects of CREAMS are used by the HELP model).

EPIC was initially developed to evaluate the impact of soil erosion on agricultural productivity and has since been modified to simulate many agricultural management processes. Because of its agricultural nature, the model contains many attributes not required of landfill covers, such as fertilization, cattle grazing, and nitrogen dynamics. EPIC does, however, possess many beneficial characteristics for landfill cover evaluation, including runoff and snowmelt calculations, a probability-based weather generator, and extensive plant characterization input parameters (more parameters than typically available for landfill cover situations). Gill et al. (1999) say that EPIC takes a more sophisticated approach to predicting evapotranspiration than HELP.

The original version of HELP was designed for EPA and released in 1984. HELP has been updated twice, most recently to Version 3.07 in 1994. HELP remains the only model to date designed specifically for landfill performance evaluation. Applications include RCRA sites, CERCLA sites, confined disposal facilities, and other land disposal systems. It is by far the most widely recognized and used landfill cover model, owing to its regulatory acceptability, free use, extensive documentation, and user-friendly attributes.

HELP contains many attributes beneficial to landfill cover modeling, including synthetic generation of weather parameters, runoff and snowmelt calculations, reduction in permeability due to frozen soil conditions, and prediction of leachate collected by drainage layers. HELP and MULTIMED are the only models in common use known to accept geomembrane property inputs.

4.4.6.3 Richards' Equation–Based Models

Richards' equation is a complex numerical solution for one- or two-dimensional unsaturated flow. The modified form of this equation uses the inputs of pressure head, saturated/unsaturated hydraulic conductivity, a sink term (evapotranspiration), and time to predict the output of soil water content (and thus flux). Empirical expressions such as the van Genuchten (1980) water-retention model help to solve the Richards' equation by correlating pressure head with soil water content.

Models that use Richards' equation are considered more "physically correct" for characterizing water movement than models that do not (simplified and enhanced water balance models). Unlike most water balance–based models, Richards' equation–based models can predict flux for soil moisture values less than field capacity (which can be significant). In addition, Richards' equation–based models capture the dynamics of varying soils types and their potential impact on water flux (i.e., naturally occurring or designed capillary barriers).

Albright et al. (2002) discuss six models in landfill design use that use the Richards' equation: HYDRUS-2D, UNSAT-H, LEACHM, SoilCover, SHAW, and TOUGH2. In addition, Scanlon et al. (2002) consider the SWIM and VS2DI models. Albright et al. (2002) state that HYDRUS-2D, UNSAT-H, and LEACHM appear to be gaining in popularity among consultants, although LEACHM may become less useful in the future as a modeling tool because it is no longer supported by the developers. SoilCover is also no longer supported by developers and has built-in program errors. The newer VADOSE/W model extends the SoilCover concepts and contains many desirable attributes for landfill cover modeling. The SHAW model has not been used extensively by the landfill industry but provides the most rigorous calculations for the impacts of snowfall, snowmelt, and soil freeze/thaw. TOUGH2 was used for the Alternative Landfill Cover Demonstration at Sandia National Laboratories (New Mexico) but otherwise has not been widely used by the landfill industry. SWIM is an Australian-developed model that has not been widely used for landfill applications in the United States. VS2DI was created by the U.S. Geological Survey (USGS) and can link with its other flow and solute transport models.

4.4.7 Attributes of Various Models

Details of the various models available for landfill applications can be obtained by the model developers from the following Web sites:

- EPIC http://www.brc.tamus.edu/epic
- CREAMS http://www3.bae.ncsu.edu/bae473/models/creams.html
- GLEAMS http://www.cpes.peachnet.edu/sewrl/
- HELP http://www.wes.army.mil/el/elmodels/helpinfo.html
- VS2DI http://water.usgs.gov/software/vs2di.html
- VADOSE/W http://www.geo-slope.com/products/vadosew.asp
- HYDRUS-2D http://www.ussl.ars.usda.gov/models/hydrus2d.htm
- UNSAT-H http://hydrology.pnl.gov/unsath.asp
- SHAW http://www.nwrc.ars.usda.gov/models/shaw/index.html
- SWIM http://www.clw.csiro.au/products/swim
- LEACHM http://www.wiz.uni-kassel.de/kww/irrisoft/drain/leachm.html
- TOUGH2 http://www-esd.lbl.gov/TOUGH2/

Albright et al. (2002) summarized the attributes, input parameters, and descriptive information for three enhanced water balance models and seven Richards' equation–based models. Slightly modified versions of these summary tables are provided in Appendix E.

No single model contains all of the attributes desired of a landfill design model. HELP contains many beneficial aspects for landfill design (i.e., runoff, snowmelt, weather generation, geomembrane characteristics, and lateral drainage) but does not quantify flow using Richards' equation. Another limitation is that a number of the models (e.g., HYDRUS-2D, UNSAT-H, SoilCover, and LEACHM) do not have a separate routine for calculating runoff. These models calculate runoff as simply the difference between precipitation rate and soil infiltration rate.

Since hourly based historical precipitation data is often not available, the models regard daily based precipitation as occurring over a 24-hour period, which leads to little or no predicted runoff.

4.4.8 Predictive Accuracy of Models

Numerous studies and demonstrations performed over the last decade have evaluated the predictive accuracy of various models for landfill cover applications. Albright et al. (2002) provide a comprehensive literature review of many of these studies. Although the studies are too numerous and the results too variable to report in this document, the general findings of several studies are summarized as follows:

- The National Research Council established the Committee on Ground Water Modeling Assessment (CGWMA) to review the accuracy of numerical models and assess whether regulatory decisions should be made based on their long-term predictions (Schwartz et al. 1990). CGWMA determined that the models appear more certain than they really are and that decision makers needed to be aware of their assumptions, idealizations, and limitations.

- Nixon, Murphy, and Stessel (1997) performed an extensive comparison of 13 models using various degrees of information for 545 landfills. They concluded that no two models will give identical results, no model has been sufficiently validated for long-term performance at landfills, and many existing models if modified could potentially provide meaningful predictions.

- Albright et al. (2002) compared the results of HELP, EPIC, UNSAT-H, and HYDRUS-2D to measured lysimeter data for an arid site (Hanford, Washington) and a high-precipitation site (Coshocton, Ohio). All four models predicted measured percolation more accurately for the high-precipitation site than for the arid site. They state that "…none of the codes tested to date are totally reliable as a water-balance model for landfill cover applications...." This study suggests that the Richards' equation–based codes (HYDRUS-2D, UNSAT-H) are better able to capture the behavior of alternative earthen covers under both arid and humid conditions than the simple water-balance codes (HELP, EPIC).

- Albright et al. (2002) performed extensive sensitivity testing for HELP, EPIC, UNSAT-H, and HYDRUS-2D. They found that "…HELP showed a nonrealistic response of increased drainage with increased water-holding capacity (increasing field capacity for a fixed wilting point), an insensitivity to total cover thickness, and consistently overpredicted drainage." In general, EPIC outperformed HELP for design sensitivity testing but underperformed UNSAT-H and HYDRUS-2D.

- Roesler, Benson, and Albright (2002) compared HELP and UNSAT-H predictions to measured lysimeter data for 17 test sections at eight locations (covering varying climates). Despite using well-defined model input parameters, they concluded that both models performed poorly for predicting percolation rates and that no general trends (over- or underprediction) were evident. Both models also struggled to accurately predict surface runoff for sites experiencing intense rainfall events.

Due to the variability of results, conclusive statements cannot be made at this time regarding the prediction of absolute percolation values for individual models or the performance of water balance models verses Richards' equation–based models. However, Richards' equation–based models provide more consistently realistic responses to changes in parameters (design sensitivity analysis) than water balance models (Roesler et al. 2002).

4.4.9 Conclusions and Summary of Recommendations for Landfill Cover Predictive Modeling

- Simulated predictions do not currently have sufficient accuracy to provide the sole basis for landfill cover regulatory decisions.

- Absolute percolation (flux) should not be considered the focus or primary outcome of landfill cover design modeling. Rather, the two most important uses of models are (a) enabling creativity in design (the code must give physically realistic responses to the addition of design features) and (b) design sensitivity analysis (the code must give realistic responses to systematic changes in design features). Ultimately, modeling results should help an owner and a regulator to establish an appropriate design (establish soil thickness, degree of compaction, vegetation type, etc.).

- Models developed with careful selection of input parameters and conservative data sets can provide a good theoretical basis for evaluation of proposed landfill cover designs.

- Design sensitivity analysis is a valuable tool that allows for creativity in design and can provide the basis for negotiations between regulator and designer/owner/operator. This type of analysis requires a model that simulates the physics of processes relevant to cover performance.

- The use of any model, including simplified water balance models, may be warranted at some sites, based upon the regulatory situation, the modeling objectives, experiences at similar sites, and/or the presence of natural analogs. The regulator and designer should consider the uncertainties inherent in the approved models.

- Richards' equation–based models are recommended for covers that use natural or engineered capillary barriers/breaks.

- The need for modeling should be determined early in the design process. In some situations, a risk-based approach may be more appropriate than a landfill cover percolation approach. Existing site data, data from similar sites, and/or natural analogs may make modeling unnecessary.

- The owner/consultant and regulatory agency should establish an acceptable modeling approach, the desired outcomes, and how the results will be used <u>before</u> initiating modeling.

- Daily or hourly based climatic data, not monthly based climatic data, should be used as model input.

- The selected climatic periods or scenarios can have a significant impact on landfill cover predicted performance. Use of weather generators is recommended for sites that have insufficient historical data or where the goal is to evaluate cover performance outside the bounds of the available historical data (e.g., to evaluate the worst-case year in a 100-year period when only 40 years of historical data is available).

- The inability of models to predict or simulate field measurements accurately is a function of each model's limitations and due to the complexities of a number of factors, of which ET, surface runoff, snowmelt, and preferential flow processes are typically the most significant.

- The use of directly measured (laboratory-determined) soil parameters (K_s, van Genuchten parameters, etc.) for cover materials is typically expected to produce less modeling uncertainty than using reference (literature) values, which are recommended primarily for preliminary modeling. However, the variability of cover materials and measurement inaccuracies add uncertainty and should be addressed in borrow source characterization.

- Many improvements are needed and expected for predictive models in coming years.

4.5 Final Design and Evaluation

A proposed alternative cover design should be evaluated with respect to its ability to meet the established cover goals, including protection of human health and the environment. Other potential aspects of the design evaluation are discussed below. This section should serve to function as a final checklist of important topics in AFC design.

4.5.1 Vegetation Selection

Selection of appropriate vegetation is critical to the proper function of most alternative cover designs. Factors to consider include drought tolerance, soil texture, transpiration characteristics (using species having high transpiration rates and both cool- and warm-season species to provide transpiration throughout as much of the year as possible), rooting depths, long-term sustainability, seed availability, resistance to erosion, and possibly even height (tall vegetation has been known to deter prairie dog invasion) (Chadwick et al. 1999). In most cases a diverse stand of native vegetation is preferred due to its demonstrated abilities to withstand natural meteorological variability and other natural adverse factors (e.g., fire) and to efficiently use available soil water (Hauser, Weand, and Gill 2001a). Native, perennial grasses are a common choice, but nonnative vegetation may also be suitable. At some sites, keeping roots out of the waste may be a cover goal, but in other cases deep root penetration might be desirable. In such cases, woody shrubs and trees are sometimes included on alternative covers. Such vegetation may be useful in stabilizing slopes, reducing erosion, increasing the potential for water storage within the root zone, and improving desirable animal habitat (Stack, Potter, and Suthersan 1999; O'Donnell, Ridky, and Schulz 1997; Hauser, Weand, and Gill 2001a). Sources of valuable information on vegetation that may be suitable for a site may include local extension service offices, NRCS field offices, and state land grant universities.

The plant species selection process for soil/vegetation covers, ET covers, or alternative RCRA covers includes a variety of considerations. The goal is to develop a mix that will result in a plant community with the following characteristics:

- adapted to local soil and climate conditions,
- stable and self-sustaining,
- capable of providing transpiration for as much of the year as possible,
- protective against soil erosion,
- suitable for long-term land use, and
- successful in achieving other site-specific goals.

4.5.2 Soil Selection

Use of suitable soils is critical to ensure acceptable performance of AFCs. The concept upon which an AFC works is much different than the concept upon which a conventional cover works, and soil requirements are also different. AFC covers rely on the soil to store water and on the vegetation to remove water from the cover. Consequently, soils must have adequate water-storage capacity and be capable of sustaining healthy vegetation having vigorous root systems that extend a sufficient depth into the cover (Hauser, Weand, and Gill 2001a). Portions of a cover that have no roots have little capacity to remove water because the soil water is not readily removed during the growing season. Soil texture, soil density, and agronomic viability are important factors. Soils should have sufficient plant-available nutrients to support robust plant growth. Such requirements are site specific and need to be determined on a case-by-case basis depending on cover goals, type of vegetation, and local climate.

In contrast to conventional covers, the saturated hydraulic conductivity of the soils in alternative covers may be relatively unimportant and only indirectly related to cover performance since performance is not achieved by use of a relatively impermeable barrier. Use of soils that are predominantly composed of clay may even be problematic for an alternative cover because of the potential for desiccation cracking. However, some studies showing the effect of desiccation cracking are inconclusive. Similarly, the significant compaction desired in a compacted clay layer of a conventional cover could harm the performance of an ET cover by restricting root growth and root penetration depths, thereby impairing the ability of the vegetation to remove water from the cover.

It is expensive to move soil long distances, so the soil used in the cover should be located within the shortest possible distance from the landfill. The ability to haul soil should be evaluated as a cost consideration of the design process. Hauling costs and locally available soil types may limit the selection of soils for use in the cover; therefore, the soils closest to the site should be evaluated for suitability. High soil water–holding capacity (>0.15 v/v water content) is most desirable. Cover thickness also controls total cover water–holding capacity; therefore, in semiarid and dry sites, lower water–holding capacity may be acceptable if the cover can be made thicker. The soil should be evaluated for each site to determine its suitability. There are sites where the quality of the soil is not sufficient for alternative cover construction, and the owner should evaluate the economics, regulatory requirements, and public reaction to transporting off-site soils to the landfill site or a different solution.

4.5.3 Percolation

One of the most important parameters to be established before beginning design is the allowable flux of precipitation through the cover and into the waste. Because there are few measurements of deep percolation except via test plots with measurement equipment and natural soils are layered and often contain layers of high soil density or other root limiting factors, natural analogs that are equivalent to a constructed alternative are rare. If the amount of water percolating through the cover is important, then some estimate of deep percolation through the proposed cover should be made.

Cover performance relative to project-specific cover flux goals should be considered in the evaluation of the suitability of an alternative cover and its design. Natural analogs may provide significant insight into the amount of percolation that might be expected to come through the bottom of an alternative cover, particularly if available natural analogs are reasonably similar to the design of a proposed cover.

Test covers may also provide good information regarding the amount of percolation that could be expected from a particular design if sufficient time is available for a reasonable testing period. Test covers can be constructed to closely represent a proposed cover design, thus offering an advantage over natural analogs if a suitable analog is not available (e.g., a natural analog for a design involving a capillary break may not be available).

Another common approach for estimating cover percolation performance is with the use of numerical models. Such models offer significant flexibility for examining the effects of varying climatic, soil, and vegetative conditions for various cover designs, but there are practical limitations to the accuracy of model predictions. At this time, no model can account for all of the potentially relevant issues regarding cover performance such as desiccation cracking, vegetation growth, and the effects of macrochannels.

The appropriateness of cover slopes should be considered on any alternative cover. Maximum slopes are contingent upon site conditions (e.g., waste type and compaction, soil type, subsurface geology, seismic hazard, etc.) and appropriate safety factors. Slope stability issues for alternative covers are similar to those for conventional covers, and methods used to evaluate the stability of slopes on conventional covers can also be used to evaluate the alternative cover slopes (e.g., see Koerner and Daniel 1997 and Bonaparte et al. 2002). However, measures taken to ensure slope stability must be evaluated with regard to their effect on the ability of an alternative cover to perform effectively. For example, soil compaction is sometimes used to increase the stability of steep slopes, but for alternative covers it is particularly important that the soils not be compacted so much that the vegetation will not develop as required to perform its necessary function of removing soil water from the cover. Consequently, the cover must meet the dual goals of having adequate slope stability and also supporting the necessary vegetative growth and root penetration. Additionally, the vegetation must adequately perform its function even on the north-facing slopes (south-facing slopes in the southern hemisphere) where solar radiation is reduced.

4.5.4 Surface-Water Control

Following is a brief discussion of the principles of surface runoff generation as directed to the problem faced by an engineer intending to design an AFC for a specific site. Typically, there are no applicable surface runoff measurements against which the designer may test possible models of cover performance for a site; so surface runoff must be estimated. Whether derived from regional information or generated via a model, these estimates are imperfect. Therefore, the runoff estimate should have been evaluated as part of the design sensitivity analysis to facilitate bounding the potential amounts of water that will be managed by the final cover design. This design sensitivity analysis should be part of a general process to determine the type and intensity of a precipitation event that may be regarded as critical for the site.

Surface runoff can begin only after rainfall or snowmelt fill storage by plant interception, surface storage, and ponding and after the rainfall rate exceeds the soil infiltration rate. Surface runoff from AFCs is derived from the precipitation that does not infiltrate into the soil surface or is removed via evaporation, transpiration, and interception; it results from several factors. Some factors affect each other, and runoff is controlled by complex interactions both before and during a storm. It is not possible to discuss all aspects of surface runoff here; excellent sources for technical details include Chow, Maidment, and Mays (1988); ASCE Manual 28 (1996), Bonaparte et al. (2002); Haan, Barfield, and Hayes (1994); and Goldman, Jackson, and Bursztynsky (1986). This section discusses key factors to consider during AFC design and construction, as listed in Table 4-3.

Table 4-3. Factors affecting amount and rate of surface runoff from AFCs

Soil	Surface	Other factors
Infiltration rate	Surface crust and tilth	Rainfall intensity
Water content	Plant type (sod or bunch grass, etc.)	Time of high intensity
Particle size distribution	Cover density	Storm duration
Frozen soil	Growth rate	Interception by plants
Bulk density	Stage of annual growth cycle	Soil surface depressions
Clay mineralogy	Biomass production	Litter on the soil surface
Macro porosity	Roughness and storage	Land slope

Terraces, ditches, and other features that are used on landfill covers manage surface runoff water and can be designed and constructed to minimize erosional damage. These features have been dealt with by traditional civil engineering design practices successfully to maintain the integrity of structures and minimize/eliminate erosion. In addition, where surface water channels are required or are part of the design, there may be increased potential for deep percolation beneath unlined surface runoff channels. The consequences of the potential increase should be evaluated in relation to cover goals. Particularly in dry climates, due to the limited duration of channel flow and the relatively small surface area of the channels, the overall increase in flux through the cover may be acceptable when compared to cover performance goals. If the anticipated flux from the channels would result in a cover's failure to achieve the established cover goals, then measures must be taken to reduce channel-related flux (e.g., avoiding the use of channels over the covers, using lined channels, including an impermeable liner beneath the channels, etc.).

Erosion caused by water and wind can have serious detrimental effects on an landfill cover system. Since the surface layer of an alternative landfill cover would be subject to the same conditions, erosion control materials and methods is the same as used for a conventional landfill cover. Bonaparte et al. (2002) discuss types of erosion and provide some recommendations for interim and permanent erosion control materials. However, because an alternative landfill cover system is dependent on the ET mechanism of the vegetation, the options presented in the EPA guidance document that involve hard armoring materials cannot be used for erosion control on alternative cover landfill systems.

Increased plant production can produce robust stands of sod grasses and may provide substantial surface storage of rainfall, thus reducing runoff. Therefore, the increased biomass serves to stabilize slopes, intercept precipitation, reduce runoff, and minimize channel flow.

The primary effect of land slope on runoff is its influence on surface water detention and storage in puddles and ponds. As previously stated, one requirement for landfill covers is to reduce water infiltration into the waste. Some researchers suggest that AFCs should be built with smooth soil surfaces to promote surface runoff, because smooth surfaces detain less water and thus reduce infiltration; however, increased surface runoff may increase the potential for erosion. Conversely, some designers prefer AFCs with a rougher surface to reduce the volume and rate of overland flow, thereby allowing the water-holding capacity of the soil and moisture removal capacity of the plants to trap and remove the moisture. Regardless of which approach is adopted, a balance must be achieved between the amount of plant biomass, smoother slopes with increased runoff and erosion, rougher slopes with decreased runoff, and allowable infiltration to be removed via ET.

4.5.5 Biota Barriers

Cover goals for some landfill covers will include a goal of preventing biota (i.e., plants or animals) from reaching the waste. Achievement of this goal may be aided by inclusion of some type of barrier against the biota. Issues related to biota barriers are generally similar for alternative covers and conventional covers, dependent more on the site than on the cover type. Koerner and Daniel (1997) provide information and references related to preventing accidental human intrusion into the waste, intrusion by burrowing animals, and intrusion by plant roots.

The effect of plant roots and burrowing animals on the performance of alternative covers may need consideration. Although the possibility of preferential flow through animal burrows or root channels in the soil has been widely discussed, Hauser, Weand, and Gill (2001b) indicate that preferential flow is unlikely to contribute significantly to water flow in a vegetative landfill cover. Experience at field test covers and evidence from natural analogs appears to show that the presence of a moderate amount of macrochannels may not compromise cover performance (Avronovici 1971, Rocky Mountain Arsenal Remediation Venture Office 1998, Dwyer 2001, Washington Group International 2001).

4.5.6 Landfill Gas

Landfill gas is an important issue with landfill covers. Alternative covers usually do not contain a relatively impermeable layer that traps landfill gas, the need for controlling landfill gas should be considered in alternative cover design and, if required, evaluated similarly to controls for conventional covers. Landfill gas management considerations for AFCs include the following:

- Gas control systems may be installed as part of an AFC system.
- In the absence of an impermeable cover, the potential impacts to groundwater may be reduced.
- Diffusion of gas through the soil/plant system may result in oxidation of methane and subsequent reduction in methane emissions.

4.5.7 Slope Stability

The appropriateness of cover slopes should be considered on any alternative cover. Maximum slopes are contingent upon site conditions (e.g., waste type and compaction, soil type, subsurface geology, seismic hazard, etc.) and appropriate safety factors. Slope stability issues for alternative covers are similar to those for conventional covers, and methods used to evaluate the stability of slopes on conventional covers can also be used to evaluate the alternative cover slopes (e.g., see Koerner and Daniel 1997 and Bonaparte et al. 2002). However, measures taken to ensure slope stability must be evaluated with regard to their effect on the ability of an alternative cover to perform effectively. For example, soil compaction is sometimes used to increase the stability of steep slopes, but for alternative covers it is particularly important that the soils not be compacted so much that the vegetation will not develop as required to perform its necessary function of removing soil water from the cover. Consequently, the cover must meet the dual goals of having adequate slope stability and also supporting the necessary vegetative growth and root penetration. Additionally, the vegetation must adequately perform its function even on the north-facing slopes (south-facing slopes in the southern hemisphere) where solar radiation is reduced.

4.5.8 Test Covers

This section discusses the use of test covers for proof of performance for AFCs. Some practitioners argue that test covers take too long, are too extensive, and do not evaluate performance over a long enough time period to provide useful design information. However, many researcher and regulators continue to use test covers as a proof of performance to evaluate proposed cover designs. Test covers offer the advantages of overcoming some of the practical limitations of numerical models and may provide more measurement precision than is available using natural analogs (Benson et al. 2001). The effect of various design variables, such as cover thickness, soil type and density, and vegetation type, can also be assessed with test covers, especially if constructed with the same equipment as specified for construction of the full-scale operational covers.

Like other methods of evaluation, test covers also have limitations. The significant time required to conduct meaningful tests limits their usefulness. Establishing reasonably mature vegetation in a test cover may take a few years, if not longer, depending on the type of vegetation being established (Chadwick et al. 1999). The range of meteorological conditions that can be tested within a reasonable testing period will necessarily be limited, although supplemental irrigation can be used to simulate wet meteorological periods (Chadwick et al. 1999). Although test covers can conceivably be tested for long time periods, time constraints for most landfill cover projects do not allow monitoring a test cover sufficiently long to assess the effects of long-term ecological changes or pedogenesis (e.g., over tens or hundreds of years) prior to cover construction.

Test covers typically consist of lysimeters, which are buried containers having open tops that collect and measure soil water (Benson et al. 2001). To evaluate a landfill cover design, the test cover is constructed within a lysimeter. Test covers can be instrumented to show the movement of soil water within the cover, but percolation from the bottom of a test cover is typically used to assess cover performance with respect to limiting deep percolation. Weighing lysimeters contain mechanisms to actually weigh the soil column to determine changes in water content and are usually limited to sizes of perhaps 1–2 m^2 (Benson et al. 2001). Larger lysimeters (100 m^2 or more) may be preferred so they can be constructed in a manner similar to the construction of an actual landfill cover (i.e., with full-scale equipment) because they may represent the heterogeneity (e.g., macrochannels) that may exist in an actual landfill cover better than a small lysimeter and will reduce the influence of edge effects.

Lysimetry has long been a research tool in the agricultural field, but a number of large lysimeters have been constructed more recently for the specific purpose of evaluating alternative covers (Gee and Ward 1997, Dwyer 2001, Chadwick et al. 1999, Benson et al. 2001). These lysimeters typically have an impermeable synthetic liner that is overlain by a drainage layer, upon which the test cover section is constructed. Drainage from the cover is collected and measured. A significant disadvantage of lysimeters is the artificial no-flow boundary induced by the barrier at the lysimeter base (Benson et al. 2001). This boundary typically does not exist beneath actual alternative covers and prevents both the downward and upward flow of water across the base of the lysimeter. Coons, Ankeny, and Bulik (2000) indicate that percolation rates measured using lysimeters can be as much as 3 mm/year too large due to the artificial trapping of water vapor by the impermeable liner. Another potential bias with lysimeters is due to a capillary break effect that may be caused by the drainage layer but may not exist under natural conditions (Khire, Benson, and Bosscher 1999). If the drainage layer has larger pores than does the overlying soil, then soil water will be held up in the bottom of the cover soils, thereby possibly causing underestimation of the amount of drainage that might occur from an actual cover. With proper design, the bias from this capillary break effect may be minimal (Benson et al. 2001).

4.5.9 Natural Analogs

Natural analogs of cover systems can provide valuable insights into the future performance of an AFC. Analogs can be thought of as long-term experiments (Waugh 1997) that are not subject to some of the limitations of theoretical evaluations (Hauser, Weand, and Gill 2001a). Besides being helpful in evaluating the appropriateness of an alternative cover system, analogs may also be helpful in communicating the results of the performance assessment to the public (Waugh 1997). An assessment of natural analogs may provide useful information regarding rates of deep percolation, the effects of long-term climate variability, vegetative succession, pedogenesis (soil development), and disturbances by animals.

Natural analogs have been used to estimate deep percolation rates. Measurements extending to a depth of 15 m in tests near Amarillo, Texas showed the soil water contents beneath the rooting zone of each of the vegetation types to be at or below the permanent wilting point, leading

Aronovici (1971) to conclude that, even though numerous preferential flow paths existed throughout the 15-m soil profile, "There has been little or no deep percolation on native or revegetated grassland within historic time where natural surface drainage occurs." This conclusion was also supported by evaluations of soil chloride and electrical conductivity data from the soil profile.

Natural deep percolation rates have also been estimated by the use of natural tracers (e.g., Wood and Sanford 1995, Stephens and Coons 1994, Allison and Hughes 1978, and Scanlon and Richter 1990). In these methods, the vertical profile of a natural tracer such as chloride or tritium is used to estimate long-term average recharge rates. Coons, Ankeny, and Bulik (2000) also suggest that tracers that are not normally in pore water (e.g., bromide or deuterium oxide) can be artificially introduced at the ground surface and the tracer profile in the soil monitored, showing the depth to which percolation carries the tracer.

Qualitative indications of recharge rates can sometimes be obtained from evaluations of the natural vegetation (Chadwick et al. 1999). Sala, Lauenroth, and Parton (1992) state that "Comparison of long-term soil water patterns and traits of the major species allows us to suggest why *Bouteloua gracilis* [a grass species] is the dominant species in the shortgrass steppe." In such regions, vegetation may differ near streams or above a shallow water table, thereby indicating that an alternative source of water is available.

Another use of analogs is to provide insights to ecological change and pedogenesis (Waugh 1997). Keeping trees off a cover in a region dominated by forests may require considerable effort. Similarly, maintaining a well-vegetated grass cover where naturally occurring vegetation is sparse may require supplemental irrigation.

Careful observance and consideration of natural analogs should not be overlooked in evaluations of the suitability of a landfill cover design. Not only might analogs provide quantitative or qualitative estimates of recharge through an alternative cover, but ignoring the information analogs might provide when designing an alternative cover may have serious consequences to long-term cover performance.

4.5.10 Design Deliverables

The design process should result in a set of design deliverables or products that serve as the foundation for the construction of the AFC, including an approved design plan, specifications, criteria, and drawings. Documentation supporting the design document can be appended.

4.5.11 Cost/Cost Savings

An important factor in AFC use is the potential for cost savings. Although landfill cover costs are site specific and heavily influenced by the cover design and soil availability, the constructed cost of an alternative cover is frequently less than the cost of a conventional cover because an alternative cover often needs no barrier or drainage layers (Weand and Hauser 1997) (see Figure 4-2) and may require less long-term maintenance. Potential cost savings from use of an alternative cover should be considered on a case-by-case basis and should consider total system costs, including costs for design, regulatory approval, construction, and maintenance.

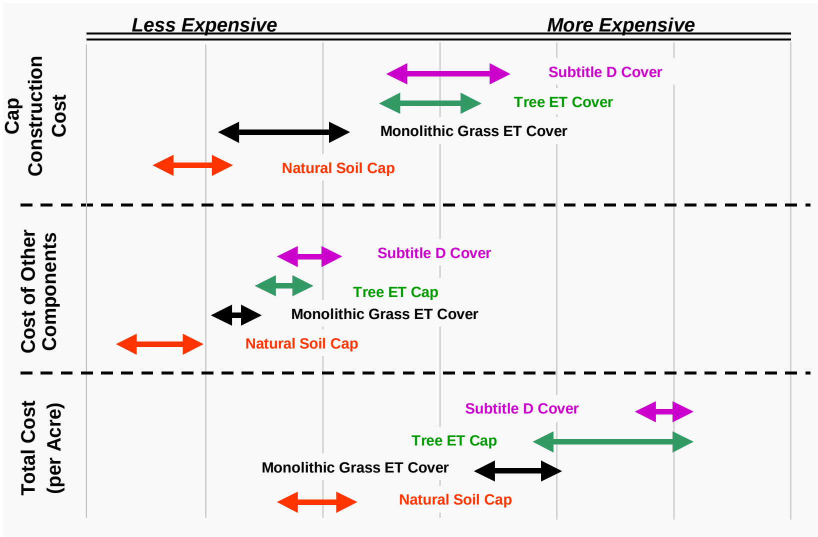

Figure 4-2. Comparison of alternative cover capital costs with those of Subtitle D (conventional) covers.

Construction costs for alternative covers are potentially lower than for conventional covers for a number of reasons. Besides the cost of constructing multiple layers in a conventional cover, clay for constructing a compacted clay layer is not readily available at many landfill sites. QC requirements associated with construction of the barrier and drainage layers of a conventional cover may be greater than for the vegetated soil layer of an alternative cover because of the conventional cover's reliance on the integrity of the barrier layer. For example, strict moisture control and compaction requirements are typically required for a compacted clay barrier. However, for an alternative cover consisting of a single vegetated soil layer, moisture control is less important, and high levels of compaction are not desired. Of course, at a site having abundant clay but not having the type of soil needed for acceptable performance of an alternative cover's vegetated soil layer, the relative cost advantage of an alternative cover may be reduced or eliminated.

Alternative covers also offer potential cost advantages related to maintenance costs. An alternative cover composed merely of a vegetated soil layer is not subject to long-term damage from wetting and drying, a process that naturally degrades compacted clay layers (Weand and Hauser 1997; Suter, Luxmoore, and Smith 1993; Landreth et al. 1991). Damage caused by differential settlement or burrowing animals can be repaired relatively easily on alternative covers compared to the cost of repairing buried barrier layers of conventional covers.

5. COVER CONSTRUCTION

5.1 Introduction

This section—designed for owners/engineers who have prepared the design and specifications for an AFC and for regulatory agency representatives during the design review and approval process for an AFC—addresses the following important steps in the process of constructing an AFC:

- identification and qualification of construction materials—Section 5.2,
- determination of appropriate construction methods—Section 5.3,
- QC testing to confirm conformance to design specifications—Section 5.4,
- record keeping during construction and QC—Section 5.5, and
- certification of construction in accord with approved design and specifications—Section 5.6.

This section does not provide a specific design, nor does it provide specifications universally applicable to AFC construction. It also does not include detailed discussion of aspects of cover construction that are not unique to AFCs. For example, although geosynthetic materials (e.g., polyethylene liners, geotextiles, drainage media, and soil strength reinforcements) might be incorporated into some site-specific AFC designs, the use of these materials is considered to be thoroughly addressed in available landfill cover design/construction references. Accordingly, that information is not repeated herein. Similarly, this section does not address the details of landfill gas management or surface-water runoff management, features common to many landfill cover types. The cover construction section is intended to provide a summary of the various aspects of cover construction that are unique to AFCs in sufficient detail to be a useful tool to owners, engineers, and regulators, but sufficiently generic to be applicable to a wide variety of AFC types, landfill types, locations, and climates.

For an AFC to function over a long period of time as required under applicable regulatory standards, requirements, criteria, or limitations, and as desired by the landfill owner/engineer, the proper materials must be properly placed to construct the cover. The process presented in Sections 1–3 of this document results in the preparation of design documents that include engineering design drawings, construction specifications, and project plans. Design drawings present, in detail, the geometric configuration of the AFC and identify the various natural and manmade materials that are to compose the cover system. Construction specifications provide very specific physical requirements for the natural and manmade components of the AFC, as well as very specific requirements for their proper placement during cover construction. Project plans cover a variety of issues (i.e., health and safety, long-term operations, maintenance, etc.), but also include the construction quality assurance (CQA) plan[1]. The CQA plan presents the planned system of activities that provide controls and assurance that the project is implemented as specified and in compliance with the design drawings and specifications.

[1] The CQA plan is a specific regulatory requirement for RCRA Subtitle C landfill covers (40 CFR 264.19 and 265.19 and corollary state regulations) and RCRA Subtitle D landfill covers (40 CFR 258.60[c][1] and corollary state regulations) and typically also is required by regulation, guidance, or site-specific permit/order/ROD/etc. for other types of landfill final covers.

Design drawings typically are prepared by, or under the direct supervision of, a professional engineer licensed by the state where the landfill is located. Federal regulations do not include specific requirements for design drawings. Some state regulations and guidance documents include certain specific requirements, such as drawing scale, applicable to design drawings, but in general the information provided on design drawings and the number of drawings necessary to present the information is left to the judgment of the design engineer.

The construction specifications will include the detailed requirements, including reference to standard material testing protocol, that must be satisfied by materials intended for use in an AFC. These requirements include physical, chemical, and other properties that must be satisfied by materials (natural and manmade) to be used in the cover and procedures that must be used for construction of the AFC, including physical properties that must be achieved when materials are placed.

The CQA plan includes all administrative requirements, including the organizations and responsibilities of CQA personnel, necessary to ensure that the constructed cover meets or exceeds design criteria and stipulations in a permit. The CQA plan is typically developed and implemented under the direction of a CQA officer who is, or works under the direct supervision of someone who is, a professional engineer licensed by the state where the AFC will be constructed.

At the beginning of this discussion of AFC construction and CQA, it is important to note that achieving satisfactory long-term performance by an AFC is directly related to strict adherence to construction specifications. Adhering to construction specifications is, in some ways, more critical to AFC performance than it is for the performance of a traditional (prescriptive) landfill cover. For example, the capacity for AFC soil components to store infiltration until plants and surface evaporation return the water to the atmosphere is directly related to soil particle size (i.e., soil classification) and soil density (i.e., compaction). A primary objective of a conventional cover is low permeability achieved by reaching a high soil density (high compaction). The objectives for an AFC are achieved by reaching a lower soil density (lower compaction). Where achieving higher soil densities (e.g., placement of soil at densities exceeding compaction criteria) can improve the performance of a conventional cover, such changes to an AFC could prevent it from holding infiltration water and making water available to plants or inhibit root development (or plant growth) and, as a result, cause the AFC to fail. Persons developing AFC designs, reviewing/approving AFC designs, and verifying compliance with specifications during construction are advised of the unique properties of AFCs.

5.2 Preconstruction Cover Material Specifications

AFC design drawings and construction specifications include specific physical and chemical property requirements for the various natural and manmade materials to be used in the cover. Suitability of the materials proposed for use in AFC construction must be confirmed by physical and chemical tests. The initial determination of material property suitability is likely to be based on the designer's experience or results of comparative analysis or test pads and presented in the construction specifications. The CQA plan then indicates specific tests and testing frequencies to be performed on materials to measure those specific material properties for comparison with the numeric requirements given in the design and specifications.

Physical and chemical property testing typically is done prior to construction during a material characterization/QC program to avoid delays during construction activities. Some testing is done during the design process to confirm the availability to the project of materials whose properties are important to design development. Additional testing is done after the design is completed but before construction commences to determine that necessary materials are available in sufficient quantities or on an acceptable delivery schedule. Preconstruction property determinations are repeated at specified intervals during the construction process to confirm that the properties of materials being obtained for use in cover construction remain within acceptable ranges. Such reconfirmation of satisfactory materials properties is particularly critical for natural materials (e.g., soil), whose properties can vary significantly as different portions of a borrow source are utilized.

Material properties confirmation, also called "materials prequalification," must be carefully and completely documented. Then the AFC construction project design engineer, CQA officer, or other person(s) delegated responsibility to provide materials approval must compare the measured material properties to project specifications and enter into the project documents (see Section 5.5) the fact that the materials considered for use do or do not satisfy the project requirements for that specific material. The types of physical properties to be specified for material types often incorporated into AFCs are as follows:

<u>Natural materials</u>—various soil layers including top soil, moisture storage layer, and capillary break:

- volume
- soil classification and taxonomy
- clay, silt, sand and coarse fragment content (particle-size gradation)
- organic matter
- bulk density as part of Proctor
- pH
- plasticity (liquid limit, plastic limit, plasticity index)
- cation exchange capacity
- moisture content
- moisture retention properties
- electrical conductance
- nitrogen (inorganic and organic)
- phosphorus
- potassium (adequate in most soils west of the Mississippi River)
- sulfur (important in a few soils)
- micronutrients (not critical in most soils)
- total salt content
- total sodium
- sodium adsorption ratio
- strength properties
- compaction properties
- hydraulic conductivity (permeability)

<u>Vegetation materials</u>—seed types and soil amendments:

- seed mix
- chemical amendments

Natural materials, primarily various native soil types, are the primary components of all AFCs. The availability of such materials from one or more location near the AFC construction site in a sufficient quantity to complete construction probably will be a primary decision factor in the evaluation of the viability of an AFC at a particular location. However, it also could be possible to import necessary natural materials from off-site locations. Such imported materials might be the primary soil material needed for AFC construction or might be a soil amendment that, when added to materials available near AFC site, will modify soil properties to make the amended local materials satisfactory for AFC construction (e.g., addition of imported clay-size materials to improve the moisture-holding capacity of the native soil). The following types of native materials could be required to construct an AFC:

- topsoil,
- clayey soil types,
- silty soil types,
- sandy soil types,
- gravel-size materials (such as for use in a capillary break), and
- cobble or boulder-size materials (such as for use in cover drainage channels that must resist erosion by water).

The type, amount, and physical properties of natural materials available for use in an AFC must be taken into consideration early in the design process. The availability of such materials from a source on or near the AFC site is the most advantageous situation, but off-site material source(s) would be acceptable where the cost of the material and the cost of material transportation are such that the AFC remains a technically and economically viable alternative. The evaluation of available natural materials, sometimes called a "borrow material investigation," is an important early component of the AFC evaluation and design process.

The detailed plan for a borrow material investigation—including the area to be investigated, the manner in which the investigation will be conducted, the type and number of samples to be taken, the sampe locations, and the physical and chemical properties tests to be conducted—differs for each site location and AFC type. Thus, providing specific guidance for conducting a borrow material investigation is beyond the scope of this document. Professional engineers, geologists, or soil scientists working for the project owner usually develop such details.

5.3 Construction Methods

After an alternative cover has been designed, careful consideration must be given to the construction methods that will be used to effectively implement the design. Achieving desired performance by an AFC is in some ways more sensitive to the use or avoidance of specific construction methods than is a conventional landfill cover. For example, contractors may be accustomed to using a specific type of equipment to load and haul large quantities of soil or to attain a high level of compaction when placing cover soils (as is generally the case with conventional covers). However, the basis of performance of an alternative landfill cover system varies significantly from that of a conventional landfill cover and requires a close look at how construction methods will achieve the design objectives. Table 5.1 lists some general principles.

Owners/operators should not prevent contractors from using their equipment fleet and expertise but must ensure that the design objectives are conveyed to a contractor in the design and specifications and then enforced during the construction phase by means of CQA planning and oversight. Specific aspects of the construction phase that are critical to the successful performance of an alternative landfill cover system are discussed below.

Table 5-1. AFC construction practices

Don't	Do
Deviate from specifications without consulting the design engineer/plant scientist	Adhere to specifications
Over compact soil layers	Loosen overcompacted areas
Use heavy, wheeled construction equipment	Use light, tracked construction equipment
Drive wheeled equipment over the completed cover	Loosen overcompacted equipment roads and tracks
Overmoisten soil when being placed	Allow soil to dry to below optimum moisture contents before being placed
Place fill in thin lifts	Place fill in thick, cushioning lifts
Create haul roads across or material stockpiles on the cover	Place haul roads and stockpiles elsewhere

5.3.1 Placement of Natural Materials

Because of the typical areal extent of most landfill covers, it usually is cost-effective to construct them using large-scale equipment similar to that used in highway or heavy construction. When full-scale projects are dependent on the successful performance of test plots, the same scale equipment should be used for their construction so that test-plot data are representative of the long-term performance of the full-scale cover. In this way, both would be constructed according to the same specifications and the same (or similar) equipment.

Unlike conventional covers, the concept upon which alternative covers function is not dependent on a soil layer having a low saturated hydraulic conductivity. Heavily compacting the cover soil in an alternative cover system, as is common in the low-permeability barrier layer of conventional covers, would inhibit development of healthy vegetation and could reduce the water-holding capacity of the soil layer. Alternative covers are expected to achieve optimal performance and durability if the soil densities are similar to those that would exist under natural conditions (Chadwick et al. 1999). Experience has determined that dry soil densities should be in the range of 1.1–1.5 mg/m^3 typically provided acceptable results (Hauser, Weand, and Gill 2001a, 2001b).

Achieving the optimal soil density is a matter of balancing engineering requirements for hydraulic performance, settlement, and slope stability with agronomic needs to maintain soil in a relatively loose condition to improve its ability to support vegetation. Research conducted by Goldsmith, Silva, and Fischenich (2001) and Gray (2002) suggests that a compaction between 80% and 85% of the standard Proctor maximum dry density provides many of the stabilizing benefits of higher soil compaction without jeopardizing the viability of vegetation development and growth. Research also suggests that there is a threshold soil bulk density value, or "growth-limiting bulk density" (GLBD) for each soil texture (Daddow and Warrington 1983), beyond which root growth is impeded due to the high mechanical resistance of soils resistance of soil (a possible result of overcompaction).

A post–field demonstration evaluation conducted at the Rocky Mountain Arsenal (RMA) near Denver indicates that an even broader range of soil densities could prove successful for use in constructing alternative covers at RMA with on-site soils. Assessment of the RMA field demonstration test plots (see Figure 5-1) along with results of soil density sensitivity modeling indicates that a compaction between 75% and 85% of the standard Proctor maximum dry density meets the cover performance requirements while providing excellent conditions for vegetation establishment and growth. It may be beneficial to convey compaction requirements to a contractor both in terms of standard Proctor and GLBD so that the objectives of soil placement requirements are fully understood.

Figure 5-1. Placing soil lift for test pad construction at the Rocky Mountain Arsenal.

5.3.1.1 Cover Placement Equipment and Methods

To achieve the proper soil compaction, it is advisable to use tracked or other low-ground-pressure equipment when working over the alternative cover area. Point-load (wheeled) equipment may be beneficial for transporting soils but probably can cause excessive compaction if used over the cover area. Excessive compaction could result in inadequate vegetation growth or ponding along the equipment travel paths unless procedures are implemented to loosen the soils after placement, such as chiseling or disking highly compacted areas. Figure 5-2 displays equipment often used to verify compaction as construction proceeds.

Figure 5-2. Nuclear gage determination of alternative cover layer compaction.

Along with the type of equipment, the procedures for placing cover soil are critical to the overall performance of the cover system. Tracked or other low-ground-pressure equipment provides a means to push soil into place until the desired layer thickness is achieved. It is recommended that a small test areas be constructed prior to full-scale implementation to validate the appropriate combination of equipment type, lift thickness, moisture content, and number of equipment passes in achieving the soil specification and design objectives.

Placing cover soil in relatively thick lifts (up to 2 feet) provides a means to control compaction.

Whether working one sloped lift or multiple horizontal lifts, the use of thick lifts provides a soil "cushion" to reduce compaction, along with the option of multiple equipment passes to increase compaction, if required. If the equipment push distance becomes too long, a network of haul roads can be established to deliver cover soil to the placement equipment. However, any haul roads should be disked, chiseled, or loosened to the full depth of excessive compaction in some way, prior to being enveloped by the cover system. Deep ripping, which might cause the development of temporary air voids within the ripped interval, is not recommended if other methods are available that can provide acceptable loosening.

5.3.1.2 Slope Stability

Cover system slope stability has been identified by Gross, Bonaparte, and Giroud (2002) as the most common type of problem encountered at landfills. The following comments are provided with respect to sol material placement with regard to ultimate slope stability.

- By placing cover soils from the bottom of the slope upward, a passive, stabilizing soil wedge is established at the toe of slope prior to placement of soil higher on the slope. The operation of construction equipment over this lower wedge tends to compact and strengthen the wedge.

- Relatively small, wide-track dozers (i.e., low-ground-pressure dozers) are recommended for placing the soil cover material. This type of equipment limits both the dynamic force imparted to the slope during acceleration and braking and the tractive force applied through the dozer tracks.

- Down-slope dynamic forces can be further limited by limiting the dozer speed on the slope and by instructing the operator to avoid hard braking, particularly when backing down-slope.

By application of the construction procedures described above, as well as others intended to prevent slope stability problems, construction-induced impacts to the stability of a cover system slope (designed to conventional slope-stability factors of safety) are minor.

5.3.1.3 Moisture Control

Alternative cover systems are designed to function under unsaturated conditions; consequently, obtaining very low saturated hydraulic conductivity is not a priority. Soil compacts to high density and achieves high strength when worked at high water contents. Because a very low initial saturated hydraulic conductivity is not the objective when placing the cover soils in an alternative cover system, compaction “dry of optimum” (ASTM D698, “standard Proctor” moisture-density relations) is usually desired to reduce the potential for desiccation cracking and to help avoid over compaction (Bonaparte et al. 2002). Generally, if most soil types are placed at no more than 90% of the optimum moisture content, satisfactory results can be obtained. Additionally, placement of soils in a dry of optimum condition is advantageous because inadvertent compaction to higher densities (e.g., greater than 85% of standard Proctor) is more difficult to achieve in dry soil. This factor allows greater flexibility in equipment selection and reduces the importance of construction methods. The water content at which it is safe to work the soil to be used should be evaluated in the field test cell.

Compaction density requirements for the cover soils should be based on consideration of the performance characteristics of the soils (determined by the water content/unsaturated conductivity relationship for the soil); erosion, settlement, and stability concerns; and plant rooting requirements. Because materials should be placed in a relatively dry condition, the objectives of a dust control plan should be reviewed with the construction contractor and any regulatory agencies providing oversight. The plan should specify dust control measures, where they can be applied, and how to prevent placing cover soils that are wetter than optimum.

5.3.3 Placement of Vegetation Materials

ET landfill covers may require a robust, healthy stand of grass or other dense vegetation to achieve the goals set for landfill covers. Although some regulatory agencies have required AFCs to achieve their design goals absent a vegetative cover, the vegetation layer serves two primary functions on AFCs: it rapidly and efficiently removes water from the entire soil cover, and it provides for effective and long-lasting control of both wind and water erosion of the soil surface.

The vegetative cover establishment process should provide temporary plant cover soon after construction because bare soil is vulnerable to soil erosion. A single rainstorm could remove enough soil to require rebuilding the surface. Because native plants may be difficult to establish and may grow slowly over two years or more, procedures should be employed to both quickly provide soil erosion control and control erosion for up to two years.

Although some regulatory agencies have required AFCs to achieve their design goals absent a vegetative cover, the vegetation layer serves two primary functions on AFCs: it rapidly and efficiently removes water from the entire soil cover, and it provides for effective and long-lasting control of both wind and water erosion of the soil surface.

5.3.3.1 Vegetation Establishment Methods

This section focuses on the establishment of grasses and forbs because they are the preferred vegetation at most sites and appropriate soil preparation (see Figure 5-3) and seeding equipment is readily available. Native grasses and forbs are difficult to establish in all climates, but especially so in semiarid and arid climates. The seeds of most native grasses and forbs are small; therefore, the maximum seeding depth is shallow. The top ½ inch of bare soil may dry below the plant wilting point in less than one day after a rain or irrigation, even in humid climates. Small seeds planted deep, where the soil remains moist longer, produce few plants because of their small food reserves. In addition, the best available seed supply usually contains some seeds of poor quality; they may produce seedlings with low vigor. Because native plants are difficult to establish and the technology is

Figure 5-3. Topsoil layer at Denver Arapahoe Disposal Site before fine-grading and seeding.

less well known to the remediation industry, this section contains more detail than may be included in other parts of this document.

Currently used methods for establishing native grasses and forbs include the following:

- hydroseeding,
- solid sod application and sprigging,
- broadcast seeding on the surface,
- drill seeding in bare soil, and
- drill seeding in standing crop residue.

Hydroseeding uses mixtures of seeds and fibers suspended in water. The seed and fiber mix is applied to the land by pumping the mixture through spray nozzles at high pressure to permit application up to 100 feet away from the mobile seeding unit. The fibers are commonly wood or straw, and chemicals are often added to bind the fibers together to reduce movement by wind or rain after placement. Hydroseeding was developed for use on steep, short slopes such as embankments along roadways where conventional seeding machines cannot operate. Hydroseeding is expensive, and in the western Great Plains, resulted in only a 10% success rate on reclaimed mine lands. Hydroseeding may deposit the seed within the fiber mulch, thus separating the seed from the soil. In addition, high winds may roll up the hydroseeded mats. Other less expensive methods are more effective for use on landfill covers.

Solid sod application and sprigging successfully establish monocultures of sod forming or stoloniferous grasses; however, both are expensive and require frequent irrigation during the establishment period. Other methods are more appropriate for establishment of grass on landfill covers, where several species are preferred rather than a monoculture.

Broadcast seeding on the soil surface, either with or without mulch cover, produces many seeding failures. Ants, mice, birds, and other creatures remove or destroy large numbers of seeds. The germinating seeds dry rapidly in both humid and arid conditions, producing high mortality rates. Accordingly, when seeds are broadcast, shallow disking or harrowing to cover the seeds can improve the success rate.

Drill seeding in bare soil—Seeds may be planted by drilling into furrows on bare soil. Erosion control during plant establishment usually requires mulch application after seeding. In arid climates or during dry periods, irrigation can improve the success rate.

Drill seeding in standing crop residue—On farms and ranches that use conventional technology without crop residue on the surface of dry lands, half (or more) of the seeding efforts result in failure (Hauser 1989). However, standing mulch cover, alone or with irrigation after seeding, substantially improves the probability for success. Drill seeding in standing crop residue is both successful and economical.

A thick cover of standing stubble can be quickly produced on a landfill cover by planting an annual grain crop such as barley, wheat, or oats. These annual grasses are easily established and produce a thick, standing cover of straw. When the grain in the heads is forming but still immature, the crop is mowed to a height of 8 inches to produce standing stubble. The standing stubble can control both wind and water erosion. The desired perennial grasses and forbs may be seeded directly into the undisturbed, standing stubble. The stubble cover reduces evaporation of soil water from the seed zone, protects the seedlings, and significantly reduces weed competition.

Field research and production experience have demonstrated that this method of seeding is the most reliable and also one of the least expensive. With the addition of irrigation water during the plant establishment phase, this method has a high probability for success

Implementation of Drill Seeding in Standing Crop Residue—Important parts of the grass establishment system include mulch cover, fertilizer, species, and equipment.

The mulch crop should be seeded during the appropriate season for the crop. The plants should be mowed 8 inches high at the dough stage of grain development (grain is filled with milky or soft material) to prevent the crop from reseeding. Permanent vegetation should be planted in the next appropriate planting season. All machine operations on the land should be minimized and designed to maintain and preserve the standing stubble, which does the following:

- controls both wind and water erosion for up to two years,
- shelters the seedlings from wind and the beating action of intense rainfall,
- reduces the rate of soil drying,
- maintains more uniform temperatures around the seeds and seedlings than bare soil,
- increases infiltration of water over that for bare soil,
- costs one-fourth to one-twentieth as much as straw mulch applied to bare soil,
- suppresses undesirable weed growth, and
- improves soil physical properties 12–18 inches deep (Schuman et al. 1980).

As examples, in the central and northern Great Plains, spring barley or wheat produces a durable and effective cover (Pinchak, Schuman, and Depuit 1985; Schuman et al. 1980). In other regions winter wheat, barley, oats, rye, or similar crops will be equally successful.

Fertilizer produces a beneficial effect on seeding success (Howard, Schuman, and Rauzi 1977); however, no fertilizer should be applied before establishment of the seeded permanent plants. Fertilizer application before seeding the permanent species encourages excessive growth of weeds during the grass establishment period. Excessive weed growth may seriously damage the plant seedlings by competition for sunlight and soil water. Fertilizer should be applied only after the seeded species are established.

Seeding Equipment—Many grass seeds have fluffy seed coats that are difficult to remove; however, good seed producers have developed methods to improve many of these seeds. Many desirable plant species have very small seeds. Seeding machinery should be tight enough to hold the seed and capable of planting uniform rates of fluffy seeds over the entire land surface.
Some cool-season grasses and forbs may be planted up to ¾ inch deep in the standing stubble, but most warm-season grasses and forbs should be planted not more than ¼ inch deep. Depth of seed placement is very important and is best achieved by furrow openers using double disks with depth control bands or wheels on each furrow opener. The furrow should be closed by dual,

angled press wheels or an equivalent device. The seeder should have adequate weight and down-pressure control to force the furrow openers into firm soil and to ensure that each furrow opener acts independently to accommodate uneven ground surfaces. Figure 5-4 shows a typical seeding operation.

Figure 5-4. Seed drill in use.

Methods for establishing native grasses or forbs include pregermination of the seed before planting (Hauser 1986) and application of water in the seed furrow (Hauser 1989). Pregermination of seeds is effective and is used commercially for vegetables; however, for grassland seeding it would require new equipment and training of personnel. Application of water in the seed furrow is an inexpensive technique that cans double the number of seedlings established as compared to no water being applied in the seed furrow. This method was proven in field tests and improves stand establishment in either moist or dry conditions.

5.3.4 Irrigation

In many humid regions, grass is easily established without irrigation. However in arid and semiarid regions, irrigation, if available, substantially improves plant establishment. Sprinkler irrigation can be controlled to avoid wetting the full depth of the cover, thus protecting the waste from drainage water.

Because native grasses should be planted less than ¼ inch deep, frequent irrigation is required to maintain the seed zone continuously wet. The seed zone can dry below the wilting point in one day, even in humid climates. When the seed zone dries to the wilting point, the possibility for successful establishment of grasses is diminished. Therefore, irrigation should maintain the surface soil in a wet condition for at least two weeks during a time when temperatures are adequate for plant emergence. In addition to maintaining adequate soil water at seed level, irrigation can also be used to soften soil crusts that form after intense rainfall.

In semiarid regions, it may be very difficult to establish many of the native grass, forb, and shrub species through conventional seeding programs and natural precipitation regimes. Under natural conditions, important factors determining seedling establishment are total annual precipitation, soil texture, and intraseasonal distribution of precipitation. Lauenroth et al. (1994) used a soil water simulation model, long-term climatic data, and detailed ecophysiological requirements for seed germination and growth of *Bouteloua gracilis* to assess the frequency of environmental conditions appropriate for seedling establishment of this important prairie grass species. That work determined that natural conditions optimum for seed germination and growth occur very infrequently, possibly only every 30 to 50 years. Accordingly, in arid and semiarid regions, irrigation can be an important method to supplement annual precipitation, as well as modify intraseasonal soil moisture conditions. In such locations it may be necessary to develop a detailed and specific irrigation schedule applicable during vegetation establishment.

Irrigation water sources vary by site but can include natural streams, lakes and reservoirs; groundwater produced from wells, and even treated potable water from municipal supply systems. Water with low total salt content and suitable for irrigation of crops is best for grass establishment. However, depending on the nature of salt in the water and the tolerance of the plants for salt, more saline water may be suitable for irrigation of some grass seedlings. In some instances, treated sewage effluent might be available and of adequate quality for irrigation of seeded grass. Distribution systems can include pumps of various sizes, above- and belowground piping, tank storage, and various types of water application systems. Systems that depend on movement of equipment over the cover soil, such as water tank trucks with sprayers, usually are not appropriate for cover irrigation.

In general, three types of irrigation systems can be used apply water to revegetated areas:

- Solid set irrigation systems are similar to standard home sprinkler systems, but are installed aboveground. Impact sprinklers are mounted on risers and set in piping. Typically, each sprinkler has a throw radius of 30–45 feet. Solid set lines are controlled by automated valves mounted into the mainline pipe. The solid set system is the most flexible of all the irrigation system choices. It will accommodate almost any terrain, including hills, dense shrubs, and heavily wooded areas. Automated valves can be programmed to open and close on any schedule, allowing the system to operate at any time. A shortcoming of the solid set system is that it requires extensive labor to install and test.

- Sideroll irrigation systems, commonly referred to as “wheel lines,” are generally used for crop irrigation. The system consists of a central mover powered by a gasoline-, diesel-, or natural gas–fueled or solar-powered engine. Sections of tubing are bolted to each side of the mover. The tubing is 40 feet in length, 4–5 inches in diameter, and has a wheel mounted in the center. The bolted sections of tubing, the torque teeth on the ends of the tubing, and the wheel mounted on the tubing cause the system to move in unison when the central mover is advanced. Sprinklers are mounted directly into each section of tubing and have a throw radius of approximately 30 feet on either side. Sideroll systems are excellent for irrigating flat, even terrain. The downside to these systems is that they are labor-intensive.

- Linear-move/center-pivot irrigation systems are commonly used to irrigate parcels ranging in size from 100 to 250 acres. Linear-move systems move laterally and center-pivot systems move in a circular pattern around a fixed pivot point. Water application rates can be programmed into the system from a control panel. The linear-move distributes water uniformly and can be the most consistent of all the irrigation systems. It also requires the least labor to operate. However, such systems are designed to irrigate large contiguous rectangular areas, which limits usage because many sites may be small, unconnected, irregular in shape, and isolated.

5.4 Construction Quality Control

This discussion of the process of verifying and documenting conformance with the very specific and detailed requirements that will be provided in AFC design documents is written to be consistent with the federal regulatory requirements for closure of RCRA Subtitle C and D landfills as contained in 40 CFR 264.19 and 265.19, and 40 CFR 258.60(c) respectively. These regulations (especially the RCRA Subtitle C regulations) include requirements for closure plans and closure certification and refer to the required documents as CQA plans and the persons responsible for verifying and certifying conformance with approved plans as CQA personnel, CQA officers, and registered professional engineers. For simplicity of reference in this manual, the terms "CQA" or "CQA officer" are used. Any conflict between the way these and related terms are used by state regulatory agencies or others interested in AFCs and the way the same terms are used in this regulatory guidance manual is unintended. This portion of the guidance manual is intended to emphasize the importance of verifying and documenting conformance to approved AFC design documents.

To ensure with a reasonable degree of certainty that the construction of an AFC system meets the design specification, a CQA plan is essential. The CQA plan, which incorporates the concepts of quality assurance and quality control, also affords a formal basis for certifying that the AFC was constructed according to design. As defined in *Solid Waste Disposal Facility Criteria Technical Manual* (EPA 1993b):

> <u>Construction quality assurance</u> consists of a planned series of observations and tests to ensure that the final product meets project specifications. CQA plans, specifications, observations, and tests are used to provide quantitative criteria with which to accept the final product.
>
> <u>Construction quality control</u> is an on-going process of measuring and controlling the characteristics of the product that is employed by the manufacturer of materials and by the contractor installing materials at the site.

The purpose of any CQA test or observation is to compare the material used or the work actually performed with the specified material or workmanship. The design specifications for the cover establish the parameters that will be evaluated for the acceptance of the materials and work. Testing of the materials prior to (for characterization) or during construction will determine whether the properties, composition, and/or performance of the material(s) or installed components are within the limits specified in the design.

Observations and testing are important and necessary CQA activities throughout all phases of the AFC construction. Observation of all component materials as they are delivered to the construction site and installed in proper sequence provides compliance with design specifications and procedures. Accordingly, the CQA plan must be developed by the facility owner/operator and approved by appropriate regulatory agencies prior to the commencement of any construction activities.

The plan should include a CQA hierarchy and structure approved by the facility owner/operator and the appropriate regulatory agencies prior to the commencement of any construction activities at the facility. The hierarchy and structure should list the "parties" involved in CQA activities. The parties list should detail the affiliation of all the personnel involved in CQA of the AFC such as indicated in Table 5-2. The CQA plan also should clearly outline the duties of CQA personnel, such as in Table 5-3. Finally, but most importantly, the documentation procedures also should be outlined in the CQA plan. The effectiveness of the CQA plan depends largely on the recognition of construction activities that should be monitored and on assigning responsibilities for monitoring each activity. This is effectively accomplished and verified by the documentation of QC/QA activities.

Table 5-2. Parties to construction quality assurance and quality control

Title	Affiliation	Responsibilities
Owner/operator	Facility owner/operator	
Engineer	Consulting engineer contracted by the facility owner/operator	Responsible for specifications, drawings, modifications
CQA consultant	Independent third party (not affiliated with contractors, suppliers, and manufacturers) contracted by the owner/operator	Confirms that the contractor's CQA activities are done in accord with the CQA plan
Contractors	Independent or affiliated with owner/operator	Timely construction and installation of the project per the plans and specifications
Soil QC laboratory	Associated with the CQA consultant and independent of the contractors, suppliers, and manufacturers	Conducts tests on soil samples taken from borrow areas, stockpiles, or earth works in place to access compliance the specifications
Geosynthetics QC laboratory	Associated with the CQA consultant and independent of the contractors, suppliers, and manufacturers	Conducts conformance testing on samples of geosynthetics to be delivered to the site to access conformance of the materials with specifications

Table 5-3 Typical duties of CQA personnel

Personnel	Typical duties
Design engineer	• Reviews specifications, drawings, and addenda • Attends resolution and preconstruction meetings • Reviews changes to the design, drawings, and specifications
Site CQA officer	• On-site representative of the CQA consultant • Manages the daily activities of the field monitors • Attends CQA-related meetings • Oversees preparation of CQA record drawings by contractors • Reports to owner and design engineer and documents in the daily and weekly reports any relevant observations reported by the field monitors • Notes and reports to owner any on-site activities the would compromise the components of the project and assists in the preparation of the final construction certification report • Reviews lab and field test results provided by contractors and makes recommendations to owner

Personnel	Typical duties
	• Assigns testing and sampling locations • Verifies calibration of on-site QC equipment • Oversees the collection, packaging and shipping of samples recovered for lab testing • Reports any unresolved deviations from the CQA plan, drawings, and specifications to the owner and design engineer
Field monitors	• Duties assigned by site CQA manager, including monitoring and documenting the construction of natural and geosynthetic components of the project

5.4.1 Acceptable Range for and Response to Out-of-Specification Results

The acceptable range (tolerance) for and response to out-of-specification results should be determined prior to the finalization of the design and specifications. Also to be determined and agreed upon prior to the commencement of the project are the responsible parties for determining construction or performance material failure and the corrective the actions to be under taken to repair areas failing to meet the required specifications. The predetermined acceptable range of and corrective action contingencies for out-of-specification results must be included in the CQA plan and approved by the appropriate regulatory agency. Documentation of any out-of-specification results and corrective actions taken to repair the affected portions of the cover should be entered in periodic CQA reports and be an integral part of the final construction certification report.

Out-of-specification reporting and corrective measures reporting should include the following:

- detailed description of the problem,
- location of the problem,
- probable cause,
- method and time frame of locating the problem,
- estimated duration of the problem,
- recommended corrective action,
- documentation of corrective action,
- suggested methods to prevent similar problems, and
- concurrence and signature of the CQA officer.

5.4.2 Natural Materials Construction

The soil in an AFC must store infiltrating water and support a robust grass cover capable of quickly removing water from the profile. The AFC design will have considered the many properties that control soil ability to achieve these goals. The design and specifications will identify important soil properties that are measurable, or will identify easily measured index properties that are reliable surrogates for the desired soil property.

5.4.2.1 Soil Properties Verification and Quality Control

The design and specification documents will identify measurement method systems that are appropriate to the purpose of the construction work. The design documents may include reference to common soil construction quality control tests, such as those provided by the American Society for Testing and Materials (ASTM), the American Association of State Highway and Transportation Officials (AASHTO), or the Unified Facility Guide Specifications (UFGS) of the U.S. military services. However, because an AFC is a specialized plant production system designed to achieve control of the water balance in the soil, the measurement systems and standards developed by the agricultural research community and used in production agriculture such as those provided by the U.S. Department of Agriculture and Soil Science Society of America (SSSA) are believed by some researchers to be the appropriate construction measurement system.

The following example illustrates the use of agricultural and USDA methods and standards. The water-holding capacity of soil is one of the most important properties of an AFC. This cover soil property is achieved by controlling certain measurable soil properties (i.e., index properties) during landfill construction, including compaction and particle-size distribution. The SSSA (1997) describes soil particle sizes as follows: clay <0.002 mm, silt 0.05–0.002 mm, and five different sand separates in the size range of 0.05–2.0 mm. During construction, soil particle-size measurements provide a convenient, practical, and low-cost procedure to ensure that soils placed in an AFC meet the requirement for water-holding capacity, as defined by the construction design specifications and an evaluation of the water-holding capacity of the borrow soil.

In some engineering work the fine particles of soil are described as those "passing the #200 sieve" (about 0.074 mm). Soil material passing the #200 sieve contains all of the clay and silt and part of the sand as defined by the USDA soil classification system. Saxton et al. (1986) developed a model for estimating soil hydraulic properties and tested it against a large database of soil property measurements. Table 5-4 estimates of soil properties were made with that model. It is apparent from the table that in some soil types the amount of soil passing the #200 sieve has little or no relation to soil hydraulic properties that are important to AFC performance. However, other researchers associated with the Alternative Cover Assessment Program have correlated soil properties with grain size distributions derived using the Unified Soil Classification System.

Table 5-4. Soil properties used in the Saxon et al. (1986) model

Soil particle size (USDA)				Soil hydraulic property estimates		
Sand (%)	Silt (%)	Clay (%)	Silt + clay (% passing #200 sieve)	Wilting point	Field capacity	Available water-holding capacity
30	60	10	70	0.10	0.27	0.17
30	10	60	70	0.34	0.45	0.11

There are differences of opinion regarding which soil classification system may best represent the soil characteristics desirable for AFCs. An important point is that, regardless of which soil classification system is used, it is worthwhile to invest the time and resources during the borrow area investigation and site characterization phases of the design process to develop reliable correlations between the desired soil properties and easily measured index properties, such as grain-size distribution, so that generally applicable, relatively quick, and low-cost verification techniques may be used during the construction process as a QA/QC mechanism.

5.4.2.2 Material Placement Verification

Some soil properties are not easily, quickly, or cheaply measured. These might include properties very important to AFC performance such as moisture retention properties. Before construction begins, site specific correlations will be developed between important but hard to measure properties and more easily measured index properties. The index properties will be used during construction as quality control measurements. On large or sensitive project it might be necessary to periodically reconfirm these correlations.

Soil tilth is important for the proper functioning of an AFC. It is defined by SSSA (1997) as, "The physical condition of soil as related to its ease of tillage, fitness as a seedbed, and its impedance to seedling emergence and root penetration." Unfortunately, "tilth" is a subjective term for which there are no direct measurement methods.

Soil bulk density (commonly called "soil density") is one of the most important soil properties that determine soil tilth. It is defined by SSSA (1997) as follows: "The mass of dry soil per unit bulk volume. The value is expressed as milligrams per cubic meter." Soil bulk density is commonly reported in units of grams per cubic centimeter (gm/cc) or pounds per cubic foot (pcf). Soil bulk density is easily, quickly, and reliably measured by standard nuclear, gravimetric, sand cone, and other methods, as provided by any of the measurement systems that may be applicable to AFC construction.

When soil density is controlled within desirable limits (typically between 1.1 and 1.5 mg/m^3), the soil tilth of the AFC should be good. As is discussed above, this soil density is expected to correspond to standard Proctor maximum dry densities (e.g., ASTM method D698) between 75% and 85%. A site-specific correlation between the desired density in the available soil and the measurement method to be employed in the field (e.g., standard Proctor) always should be developed. The soil bulk density specified in design documents that will include requirements such as the following:

> Soil density should be measured for each soil lift during construction so that excess compaction can be corrected before the lift is covered. Soil density in each lift should be measured at random locations at a frequency of at least two measurements per acre of surface. In addition, the density of the soil under any visible wheel track on the soil lift should be measured for each 100 feet of track. Site conditions may indicate need for more intense density monitoring.

Wheel traffic on the soil should be prohibited during construction. Even lightweight trucks or automobiles can compact moist soils above the limits for good tilth. After construction, only machines mounted on tracks or lightweight wheeled machines mounted on low-pressure tires should be allowed on the cover.

5.4.2.3 Placed Material Thickness and Uniformity

Figure 5-5. Intermediate cover layer at Denver Arapahoe Disposal Site, grade stake marked for placement of other layers.

The thickness of each lift, or construction layer, of soil is important. More uniform and desirable soil properties will result from uniform lift thickness over the landfill surface. (Figures 5-5 and 5-6).

Figure 5-6. Intermediate cover (dark soil) at Denver Arapahoe Disposal Site, alternative cover layer placement (light soil) in the distance.

The total thickness of the soil in an AFC is directly related to the water-holding capacity of the cover and is therefore very important. A soil thickness less than the design thickness may permit excessive water penetration into the waste. Typical design specifications will include requirements such as the following:

> Measure the cover thickness in at least two locations for each acre of surface. If the thickness of any part of the cover is less than 95% of the design thickness, the cover should be repaired. Up to 5% of the measurements can be between 95% and 100% of the design thickness; and the remaining 95% of the measurements should meet or exceed the design specifications.

Constructed soil thickness greater than the design thickness should not be detrimental under most conditions. If the cover is used on a landfill where some water is required to percolate through the cover and into the waste to support natural decay, then any excess thickness might have an adverse impact and should be controlled.

5.4.3 Final Cover Geometry

The geometry of the various components of the AFC will be determined during construction in accordance with the specifications contained in the CQA plan. Cover component geometry specifications typically will be defined by horizontal and vertical coordinates. Such coordinates usually tie to a project or facility grid system where horizontal coordinates (e.g., "x" and "z" values) are referenced to a specific primary control point on the property. The primary control point often is tied to a State Plane Coordinate system. But, for convenience, such primary horizontal control points (e.g., "x" and "y" values) sometimes are assigned a grid coordinate of 10,000 feet north (or south) and 10,000 feet east (or west) so that horizontal geographic references are positive values. Vertical coordinates (e.g., "z" values) usually are tied to National Geodetic Vertical Datum (NGVD).

Geometric control for AFC components typically consist of coordinates describing the horizontal limits of the particular components. In addition to horizontal coordinates, the acceptable variation in the as-built horizontal limits of a cover component should be included in the CQA plan. In most instances, such acceptable variability will be on the order of ±0.5–1.0 feet; however, a project might assign lesser or greater ranges to acceptable variability based on site-specific design features.

The thickness (vertical limits) of particular components are specified either as fractional feet (e.g., a 0.5-foot-thick topsoil layer or a 3.0-foot-thick soil cover layer), or as by the specified use of a manmade material of a particular thickness (e.g., 80-mil- or 0.080-inch-thick geomembrane). The acceptable variation in the as-built vertical thickness limits of a cover component should be included in the CQA plan. Acceptable variability from the design thickness likely will not exceed 5% or 10% of the design value.

During construction, geometric limits (also called lines and grades) should be staked by a qualified surveyor and verified in accordance with the CQA plan using standard surveying and visual inspection/measurement techniques. Verification of AFC final geometry should be done by topographic mapping by standard survey methods, GPS survey methods, or photogrammetric survey methods.

The CQA Officer then will be responsible for verifying acceptable cover geometry by checking survey data for compliance with the design drawings. Deviations from project specifications should be documented and addressed with appropriate project management personnel, who might include regulatory agency personnel, so that an appropriate response (e.g., accept deviation or require regrading) can be made.

5.4.4 Seeding Quality Control

A variety of mechanisms can be used to control and ensure high-quality seeding operations. The seeding contractor should be required to develop and submit a seeding plan detailing all seeding equipment to be used, fertilizer types, and mulch sources for inspection prior to initiation of work. Seed and fertilizer formulation certifications from the suppliers should be submitted prior to material use. A task-specific health and safety plan should be developed and approved prior to initiation of work. Daily quality control logs should be maintained.

Qualified seeding contractors and operators should be employed. Seeding native seed mixes requires experience and familiarity with the various seed types to ensure proper planting. The proper equipment for seeding the specified native mix must be used. Not all seed drills are capable of proper planting of native grass/forb mixes.

Seed and seed mixtures should be delivered in sealed containers. Wet, moldy, or otherwise damaged seed or packages should be rejected and unacceptable materials removed from the job site. All labeling required by law should be intact and legible. After delivery to the work site, seeds should be stored in a cool, dry, and weatherproof and rodent proof place or container in a manner that protects the seed from deterioration and permits easy access for inspection.

All seed should be subject to inspection and concurrence by the contractor before the subcontractor is authorized to proceed with the seeding operation. Seed should be tested according to the Association of Official Seed Analysts, International Seed Testing Association, and the Federal Seed Act standards. A certificate of analysis from a certified testing laboratory should accompany seed. Certify the following individual seed tests:

- Purity and germination: Before seed is used, retest for germination all seed stored over six months from the date of the original acceptance test, and resubmit the results for inspection.
- Prohibited noxious weed seed: Seed should not contain any federal- or state-listed prohibited noxious weed seed (an amount within the tolerance of 0%) as determined by a standard purity test.
- Restricted noxious weed seed: Seed should contain no more than 40 seeds per pound of any single species, or 150 seeds per pound of all species combined, of restricted noxious weed seed.
- Weed seed: Seed should contain no more than 1% by weight of weed seed of other crops and plant species as determined by standard purity tests.

Certification from a certified seed-testing laboratory for seed testing within six months of date of delivery includes the following:

- name and address of laboratory,
- date of test,
- lot number of each seed type, and
- results of tests, including name, percentage of purity and germination, percentages of weed content for each kind of seed furnished, hard seed content, and in case of seed mixtures, pure live seed (PLS) proportions of each kind of seed as specified.

The seed vendor on each standard sealed container label can provide information regarding the seed mixture. The labels should include the following information:

- seed mixture name,
- lot number,
- total net weight and PLS weight of each seed type,
- percentages of purity and germination,
- seed coverage (in acres) on a PLS basis, and
- percentage of maximum weed seed content clearly marked for each seed type.

The vendor should package seed such that the acre coverage of each container is equal for convenience of inventory. Prior to planting any seed, the seed labels and certification documentation should be inspected by CQA personnel to ensure the seed provided meets the requirements specified.

Equipment proposed for use and the methods of seeding should be inspected for concurrence prior to the commencement of seeding operations. The equipment should be checked for compliance to safety requirements (in the contractor's health and safety plan) prior to the commencement of seeding operations. Equipment calibration tests should be conducted immediately prior to commencement of seeding operations and when the seed mix changes or different equipment is used.

Consider environmental conditions and perform seeding operations only during periods when successful results can be obtained. When drought, excessive moisture, or other unsatisfactory conditions prevail, seeding operation should be discontinued.

5.5 Record Keeping

The federal regulation governing closure of municipal solid waste landfills, 40 CFR Part 258, Subpart F (Closure and Post-Closure Care), Section 6 (h) states, "Following closure of each MSWLF unit, the owner or operator must notify the State Director that a certification, signed by an independent registered professional engineer or approved by Director of an approved State, verifying that closure has been completed in accordance with the closure plan, has been placed in the operating record." Similarly, the federal regulation governing closure of hazardous waste landfills, 40 CFR Part 264, Subpart G (Closure and Post-Closure Care), Section 264.115 states:

> Within 60 days of completion of closure of each hazardous waste surface impoundment, waste pile, land treatment, and landfill unit, and within 60 days of the completion of final closure, the owner or operator must submit to the Regional Administrator, by registered mail, a certification that the hazardous waste management unit or facility, as applicable, has been closed in accordance with the specifications in the approved closure plan. The certification must be signed by the owner or operator and by an independent registered professional engineer. Documentation supporting the independent registered professional engineer's certification must be furnished to the Regional Administrator upon request until he releases the owner or operator from the financial assurance requirements for closure under §264.143(i).

These or similar provisions typically are cited or are included in state regulations governing solid and hazardous waste landfill closure. For a professional engineer to provide such a certification for the final landfill cover, typically the most significant constructed aspect of a closed landfill, the cover must have been constructed in accordance with an agency-approved design. The responsible professional engineer (or other persons under his supervision) must observe, test, and thoroughly document the materials and construction methods actually used in the cover. Such documentation typically will address the degree to which

- cover geometry (horizontal and vertical limits) satisfies the cover design drawings,

- cover materials satisfy material specifications contained in the cover specifications, and
- cover construction satisfies construction QC specifications contained in the CQA plan.

5.5.1 Documentation of Preconstruction Material Qualification

Prior to the installation of any components of an AFC system, the material sources—including soil and manufactured components—should be tested to verify that they meet the requirements for specified work elements. Samples taken for field or laboratory conformance testing should be obtained and handled in accordance with applicable sampling protocols. Where allowed by the construction contract, the CQA officer may use certificates of compliance and conformance to establish the acceptability of materials. Such certificates generally state that the material is in compliance or conformance with a particular standard or specification. The certificates may be used for acceptance of a product before of or in place of testing if allowed by the specifications.

The CQA consultant should review and approve all preconstruction material documentation reports prior to construction. Such reports should include the following:

- date issued;
- project title;
- testing laboratory name, address, and telephone number;
- name and signature of laboratory technician;
- date and time of sampling;
- record of temperature and weather conditions;
- date of test;
- type of tests (lab or field);
- results of tests and compliance with specifications; and
- project engineer/scientist acceptance of the materials proposed for use in AFC construction.

5.5.2 Documentation of Construction Quality Control

Record keeping by persons responsible for observing cover construction should include a chronological record of construction activities. Such a record can provide the framework within which other construction records, including QC testing, can be referenced. The chronological records can include the following types of information:

- project name, location, and other identification;
- date and times;
- weather conditions, including measurements or estimates of temperature, precipitation, and wind speeds during the project;
- equipment and personnel employed at each location;
- descriptions of active work areas and work under way;
- descriptions of inspections or tests conducted;
- description of construction materials received, including any quality documentation;
- descriptions of materials used in construction; and
- construction meeting notes and construction decisions made.

The final documentation of construction quality control typically will include the following types of records:

- CQA representative's construction diary,
- QC testing records,
- photographs,
- completion survey by licensed land surveyor, and
- as-built drawings of the completed AFC.

5.6 Construction Certification

Following completion of AFC construction (Figure 5-7), the CQA officer, design engineer, or other person delegated such responsibility will prepare a final construction certification report. Federal and/or state regulations require that such certification be provided (i.e., signed) by a professional engineer registered in the state where the AFC is constructed. The certification report, including any inspection data sheets, should be retained at the facility for future reference.

Figure 5-7. A newly completed AFC over a RCRA solid waste management unit in Missouri.

The certification report should include descriptions of each phase of construction, construction materials used, construction methods employed, and QA procedures and test results. The following types of information typically are included in the construction certification report:

- daily inspection summary reports;
- laboratory and field test results summary sheets for all preconstruction QC testing required by the CQA plan, including manufacturers QA/QC submittals for geosynthetic materials;
- laboratory and field test results summary sheets for all construction QC testing required by the CQA plan;
- problem identification and corrective measures reports (including soil density repairs);
- documentation of design changes or clarifications;
- minutes of preconstruction meetings and weekly meetings;
- construction photographs; and
- as-built drawings.

6. POST-CLOSURE CARE

6.1 Introduction

In many respects, closure of a facility with an alternative final cover is no different than closure of any other waste disposal facility.

In many respects, closure of a facility with an alternative final cover is no different than closure of any other waste disposal facility, be it a waste pile, a construction and demolition debris landfill, an industrial landfill, a municipal waste landfill, or a hazardous waste landfill. These facilities may have different closure requirements based on the risk associated with the waste streams disposed in the facility, and the length of the post-closure care period may vary with the type of waste in the facility. However, the underlying goal of closure and the post-closure care period is always to provide long-term protection to human health and the environment. It is important to note that, although this document primarily deals with landfills or waste disposal facilities, the concept of AFCs may apply to other types of facilities, such as lagoons, spill sites, spoil piles, or any other facility needing a final cover system.

With respect to landfills, four basic issues are associated with closure and the post-closure care period (see Figure 6-1): cover integrity, leachate management, groundwater monitoring, and landfill gas monitoring and management. Of the four, perhaps the cornerstone of a successful AFC application is cover integrity. Maintaining the integrity of the cover during the post-closure period ensures that the cap is functioning as designed. As long as this is the case, leachate quality and quantity should be within expected limits. Further, good cap integrity minimizes the possibility of groundwater quality issues and ensures that methane generation rates are as predicted.

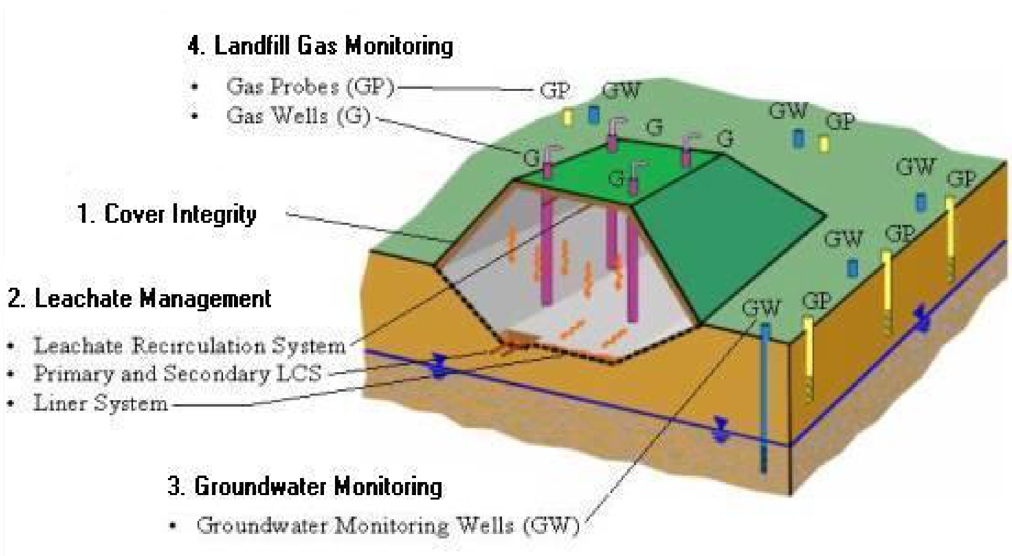

Figure 6-1. Major elements of post-closure care.

Every landfill situation is different; therefore, closure and post-closure care issues should be tailored to site- and facility-specific considerations. The regulatory program under which a site is closed largely defines the necessary level of post-closure care. Some sites using an AFC may not be required to perform all of the actions discussed in this section.

6.2 Flux Monitoring

As regulatory agencies become more confident that alternative covers are capable of providing an acceptable level of protection to the environment, the installation of flux monitoring devices may no longer be required.

As AFCs gain increased acceptance, it may be necessary to measure or estimate the flux through the cap, with two main goals in mind: to ensure that the landfill cover has been constructed to design standards and to ensure that flux through the cover is consistent with predicted or allowable levels. As regulatory agencies become more confident that alternative covers are capable of providing an acceptable level of protection to the environment, the installation of flux monitoring devices may no longer be required. At this writing, there is no industrywide acceptable level for flux through an AFC and no commonly agreed upon method of demonstrating performance. A complicating factor is that current flux monitoring devices contain uncertainty inherent in their operation. Simple maintenance can cause variability in the quality of data they collect.

There are currently two common methods of monitoring flux through a cover. Various forms of lysimetry give a direct measurement of performance by capturing and measuring flux through a given area of the cover (see Section 4.5.8). Calculations using data from soil moisture probes give an estimate of performance. The pan lysimeter measures deep percolation and is typically installed at the base of the cover system. Soil moisture probes can be installed anywhere in the cover system but do not provide a directly quantifiable number for amount of moisture percolating through the cover system. The uncertainty associated with estimates of flux calculated from probe data may well be much larger than the estimates.

During closure and the early post-closure care period, flux monitoring devices may be needed to determine whether an AFC is functioning in accord with approved design (including operational and monitoring compliance criteria and specifications). Data from flux monitoring devices alone may not be sufficient cause to trigger corrective action on an AFC but may trigger further actions, such as increased monitoring or evaluation of the system. Upon receipt and confirmation of consistent suitable flux rates, it may be possible to stop monitoring flux for the remainder of the post-closure care period, provided cap integrity is properly maintained. A good overall indicator, and a RCRA C requirement, of cap/landfill system performance is monitoring the leachate generation rates.

6.3 Cover Integrity Monitoring

6.3.1 Cover Inspections

After construction, standard inspections of AFCs are required to indicate the need for maintenance. Site inspections should be conducted as part of a long-term surveillance or monitoring program. The general site inspection consists of conducting visual observations of the AFC. Drainage channels and swales should also be inspected for any erosion damage. Notable damage to or degradation of the soil cover—including the formation of rills, loss of vegetation over significant portions of the cover, or development of visible animal burrows or trails over the soil cover—should be documented and report. Site inspections should be conducted in accordance with approved plan. These inspections may consist of conducting such operations as on-site visual inspection along transects at a predetermined spacing, aerial photography, taking measurements at erosion control monuments, collecting vegetation data, photographing and staking deficient areas, and documenting the findings in site inspection reports.

The first two years following construction completion are critical to the establishment of vegetation and for gathering information regarding the potential degradation mechanisms for the soil cover. Therefore, comprehensive and general site inspections should be conducted more frequently during this period. Beyond the first few years following construction completion, vegetation will have been established and substantial operations and maintenance records will have been collected to support the request for reduced frequency of both informal and formal site inspections.

Inspections should be conducted in strict accord with the requirements of the task-specific health and safety plan for conducting long-term operations and maintenance of the site.

Routine maintenance and repair activities should be defined and conducted as needed. Other nonroutine repairs that are not defined may require documentation in a repairs and verification report for review and acceptance by the regulatory agencies. This report could include the following:

- plan objective,
- description of deficiencies requiring repair or maintenance,
- proposed action to address deficiency,
- implementation plan and schedule, and
- supporting documentation

Inspections and repairs should not be initiated when conditions exist that could damage the cover system. Such conditions include excessive soil moisture following a precipitation event and excessive dry soil and windy conditions.

6.3.2 Settlement Monitoring

Subsidence inspections can be used to determine the location and amount of settlement that has occurred underneath or within a cover. Settlement plates physically measure the amount of settlement for the cover and foundation materials and can be used to distinguish the difference between cover and foundation settlement.

The settlement plate is placed on the foundation material during construction and cover materials are placed at the specified density around the vertical rod to the marking ring located on the rod. Measurements are taken of the northing, easting, and elevation of the rod tip and recorded for later comparison.

During inspections, the northing, easting and elevation of the respective settlement plate rod tip can be measured using a global positioning system (GPS) with a horizontal and vertical accuracy of ±0.10 feet. Movement of the surface of the soil in reference to the marking ring on the rod indicates that either erosion or settlement of the cover materials has occurred. If the rod tip has moved from the reference measurement, settlement below the cover has occurred.

The surface should also be inspected for areas where water has ponded or where soil cracking or sliding is occurring.

6.3.3 Erosion Monitoring

The soil cover should be inspected regularly for the following:

- rills (cracks or small channels measuring up to 6 inches wide by 4 inches deep),
- gullies (cracks or small channels measuring greater than 6 inches wide by 4 inches deep),
- increased exposure of erosion control monuments,
- intrusion by humans or animals,
- trails showing human or animal activity, and
- damage from vehicular traffic such as ruts and tire marks.

Erosion inspections should determine the location and amount of erosion that has occurred at the surface of the cover. Erosion measurements can be used to determine the corrective action necessary.

Erosion control monuments can be installed during construction to indicate the amount of subsequent surface erosion. Each erosion control monument is placed at an elevation that is representative of the surrounding ground elevation. The elevation and state plane coordinates of erosion control monuments should be surveyed in conjunction with the topographic survey performed at the completion of the project.

To determine erosion, measure the cover surface at each erosion control monument and at four elevations evenly spaced and approximately 10 feet from the control monument using a GPS with a horizontal and vertical accuracy of ±0.10 feet. The measurements can be taken in the four cardinal directions (north, south, east, and west) as determined by GPS.

The average of the four measurements can be compared to the baseline established during the initial site survey to assess the extent of and/or potential for erosion. Surveying the elevations outward from the erosion control monument and comparing those elevations to the base line elevations determines the extent of the deficient area.

6.3.4 Vegetation Monitoring

Inspect cover vegetation for burned areas, overall vigor, excessive grazing, disease or pests, and weed infestations. Vegetation may also require formal sampling to demonstrate compliance with predetermined performance requirements.

6.3.5 Sampling Protocol

All areas to be sampled in any given year for assessment with respect to vegetation performance criteria as specified in the approved design and operation and maintenance plans should be considered as a single treatment area for sampling purposes. Designs typically specify a percentage of ground cover required to sustain an AFC.

Sample transect locations should be randomly selected and mapped in the areas to be sampled each year. A sample size of 20 should provide a body of data at least sufficient to detect a 10% reduction in the mean with 90% confidence. Sample locations can be newly established each year (that is, not permanently marked) at new randomly selected points. Maps showing the location of random samples can be included with an annual report. Transects may be efficiently located in early summer to facilitate unimpeded progress during the actual sampling period beginning no earlier than August 1 and being completed no later than 1 October.

6.3.5.1 Data Collection

A variety of methods can be use to collect vegetation cover data, but the point-intercept method is standard and efficient. The point-intercept method of cover data collection is efficiently accomplished using an optical sighting device, but other equipment is available. A single feature such as bare soil, litter, standing dead, rock, or live plant, is recorded as a "hit" at each of the 100 points. "Standing dead" is dead plant matter that has not yet fallen to the ground, where it would then be called "litter." "Rock" is any mineral particle with a maximum dimension ≥1 cm.

Personnel typically work in teams with one observing ground cover and the other recording each "hit" as a "tick" mark. Data collection sheets can be used to tally hits on bare soil, litter, standing dead, rock, and live plants by species. Plant species present within sampling transect can be tallied with a "P" or other distinctive nonnumerical indication so that the existence of infrequent species is made apparent. The tally of all species can be used to calculate a measure of species density (number of species per 100 m^2), which, in conjunction with the "frequency" (actually constancy) calculated for each species among all sampled transects, contributes a useful and comparable view of species richness for use in later interpretation. The resulting information may prove to be very useful during succeeding years as vegetational trends are evaluated.

Plant species that cannot be accurately identified in the field will be recorded as "UNK#1," "UNK#2," and so on, and placed in a plastic bag labeled with the date, location, and transect number. Qualified personnel can properly identify unknown plants at a later date. Once identified, the plant species name should be written on the data collection sheet and the plant specimen discarded or pressed for later use as a herbarium reference specimen.

6.3.5.2 Equipment

Each team in the field requires the following equipment in good working condition:

- optical sighting device,
- tripod (pistol-grip panhead suggested for maximum efficiency),
- 50-m tape (meter marks highlighted on both sides for maximum efficiency),

- steel surveyor's arrow (for anchoring end of tape),
- data collection clipboard with blank forms and species list,
- meter stick, and
- compass (for sighting random azimuths).

6.3.5.3 Reporting

The annual report of the vegetation monitoring of the site should include the following:

- A brief introduction with general description of environmental conditions of note such as notes on wildlife use, weed invasion, insect abundance.
- Recitation of methods, including any variance from the above-prescribed standard procedure.
- Review of climatic data since the previous year's sampling using any site data available or the closest available data.
- Presentation of collected data, including individual transect data and mean cover values by vascular plant species, cryptogams, bare soil, litter, standing dead, and rock as well as total vegetation cover and total ground cover (vegetation + litter + standing dead + rock). Standard deviation (n-1) should be shown for the latter two totals. Relative cover values should also be presented. Overall species density should be presented by transect and as a mean in number of species per 100 m^2. Frequency (constancy) should be shown by species. Relative frequency and importance values may be calculated also.
- A species presence table can be provided in which all species encountered during the year's sampling are presented by life form and provenance (native or introduced).
- Compilation of previous year's data for convenient and direct comparison of current year's values to previous values. This compilation should present mean values by species as well as bare soil, litter, standing dead, rock, total vegetation cover, and total ground cover.
- A direct statement as to the status of the vegetation compared to the predetermined performance criteria.

6.4 Leachate Management for Solid Waste Landfills

6.4.1 Introduction

Subtitle D of RCRA requires certain design and operating criteria for hazardous and solid waste landfills. Once a landfill is closed, the site owner must monitor and maintain the site for what is referred to as the "post-closure care" period. Post-closure care activities provided for under Subtitle D include leachate monitoring and management as necessary, groundwater monitoring, inspection and maintenance of the final cover. Subtitle D specifies a 30-year post-closure care period unless this period is extended or shortened by the regulatory agency on a site-specific basis. The decision to extend or shorten the post-closure care period is partially based on whether the landfill is a threat to human health or the environment.

6.4.2 Current Subtitle D Requirements for Post-Closure Care for Leachate Management

The federal regulations promulgated under Subtitle D are designed to minimize environmental impacts from MSWLFs and require that post-closure care activities be conducted at all closed facilities to ensure long-term protection to human health and the environment. These regulations are codified 40 CFR Part 258. These regulations establish requirements for owners and operators to maintain leachate collection systems that will maintain less than 30 cm of leachate on the liner of the closed waste landfill and monitor environmental conditions. One of the key components of the federal regulations is the implementation of a minimum 30-year post-closure period for leachate management with an alternative time frame available.

6.4.3 Leachate Quality

Land filling solid waste creates an anaerobic environment and leads to decomposition of the putrescible fraction of organics in the waste stream. The process is similar to organic digestion of sewage sludge and static pile anaerobic composting. There are chemical, physical, and biological processes of degradation that are well known and ultimately lead to an inoffensive end product. This transformation of the organic solid waste material initially is started by infiltration of rainwater that leaches out the easily degradable organic compounds (Figure 6-2). Facultative anaerobic bacteria predominate during this stage and convert carbohydrates, proteins, and fats into organic acids and alcohols. During this phase of degradation, referred to as the "acid" or "acetogenic" phase, pH levels decrease briefly from near neutral to around 5.5–6. The organic acids produced (also referred to as "volatile fatty acids" [VFAs]) are primarily acetic, propionic, butyric, and valeric acids. The soluable organic content of the leachate during this phase (expressed as chemical oxygen demand [COD] and biological oxygen demand [BOD]) also increases substantially into the 10,000–30,000 ppm range with high ratios of BOC/COD near 1.

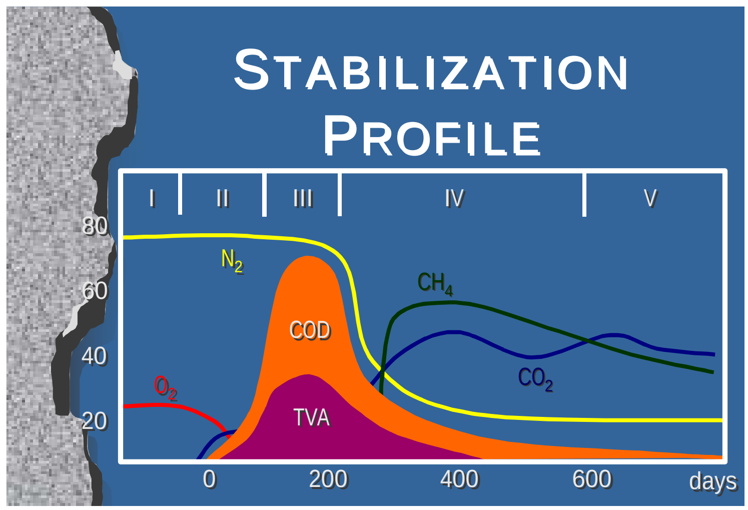

Figure 6-2. Stabilization profile.

During the gas production phase described above, as the food sources (VFAs) are depleted, organic acid production decreases and pH increases, allowing anaerobic methane-fermenting bacteria (methanogens) to increase in population and convert the organic acids and alcohols into methane and carbon dioxide. During this phase of the landfill life, as more methane is produced, a concurrent decrease in leachate BOD and COD can be observed. Methanogens then become the dominant type of bacteria, and significant decomposition of cellulose and hemicellulose organics begins. The methane gas production phase can last for considerable time, depending on the moisture available to the waste. In this phase of where VFAs or carboxylic acids are depleted, the BOD/COD ratio is relatively low due to rapid degradation of any dissolved organic material. Several researchers have determined that, when the BOD/COD ratio is <0.1 (as reviewed by Barlaz et al. 2002), the leachate is organically stable, and concentrations are expected to decline further with time. This effect, meaning that the source strength is stable and declining, is observed in most closed landfills when gas production typically increases in the first year after closure and also declines with time. The closed landfill may have recently disposed waste in the upper levels still producing gas and leaching organics, but the lower layers, typically partially saturated and degraded, serve as a biofilter or bioreactor that consumes degradable organics and attenuates metals (Kjeldsen et al. 2002, Barlaz et al. 2002, Terashima 1989, Stegmann 1983, Ham 1982). Long-term data for metals are presented in these references. Volatile organic compounds (VOCs) also were reviewed by Barlaz et al. (2002) and Kjeldsen et al. (2002). They concluded that long-term trends were confounded by changes in waste composition, since some of their historical data came from sites that were pre-Subtitle D and accepted industrial liquids and sludges. Leachate data from municipal solid waste–only sites, especially Subtitle D sites, show fewer types and lower concentrations of VOCs. A model was developed by these authors to evaluate long-term behavior of VOCs based on phase distribution mechanisms and first-order degradation. The model shows that VOCs will be released in landfill gas within a decade after closure. The authors also concluded that leachate quality from closed landfills does not represent a long-term threat to the environment. The only chemical constituent described in the literature and studies cited above that increases with time is ammonia nitrogen, a typical by-product of anaerobic digestion/degradation, due to degradation of proteins.

EPA regulations provide that leachate no longer has to be managed if it is not a threat to the environment, but a landfill owner wanting to use this provision must perform additional monitoring and data collection. It is suggested that leachate from either separate waste management units (WMUs) or composite samples from the entire site be monitored for applicable surface and groundwater standards and to assess the potential risk that the leachate may pose to human health and the environment. The frequency of analyses can be based on leachate quantities generated, since as discussed in the next section, most sites will show a decline in quantity over time and semiarid to arid sites may have very low leachate quantities even just after closure. Evaluation of monitoring results based on leachate indicator parameters, as may be described in applicable guidance or regulation or developed with site specific information, may support a request for less frequent monitoring

Also, background concentrations in groundwater monitoring wells should be taken into account since some constituents required for groundwater monitoring may be above concentrations in leachate (either due to natural conditions or off-site contamination) and therefore would not be detectable in downgradient wells in the event of a leachate release. There may be off-site contaminants caused by upgradient sources not attributable to the landfill. In this case, if certain constituents in upgradient groundwater are present at levels above their MCLs, then the upgradient concentrations become the “new” compliance concentration for which release from the landfill are assessed. This is important in determining if leachate quality is a threat to the environment from the landfill.

6.4.4 Leachate Quantity

The quantity of leachate during post-closure (i.e., after capping) is generally much lower than during the active phase of the landfill due to very low infiltration and increasing runoff. Bonaparte, Daniel, and Koerner (2002) reviewed leachate generation rates for landfills located in different geographical areas of the United States and evaluated leachate generation rates of more than 71 MSWLFs, located mostly in the midwest/northeast (MW/NE) and southeast (SE) parts of the country. Only two were located in the West.

As expected, the leachate generation rates are the highest during the initial stages of filling when the landfill cell bottom is exposed to rainfall and waste is initially filled. It is sometimes difficult to separate waste from rainfall falling on the rest of the unfilled liner. In the active phase of filling, when waste has covered the cell bottom entirely and several lifts of municipal solid waste are in place, leachate flow rates decrease by factors of up to 3–5 from levels during the initial period due to absorption within the waste. Table 6-1 shows the average flows for these periods, where the MW/NE has average values to those of the SE. Data for the MW/NE after closure show flow rates decreasing by one order of magnitude compared to the active phase within several years after capping.

Table 6-1. MSWLF leachate generation rates, in gallons/acre/day
(Range of total monthly flow average over entire period. Values in parentheses are average mean flow for all facilities in data set.)

Period	NE	SE	W
Initial period of operation	105–3990 (1000)	148–4370 (1000)	
Active period of operation	4–1770 (350)	30–1090 (290)	5–10 (8)
Post-closure period	5–69 (40)		

An extension of the curve for leachate control and removal system (LCRS) flow rates versus years after closure, if modeled, should show zero flow in about year 15 for the average landfill in the MW/NE and SE (Figure 6-3). (It is interesting to note that the average leachate flow is five times greater after several years for post-closure of MW/NE sites than during the active period of operation for western sites. This may show that existing leachate generation rates for active sites should have a role in determining the type of cap or cover that is suitable for the landfill at closure.) The report also concluded that the HELP model showed leachate generation rates in the same order of magnitude as the observed rates (see Figure 6.4), but the use of HELP default values typically results in conservative estimates.

The quantity of leachate should be tracked whenever leachate is removed for treatment. Flow meters at each sump or WMU or composite for the entire site should be used or truckloads counted. Flow meters require maintenance and calibration and should be selected considering these factors. The flow data is important, especially if a model is used to estimate potential leachate impacts to groundwater and surface water since the mass of potential pollutants that may be released to the environment need to be estimated in transport models used to evaluate potential risks, as shown in the conceptual model recommended for evaluating leachate management options.

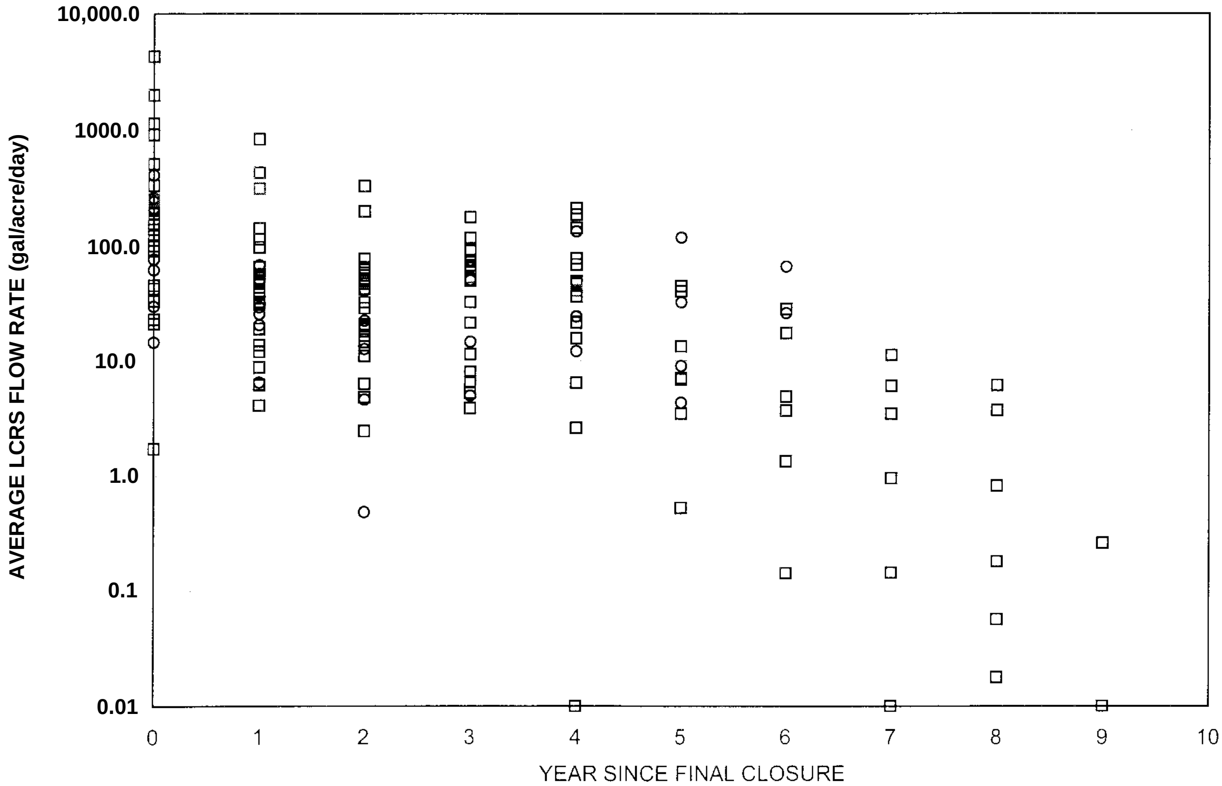

Figure 6-3. Average leachate collection and removal system flow rates after closure for 11 municipal solid waste cells (circles) and 22 hazardous solid waste cells (squares).
Source: Adapted from Bonaparte, Daniel, and Koerner (2002).

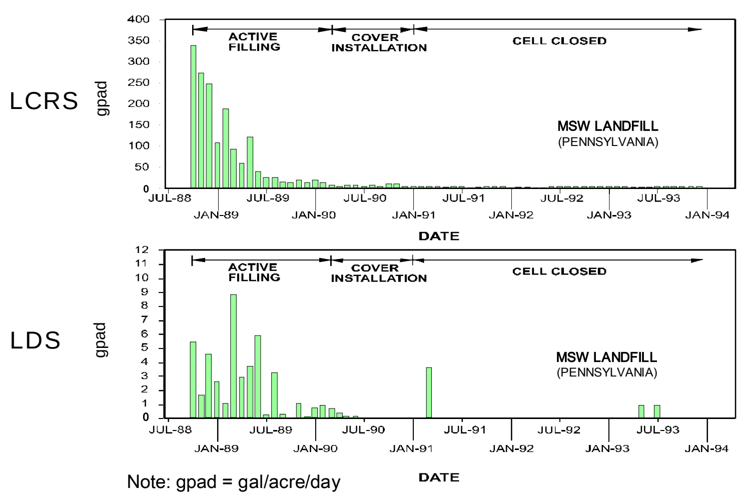

Figure 6-4. Leakage control and recovery system flow rates and leakage detection system flow rates.

6.5 Post-Closure Monitoring System Evaluation

6.5.1 Groundwater Monitoring

The primary goal of groundwater monitoring is to detect any harmful release from a facility as soon as possible. With this simple concept in mind, the groundwater monitoring system for a facility with an AFC design is no different than for a facility with a prescriptive cover system in place. The basic components of a sound groundwater monitoring system should be based on a thorough understanding of the hydrogeologic properties of a site.

In the case where a groundwater monitoring system is already in place at the time of closure, then in all likelihood all that will be required is the continuation of the monitoring program for the post-closure care period. In a situation where groundwater monitoring is not already in place, then a comprehensive groundwater monitoring system evaluation is performed and a groundwater monitoring plan implemented. A complete groundwater plan would address such items as a sampling and analysis plan, a groundwater monitoring plan, and a statistical analysis methodology for data evaluation.

Paramount to the installation of an adequate groundwater monitoring system is a determination of the geologic and hydrogeologic properties of the site to be monitored. With a thorough understanding of the hydrogeologic properties, monitoring well placement can be optimized. When monitoring wells are placed with a sound understanding of the hydrogeologic properties of a site, the shotgun approach to monitoring well placement can be avoided. The result is the installation of fewer, but better placed, monitoring wells, which are better capable of monitoring the groundwater quality around the facility.

Groundwater monitoring parameter lists are designed to detect those constituents that could reasonably be expected to leach from the waste streams disposed in the facility. This list contains constituents that are generally more mobile and are expected on the leading edge of any contaminant plume originating from the waste disposal area. Alternatively, a list of chemical constituents that are indicators of changing groundwater chemistry could be monitored. In either case, should routine groundwater monitoring detect a problem, an assessment mode of monitoring is adopted. This situation typically requires monitoring an increased list of parameters, possibly on a greater frequency. Additional monitoring points are usually installed to further define the extent of contamination and to help with the design of a remedial system to address the groundwater contamination should action be deemed necessary.

Where an AFC is installed, consideration should be given to factors that may affect the groundwater monitoring system, such as amount of annual precipitation, design of the landfill liner system, if applicable, hydrogeologic properties of the site, and construction parameters of the actual cover system.

6.5.2 Landfill Gas Monitoring

Landfill gas is composed of three major components—methane, carbon dioxide, and water. This section discusses primarily methane because its monitoring is specifically addressed in most landfill regulations. On installation of a landfill cap for landfill closure, conditions become favorable for the production of landfill gas. Once a landfill cap is installed, organisms present in the waste pile quickly use up available oxygen, and conditions become anaerobic. Methane is one of the major byproducts of the anaerobic digestion of organic material contained in the waste pile. Methane can become an explosion hazard if allowed to accumulate in confined areas such as structures located on or close to the landfill, so its migration from a landfill is of particular importance.

Several factors control the amount of methane generated by a waste pile, including amount and types of organic material present, presence of oxygen, and perhaps most importantly, water content in the waste pile. As methane production starts to increase, pressure is generated in the waste pile, leading to migration of the methane gas. Two main transport pathways exist for the migration of methane: diffusion through the landfill cover and lateral migration out the sides of the landfill. The lateral extent of methane movement varies with the characteristics of the surrounding soils, with off-site migration considerable distances possible under the right conditions. Since methane is lighter than air, it naturally tends to rise in the waste pile and start to diffuse through the landfill cap. This should be a major consideration when designing an ACF to ensure compliance with applicable regulations during the post-closure care period.

Sites that use an AFC have several issues regarding landfill gas that should be addressed during the post-closure care period. Methane should be routinely monitored at the property boundary and in structures on site. The operation and maintenance of a landfill gas extraction system, if present, should be accounted for. Upgrades and repairs to existing landfill gas management systems should be performed. Likewise, if off-site migration of methane is detected, mitigation measures should be put into effect. In most large landfills, the New Source Performance Standards of the Clean Air act will require that a landfill gas control system be put in place. Again, these requirements are not much different than those of a landfill using a prescriptive cover system.

Typically, alternative covers are more permeable than prescriptive covers and allow diffusion of methane gas through the cover at a greater rate.

The actual design of the alternative cover influences the importance of each of these issues. Typically, alternative covers are more permeable than prescriptive covers and allow diffusion of methane gas through the cover at a greater rate. Depending on the size of the landfill, this fact may cause compliance problems with applicable air quality permits and may allow for excessive buildup of explosive gases in on-site structures. Methane and other landfill gases could also be toxic to the vegetative cover for a landfill cap, which may be a major design feature of the alternative cover, and could cause the cover to not function as designed. Similarly, due to the potential greater permeability, additional water may make its way into the waste pile, causing even greater methane generation rates. This scenario is not necessarily bad and in fact may be part of the overall design goal of an AFC. In either case, it should be accounted for in the post-closure care plan.

Once methane production reaches certain levels, the gas must be evacuated from the landfill to control its migration. This evacuation is usually accomplished by installing either a passive system or an active system. Passive systems consist of a series of cased boreholes placed in the landfill with a permeable screen, which gives the landfill gas a direct pathway through the cover system to vent into the atmosphere. Internal pressures generated by the gas provide the mechanism to drive landfill gas to the vents. The second way is the installation of an active system consisting of a series of wells and piping with a vacuum applied to pull gas from the waste pile. The collected gas is then flared or treated and used in some beneficial manner. During the post-closure care period, methane generation rates may level off to the point where an active system is no longer needed. The system can then be converted to a passive system and routinely monitored. In any case, provisions must be placed in the post-closure care plan to account for the operation, maintenance, and possible abandonment of these systems.

Odor control, although typically not covered in regulations, is an issue associated with certain types of landfills. When using AFC systems, depending on the location of the landfill with relation to the public, additional provisions may need to be included in the post-closure care plan for odor control measures.

6.6 Post-Closure Considerations in Alternative Final Cover Design

6.6.1 Introduction

All landfills require care after they have been closed to prevent post-closure escape of waste, leachate, or landfill gas to the environment at levels that would be a threat to human health and the environment. The purpose of the landfill cover is to prevent such escape during the post-closure care period. The regulatory requirements for post-closure care of cover systems are addressed in the Municipal Solid Waste Landfill Regulations R. 258 Subpart F and the Hazardous Waste Management Regulations R. 264 Subpart G, as well as in the regulations of states approved to implement these regulations. These regulations typically require the following:

- a plan for inspection and maintenance of the cover;
- measures to be taken in the event that problems develop during the post-closure care period that could result in the release of leachate, landfill gas, or waste to the environment; and
- a description of the proposed use of the property during the post-closure period.

The typical standard for acceptable post-closure care of a cover is the success of the cover in protecting human health and the environment (i.e., its performance).

Most post-closure regulations do not provide detail on how to implement post-closure care, except that post-closure care is typically required for a period of at least 30 years after construction of the final cover system. Instead, most regulations allow considerable flexibility to the owner or operator during post-closure care. The typical standard for acceptable post-closure care of a cover is the success of the cover in protecting human health and the environment (i.e., its performance). In fact, many post-closure regulations suggest that the activities and duration of post-closure care could evolve during the post-closure period based on the performance of the cover. For example, in the *Solid Waste Disposal Facility Criteria Technical Manual* (EPA 1993b), EPA specifically allows owners and operators to shorten the post-closure care period or to stop managing leachate (upon agreement of the director of an approved state) if such activities are no longer needed to protect human health and the environment. Because such flexibility is allowed, the benefits of alternative covers can be incorporated into post-closure care plans without violating the intent of existing regulations.

The following guidelines for post-closure care at alternative final cover landfills focus on the manner in which post-closure care can be simplified or minimized through the use of AFCs.

6.6.2 Performance Requirements for Landfills During Post-Closure Care

6.6.2.1 Overview

As described in Section 3.3, the purpose of a landfill cover is to prevent the escape of materials from within the landfill that would cause a threat to human health and the environment. The materials in the landfill that could affect the environment are waste, leachate, and gasses that were either disposed in the landfill or that are the products of decomposition that has occurred in the landfill. To prevent escape of these materials, the cover must provide containment of the materials until such time that they are no longer a threat to human health and the environment. The post-closure care period is defined as time during which such containment is required. In this section, performance requirements are provided regarding the containment of waste, leachate, and landfill gas during the post-closure care period. In general, the goal of the post-closure care plan (as described in more detail in Section 6.6.3) is to maintain containment of the wastes and to determine whether post-closure care is still needed.

6.6.2.2 Comparison to Design Goals/Post-Closure Uses

Design goals should be periodically evaluated against the initially anticipated post-closure land use. Corporate and business goals and economics change with time. Changes may dictate alternative forms of property management, such as redevelopment or configuration. Revised property management schemes may even include liquidation of the property. Redevelopment may include reuse of the property for an industrial exposure scenario for continued industrial use either by the current owner or future owners. Conversely, reuse may be very different than the historical property configuration. Industrial complexes have been sold or donated to municipalities for reuse as amusement parks, sport fields, wildlife refuges, and open space.

The post-closure mechanism may simply identify the requirement that if future land uses change, then the owner/operator and regulatory agency will develop a process that will address any modifications of the landfill and its associated monitoring.

It appears that future changes in property configurations can be expected, or at least anticipated, for many existing solid and/or hazardous waste landfills. Potential changes in the use of these landfills may be accounted for if the regulatory mechanisms (post-closure care permits and orders) include procedures and processes to modify the existing post-closure care plans to accommodate the future land use criteria. Varying degrees of regulatory flexibility may be built into the post-closure care mechanisms. Alternatively, the post-closure mechanism may detail the processes and procedures for developing plans to accommodate alternative future land use options. One key to a successful post-closure care mechanism is to envision potential alternative land uses for the landfill and be able to meet the owner/operator's, regulators', and public stakeholders' needs during the transition and continued long-term care.

6.6.2.3 Waste Containment

Factors to consider regarding waste containment:

- *Stability*
- *Erosion*
- *Animal intrusion*
- *Vandalism*
- *Settlement*

The final alternative cover must contain the waste in the landfill as long as prevention of uncontrolled releases of the waste is needed. To ensure that the waste is contained, actions should be taken during the post-closure care period to verify that the cover is intact and shows no signs of damage that could result in uncontrolled release of waste.

Stability. Foundation or slope instability can cause in movement of the waste in the landfill, which can result in damage or breaches in the cover system and uncontrolled release of the waste in the landfill (see Figure 6.5). Foundation instability results from foundation soils that have inadequate shear strength to resist the loads applied by the overlying waste; this can be caused by either excessive loads (e.g., from waste that is too high or too steep or too dense, or from excessive buildup of water within the landfill) or from inadequate foundation shear strength (e.g., weak soils, high groundwater conditions, erosion of soils at the toe of the landfill, or excavation at or near the toe of the landfill). Slope failures can be caused by either instability of the waste materials (resulting in lateral movement of waste, usually damaging the cover) or instability of the cover (which can result in sliding of the cover down the slope). Slope failures in the waste are usually caused by weak waste, waste that is too high or too steep or too wet, or excavations on the side slope. Cover failures can be caused by buildup of water in the cover, excessive landfill gas pressure beneath the cover, excessively long or steep cover slopes, or excavation at the toe of the cover.

Erosion prevention—Erosion can cause breaches in the cover, leading to exposure and eventually uncontrolled release of waste. Erosion can be caused by either water or wind. When water or wind flow over soil or rock particles, they apply a lateral force (i.e., tractive force) to the particle that can dislodge the particle; erosion results from storm-water runoff or winds at velocities that cause a tractive force too great for the particle to resist. High storm-water velocities usually occur at locations where runoff is concentrated, where the increased flow depth usually causes increased flow velocities and higher tractive forces. High wind velocities occur at concentrations of wind flow (e.g., corners of cover systems). Erosion can be minimized by maintaining vegetative cover on soils, by providing additional protection (e.g., riprap, erosion mat, or other channel linings) in areas where storm water or wind flows tend to concentrate and by reducing the velocity of storm-water flows to a level that does not dislodge soil or rock particles or damage other slope protection.

Prevention of animal intrusion—Animal intrusion can cause holes in the cover, which can cause water flow into the landfill, landfill gas escape from the landfill, or concentration of storm-water flows that can cause progressive erosion leading to uncontrolled release of waste from the landfill. Animal intrusion is typically a problem near populations of burrowing animals. Such intrusion can be prevented by installing an intrusion barrier (e.g., rocks or cobbles).

Figure 6-5. Poor cover design, resulting in both surface-water erosion failure (left) and sloughing of cover system due to excess buildup of pore water in cover drainage layer (below).

Vandalism or uncontrolled access—Vandalism caused by uncontrolled access to the cover can result in a variety of problems on the cover, from direct damage (e.g., holes, tears, vegetation damage) to minor impacts that could lead to larger problems (e.g., motorcycle trails that concentrate storm-water runoff in locations that are not adequately protected, resulting in erosion and exposure of waste). Vandalism can be controlled by limiting access to the site or, if necessary, through surveillance of the site.

Excessive settlement—Excessive settlement can cause damage to the cover, which could result in a variety of problems that could lead to uncontrolled release of waste. Problems caused by excessive settlement include (a) ponding on the cover, which can lead to increased infiltration and buildup of water in the landfill and instability; (b) cracking of the cover, which can lead to increased erosion or infiltration into the landfill and resulting instability; (c) damage to the storm-water management system, which can concentrate storm-water runoff in areas that are not resistant to the erosive forces of the concentrated flow. Excessive settlement cannot be prevented (although settlement can be minimized by using a lightweight cover), but proper maintenance (as described in Section 6.6.3) can prevent uncontrolled release of waste due to excessive settlement.

6.6.2.4 Leachate Containment

The final cover must contain the leachate in the landfill as long as uncontrolled release of leachate could harm human health or the environment. To ensure that the leachate is contained, actions should be taken during the post-closure care period to verify that the cover is intact and shows no signs of damage that could result in uncontrolled release of leachate. Factors to consider regarding leachate containment are described below.

Prevention of seeps—Seeps occur when leachate in the landfill flows laterally to the cover and migrates through a hole. Seeps are typically isolated and are caused by pockets of leachate that are recharged from the landfill or from infiltration through the cover. Seeps can cause a variety of problems, including damage to surface-water quality, minor erosion (which can progressively lead to significant erosion), and escape of landfill gas. The occurrence of seeps can be minimized by maintaining the cover and by minimizing lateral migration pathways in the landfill (e.g., low permeability or laterally extensive intermediate cover layers).

Maintaining leachate quality—As described above, one of the purposes of the cover is to contain leachate as long as uncontrolled release of the leachate could be a threat to human health or the environment. Therefore, leachate quality must be monitored to evaluate the need for further containment of the leachate. Leachate quality can vary throughout the post-closure care period in response to changes in the chemistry of the landfill (as described by Shimaoka, Matsufuji, and Hanashima 1993) and in response to settlement of the landfill, which may change the vertical flow paths of infiltration water. Significant changes in leachate quality can also result from breaches in the cover, which can result in either increases or decreases in the concentrations of leachate indicator constituents.

Maintaining leachate quantity—Leachate quantity must also be monitored to evaluate the need for further containment of leachate and to directly measure the effectiveness of the cover system at controlling infiltration. During the design of the cover (see Section 3), an estimate is made of the quantity of water that will likely infiltrate through the cover. If the quantity of leachate collected from the landfill significantly exceeds the estimated amount or if there are sudden increases in the leachate flow rates, then there may be a problem with the cover system (e.g., development of a hole, infiltration at the toe, infiltration through decayed roots, seepage along or through gas wells, etc.).

6.6.2.5 Landfill Gas Containment

The final cover must contain landfill gas as long as uncontrolled release of the landfill gas could harm human health or the environment. To ensure that the landfill gas is contained, actions should be taken during the post-closure care period to verify that the cover is intact and shows no signs of damage that could result in uncontrolled release of landfill gas. Factors to consider regarding landfill gas containment are described below.

Minimization of vegetative stress—Vegetative stress can be an indication of uncontrolled release of landfill gas from the landfill. Vegetative stress is usually caused by excessive methane concentrations in the root zone of plants. Plant roots require oxygen to function properly.

Because there are typically microbes in the root zone that consume methane, roots can tolerate some methane. However, if all of the oxygen in the root zone is displaced by methane, then the roots cannot survive. Vegetative stress from methane can be minimized by efficiently collecting or venting landfill gas from beneath the cover, by ensuring that the soil cover is aerated, and by preventing ponding on the cover (which can displace oxygen and cause rotting or methane intrusion).

Prevention of odors—The final cover must function in a manner that prevents odors, which are typically caused by the release of landfill gas from locations where it is concentrated. Such concentrations can occur at cracks in the cover, at penetrations through the cover (e.g., gas wells or monitoring wells), at the edges of low-permeability portions of the cover, and at the toes of slopes of the landfill cover. Gas can also become concentrated when the cover is oversaturated, which can occur in poorly drained parts of the landfill (i.e., areas having a slope too flat to drain rapidly) or in differential settlement areas (e.g., ponded areas).

Prevention of off-site migration—Off-site migration of landfill gas can occur when gas is generated in quantities greater than the capacity of the gas-extraction system to control it. Migration typically occurs at the from the edges of the landfill to either air or to the vadose zone, where the gas may migrate to or beyond the property boundary. Off-site migration in air can be prevented by ensuring that the cover is intact and by operating the landfill gas management system properly; off-site migration through the vadose zone can be prevented through the use of lateral trenches at the perimeter of the landfill and through proper operation of the landfill gas management system.

6.6.3 Post-Closure Care Plan Contents

6.6.3.1 Overview

A post-closure care plan must be prepared and followed for all landfills. Following are recommendations for preparing post-closure care plans for landfills that have been closed using an AFC. For each suggested element of the post-closure care plan, a suggested monitoring or maintenance activity is provided; where appropriate, the suggested activity is followed by suggested contingency actions in the event that monitoring results indicate a problem with the performance of the alternative cover.

Stability:

- Monitor liquid levels in landfill; if levels approach a height greater than expected, then evaluate the source of the leachate and the possible impacts to the leachate management system, landfill gas management system, and groundwater and surface-water quality (e.g., via seeps).
- Prevent excavation at toes of slopes, which could lead to instability.
- Do not exceed permitted heights or final cover grades; if heights are exceeded, evaluate implications to stability and stabilize affected areas accordingly.
- Inspect for cracks at crests of slopes, bulging at toes of slopes, or “leaning” vegetation, all of which could be an indication of slope movement.

- Increase monitoring frequency during periods of high infiltration potential (e.g., spring melting, rainy seasons, after significant storm events); if excessive water flows are encountered from the cap, then evaluate the potential for slope instability resulting from excess buildup of water in the cover system.
- Inspect for bulges in slopes that may be caused by excessive gas pressure buildup; if any such bulges are identified, then evaluate approaches for relieving the pressure.

Erosion prevention:

- Inspect for erosion gullies, surface erosion, and vegetation stressed by surface-water flow; repair such problems as soon as possible to prevent progressive erosive degradation of cover integrity.
- Inspect for areas of unexpected concentrations of surface-water flows (e.g., settled areas, etc.) and manage flow in such areas to prevent excessive scour or erosion of the cover system.
- Inspect along toes of slopes and inverts of channels to see if there is any evidence of impending erosion; if such evidence of impending erosion exists, then repair any problems and evaluate design alternatives (e.g., rounding transitions in slopes, energy dissipaters, etc.) that could prevent such problems in the future.
- Inspect edges of the cap where wind concentrates to see if there is evidence if wind erosion; if such evidence exists, then repair any erosion problems and evaluate design alternatives that prevent such concentrations of wind forces.

Prevention of animal intrusion:

- Check for evidence of animal traffic on cover (e.g., tracks, trails, droppings, etc.); if such evidence exists and the animals are of a type that could damage the integrity of the cover system, then consider institutional controls to prevent animal access to the cover area.
- Check for animal holes in the landfill, which could be a conduit for liquid migration into or gas migration from the landfill; fill such holes as needed and consider the need for features that prevent animal intrusion (e.g., rock barriers, etc.).
- When evaluating the cause of seeps, consider the possibility that the seeps could have been caused by animal intrusion.
- Recognize that, if there is one animal intrusion hole, there are likely many such holes; when finding one hole, consider performing a more comprehensive survey for additional holes and consider a more broad remediation program.
- Fill animal intrusion holes as soon as possible to discourage population increase.

Vandalism or uncontrolled access:

- Inspect for breaches in access controls (fences, gates, natural barriers) and repair such breaches.
- Check for evidence of on-site activity (e.g., motorcycle tracks, trails, etc.) as evidence of uncontrolled access and potential damage to the cover system or related components.
- If vandalism or uncontrolled access activities could damage the cover (e.g., could result in holes or cover damage or concentration of surface-water flows in inappropriate areas), then mitigate damage and consider more effective measures to prevent vandalism or uncontrolled access.

- Consider increasing surveillance if uncontrolled access is a persistent problem.

Excessive settlement:

- Perform periodic surveys to evaluate the rate of landfill settlement as long as settlement continues at a significant rate (i.e., more than 1% of the volume of the total amount of post-closure settlement). Consider increasing inspection frequency for areas that exhibit increasing or problematic settlement.
- Visually inspect landfill for evidence of differential or local settlement that could be a problem (e.g., resulting in ponding, etc.). Focus inspections and maintenance activities at special features of the alternative cover (e.g., settlement may be greater at trees, which could cause a preferential location for infiltration or gas migration).
- If settlement continually affects the performance of the surface-water management system, then consider reestablishing grades to promote positive drainage.

6.6.3.2 Leachate Containment

- Monitor for seeps; if frequency of seeps does not decrease after cap placement, then consider evaluating sources of liquid for the seeps and correcting the conditions that caused the seeps.
- Because seeps can sometimes be difficult to remediate (as a result of the persistence of water in the landfill behind the seep location), pay extra attention to areas that have historically been a problem. In areas where seeps are persistent, consider improving the cover system to further prevent infiltration.
- When seeps are encountered, check for related problems (e.g., vegetation stress at seeps, which could indicate gas escape, or erosion, which could indicate a high-volume seep). Remediation-related solutions as a means to address seep problems include the following:
  - Fix seeps as quickly as possible by excavating through the low-permeability layer beneath the seep and covering the repaired area with low-permeability soil.
  - Check for evidence of locations near the seep where surface water might have been inadvertently routed to a breach in the cover, resulting in the seep.

6.6.3.3 Maintaining Leachate Quality

- Monitor leachate quality for compliance with discharge limitations and health-based standards.
- Evaluate data for evidence of changes in leachate quantity, which could be an indication of a breach in the cover. Increases in concentrations of leachate constituents may be an indication of increased biological activity caused by increased seepage through the cover, which could be an indication of a problem with the integrity of the cover system.
- If changes in quality are identified, define the location of the problem if possible and check the cover in the area for evidence of a breach or excessive settlement.

6.6.3.4 Maintaining Leachate Quantity

- Monitor leachate quantity for increases or decreases. Increases in leachate quantity could be an indication of a breach in the cover.

- In the event of increases in leachate quantity, check to see whether the increase is significant or just temporal.
- If changes in quantity are identified, define the location of the problem if possible, and check the cover in the area for evidence of a breach or excessive settlement.
- A decrease in leachate quantity may be the result of landfill stabilization or a jeopardized leachate collection system

6.6.3.5 Landfill Gas Containment

Minimization of vegetative stress:

- Monitor the entire cover for evidence of vegetative stress, which could be an indication of a breach in the cover and escape of landfill gas through the breach.
- Note the areal extent and degree of stress for comparison with future surveys.
- Evaluate the cause of the stress (e.g., landfill gas, excessive water, poor sunlight, lack of soil nutrients, too little water, etc.).
- If the stress is caused by landfill gas escape through a breach in the cap, then check for evidence of other landfill gas problems that could also result from a breach in the cover (e.g., odors, off-site migration).

Prevention of odors:

- Monitor for the presence of odors.
- Keep a log of odor occurrence and correlate the occurrences with weather events, season, and other potential contributors.
- Check for locations where landfill gas might have concentrated and caused significant odors (e.g., at passive gas vent pipes, in low areas, etc.).
- In the event of a breach in the cap (e.g., at a penetration or through a crack), seal the breach and pay extra attention to those locations during future inspections.

Prevention of off-site migration:

- Check landfill gas monitoring results for evidence of off-site migration problems or the potential for such problems.
- If problems exist or may exist, then check the cover for evidence of a breach.

6.6.4 Post-Closure Costs

6.6.4.1 Final Cost Savings Analysis

Economics in conjunction with governing policies, public stakeholders, and regulations drive many of the decisions associated with the current and future uses of landfill facilities. Economic scenarios and projections are an integral part of the design process, and they should also incorporate the costs associated with the long-term care of the AFC landfill. More complete financial information may form the basis of better economic decisions associated with each facility. One way to integrate the permitting, design, testing, construction, and post-closure phases of landfills is to use the life-cycle costing approach to economic analysis.

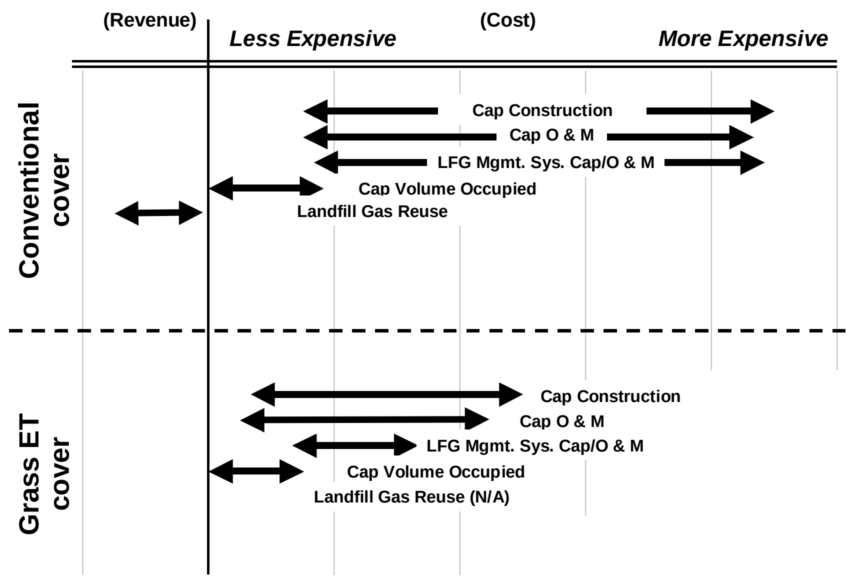

Figure 6-6. Comparison of grass ET cover life-cycle costs with those of conventional covers.

The life-cycle costs should include all costs associated with the actual permitting process, design, testing, construction, QA/QC, reporting, and long-term operation and monitoring. A project specific comparison of the range of life cycle costs is presented in Figure 6-6. Long-term operations may include activities such as leachate removal and disposal, corrective actions of facility conditions such as security features, cover elements, diversion ditches, etc. Long-term monitoring costs can include the inspection of groundwater monitoring wells, fences, signs, drainage ditches, and associated groundwater monitoring, sampling, analysis, and reports to regulatory agencies.

The life-cycle cost should incorporate anticipated changes in monitoring criteria and frequencies. For example, in Colorado hazardous waste disposal facility inspections may be conducted more frequently during the initial post-closure care operation period than during the later phases of the post-closure care period. The frequency of inspections may be reduced over time pending the stability and integrity of the cover. Some inspections may be reduced from weekly to monthly to quarterly, and eventually semiannually. In addition, post-closure cost estimates should integrate modification of the groundwater monitoring analytical suite and frequency. Some facilities may have a reduced analytical suite for three quarters, with and expanded analytical suite during one quarter of an annual groundwater detection monitoring program. In addition, the groundwater monitoring frequency may be reduced from quarterly to semiannual based on the stability and integrity of the cover and the lack of detection of analytes in the groundwater and/or leachate.

6.6.4.2 Alternative Construction Compared to Federal Standards

For the purposes of performing an economic baseline study for comparative analysis purposes, the typical legally binding regulations for the site are applied. These could be the federal, state, county, or other local regulations for solid or hazardous waste facilities. The average baseline cost per acre for the design and construction of a regulatory prescriptive cover can be estimated in a particular area from historical construction projects. The average cost per acre for a prescriptive solid waste disposal facility based on the federal solid waste regulatory requirements is about $100,000 per acre; the average cost per acre

Cost estimates for an AFC may indicate significant savings from more readily available construction materials, less energy required for the construction of the engineered soils, less QA/QC testing required related to fewer components, and possibly less expense associated with reduced geosynthetic materials.

based on the federal hazardous waste regulatory requirements is $150,000 per acre.

An AFC disposal facility cost should be based on the site-specific facility design, or at least a conceptual version, once agreed to by the approving regulatory agency. Cost estimates for an AFC may indicate significant savings from more readily available construction materials, less energy required for the construction of the engineered soils, less QA/QC testing required related to fewer components, and possibly less expense associated with reduced geosynthetic materials. All of these factors should be incorporated into the AFC cost estimate when comparing conventional and AFC systems.

In addition to closure system construction costs, it may be valuable to consider the life-cycle costs of the cover design. In general, the life-cycle cost of a cover system is the entire cost to construct, operate, and maintain the cover throughout the post-closure care period. Because the cover system affects so many other aspects of the post-closure cost of the landfill, it may be useful to consider all landfill post-closure costs instead of just cover system costs when comparing cover system alternatives or when predicting estimating the requirements for post-closure financial assurance for a landfill. The life-cycle cost may consist of landfill gas management system costs, leachate management system costs, and the cost or value of disposal airspace that is occupied by the cover (i.e., thicker cover systems occupy disposal capacity that may be of significant value). For sites that generate a significant quantity of landfill gas (e.g., large MSWLFs), the value of the landfill gas resource should be considered; for example, more permeable cover systems (e.g., phytocovers) will likely transmit more landfill gas than less permeable cover systems (e.g., geomembrane covers), which may result in a significant economic loss over the post-closure care period. Finally, some consideration should be made of the risk of implementing more innovative cover systems or cover systems that are more susceptible to catastrophic damage. When comparing life-cycle costs of alternatives, noncost factors should be carefully considered (e.g., reduced pollution potential, increased potential for post-closure use, aesthetics, etc.).

7. STAKEHOLDER INPUT

Stakeholders should be involved at every stage of the evaluation, selection, and permitting (if necessary) of waste containment systems. Experience has shown that project benefit from stakeholder input. While these outreach efforts make exceed the specific regulatory requirements, they create a more cooperative partnering between the facility and the community. Stakeholder involvement could benefit from the development and implementation of a public involvement plan, public meetings, and public facility technology working sessions.

Stakeholders could include local, state, and federal government officials, representatives of affected tribes, facility owners and operators, nearby residents, and environmental groups. This outreach should, at a minimum, address the local, state, and federal statues, regulations, guidance, and policy provisions for community input. In addition, efforts beyond those specifically mandated may be warranted at individual sites on a case-by-case basis. Such involvement can lead to better, more defensible solutions and expedite site closure. One of the objectives of the responsible parties should be to integrate tribes and stakeholders into all of their processes. Stakeholder discussions should clearly define the specific cleanup goals and criteria.

Since AFCs are relatively new technologies, when such technology is being considered for permitting or deployment, stakeholders and tribal representatives should be given the opportunity to comment on it and to make their issues, needs, and concerns known. Information about the technology, including alternatives analysis, should be made widely available for public comment.

AFCs may have the potential benefit of providing a better long-term stability using different construction techniques and may be regarded favorably by tribes and stakeholders. However, since AFCs involve design and construction principles different from those used in traditional, low-permeability cover designs, tribes and other stakeholders will have the obvious question "Will it do any harm?" This question must be addressed carefully and honestly.

In some instances, one can cite the examples where the technology has been tried before and report on its success or failure in each situation. In the case of an evolving technology, one may be proposing a solution that is believed to be likely to work but has not been tried previously in a parallel situation. In this situation, accurate and honest information should be given. Explain all of the reasons why the technology is likely to work. Give the details of the possible failure scenarios. How likely is the technology to fail? What damage might be done? Have public discussion about the alternatives. It is possible that tribes and stakeholders will embrace an opportunity to try a new solution to a contamination problem, particularly if there is a good chance that it may succeed where other solutions are likely to fail. Be open about the potential risks and benefits. The affected tribes and stakeholders must be given the opportunity to weigh the potential risks against the potential benefits, since they are often the ones most directly affected by the contamination and by the success or failure of the technology. In certain cases, they are also the ones who bear the cost of the cleanup or, at the very least, as taxpayers in practice serve as the insurer of last resort.

In 1997, the Tribal and Stakeholder Working Group (TSWG), working with the DOE Office of Science and Technology, developed a set of principles for the integration of tribes and stakeholders into the process of evaluating and developing new technologies for the treatment of mixed low-level waste. Below is discussion of the applicable TSWG principles and how they translate to a situation where in situ surfactant/cosolvent flushing is being considered for the remediation of subsurface contamination.

- Minimize effluents—Clean up contamination as quickly as possible. Avoid the generation of reaction side products and new contaminants.

- Minimize effects on human health and the environment—Protect present and future drinking water supplies. Minimize the potential for accidents.

- Minimize waste generation—Minimize the production of waste from the cleanup effort.

- Address social, cultural, and spiritual considerations—Minimize land use and habitat destruction in the cleanup process. Discuss the transport of chemical reagents with tribes and stakeholders and adapt such transport to address their concerns. Respect the social, cultural, and spiritual values of specific sites. Minimize noise and traffic. Protect local vistas. Include the costs of tribal and stakeholder participation in cost estimates and budgets. Include the costs of compliance with intergovernmental agreements in cost estimates and budgets. These cost estimates may also include evaluations of the energy use throughout the remedy's life cycle. If possible, these could include comparative remedy evaluations that are presented at stakeholder meetings.

- Provide timely, accurate, complete, and understandable information in a time frame to consider prior to final decisions and determinations so stakeholders may have an impact on the remedy selection process: Explain the technology screening and evaluation process. Provide information about any previous applications of the technology. Provide information about the hazards and risks and also potential hazards and risks, as well as benefits and potential benefits. These evaluations could include impacts on local and private wells, transportation, dust, noise, and air buffer zones. Keep the tribal and stakeholder representatives involved and informed throughout the evaluation, selection, permitting, and deployment processes. The upper levels of management of the company implementing the remedy need to understand the community concerns and be vested in the remediation process. Independent technical advisory resources should be made available to the tribes and stakeholders whenever feasible.

- Incorporate tribal and stakeholder involvement into the responsible party's procurement process, the permitting process, and the performance evaluation of contractors.

When an evolving technology such as AFCs is considered for application to a waste containment situation, there are uncertainties about the efficacy and risks of the technology in a given situation. Public acceptance of a new technology is more likely if tribes and stakeholders are involved in a timely and meaningful manner in the evaluation process. Such involvement will enable the early identification of significant issues and the joint resolution of these issues. In turn, public involvement promotes faster and more efficacious closure or containment and increases public acceptance of novel approaches to such cleanup.

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APPENDIX A

Acronyms

ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
ACAP	Alternative Cover Assessment Program
AFC	alternative final cover
ARAR	applicable or relevant and appropriate requirements
ASTM	American Society for Testing and Materials
AWC	available water-holding capacity
BOD	biological oxygen demand
CEC	cation exchange capacity
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
CGWMA	Committee on Ground Water Modeling Assessment
COD	chemical oxygen demand
CQA	construction quality assurance
DOE	U.S. Department of Energy
DSA	design sensitivity analysis
EPA	U.S. Environmental Protection Agency
ET	evapotranspiration
FML	flexible membrane liner
FR	Federal Register
GLBD	growth-limiting bulk density
GPS	global positioning system
ITRC	Interstate Technology & Regulatory Council
LAI	leaf area index
LCRS	leachate control and removal system
MSR	modified surface runoff
MSWLF	municipal solid waste landfill
NRCS	Natural Resource Conservation Service
PET	potential evapotranspiration
PLS	pure live seed
QA	quality assurance
QC	quality control
RCRA	Resource Conservation and Recovery Act
RMA	Rocky Mountain Arsenal
SSSA	Soil Science Society of America
TSWG	Tribal and Stakeholder Working Group
UFGS	Unified Facility Guide Specifications
USCS	Unified Soils Classification System
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
VFA	volatile fatty acid
VOC	volatile organic compound
WMU	waste management unit

APPENDIX B

Alternative Final Cover Survey Results

ALTERNATIVE FINAL COVERS SURVEY RESULTS

Total responses: 12

The tables below show responses by count, percentages based on total respondents (% BTR), and percentages excluding those who gave no answer (% XNA).

Questions 1–3 relate to this federal regulation:

> The owner or operator will be exempted from the requirements of paragraph (a) of this section if the Regional Administrator finds, based on a demonstration by the owner or operator, that alternative design and operating practices, together with location characteristics, will prevent the migration of any hazardous constituents (40 CFR § 264.93) into the ground water or surface water at any future time. In deciding whether to grant an exemption, the Regional Administrator will consider 40 CFR § 264.301(b)....

1. Has your state adopted the preceding federal hazardous waste regulation or a similar exemption referring to 40 CFR § 264.301(b):

Response	Count	% BTR	% XNA
Yes	6	50	67
No	3	25	33
No answer	3	25	

2. Has your state modified the referenced regulation?

Response	Count	% BTR	% XNA
Yes	1	8	10
No	9	75	90
No answer	2	17	

3. Has your state approved, or is it in the process of reviewing, a hazardous or solid waste landfill with an alternative design cover system?

Response	Count	% BTR	% XNA
Yes	5	42	50
No	5	42	50
No answer	2	17	

Questions 4–6 relate to the federal solid waste regulation 40 CFR § 258.60 for final design cover, stating:

> (b) The Director of an approved State may approve an alternative final cover design that includes:
> (1) An infiltration layer that achieves an equivalent reduction in infiltration as the infiltration layer specified in paragraphs (a)(1) and (a)(2) of this section, and

(2) An erosion layer that provides equivalent protection from wind and water erosion as the erosion layer specified in paragraph (a)(3) of this section.
(3) The Director of an approved State may establish alternative requirements for the infiltration barrier in paragraph (b)(1) of this section, after public review and comment, for any owners or operators of MSWLF that dispose of 20 tons of municipal solid waste per day or less, based on an annual average. Any alternative requirements established under this paragraph must: (i) Consider the unique characteristics of small communities; (ii) Take into account climatic and hydrogeologic conditions; and (iii) Be protective of human health and the environment.

4. Has your state adopted federal solid waste regulation 40 CFR § 258.60?

Response	Count	% BTR	% XNA
Yes	3	25	30
No	7	58	70
No answer	2	17	

5. Has your state modified the referenced regulation?

Response	Count	% BTR	% XNA
Yes	2	17	25
No	6	50	75
No answer	4	33	

6. Has your state approved, or is it in the process of reviewing, a hazardous or solid waste landfill with an alternative design cover system?

Response	Count	% BTR	% XNA
Yes	6	50	75
No	2	17	25
No answer	4	33	

7. Do any of the agency groups in your state (hazardous waste, solid waste, superfund, mining, voluntary cleanup, etc.) allow the use of computerized predictive models in the predesign, design, construction, post-closure care, or monitoring of landfills?

Response	Count	% BTR	% XNA
Yes	7	58	70
No	3	25	30
No answer	2	17	

8. Has your state approved the full-scale construction of a landfill based solely on model results?

Response	Count	% BTR	% XNA
Yes	1	8	10
No	9	75	90
No answer	2	17	

9. If so, check the type of landfill(s):

Response	Count
Solid waste	2
Hazardous waste	1
Municipal waste	2
Industrial waste	0
Mixed (municipal/industrial)	0
No answer	9

Questions 10–14 relate to this question: Does your organization prefer consideration of net infiltration volume (flux) through the cover, total leachate generation, risk (to human health or the environment) or a combination of these criteria when designing a landfill?

10. Hazardous waste

Response	Count
Flux	4
Total leachate collection	3
Leakage rate through liner	3
Groundwater monitoring	2
No answer	8

11. Solid waste

Response	Count
Flux	7
Total leachate collection	7
Leakage rate through liner	8
Groundwater monitoring	4
No answer	3

12. Superfund

Response	Count
Flux	0
Total leachate collection	1
Leakage rate through liner	1
Groundwater monitoring	1
No answer	10

13. Voluntary cleanup

Response	Count
Flux	0
Total leachate collection	1
Leakage rate through liner	1
Groundwater monitoring	0
No answer	11

14. Mixed municipal and industrial waste

Response	Count
Flux	3
Total leachate collection	4
Leakage rate through liner	4
Groundwater monitoring	2
No answer	8

15. If flux is a design criterion, does your organization apply a specific flux rate (volume/time) at a specific point in the landfill system (cover, waste, liner, other)?

Response	Count	% BTR	% XNA
Yes	3	25	43
No	4	33	57
No answer	5	42	

16. Does your state consider site characteristics (e.g., depth to water, geology, etc) to establish landfill performance requirements?

Response	Count	% BTR	% XNA
Yes	8	67	80
No	2	17	20
No answer	2	17	

17. Indicate which landfill types have alternative cover designs in your state. Check all that apply.

Response	Count
Pre-Subtitle D (no liner)	1
Subtitle D (liner)	5
Pre-Subtitle C (no liner)	0
Subtitle C (liner)	1
No answer	6

18. Indicate which landfill types require test pads as part of an alternative landfill cover design process.

Response	Count
Pre-Subtitle D (no liner)	0
Subtitle D (liner)	0
Pre-Subtitle C (no liner)	0
Subtitle C (liner)	1
No answer	11

19. Indicate which landfill types have used data extrapolated from other alternative landfill designs to reduce or eliminate site specific testing and/or demonstrations.

Response	Count
Pre-Subtitle D (no liner)	0
Subtitle D (liner)	1
Pre-Subtitle C (no liner)	0
Subtitle C (liner)	4
No answer	6

20. Has your state approved the full-scale construction of a landfill without construction and evaluation of a test pad or modeling results from information from a similar setting?

Response	Count	% BTR	% XNA
Yes	5	42	63
No	3	25	38
No answer	4	33	

21. If so, please check the type of landfill:

Response	Count
Solid waste	3
Hazardous waste	2
Municipal waste	1
Industrial waste	0
Mixed (municipal/industrial)	0
No answer	7

APPENDIX C

Examples of State Regulatory Flexibility

EXAMPLES OF STATE REGULATORY FLEXIBILITY

California

To validate the use of AFCs, site-specific cover monitoring should be performed to determine whether infiltration is causing increases in gas or leachate production. Since the intent of Subtitle D final covers and 27 California Code of Regulations (CCR) is “engineered containment” to minimize infiltration and control gas and leachate production via a barrier layer with a specified hydraulic conductivity, some type of equivalent infiltration criteria may be necessary for sites not adhering to the specified hydraulic conductivity. Based on the 27 CCR conventional standard of 1.0×10^{-6} cm/sec, up to 12 inches/year of infiltration would be allowable (given saturated flow with a constant head condition). For a cap with a 1×10^{-5} cm/sec barrier layer, 124 inches/year based on saturated flow with a constant head condition would be allowable. The following are some typical questions requiring consensus in the regulatory community:

- Is a “zero” infiltration standard technically feasible?
- Should an alternative cap be compared to geosynthetic cap performance?
- Should equivalency cover performance be compared to performance of desiccated clay liner?
- Should an arbitrary standard be developed and applied (300–500 gallons per acre per year; used by Defense Department installations to define “minimal” or insignificant?
- Could infiltration rate be tied to a percentage of annual rainfall (allow 15% of annual rainfall)?

Subtitle D (40 CFR Part 258) Closure & Post-closure (Subpart F) regulations require landfill owners/operators to install final covers for MSWLFs which minimize infiltration and erosion. Subtitle D specifies a minimum 6-inch erosion layer and an 18-inch infiltration layer with a permeability not greater than 1.0×10^{-5} cm/sec. 27 CCR Section 21090 requires that MSWLFs have a final cover that consists of a 2-foot foundation, a 1-foot low-hydraulic-conductivity layer exhibiting a permeability of 1×10^{-6} cm/sec, and a 1-foot vegetative layer (erosion control layer). 27 CCR Section 20950 states that the purpose of the final cover is to minimize infiltration into the waste, thereby minimizing the production of leachate and gas.

Engineered AFCs are required to meet performance standards. While there is a conventional cover design, it does not have performance criteria that are meaningful; therefore, there is nothing meaningful to compare to alternatives cover designs. Conventional caps work when maintained at optimum moisture content (i.e., near saturation).

<u>Equivalent performance</u>

There are several MSWLFs in southern California which have been approved or conditionally approved to use an AFC for closure. Most conditional approvals have been based on verification of performance of the final cover from soil-moisture monitoring data collected using moisture-monitoring probes installed in the cover profile.

Montana's Tiered Approach to the Implementation of Alternative Final Covers

The discussion below follows the order of apparent decreasing effect on AFC design and implementation. The analysis is based on the relative effects of (a) conventional numeric design standards of basal/cap permeability, percolation, and thickness; (b) numeric performance standards of contaminant levels; (c) narrative standards of human or environmental health; and (d) the concept of equivalence. The discussion is more of a summary than an in-depth analysis of the issues addressed by each rule listed.

Prescriptive Numeric Design Standards

Montana solid waste regulations [Administrative Rules of Montana (ARM) 17.50.506(17)] require that landfill units and lateral expansions be designed, constructed, and operated in a manner to "prevent harm" to human health and the environment. A broad performance standard that would prevent all forms of harm would at a minimum depend on the amount of precipitation, the type and concentrations of specific contaminants present in the leachate, the permeability of the liner barrier, the subgrade permeability, depth to groundwater, groundwater quality, proximity and hydraulic connection to drinking-water supply aquifers and wells, and other factors that limit the ability of water percolating through the cap to reach pathways that pose a reasonable risk to human or environmental health.

Interpretation of this rule could be based on risk, and in that case the demonstration burden could be quite massive. However, due to its breadth, other interpretations are also possible. Landfill statutory exemptions from nondegradation and groundwater permitting for mixing zones assume that the waste management system is taking care of these issues by limiting the release of contaminants.

The level of harm remains undefined, so low levels like those defined for nondegradation or carcinogen "action levels" (e.g., trigger values or aquatic life chronic levels in ground- or surface water, respectively) could be used as the numeric standard. Analysis of surface water could even include the solid fraction for some analytes. The water quality classification standards based on the intended beneficial use of the surface water in question (for leachate or groundwater seeps) could also apply.

The method of observation and the media concerned are not specified, so the effects of vapors are also implied. Equivalence is not directly addressed. Designs that meet all requirements of items below may not meet some aspect of this broad rule.

Numeric Performance Standards of Contaminant Levels

Montana solid waste regulations [ARM 17.50.506(1)(a)] requires that landfill units be constructed in a manner that MCLs listed in Table 1 will not be exceeded in the uppermost aquifer at the relevant point-of-compliance groundwater monitoring wells. This specific performance standard requires the adequate location of a sufficient number of wells within the proper saturated zone, so the observations strongly depend on the aquifer characteristics and the nature of the pathway leachate or contaminated gas would follow to reach the aquifer. The spectrum of contaminants is more limited than those of the previous item, and it is assumed that the filtered liquid product or dissolved fraction of each contaminant would be transported by groundwater to be ingested by humans who drink it. The level of risk depends on the proximity and number of drinking water supply wells in hydraulic connection to the aquifer containing the contaminant plume.

Alternative cover designs must minimize percolation to avoid production of gas and leachate that can contaminate groundwater. In this case, however, evaluation of the alternative cap performance is no better than the location and number of the monitoring wells or the suite of contaminants analyzed. Designs that meet all requirements of items below may not meet some aspect of this groundwater contaminant rule.

<u>Narrative Standards of Human or Environmental Health</u>

Montana solid waste regulations [ARM 17.50.530(1)(b)(i) and (ii) and (3)(b)(i) and (ii)] are based on equivalence of the infiltration layer to at least the performance of a conventional cap in reducing the "infiltration" to a quantity similar to the quantity anticipated to pass through an 18-inch-thick layer of permeability 1×10^{-5} cm/sec or greater if the subgrade or liner permeability is greater. The regulations also restrict root damage to the 6-inch-thick topsoil layer.

Infiltration is not the same as percolation, although limitation of the former also restricts the latter. If that rule is strictly interpreted, a well-developed shallow-rooted vegetative cap must limit infiltration without the help of moderate- to deep-rooted plants that would limit downward percolation. Plant root depths are also restricted to the top 6 inches. This language provides a significant legal barrier to alternative design, because percolation will occur when the shallow-rooted plants are dormant during the winter. Thus, the alternative cap must provide at least the same permeability throughout the upper 18 inches of the infiltration layer, but permeability may vary below that depth.

On the other hand, if we can substitute "percolation" for "infiltration" in the rule language, the concept of equivalence requires the amount of free drainage at the base of both layers to be equal, assuming the same distribution in space and time of precipitation and freezing.

There is no specification of the materials required to achieve either the conventional standard or the alternative cap equivalence, although it is recognized that an FML component is required in the conventional standard if a composite liner is matched. The alternative design permeability cannot be known to any greater accuracy than the estimate of subgrade permeability, which is usually provided by a remolded lab test (one order of magnitude) rather than better estimates using in situ methods. The effects of frost depth on the prescriptive permeability standard, if simply accounted for by overcompaction, add at least another order of magnitude error in estimates of the alternative design permeability.

In this case, there are no numeric standards that directly restrict the levels of observed contaminants in any way, so there is no direct connection to human or environmental health.

APPENDIX D

Key Terms

Key Terms

autecological—the study of how individual organisms or species interact with their environment.

available water—the amount of water released between in situ field capacity and the permanent wilting point (usually estimated by water content at soil matric potential of -1.5 MPa). Not the portion of water that can be absorbed by plant roots, which is plant specific.

While this definition is scientifically correct, it is impossible to apply these terms exactly to engineering design of a real cover. However, there are approximations that are sufficiently accurate for good engineering design.

The permanent wilting point is commonly called "wilting point" and may be estimated from laboratory measurements of soil properties on a pressure plate or similar device. A satisfactory estimate of the wilting point is the laboratory measured water content at −1.5 MPa (−15 atmospheres) pressure. It is important that the soil sample represent the soil to be placed the field.

A satisfactory estimate of field capacity is the laboratory measured water content at –0.03 MPa (–0.3 atmospheres) pressure. The estimate at –0.03 MPa is more conservative for AFC design than the –0.01 MPa value that is sometimes suggested.

The "available water" definition above states that this value is plant specific. In addition, the wilting point soil water content is low where potential ET is low and high where potential ET is high; thus potential ET may affect available water content. However, for AFC design, the plants that are usually selected have similar ability to remove water from the soil. A satisfactory approximation to plant-available water capacity is the difference between field capacity and wilting point.

cultivar—a cultivated subspecies of a plant; a variety of a plant species selected and grown for particular traits such as forage production or drought resistance.

field capacity—the content of water on a mass or volume basis, remaining in a soil two or three days after having been wetted with water and after free drainage is negligible.

harmful constituents in soil—Landfill cover soils should be free of harmful amounts of manmade chemicals, oil, and natural salts. The salts of calcium, magnesium, and sodium occur naturally and can create high salinity in the soil solution. Soil salts may raise the osmotic potential of the soil solution high enough to prevent plants from using all of the soil water. In addition to its contribution to soil salinity, sodium can cause deflocculation (i.e., dispersion) of clay particles, thereby causing poor soil tilth.

infiltration—water that passes the from the atmosphere through the soil interface.

percolation—water that escapes the surface processes of evapotranspiration and becomes recharge or leachate.

permanent wilting point—the largest water content of a soil at which indicator plants, growing in that soil, wilt and fail to recover when placed in a humid chamber. Often estimated by the water content at −1.5 MPa soil matric potential.

plant response to soil properties—Understanding of important plant requirements is critical to correct selection of materials, design, and construction of the soil layer in an AFC. The success of an ET cover is ensured by optimizing all factors controlling plant growth except for soil water supply. The goal is to make soil water content a limiting factor to plant growth several times during each normal growing season. The soil water reservoir should be empty or nearly so at the beginning of severe or critical events that stress the capacity of the cover to control precipitation.

plant roots—Water removal from the cover soil is controlled by plant roots, so it is necessary to understand the role of roots in the system and their requirements. Under optimum conditions, some plant roots may grow 2 cm (0.8 inches) per day; however, for most of the time, limiting factors reduce the rate of root growth below the optimum for the plant in question. Root growth limitations reduce the ability of the plant to extract water and plant nutrients from the soil. Rendig and Taylor (1989) discuss factors that may limit root growth, including the following:

- high soil strength and related physical factors, controlled by
  - soil density
  - particle size distribution
  - soil water content
- unsatisfactory soil pH (Note: low pH may be corrected during construction.)
- soil temperature
- salinity of the soil solution (caused by excess Ca, Mg, Na, and other salts)
- soil oxygen
- air-filled porosity in the soil
- chemical toxicity (e.g., pH, Al, Be, Cd, Pb, Cu, Cr, Fe, Hg, Zn, NH_3, B, and Se)
- allelopathic toxicants

potential leaf area index—the potential area of foliage produced by a plant under ideal moisture and nutrient conditions.

relict—pertaining to a plant community that is relatively undisturbed and contains an assemblage of plant (and animal) species reflecting native conditions.

rhizomatous—a plant species with rhizomes, i.e., prostrate underground stems or branches producing roots at nodes. Differs from roots in producing nodes and internodes and usually scale leaves.

root growth and distribution—the mass and distribution of living plant roots in soil controls the drying of each soil layer. Figure D-1 illustrates possible root distribution patterns. When all soil layers are adequately wetted, roots often develop as shown for condition 1; the majority of the roots are near the surface. However, as the soil dries from the surface downward later in the season, the rooting pattern may shift to the condition shown by condition 2. During and after drought, most of the active roots will be found deep in the soil profile. Many plant roots die but later regenerate in a given soil layer in response to changes in resources and conditions in each soil layer (Camp et al. 1996, Stewart and Nielsen 1990, Merva 1995).

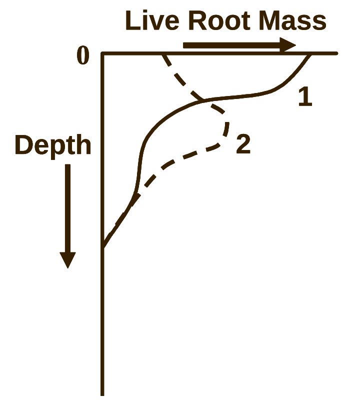

Figure D-1. Root distribution in response to soil water.

It is vital that soil conditions allow rapid growth of new roots for the plant cover to remove the stored soil water quickly after a storm. Under favorable conditions, root axes may grow 2 cm/day and root laterals may grow 0.5 cm/day; however, some investigators report growth rates up to 6 cm/day (Russell 1977). Adverse soil density is a major controller of root growth rate and potential depth of rooting. Many native soils contain layers of high density that limit rate and depth of root growth. However, if the soil is correctly placed in the AFC, density can be removed as a limitation and good tilth established in the soil. Figure D-2 illustrates the difference in live root mass that may result between a native soil with high-density layers and that in a correctly placed ET cover using the same soil placed to achieve optimum soil density. Deep rooting and good soil tilth allow rapid and complete removal of water stored in the cover soil.

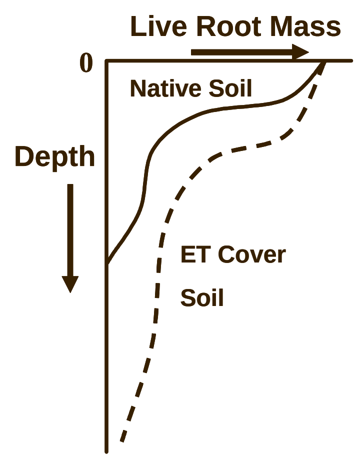

Figure D-2. Root distribution in response to soil tilth and density.

Most native grasses or associated species have the potential to root to depths greater than 8 feet. At many natural sites, soil characteristics—rather than the plant potential—limit the rooting depth. It is inexpensive to optimize soil physical properties during ET cover construction. The soil conditions for root growth should be optimized throughout the full depth of the cover at all vegetative landfill cover sites to allow root growth to the bottom of the cover soil.

soil aeration properties—Air-filled porosity in the soil is important because each root requires oxygen and because, during rain or irrigation, these pores become channels for water and air to move rapidly through the soil. Soil pore space includes a range of sizes from extremely small to very large. Small pores contribute little to the movement of air, but much of the water is stored in small pores. In an optimal soil structure, large and small pores are connected so that water and air may move freely and there is a desirable distribution of pore size. Sandy soils tend to have large pore spaces and be well aerated. Clay soils often contain more total pore space than sandy soils, but most of the pores may be small. Excess compaction removes most large pores from soils, thus limiting air and oxygen exchange from the atmosphere to the soil air.

Total pore space and soil bulk density are inversely related as illustrated in the following equation:

Porosity = 1.0 − (soil bulk density/particle density)

(Particle density may be assumed = 2.65 for most soils [Hillel 1980].)

Dense soils have little pore space, and low-density soils have higher porosity.

soil bulk density—The road and building construction industry expresses soil compaction as "percent of standard Proctor". The standard Proctor density is specific to a single soil sample and specified water content. The standard Proctor density evaluates the potential soil strength and other structural properties that may be achieved with given soil materials. It is a useful measurement for road and dam construction and other building activities. The goal is high soil strength. However, in an AFC, the soil <u>must</u> be weak in a successful soil cover.

Bulk density is the "mass of dry soil per unit bulk volume. The value is expressed as Mg per cubic meter, Mg m^{-3}" (SSSA 1997). For AFCs, the bulk density should be measured in the field with standard methods. Soil density is easily controlled in the field by controlling both soil water content and limiting soil compaction during placement. Densities should be low enough to encourage active root development throughout the cover profile and high enough to prevent differential settlement, which can cause surface ponding.

soil humus content—often called "soil organic matter," an important component of soils (SSSA 1997). It is composed of organic compounds in soil exclusive of undecayed organic matter. Humus is resistant to decay, provides significant cation exchange capacity in addition to that of clay minerals, and improves soil structure. It is commonly believed that large amounts of humus are required for best plant growth; this is not true. Plants grow well in fertile soils that contain little humus (such as soils of the southern Great Plains and the irrigated deserts of the 11 western states). Manure, compost, and grass clippings are organic matter or materials, but they are not humus. The addition of organic material to soil to improve its properties usually improves soil tilth and fertility temporarily, but it may not be worth the expense in a landfill cover because most of the added material oxidizes and disappears in a few months or years, after which soil properties revert to those of the original soil material.

soil strength properties—Soil strength is an important physical factor in soils supporting plant growth because excessive strength can reduce or stop root growth (Rendig and Taylor 1989). Soil strength is controlled by several factors, including bulk density, particle size distribution, and water content. It is possible to control soil bulk density in an AFC during construction, and if it is controlled within a desirable range, the resulting soil strength is usually satisfactory.

In most soils, plant root growth is reduced when soil bulk density exceeds 1.5 Mg m^{-3}, but values above 1.7 Mg m^{-3} may effectively prevent root growth (Eavis 1972; Monteith and Banath 1965; Taylor, Robertson, and Parker 1966; Jones 1983; Timlin, Ahuja, and Heathman 1998; Gameda et al. 1985). Particle size distribution in the soil combines with soil bulk density to control root growth. Roots usually grow better in sandy soils than in clay at the same density. However, the low water-holding capacity of sandy soils discourages their use in AFCs.

Jones (1983) demonstrated that plant root growth is reduced at soil bulk density greater than 1.5 Mg m^{-3} for most soils and reduced to less than 0.2 optimum root growth for all soils containing more than 30% silt plus clay and having bulk density greater than 1.6 Mg m^{-3}. Grossman et al. (1992) summarized 18 laboratory studies and found that root growth was only 0.2 of optimum for soil bulk density greater then 1.45 Mg m^{-3} except for three soils in which root growth was restricted at soil bulk density of 1.3 Mg m^{-3}. In addition to inhibiting root growth, high values of soil bulk density result in low soil water-holding capacity because pore space is reduced in compacted, dense soils. Compacted soils have few large pore spaces, thus limiting soil air movement and oxygen diffusion to roots.

Because of the risk of settlement, a minimum bulk density should be established. However, because of the nature of an AFC, settlement less than 5% of the cover thickness is unlikely to create problems. For many soils a minimum bulk density of 1.1 Mg m^{-3} or less should produce substantially less than 5% cover soil settlement. During cover construction, the principal threat to cover properties is high soil density, not settlement. The soil bulk density should be controlled to values between 1.1 and 1.5 Mg m^{-3} during construction of AFCs.

soil tilth—"the physical condition of soil as related to its ease of tillage, fitness as a seedbed, and its impedance to seedling emergence and root penetration" (SSSA 1997). Good soil tilth significantly improves plant growth; it is controlled by particle size distribution, water content, aggregation of soil particles, and soil bulk density. Unfortunately, there are no quantitative measures for soil tilth. However, bulk density, particle size distribution, and water content are easily measured and optimum values of each are known.

soil water-holding properties—The water-holding properties of ET cover soils are important to success. Soils that hold much water achieve the desired water control with a thinner layer of soil than those with low water-holding capacity. The water-holding properties should be expressed as volumetric water content to make estimates of required cover thickness easier to understand.

suction head—the negative pressure of water held above the water table results in attractive forces between particles is referred to as "suction head."

synecological—the study of interactions within and among ecological communities; multispecies interactions.

topsoil—generally the A horizon or surface layer of a soil column containing increased organic matter in which plants have most of the root system. Not dirt.

transpiration—the transfer of soil moisture through roots, stems and pores in leaves into the atmosphere.

wilting point—Before considering the wilting point of soil, it may be useful to understand how water is stored in soil. Within the soil system, several different forces influence the storage of water. The strongest force is the molecular force of elements and compounds found on the surface of soil minerals. The water retained by this force is called "hygroscopic water," and it consists of the water held within 0.0002 mm of the surface of soil particles. Hygroscopic water is held by soil particles at a force of about 15 bars. It is essentially nonmobile and can be removed from the soil only through heating. Matric force holds soil water 0.0002–0.06 mm from the surface of soil particles. This force is due to two processes: soil particle surface molecular attraction (adhesion and absorption) to water and the cohesion that water molecules have to each other. Capillary action moves this water from areas where the matric force is low to areas where it is high. Because this water is moved primarily by capillary action, it is commonly referred to as "capillary water." Plants can use most of this water by way of capillary action until the soil wilting point is reached. Water in excess of capillary and hygroscopic water, called "gravitational water," is found beyond 0.06 mm from the surface of soil particles and moves freely under the effect of gravity. When gravitational water has drained away, the amount of water that remains is soil's field capacity.

The wilting point of a soil is the amount of water held in the soil that is strictly unavailable to plants. About 40%–60% of the water in the soil at its field capacity is unavailable to plants because it is held very tightly (i.e., >15 bars) in very small soil pore spaces (called "micropores"). As soil moisture is reduced through ET, the wilting point of a soil is reached when the rate of water leaving plants' leaves is greater than the water uptake by the roots. At this point plants lose turgidity and may fail to recover. Wilting point varies based on soil type/characteristics and plant species. Soils with higher clay content may have higher percentage soil moisture at the wilting point than more coarse soils. Some plant species (e.g., many arid climate plants) are better adapted to removing soil moisture tightly bound to soil particles and therefore have a lower wilting point.

In shallow soil layers water depletion continues beyond the wilting point since evaporation is still active. Deep soil layers, however, are not affected by direct evaporation and remain at the wilting point water potential. This minimum point depends on the physiological attributes of the plants that explore that soil. Desert shrubs cut their water use at a much lower water potential than wheat plants. In a system where water recharges are frequent, this point of minimum water potential is probably never reached. In arid systems, the minimum water potential may occur during extended periods, and plants that can withdraw water unavailable for other species have a particular advantage.

APPENDIX E

Attributes and Inputs of Cover Design Models

Table E-1. Processes and attributes of landfill cover models
(adapted from Albright et al. 2002)

Processes/attributes of the models	EPIC	CREAMS	GLEAMS	HELP3.07	VS2DI	VADOSE/W	HYDRUS2D	UNSAT-H	SHAW2.3	SWIM	LEACHM	TOUGH2
Water storage routing–based model for unsaturated flow	X	X	X	X								
Richards' equation–based model for unsaturated flow					X	X	X	X	X	X	X	X
Stochastic capabilities (can utilize statistically based input to reflect an uncertainty, such as the variability of soil texture distribution)					X		X					X
How precipitation is input:												
Historical data available	X	X	X	X		X						
Weather generation	X	X	X	X								
Manual input	X	X	X	X	X	X	X	X	X	X	X	X
How potential evaporation is determined*	C	C	C	C	I	C	I	C/I	C	I	C/I	I
How runoff (due to rainfall, not snowmelt) is determined:												
Infiltration based (runoff = precip. rate – infiltration rate)	X	X			X	X	X	X	X	X	X	X
SCS or modified SCS curve number method	X	X	X	X								
Erosion	X	X	X									
Vertical drainage (percolation)	X	X	X	X	X	X	X	X	X	X	X	X
Lateral drainage	X			X	X	X	X					X
Preferential flow					X	X	X					X
Snowmelt	X	X	X	X		X			X			
Vapor flow						X		X	X	X	X	X
Solute transport	X		X	X	X	X	X		X	X	X	X
Heat transfer					X	X	X	X	X		X	X
Plant growth	X	X	X	X		X		X	X	X	X	
Root growth distribution/density	X	X	X	X	X	X	X	X	X	?	X	
Soil property menu (hydraulic property reference values provided based on soil texture)	X	X	X	X	X	X	X	X	X	X	X	
Geomembrane properties				X								
Windows compatible	X		X	X	X	X	X	**	X			X

*C = property is computed; I = property is input. Input properties may not be required depending on the processes included in the simulation.

**Windows versions of UNSAT-H (WinUNSATH) are now available.

Table E-2. Pertinent input parameters and descriptions for landfill cover models
(adapted from Albright et al. 2002)

Specific parameter/attribute	EPIC	CREAMS	GLEAMS	HELP3.07	VS2DI	VADOSE/W	HYDRUS-2D	UNSAT-H	SHAW 2.3	SWIM	LEACHM	TOUGH2
General												
Time step	d/h	d	d	d/m/y	Any	Any	Any	Any	Any	Any	Any	Any
Physical properties												
Soil texture	I	I	I	I	I	I	I		I		X	
Bulk density	I	I	I	I	I	I	I		I	I	I	I
Max # of soil layers	10	7	10	20	Any	Any	Any	Any	50	Any	15	Any
% organic matter	I	I	I						I			I
Effective porosity	C	I	I	C	C							I
Soil albedo	I			C[1]				I	I			
Topography/slope	I	I	I	I	I		I		I			I
Site elevation	I		I		I	I		I	I			
Initial soil temperature	C	C	I	C	I	I	I	I	I		I	I
Maximum ponding depth					I	I			I	I		
Land area	I	I	I	I	I	C	I					
Hydraulic properties												
Wilting point (15 bar)	C/I	I	I	I	I	I	C/I				I	
Field capacity (0.3 bar)	C/I	I	I	I	C		C/I					
Soil water retention parameters (theta-h function)				BC	BC VG O	O	BC VG O	BC VG O	BC	BC VG O	O	VG O
Saturated water content/porosity	C	I	I	I	I	I	C/I	I	I	I	I	I
Saturated hydraulic conductivity, K_s	I	I	I	I	I	I	I	I	C/I	I	I	I
Unsaturated hydraulic conductivity, K_h				C	C	C/I	C	C	C	C/I	C	C
Depth to aquifer	I					I	I				I	I
Initial water content/head	I	I	I	C/I	C/I	I	I	I	I	I	I	I
Hysteresis							X	X		X		
Plant properties												
Potential transpiration	C	C	C	C	C/I	C	I	C	C*	I	I	
Evaporative depth	C	C	C	I	I	C			C			
Growing season length	C	I	I	C/I	I	I	I	I	C		I	
Leaf area index	C	I	I	I		C		I	I		I	
Leaf size/plant size and orientation	C			C[2]					I			
Root density	C				I		I	I	C/I	I	I	
Root depth	C	C	C	I	I	I	I	I	I	I	I	
Canopy albedo	X							I	I			

Climate												
Precipitation time scale	d/h	d/h	d	d	Any	Any	Any	d/h	d/h	Any	Any	Any
Relative humidity or dew point temperature	C/I		I	I	I	I	I	I	I			I
Snow density and depth	C	C	C			C			C			
Air temperature (max/min/mean)	C/I		I	C	I	I		I	I		I	I
Temperature time scale	d	d	d	d	Any	Any	Any	d	d/h		d	Any
Solar radiation	C/I	I	I	I		I		I	I			
Cloud cover								I	C			
Wind speed	C/I		I	I		I		I	I			
Latitude/longitude	I		I	I		I		I	I			

Abbreviations:

VG = van Genuchten model, BC = Brooks Corey model, O = other than BC/VG

y = year, m = month, d = day, h = hour

C = property is computed**;** I = property is input. Input properties may not be required depending on the processes included in the simulation.

*SHAW model computes actual transpiration directly from the energy balance and vapor gradients; potential transpiration is not computed.

**Available in the HELPQ model.

1 = Soil albedo available in HELPQ for snow.

2 = Maximum leaf area index is input.

APPENDIX F

Response to Comments

RESPONSE TO COMMENTS

1. **Comment:** The document has some good information on regulatory issues; however, it does get involved. So a question came up as to who the audience is or who will use this report and for what purposes—this wasn't clear in the beginning. Some of the more technical details could go into appendices.

Response: Text was modified in Section 1.1 to identify purpose and audience.

2. **Comment:** Most important comment: Strongly disagree with the paragraph on page 1-4 which refers to the Navy Hawaii project as being a failure. This paragraph misrepresents the project/report—it definitely was not a failure.

Response: Revised language from the Navy was inserted into the document.

3. **Comment:** Section 1.3 list types of alternative landfills but doesn't describe them in detail. It doesn't include an ET or vegetative covers as a type to be discussed, but does discuss their failures. Although there's a section later (2.6) with advantages and disadvantages of AFC versus traditional RCRA covers. Recommend discussing all types of covers and put this 2.6 in the 1.3 area of the report.

Response: Section 2.6 was moved before 1.3, and an introductory section on ET and PET as they relate to AFCs was inserted.

4. **Comment:** Page 4-19—The text discussed LAI but did not mention the criteria to be considered for the value to be input into a model. LAI can be 0 during the nongrowing season and high during the growing season. What is the acceptable method by practitioners? Average? Peak? Depends on the scenario that you are using? We also indicate a good stand or poor stand of grass must be based on stem count, not on whether the grass is a good stand for the area.

Response: LAI is a site specific variable as are input parameters and operation of an appropriate model.

5. **Comment:** Page 2-5—The topic for section 2.4 needs to be changed or the text needs to be moved to section 4.2.1? Title and text do not match!

Response: The equivalency language and very method-specific snowmelt language was deleted. Snowmelt is addressed in Section 4.

6. **Comment:** Page 6-1—Any reason why the word "perceived" is still in the text in paragraph 1 of section 6.1?

Response: Deleted the term from text.

7. **Comment:** It is quite apparent that the document has been written by different folks, and that coordination between the different sections needs some work. On multiple topics, there are redundant write-ups in different sections. However, the redundancy is sometimes limited to the topic, not to the information, which is sometimes contradictory. For example, there is a section on cover costs in Section 4, and another one in Section 6. They are similar in some respects, but much different when it comes to dollar amounts. There are design sections on erosion control in two or three sections, design sections on landfill gas in two or three

sections, design sections on surface runoff control, etc. Some reorganization is necessary. Otherwise, a reader can find one section on slope stability (or surface runoff, or costs, or biota barriers, or landfill gas, etc.) and think he knows what our guidance document says on design with regard to that topic. Another reader could find the same topic in a different section, read something different, and think he knows what the guidance document says. However, the two readers would have read sometimes substantially different material, with sometimes contradictory information/guidance.

Response: These issues are addressed as they appear in the document.

8. **Comment:** Sections 1.2 and 1.3 seem somewhat redundant. Section 1.2.1 is named "Alternative Cover Concepts" and Section 1.3 is named "Types of Alternative Covers," but both sections include a discussion of various types of designs of AFCs.

Response: These sections were reviewed and edited to eliminate redundancy.

9. **Comment:** Why have a Section 1.2.1, when there is no 1.2.2? Same question regarding Section 4.2.1 and Section 6.2.1.

Response: 1.2.1 is deleted, 4.2.1 is deleted, 6.2.1 is deleted.

10. **Comment:** The 4th sentence of the last paragraph of Section 1.2.1 states the "primary purpose of this document is to provide adequate guidance to design engineers and regulators to *design*…AFCs." I thought we did not intend this to be a document that outlines how to design AFCs. In fact, some of the sections do seem to be telling a designer how to design. Do we want that?

Response: The text was modified to reflect decisions associated with AFCs.

11. **Comment:** Section 2.4 seems completely out of place in Section 2, and I question its suitability anywhere in the document, except possibly in an appendix. Section 2 is on cover goals and regulatory flexibility, and Section 2.4 goes into detail about one way to model snowmelt! It's OK to discuss reasons for possibly needing to model snowmelt in the modeling section (Section 4, not Section 2), but even in Section 4 I don't know why we would zero in on only one of many ways to model snowmelt. It's not the most accurate way, nor is it the simplest way. It's merely one of many ways that could be considered.

Response: See Response 5.

12. **Comment:** I wonder about Section 2.5. Wouldn't it be better in an appendix, with the main text in Section 2 mentioning more generically that (and possibly how) various states have utilized regulatory flexibility.

Response: The information has been moved to Appendix C including examples of regulatory flexibility in California and Montana.

13. **Comment:** In the last paragraph of Section 3.1.2, the text states that EPA recommends a 0.1–1 mm/yr percolation criterion. If that is mentioned here, shouldn't we comment on it in some way rather than to let it stand unchallenged? In our modeling section, we imply that it is acceptable to design for higher fluxes than that, and we state that even conventional covers often don't meet the high EPA goal.

Response: **T**he language was revised as follows: If EPA promulgates regulations or publishes guidance regarding flux rates, those criteria should be considered in the design decision process.

14. **Comment:** It seems we vacillate between recommending modeling of a cover and leaving that to the designer/regulator to decide. In the first paragraph of 4.1, we list "numerical simulation" as one of four typical steps in the design process. The 2nd paragraph says design should be refined through "numerical simulation." The last sentence in Section 4.4 says "The design should be refined through numerical simulation.…" However, Step 7 of Section 4.8.10 says to "Determine the need for modeling early in the design process. In some situations, a risk-based approach may be more appropriate than a landfill cover percolation approach."

Response: The text in the referenced sections was modified to indicate that the authors' experience indicates that models are "typically" used in the design process and that the authors recommend modeling be done as part of the design process.

15. **Comment:** Perhaps the phrase "numerical simulation" is not intended to mean the same as computer modeling. If not, however, I do not think the real intent is clear, and that it could easily be construed to mean that computer modeling "should be" performed, when I do not think that is our intent.

Response: See Response 14.

16. **Comment:** The text seems to repeatedly imply, or state, that cover modeling/design should be performed for some maximum event, storm, or period. I'm aware of a few different AFC sites where the regulators were interested in percolation averages (not to be confused with percolation from average precipitation), not extremes. For example, the last paragraph in Section 4.2 states "The maximum stress event, critical event, will need to be negotiated with the regulators". Similarly, the first paragraph of 4.2.1 mentions designing for "future extreme events". Section 4.7.1 talks again about extreme events. Although Section 4.8.3 mentions that "average climatic conditions" might be used, I think the text seems to show a strong bias for modeling for extreme conditions. For surface runoff control facilities that is reasonable, but for percolation I believe that average percolation is probably more relevant to the long-term suitability of a cover (i.e., the generation of leachate, migration of contaminants, etc). Some regulators appear to agree with that. I think we should present a more balanced position on the matter.

Response: Section 4 text was rewritten generalizing the concepts to fit the scope of this document without detailing specific calculation methodologies and the pros or cons. The model conditions, whether extreme or not, should be discussed between the facility and the regulators. In addition the storm-water text has been revised to reflect management of the water as separate design element from the AFC.

17. **Comment:** In 4.5.1.2, part 4, we mention Chadwick et al 1997, when it should be 1999.

Response: Thank you.

18. **Comment:** There is also a sentence that states "The upper limit on the fines content was defined based on vegetation growth considerations." However, in the article referenced there

was no upper limit on the fines content. I recommend deleting the erroneous sentence. The correct point is made with the last two sentences of the paragraph.

Response: Sentence deleted.

19. **Comment:** In 4.5.1.2, towards the end of part 5, there is a parenthetical statement saying "(typically three parameters)". It is typically five parameters, not three.

Response: Done.

20. **Comment:** In the last part of the 3rd paragraph of Part 6 of Section 4.5.1.2 (just before the paragraph on Soil Shear Strength, which is misplaced in this section on unsaturated hydraulic conductivity), the text mentions "the direct measurement of soil water characteristic curves is needed for design purposes." Maybe it's a fine point, but we don't directly measure soil water characteristic curves. We estimate the curves based on some moisture retention data. The sentence would be better if it ended as follows: "...is useful for quality control programs, estimation of the soil water characteristic curve from measured moisture retention data should be more accurate."

Response: This text was revised.

21. **Comment:** Part 7 seems out of place in Section 4.5.1.2 on "Parameter Descriptions." Part 7 talks about how to design stable slopes. The other parts in 4.5.1.2 are more like definitions. Design info on slope stability, if needed, belongs in Section 4 on design (perhaps a new subsection in Section 4.10).

Response This section was deleted, as requested by multiple comments because it is not an engineering design parameter, but rather a design consideration.

22. **Comment:** Table 4-4 Borrow Assessment Soil Tests—I don't see where this table is referenced in the text. Also, we should not give the impression that every test listed on this table is important to measure. This is a list of tests to consider. For example, determination of shear strength may be of little or no value to some AFCs (e.g., at the Rocky Mountain Arsenal we have done a large amount of soil testing, but we have not performed shear strength tests since they are of little relevance on covers that are built with only minimum slopes).

Response: Complete.

23. **Comment:** Much of what is in Section 4.6 relates only to modeling, yet this is not the section on modeling. For example, 4.6.5 starts out describing how reasonable estimates for use in modeling can be obtained. Section 4.6.6 also seems to be written solely for a modeler using a particular model (it defines % bare area as used in UNSAT-H—I doubt the statement on how % bare area is related to leaf area index values is relevant for any other model). We haven't even gotten to the modeling section yet. It seems this section should be discussing how to generally characterize a site (what kind of vegetation exists, what are its characteristics, etc), not developing modeling parameters and certainly not defining them in a way that is specific to a particular model.

Response: The references to models were deleted from this section. The portion about leaf area index was retained as an educational issue, even though it is somewhat detailed in this text.

24. **Comment:** Section 4.7 indicates that estimating surface runoff is important in a cover's water balance, and therefore important in designing a cover. However, much of the section focuses on storm runoff (e.g., Section 4.7.1, 3rd paragraph, mentions the "type of storm" should be negotiated with regulators, and mentions 24-hr, 100-yr storms, etc., for use in designing a cover that will keep percolation out of the waste). I have never yet seen a case where a "storm" was used to design a cover thickness. Storm runoff modeling is appropriate for use in designing surface runoff control features, but Section 4.7 seems to be mostly talking about storm runoff as it relates to water-balance modeling.

Response: See Response 16.

25. **Comment:** Our section on modeling the percolation performance of the covers is in Section 4.8. That modeling includes modeling surface runoff (related to the water balance, not sizing ditches). I think that, when we are discussing surface-runoff modeling as it relates to the water-balance modeling, it belongs in the section on water-balance modeling. I would recommend splitting out the portion of Section 4.7 that relates to the water-balance modeling, and including the important part in Section 4.8. The part of 4.7 that is applicable to design of runoff control facilities could stay.

Response: See Response 16.

26. **Comment:** I also think Section 4.7.3 should be dropped. Certainly it should be easier to use a model that automatically links its runoff algorithm with its water budget algorithm, but if use of one of the better water-budget models is improved by having the precipitation data first preprocessed through a runoff algorithm (and/or snow and snowmelt algorithms), why discourage that? It's true that use of the two models "may increase the errors in runoff estimates," but it's also true that use of the two models may decrease the errors in runoff estimates.

Response: See Response 16.

27. **Comment:** I think Section 4.7.4 goes into way too much detail on the SCS CN method. For example, why should our text get into discussions of what CNs to use for wheat, fallow after wheat, fallow after sorghum, etc? What does that have to do with AFCs? If we wanted to mention CNs, why not mention ones that might be relevant? But that would take lots of space, which I don't recommend. There are lots of "how to" references on the SCS CN method. We should not devote the space in this document to do as well as they do. Why not just mention the method, its applicability to AFCs (i.e., a good method for sizing runoff control features, a potential way to preprocess precipitation data to provide inputs to a water-budget model, and a built-in runoff estimating procedure in some of the water-budget model codes [e.g., HELP and EPIC]), mention its pros and cons, provide some good references, and leave it at that?

Response: See Response 16.

28. **Comment:** Last paragraph of Section 4.8.3 states, "It is strongly encouraged to be wary of "preliminary" modeling." It goes on to state the "preliminary approaches can provide vastly different results than obtained by more rigorous modeling.…" If true, then why are we outlining a typical preliminary design approach in Section 4.4 that uses such preliminary modeling? These sections seem to contradict each other.

Response: Use of preliminary modeling should be limited to estimating the cost/benefit. (economic feasibility). The text has been modified.

29. **Comment:** Section 4.8.4.2 lists evaporative depth and rooting depth and rooting density as "secondary factors that influence model results." These two factors should be moved to 4.8.4.1 under primary factors, as they are typically among the most important factors in determining the appropriate cover thickness. Rooting depth is probably more important than most of the factors listed in 4.8.4.1 in many or most situations and should not be relegated to the list of secondary factors.

Response: Information has been combined into a single list.

30. **Comment:** Item 4 of 4.8.8 lists a quotation that must be wrong. It says "HELP showed a nonrealistic response of increased drainage with increased water content (increasing field capacity for a fixed wilting point)…." I don't have the quote, but the term "water content" is incorrect. It should be "water-holding capacity" (or something like that). As is, the statement says it is nonrealistic to have increased drainage with increased water content, which is incorrect.

Response: Done.

31. **Comment:** In the title of Table 5-1, I recommend changing "Important" to "Potentially Important." Otherwise, regulators might use the table as justification to require measuring all the parameters. For example, the strength properties may not be relevant at sites with nearly flat slopes.

Response: Done.

32. **Comment:** Section 5.2.1.2 lists "Important soil properties that should be defined in the design and construction specifications…." It then goes on to mention wilting point, field capacity, and unsaturated hydraulic conductivity. It would be a rare project that would actually define these parameters in the design and construction specifications (I've never heard of one) because of the high expense and significant time to make such measurements and because adequate control of more easily measured parameters (e.g., texture and density) have been found to provide adequate control of the unsaturated parameters.

Response: Text was added in Section 4.3.2 and at 5.4.2.2 to indicate that some properties are not easily measured and are represented by more easily measured "index properties" such as grain size distribution or plasticity that correlate reliably with the desired physical property.

33. **Comment:** It seems that most of Sections 5.2.1.2 and 5.2.2.1 belong in the design section, not the construction section. For example, if pH is deemed important to control within a certain range, that should be discussed as a design item in Section 4. It seems that the construction section should be talking about how to control pH within the specification limits (if such a discussion is necessary), but the design section should be talking about what the desirable pH should be (if necessary). Same with the discussion of conductance, sodium, need for topsoil, need for soil amendments, need for fertilization, etc.

Response: Section 5.2.1.2, including the table was eliminated. Similarly, Section 5.2.2.1 was eliminated. In both instances, information pertinent to design was moved to the appropriate location in Section 4.

34. **Comment:** The first three paragraphs of Section 5.3.1.2 seem pretty redundant with the information provided in Section 4.5.1.2 (part 7). This type of design information seems to belong in Section 4 on design, not in the section on construction.

Response: The portions of the cited text in Section 5.3.1.2 that are more appropriately presented under design have been incorporated into Section 4.5.7, "Slope Stability." The portions that cite a draft USEPA document have been eliminated. Text remaining in Section 5.3.1.2 relates directly to cover construction.

35. **Comment:** The first paragraph of 5.3.2 mentions that "…if most soil types are placed at a moisture content of 0.9 times the field capacity values, satisfactory results can be obtained." I believe the phrase "0.9 times the field capacity values" should be replaced with "at no more than 90% of the optimum moisture content" (or something to that effect). For a number of soils I have spot-checked, 90% of field capacity was always much wetter than the optimum moisture content (Proctor), but the text states a strong preference for being drier than optimum, not wetter.

Response: The change has been made.

36. **Comment:** It seems that the information in 5.3.4.1 on drainage features and 5.3.4.2 on erosion control features belongs in the design section (Section 4), not in the construction section (Section 5), as they relate specifically to design, not construction. Be careful about just moving them there though, since Section 4 already has some info on the topics (e.g., 4.10.4 on surface water control). The info in Section 4 should be compared to these Section 5 sections, and expanded, if desired.

Response: The text was moved to Section 4.

37. **Comment:** The second paragraph of Section 5.3.4.2 mentions that "Evapotranspiration (ET) landfill covers with covered slopes up to ½ mile long and with slopes up to at least 15 percent suffer virtually no erosion without using erosion control measures such as terraces and waterways on the cover." That sounds like a pretty strong statement. I doubt we have a consensus to that effect, and it seems to contradict other guidance that is published on landfill covers. It seems preferable to be more generic and mention that site-specific conditions need to be considered in determining the design of appropriate surface water control features. Perhaps we could mention that one author/study has concluded that in some circumstances "…covered slopes up to ½ mile long…" etc.

Response: The cited text has been modified and the storm-water section has been generalized deleting these specific details.

38. **Comment:** I have the same concern regarding the statement in the sidebar within 5.3.4.2 that "The landfill cover is vulnerable to significant erosion only during the grass establishment period." It seems that statement might apply to some climates/conditions, but not others.

Response: Deleted the word "only."

39. **Comment:** Section 5.3.5 on irrigation seems to go into excessive detail to me. I think it would be better to have a page or less mentioning how/when irrigation might be beneficial,

discussing how to determine appropriate amounts, perhaps briefly mentioning different methods and preferences, and refer the reader to other sources for more information.

Response: The discussion on irrigation has been revised and generalized. Save 5.3.2 (keep first large paragraph) and 5.3.2 and delete the remainder (up to what was 5.4). Much of the detail previously included in 5.3.5 (now renumbered as 5.3.4) has been eliminated. The remaining text has been edited to address the subject in general terms.

40. **Comment:** Section 6 on post-closure care seems to be written for the big-budget, large sites. If this guidance were to really be followed, I suspect that many of the smaller subtitle D facilities would give up consideration of an AFC. For example, the sampling protocol listed in Section 6.3.5 seems to be more than would be required/warranted at many sites. Couldn't this be written so that it can be adapted to both large sites as well as to small, low-risk sites? Perhaps the section could be written as being things that might be considered for large, sensitive projects, but that for many (most?) sites something less rigorous is probably appropriate and that the actual plan should be determined on a case-by-case basis.

Response: Text was added indicating that not all of the conditions are required at all facilities.

41. **Comment:** Additionally, much of Section 6 seems to go into excessive amounts of detail (e.g., mentioning in Table 6-1 that an inspector might bring a clipboard, a pen, and a permanent black marker, seems excessively detailed, etc.).

Response: The table was deleted as it was determined to be too detailed.

42. **Comment:** The 2nd sentence of the 2nd paragraph of 6.2.1 mentions two devices that are used for measuring flux. Lysimeters do measure flux, but soil moisture probes do not measure flux. They measure only soil moisture data, from which flux estimates are made. The Colorado Department of Public Health and the Environment recently wrote a white paper on the topic that emphasized the large inaccuracies that are possible in flux estimates based on data from soil moisture probes.

Response: Probe information was clarified in several locations within the document.

43. **Comment:** Section 6.6 contains information on design. Shouldn't the relevant parts be moved to Section 4 on design (if not already covered there)? For example, Section 6.6.2.3 talks about designing to prevent animal intrusion, to prevent excessive settlement, to provide stable slopes, etc. To the extent that these items should be considered in design, they belong in Section 4 on design (some already are there).

Response: This section is not intended to establish design criteria. It is a guide to establish an effective monitoring program. The regulatory citations were deleted.

44. **Comment:** Much of what is in Section 6.6.4 on costs is somewhat redundant with Section 4.13 on costs. Other information is contradictory. We ought to generally eliminate most of the redundancy and resolve the contradictions. For example, 6.6.4.2 says that prescriptive solid waste covers (other parts of the document have intentionally avoided use of the word "prescriptive," and used "conventional" instead) cost an average of $100,000/acre, and prescriptive hazardous waste covers cost $150,000. However, Section 4.13 quotes a reference that says the <u>cost difference</u> between AFCs and conventional covers is $150,000! We probably need to either resolve the difference or say more about the range of costs.

Response: Cost information has been revised.

45. **Comment:** In the last definition in Appendix A on Suction Head, the definition was written facetiously by the author, as it is the definition for Net Positive Suction Head, which applies to pumps and has nothing to do with suction head in soil. The statement either needs to be dropped out, or replaced with the right definition.

Response: See definition in Key Terms, Appendix D.

46. **Comment:** Section 4.1 Paragraph 2 add language clarifying how much deep percolation is acceptable.

Response: See Comment 13.

47. Comment: Section 4.1.2 last paragraph should be deleted.

Response: Deleted.

48. **Comment:** Section 4.2 paragraph 6 delete the following: "This situation could create a significant potential for precipitation to infiltrate through the cover."

Response: Deleted.

49. **Comment:** Section 4.2 1st paragraph add the following at the end of the paragraph: "Few weather records contain accurate data for more than 60 or 70 years, and they may not reveal extremes that are important to ET cover design. Likewise, it is not known whether the existing data represent above average or below average conditions that might be demonstrated by longer records if they were available for the site. For these reasons it might be useful to employ software that can extrapolate future meteorological conditions from past records."

Response: Long term climatic impacts on AFC design may be evaluated during the design sensitivity analysis.

50. **Comment:** Section 4.2.1 2nd paragraph delete the following sentences: "This situation could create a significant potential for precipitation to infiltrate through the cover....Few weather records contain accurate data for more than 60 or 70 years, and they may not reveal extremes that are important to ET cover design. Likewise, it is not known whether the existing data represent above average or below average conditions that might be demonstrated by longer records if they were available for the site...."

Response: Done.

51. **Comment:** Section 3.1.2 Add the following sentence as the second sentence in paragraph 6: "EPA currently recommends that MSW cover systems be designed to allow no more than 0.1 to 1 mm/yr of percolation."

Response: The team has reworded this sentence and removed this language. See Comment 13.

52. **Comment:** Section 4.6.3—Can we include a couple of methods, or sources of the methods, used to determine the percent of ground cover?

Response: Method was inserted into the document.

53. **Comment:** Section 4.7.2 1st paragraph—What other methodologies are available for estimating runoff that are used in geotechnical design practice?

Response: 4.7 has been deleted please see standard engineering references.

54. **Comment:** Section 4.7.2 3rd paragraph—This sentence needs to be discussed and verified with the team: "Annual or monthly estimates of runoff have little use in design of AFCs."

Response: See Comment 53.

55. **Comment:** Section 4.7.3—Please provide justification and documentation for this statement. Are there any side by side comparison studies? The sentence must be deleted if it is not documented: "Therefore, the use of two models may increase the errors in runoff estimates."

Response: See Comment 53

56. **Comment:** Section 4.7.4—Please explain how this part of the discussion pertains to AFCs: "Their work demonstrates the need for caution in applying the CN method under dry conditions."

Response: See Comment 53.

57. **Comment:** Section 4.7.4 next to last paragraph. What engineering firm survey or other information is this statement based on? "The ASCE Manual 28 (1996) discusses 18 engineering design models that compute surface runoff; some of them use infiltration equations to estimate surface runoff. One of the models used the "Richards equation" to estimate infiltration. One used the Smith & Parlange infiltration equation and two used an "index". Two models could use either the SCS curve number method or the Green-Ampt infiltration equation. Nine of the models used the SCS curve number method and six used the Green-Ampt infiltration equation. The SCS curve number method and the Green-Ampt infiltration equation are by far the most popular methods for estimating surface runoff in engineering design models."

Response: See Comment 53.

58. **Comment:** Section 4.5.3, Assessment of Borrow Sources, 1st paragraph, change to read as below:

    The assessment and evaluation of potential borrow sources is an essential phase of the design and construction of an AFC. The purpose of this assessment is to determine the actual engineering and agronomic soil characteristics of the soils available to construct an AFC. Evaluation of available soils consists of preliminary investigations, soil sampling, and laboratory testing. In addition to determining soil characteristics, it is important to determine the volume of soils available for use and the total costs to have a suitable soil available on-site. The soil source costs may include the cost for transportation and/or costs to process/blend soil(s) to produce a suitable material. <u>Because the soil geotechnical and agronomic properties are not expected to change during transport or over time, it may be beneficial to conduct an extensive QC program during the borrow area characterization and then allow for some confirmation (QA samples) during construction. This will save time waiting for laboratory analysis during construction and reduce or eliminate the number of rejected loads during cover soil placement.</u> It is recommended that a borrow source assessment report be prepared to document the investigation.

Response: Comment rejected since the team cannot agree that the insert is correct.

59. **Comment:** Page 4-20, section 4.6.7
    Problem Text: TR5 does not adequately explain either potential ET or actual ET and how they relate to performance of ET landfill covers.
    Reason: Actual evapotranspiration is the largest term in the site water balance for a landfill cover and dominates performance estimates and design issues.
    Solution: Insert a new section 4.1.1 and renumber and rename the current section 4.1.1 to 4.1.2 Design Mechanisms. The new text is contained in the 3-page document enclosed and labeled *4.1.1 Evapotranspiration*. Delete the current section 4.6.7, which is replaced by the attached new text.

Response: ET and PET text was inserted in Section 1 and section 4 to further explain the concepts

60. **Comment:** Page 2-1, section 2.2.1, paragraph 1 and Page 2-5, section 2.3.1, paragraph 1
    Problem text: The results of the ITRC/ALT "survey" are mentioned but not presented.
    Reason: It is presumed that the survey contains information of value to the reader.
    Solution: Complete survey results should be presented and interpreted for the reader. The survey results are not available to the Air Force; therefore, others must supply this section.

Response: See Appendix B.

61. **Comment:** Page 1-3, second line
    Problem text: "Inclusion of an impenetrable layer in an ET cover could also be considered."
    Reason: This statement is contradictory to the definition of an ET cover, which requires that the cover contain no barriers.
    Solution: The sentence should be deleted or modified to show the true meaning or intent of this statement. A possible modified statement is, "Another alternative landfill cover is named _________, (show reference) and uses vegetation and soil on top of an 'impenetrable' barrier installed for the purpose of _________________(show reference if appropriate)."

Response: We appreciate the comment and have revised the sentence to clarify the issue and avoid confusion between impermeable and impenetrable. "On occasion it may be necessary to include nontraditional layers to the ET cover to handle special functions."

62. **Comment**: Page 4-11, last paragraph
    Problem text: "Atterberg Limits: The use of high plasticity materials is undesired to minimize soil volumetric changes (shrinkage) induced by moisture fluctuations. Low plasticity soils may also be undesirable because of their friable nature and consequently high hydraulic conductivity."
    Reason: These contradictory statements prevent the use of most soils in ET landfill covers, even though most would be acceptable. These statements incorrectly apply the Atterberg limit concept to ET landfill covers. The topic of "Atterberg limits" is misspelled in some instances and mentioned on page 4-10, Tables 4-3 and 4-4, and in the table on page 5-6. It is not appropriately defined nor is its use in an alternative cover explained.
    Solution: Delete this paragraph and the other text that mentions "Atterberg limits." No alternative text is offered because the use of this concept in other alternative landfill covers is not explained within the document and is therefore unknown.

Response: The majority of the team disagrees, and the language regarding Atterberg limits was retained in the document. There is no requirement to use Atterberg limits, but some regulators appreciated the parameter, even in AFCs.

63. **Comment:** Page 3-2, last paragraph (continues on page 3-3)

    Problem text: "If a performance-based (allowable leakage/flux) goal is used, the following options should be considered:

    1) Determine allowable flux through the cover based on equivalency to a conventional cover (established by computer modeling in most situations),
    2) Determine allowable flux through the cover based on a set of criteria,
    3) Determine an allowable flux rate through the cover and waste, or at some other point of compliance,
    4) A combination of 2 and 3 evaluating the landfill system in an holistic approach,
    5) Test the conventional and alternative covers in a side-by-side demonstration, and/or
    6) Use performance data, via test covers or models, for similar conventional and alternative cover studies"

    Reasons:

    <u>Item 1</u>: The term "equivalency," if used, prevents use of the ET landfill cover because the ET cover cannot be equal to the design requirements contained in current rules and regulations.

    <u>Item 5</u>: Testing of an already proven concept will add several unnecessary years to the remediation process, add significant expense, and is unlikely to be conclusive. The ET landfill cover can provide performance that is equivalent to current requirements. Demonstration or short-term tests (e.g. 5 years) are unlikely to be conclusive because they do not adequately sample climate and, at some locations, at least half of the test duration time may be required to achieve full effectiveness of the vegetation cover.

    Solution: Replace this paragraph with the following:

    "After landfill remediation requirements are agreed upon, establish the allowable flux through the cover. The following steps may then be employed:

    1. Assure that the design meets requirements by estimating the long-term average and maximum daily flux rate through the cover for an adequate design time period (e.g. 100 years). Use a computer model validated for the purpose.
    2. After construction, monitor performance of the cover by groundwater quality measurements downgradient from the landfill."

Response: The term "equivalency" was eliminated from the document and replaced with performance or performance criteria. **Item 5:** As stated during previous comment session and meetings, the majority of the team does not believe that we cannot eliminate test covers regardless of the additional cost and it should be an option in all cases but not a requirement.

64. **Comment:** Page 4-7, paragraph 3, lines 4-11, and related comment in paragraph 4 (part of section 4.2 SITE SCREENING).

    Problem text: "The maximum stress event, critical event, will need to be negotiated with the regulators. The design may be based on estimated future extreme events predicted from models or extrapolated from available records. However, some regulators have chosen other criteria that the critical event as a design basis. As an example some regulators may whish to determine the impact of a long duration low intensity storm where precipitation does not exceed the rate of infiltration. This scenario may not present a deleterious erosional impact on the cover, but could place the maximum amount of stress on the cover by causing the greatest amount of water to infiltrate into the cover materials."

Reason: A qualified design engineer will determine the type of storm, amount of precipitation, soil water storage, and other important features of the "critical event" during design activities for an ET landfill cover. The nature of the critical event is seldom known before design activity and model evaluation for the site and, therefore, cannot be negotiated. The critical event is determined by site climate and its interaction with soil and plants.

Solution: Delete the last two paragraphs of section 4.2, Site Screening. The paragraphs may be replaced with: "Site screening should precede design. The suitability of the climate at the site for an ET landfill cover or other remediation effort depending on ET is very important to selection of the appropriate remediation methods. If the annual potential ET (PET) is greater than annual precipitation (PRCP) then the ET cover may be appropriate for the site. Because there are numerous other factors that affect suitability, site screening should be based on a more conservative PET/PRCP evaluation. A PET/PRCP ratio greater than 1.2 provides a conservative first estimate (Hauser and Gimon, 2001). In all cases, a more detailed evaluation with data from the site is required to verify the assumptions associated with the 'Site Screening' estimate."

Response: The document retains an allowance for screening tools used with selecting AFC location. In addition the document reflects that AFCs may be constructed in virtually all environments provided the applicable performance criteria. PET and ET were addressed in section 4.

65. **Comment:** Page 4-8 (a), paragraph 1, lines 2-8 (A part of section 4.2 SITE SCREENING)

Problem text: "However, some regulators have chosen other criteria than the critical high intensity event as a design basis. As an example some regulators may wish to determine the impact of a long duration low intensity storm where precipitation does not exceed the rate of infiltration. This scenario may not present a deleterious erosional impact on the cover, but could place the maximum amount of stress on the cover by causing the greatest amount of water to infiltrate into the cover materials. This situation could create a significant potential for precipitation to infiltrate through the cover. A similar situation may be created by snowmelt."

Reason: Estimation of the "critical event" is not part of "site screening." The critical event is site specific because climate is site specific. These sentences imply that the outcome of the design process is known before beginning the design of the ET landfill cover.

Solution: Delete these sentences. Replace the paragraph in section 4.2.1 (beginning on page 4-7) with:

"4.2.1 Climate Statistics Useful for Site Screening.

During site screening, determine the quality of climatic data for the site. Even a short record measured at the site is valuable. Collect climate data for the nearest stations that represent the climate at the site. In mountainous regions, elevation is an important criterion for assessing climate data. The minimum climate data required for site screening is daily rainfall and daily values of maximum and minimum air temperatures. Additional measurements add value to the data set. Long records are preferred. Records longer than 70 years are preferred where the performance of the cover must be evaluated for a century or more."

Response: See comment 64.

66. **Comment:** Page 4-8 (b), Section 4.4, bullet 2, last two sentences

Problem text: Paragraph topic—depth of water required to be stored in the ET cover soil: "There is no prescribed procedure for this determination; rather it is typically a result of negotiation between design engineer and regulator. Design personnel are strongly advised to consult the appropriate agencies prior to proceeding with design activities."

Reason: The principles required to make this estimate are well known to hydrologists, soil scientists, soil physicists, and agricultural engineers. After the design storm is identified, the process is straightforward from known principles. The site-specific procedure required will be revealed by a good engineering design process and cannot be known before design begins; therefore, this requirement may stop the use of the ET landfill cover.

Solution: Delete both sentences because the estimating principles are well known and regulators need only be kept apprised of the design process and outcomes.

Response: The following replaces the deleted sentences: "There are a variety of procedures available for estimating these parameters which should be negotiated and disclosed to regulators and documented in plans to the regulators. These procedures will be refined during the design process and sensitivity analysis."

67. **Comment** Page 4-10, Paragraph 5, Lines 7 and 8

Problem text: "Measurement of the natural in-situ values of soil density should provide an acceptable starting point for evaluation of desired density."

Reason: Application of this requirement may result in ET landfill cover failure. This sentence in TR5 is untrue. The density of many natural soils is high enough to reduce root growth when the soil is wet to field capacity and to stop root growth when the soil water content is less than field capacity. Because an ET cover requires robust root and plant growth to achieve control of soil water, this criterion will prevent use of the ET cover at many sites.

Solution: Delete the entire paragraph because all issues are more completely discussed in section five.

Response: The comment is rejected. This is an integral part of preliminary characterization of the soils and does not constitute the final soil material for the cover. The soil may be amended for the final cover material.

68. **Comment:** Page 4-28, Section 4.8.3, paragraph 2

Problem text: "It is recommended that the following issues be agreed upon in writing prior to modeling:"

Reason: Agreements of this type compromise and limit the authority of regulators to question finished designs. This paragraph implies that the outcome of the design process is known before design begins. This is not possible and prevents further progress toward use of the ET landfill cover. Compliance with these demands will require a complete design before the final design. These issues are unknown before the design process begins. Qualified design engineers must seek, find, and use the best information available during the design process.

Solution: Replace the first sentence with: "It is recommended that the design team provide the regulators the rationale for each of the following design decisions:"

Response: Changes were made during the October team meeting and refined during the final rewrite to allow flexibility but emphasize the intent to have regulator input.

69. **Comment:** Page 4-28, last two lines on the page

Problem text: "It is strongly recommended to not consider absolute flux the focus or primary outcome of landfill cover design modeling."

Reason: This statement will preclude acceptance of ET landfill covers. A primary reason for installing landfill covers is to control percolation of precipitation through the waste; therefore, flux through the cover must be central in the design process. This statement confuses the reader because in numerous other statements within the TR5 document control of water moving through the cover and into the waste is stated or implied as a goal of remediation.

Solution: Delete this sentence because it does not impact the rest of the paragraph and the issue is discussed in several sections of the document.

Response: The importance of flux in the design of AFC is not in question; however, the measurement of "absolute" flux is uncertain and cannot be the sole basis of design. The thought will be reworded to express the positive attributes and necessity of flux measurements.

70. **Comment:** Page 4-41, paragraph 1, lines 3-5

Problem text: "Use of soils that are predominantly composed of clay may even be problematic for an alternative cover because of the potential for limiting vegetative growth and the potential for desiccation cracking."

Reason: This statement will preclude use of ET covers at sites where the soils in the area are high in clay content. Contrary to the statement, clay soils produce robust vegetative growth. Examples of vegetative growth in clay soils include the Texas Blackland soils, black soils of Alabama, and black soils of Australia; all of them are famous examples of highly productive soils that are very high in clay content. Expansive clay soils may produce large cracks where mankind has changed the environment (e.g., along sidewalks, between the rows of row crops, etc.). However, when covered with a good grass cover, the cracks in clay soil, although numerous, are small and do not foster deep percolation. An example of water movement within an expansive soil is found in the paper by Aronovici (1971), which shows that although the Pullman soil can produce large cracks, water did not percolate below the root depth of grasses.

Solution: Delete this sentence because it will not impact the rest of the paragraph and the topic is adequately discussed in section five.

Response: The team disagrees with the comment on desiccation cracking but will remove the section of the sentence describing clayey soils limiting plant growth.

71. **Comment:** Page 5-11, section 5.3.1.1, paragraph 3, last sentence

Problem text: "Deep ripping is not recommended as a means to loosen the soil as it may cause subgrade voids, which could subsequently lead to settlement or "piping" problems."

Reason: This statement is untrue and may cause use of alternative construction methods that greatly increase construction costs. Construction of ET covers may require haul roads on the cover surface to reduce costs. The wheel traffic on these roads is likely to compact the soils to densities well above the required design density for the cover. Excessive soil density may cause the ET cover to leak. One of the most effective and also economical ways to correct the problem is by deep ripping or chiseling the soil. The cover soil of an ET cover is designed so that the soil water pressures are below atmospheric almost all of the time. In this regard, they are similar to dryland fields or pastures. Water may exist above atmospheric pressure within the soil for very short time periods. When soil water pressure is at or below atmospheric, water cannot enter large pores or cavities within the soil mass. It is therefore, nearly impossible for soil ripping, especially if performed on the contour, to cause the problem stated. It poses a small risk.

Solution: Delete this sentence because it does not impact the rest of the paragraph and the issue is discussed in several sections of the document.

Response: The team agrees with the comment and will delete this sentence but add that controlled chiseling or disking can be used in highly compacted areas.

72. **Comment:** Page 6-2, section 6.2.1 Field Methods (entire section)

Problem text: "6.2.1 Field Methods

"Until such time as alternative final covers gain widespread acceptance, it may be necessary to take direct measurements of water flux through the cap. This would be done with two main goals in mind, to ensure that the landfill cover has been constructed to design standards (e.g., flux would relate to sum of all of the design standards and criteria, but would not supplant construction QA/QC), and to ensure that flux through the cover is consistent with predicted levels. As regulatory agencies become more comfortable that alternative covers are capable of providing an acceptable level of protection to the environment, it is conceivable that the installation of flux monitoring devices would no longer be required. At the time of publication of this document, there is no industry wide acceptable level for flux through an alternative landfill cover, and no commonly agreed upon method of determining if an alternative final cover is performing at the same level as a prescriptive cover. It is important to understand that current flux monitoring devices contain uncertainty inherent in their operation. The simple act of maintenance of this equipment can cause variability in the quality of data collected.

"Flux monitoring devices are installed in a landfill cap to determine if the cover is performing at design levels. Two devices are commonly used to actually measure flux, a pan lysimeter, and a soil moisture probe. The pan lysimeter is used to measure deep percolation and is typically installed at the base of the cover system. Soil moisture probes can be installed anywhere in the cover system, but do not provide a directly quantifiable number for amount of moisture percolating through the cover system.

"During closure and the early post-closure care period, flux monitoring devices may be needed to determine if an alternative final cover is functioning in accordance with approved design (including operational and monitoring compliance criteria and specifications). Data from flux monitoring devices by itself may not be sufficient cause to trigger corrective action on the alternative final cover, but may trigger further actions such as increased monitoring of the system. Upon receipt and confirmation of suitable flux rates, it may be possible to stop monitoring flux for the remainder of the post-closure care period, provided cap integrity is properly maintained. An acceptable alternative to lysimeters and soil moisture probes, and a good overall indicator of cap performance, may be close monitoring of leachate generation rates, and routine analyses of how these rates compare to precipitation rates."

Reason: This requirement could prevent use of the ET landfill cover. While this section is labeled "Field Methods," it discusses <u>research methods</u> that have been used in <u>field research</u>.

If applied, they will likely double the lifetime cost for an ET landfill cover. The last two sentences of paragraph 1 demonstrate that they are likely to produce data of questionable quality, which could result in expensive future revisions of remediation activities at the landfill. This section assumes that the ET cover concept has not been proven; however, that is not true. The ET landfill cover concept has been proven and numerous research papers document the proof.

Solution: Delete all three paragraphs of the current section. Replace the text with the following:

"Measurement of the flux through the AFC should not be necessary under most conditions. However, where needed, the following estimates of flux will assist with post-closure monitoring and assessment.

1) Measure the leachate collected by the leachate collection system installed in the landfill bottom liner.
2) For landfills with no bottom liner, estimate flux through the cover by one of the following methods:
   a) Measure soil water content, soil water pressure, and the unsaturated hydraulic conductivity curve for the soil. Make the measurements at weekly or more frequent intervals; or recorded with automatic field recorders. Estimate flux rate from the field measurements.
   b) Install lysimeters within the cover to measure flux directly. Service and record results on a weekly or more frequent basis to secure reliable data."

Response Will modify paragraph 2 above. Paragraphs 1 and 3 will remain essentially as is.

73. **Comment:** Page 3-3 (b), last paragraph of section 3.1.2
    Problem text: "If an owner or regulator decides to set a flux rate through the cover, EPA currently recommends that MSW cover systems be designed to allow no more than 0.1 to 1 mm/yr of percolation, with a specific value in that range selected based on the nature of the contained waste, the hydrogeological vulnerability of the site, and other factors (as mentioned above in Section 3.2.2.1). However, EPA also states that these rates may be lower than the accuracy of the numerical models and field methods that are currently used to assess cover system hydraulic performance, and recognizes that different site-specific percolation rates may be acceptable for certain sites. In addition, measurements made below the accuracy of existing devices and used a model input values will decrease the precision of the model results."

Response: Agree, see Response 13.

74. **Comment:** Page 3-3 (c), section 3.1.3, one paragraph
    Problem text: "EPA states in their draft 2002 EPA Technical Guidance for RCRA/CERCLA Final Covers that their recommended percolation ranges for MSW landfill cover systems (0.1 to 1 mm/yr) is likely conservative with respect to preventing the "bathtub" effect since MSW generally has the capacity to absorb a substantial amount of water. However, the EPA also states that hazardous waste cover systems may require a higher level of performance to prevent the "bathtub" effect."

Response: Agee, see Response 13.

75. **Comment**: Page 4-27, Section 4.8.2, Paragraph One, Lines 10-13

Problem text: "There is current widespread interest in reducing percolation into landfills to a very few millimeters, 0-5 mm/year, in many cases. Acceptable bounds on accuracy of predictions of performance are often thought to be in the 1-3 mm/year range. In fact EPA's current guidance recommends flux rates through landfill covers between 0.1 and 1.0 mm/yr."

Reason: It is impossible for landfill owners to meet this requirement. The percolation rates of 0.1 to 1 mm/year are not official EPA regulations. Inclusion of this text in an ITRC document lends the proposed, but not required concept, credibility. This requirement is similar to the commonly accepted myth that barriers in conventional landfill covers are "impermeable". In all three instances, the TR5 version of the guidance quotes or refers to text contained in draft EPA guidance (Bonaparte et al. 2002). The text cited is found on pages 1-11 and 1-12 of the EPA draft guidance document. The EPA draft also states "…percolation rates for MSW landfill cover systems is likely conservative…", and "EPA is not yet recommending a design percolation rate for HW landfill cover systems". The draft EPA guidance also shows leachate generation rates for 34 landfills on page 1-15 (Figure 1-9). The data reveal that in the fourth year after closure, 31 of 34 landfill covers were leaking more than 3 times the proposed 1-mm rate. A recent separate research test by Dwyer (2001) of six landfill covers in a very dry climate revealed that conventional barrier-type landfill covers leaked in excess of 5 mm/year at a location where total annual precipitation was reported to be less than 130 mm.

Solution: page 3-3, last paragraph of section 3.1.2. Replace the paragraph with the following:

"Before selecting the kind of landfill cover, all interested parties should agree on the requirements for remediation including performance of the cover. Then the owner can select and use any cover that meets the performance requirements."

Response: The original paragraph is accurate based on practitioners' experience who have successfully negotiated with regulators in a number of states, had test covers approved, constructed, and the resulting data evaluated. Therefore, the language will remain. The EPA guidance language was replaced as discussed in Response 13. The intent of the proposed "solution" language is already addressed.

Solution: Page 3-3, section 3.1.3. Replace the paragraph with the following:

"This goal is stated in RCRA as a minimum technical requirement under both Subtitles C and D regulations. The Subtitle D requirement also states that the permeability must be no greater than 1×10^{-5} cm/sec. The intent of this regulation is to reduce the amount of water migrating through the cover resulting in a decrease or elimination of leachate migrating through the waste. AFCs can control infiltration of precipitation. Therefore, the AFCs will satisfy the intent of the regulations by limiting the flux of water through the cover that could become leachate migrating through the waste. Essentially, the evaluations conducted under Sections 3.2.2.1 and 3.2.2.2 should result in compliance with this goal."

Response: The text is accurate and will be retained. The initial regulations and guidance do in fact reference the use of low-permeability layer. In addition, AFCs do function differently.

Solution: Page 4-24, section 4.8.2, paragraph one. Replace the paragraph with the following:

"The predictive accuracy of hydrologic models for landfill applications is still being debated, with special emphasis given to percolation through covers. A number of lysimeter studies performed over the last 10 years provided data required to compare actual results (within the confines of the measurement capabilities) with modeled results. These studies were performed on a variety of cover types/configurations and climate regions. Although models have performed well in some instances, their accuracy was questioned in others. The presence of uncertainty in simulated results always presents difficulties. Regulators and designers alike are well advised to accept that models are just that, models, and not reality. Currently, several (but not all) of the practitioners involved with this (ITRC) guidance believe that no single computer code predicts landfill cover performance with accuracy adequate to meet regulatory requirements for uncertainty."

Response: The language indicating that "(but not all)" was added to the text.

76. **Comment:** Page 7—Capillary break durability is first mentioned, together with two of the reports indicating the potential for failure/degradation. Somewhere in the document, we should mention that observing the performance of the capillary break's performance is difficult if not impractical. Also, there are only two ways that a capillary break can be expected to last long times. 1) The fines over coarse arrangement is mechanically stable, analogous to damn construction. As Stormont 1997 points out, this might require a very conservative design. 2) There is a liner in between the fines/coarse that is expected to prevent mixing of the fines into the coarse for the required time period. This would seem to be inconsistent with the general unwillingness to credit plastics or geosynthetic clay liners for long time periods.

Response: Text was integrated into the section on cover concepts.

77. **Comment:** Page 16—"Have a permeability less than or equal to the permeability of any bottom liner system or natural subsoils present, or a permeability no greater than 1×10^{-5} cm/sec, whichever is less.…"

Response: Change accepted and made in text.

78. Page 25—"Essentially, the evaluations conducted under Sections 3.2.2.1 and 3.2.2.2 should result in compliance with this goal." I suspect those section numbers refer to the original EPA documents; they do not refer to section numbers in this ITRC document. That should be clarified. Somewhere (perhaps page 25), it would be helpful to remind readers that most of the degradation processes discussed in this document suggest that the cap will degrade faster than the liner. Thus, maintaining the EPA requirement on page 16 would seem to become more difficult with time and relatively difficult to test/observe.

Response: The section references have been removed.

79. **Comment:** Page 24—I particularly like the discussion here regarding infiltration, percolation, etc. I think it puts the current EPA percolation guidance (page 25) into proper perspective.

Response: Thank you

80. **Comment:** Page 72—I note that this first place that human intrusion (accidental or deliberate/malevolent). I concur with the sources of information given on intrusion-related matters. Although in some circles there seems a desirability to make caps thicker on the grounds that it will take humans longer to deliberately steal hazardous materials, my personal belief is that anything humans can engineer, humans can un-engineer.

Response: Language was added to the post-closure care section.

81. **Comment:** Page 2-6; Section 2.4: A lot of the section does not discuss regulatory flexibility.
Response: Text not related to regulatory flexibility was either moved or deleted.

82. **Comment:** Page 2-7; Section 2.5.1.1: How is probe data used to verify performance?
Response: This is now addressed in Section 4. Text indicates that probes provide data for calculation to estimate flux that can be off several orders of magnitude.

83. **Comment:** Page 2-9; Section 2.6: Item 1b may not be true; sometimes the AFCs are harder to build. Item 1d QA/QC may not be much lower.
Response: Text moved to Section 1.3. List is of "potential" advantages and included references to indexing techniques.

84. **Comment:** Page 3-1; Section 3.1.1.; item 5: Why is grade fill included in the list?
Response: Grade fill was included as a potential limiting factor as was noted in previous failures, and is a site condition parameter.

85. Page 3-4; Section 3.1.8: Section 3.1.8 does not appear to add anything to the topic.
Response: This was included from the DOE perspective as a function of protecting human health and the environment (i.e., managing risk translates to protecting human health and the environment).

86. **Comment:** Chapter 4: This chapter does not flow in a logical fashion. There is a 4 step process identified in the introduction, but the first step doesn't show up until 7 pages later and then there is nothing of substance in it. Section 4.1.1 through 4.2 should go ahead of the preliminary design discussion. Section 4.6 doesn't relate to the chapter.
Response: Agreed. Text was rearranged to facilitate the flow of the document. The vegetation section was redone to capture relevant design information.

87. **Comment:** Page 4-1; Figure 4-1 is not very helpful.
Response: The figure was retained but moved into section 3.0 to discuss goals as they might relate to performance.

88. **Comment:** Page 4-6; Section 4.1.2: The last paragraph is in the Section 4.1 introduction.
Response: The repeated text was deleted.

89. **Comment:** Page 4-8; Section 4.2.1: Text from section 4.1.1 is repeated in section 4.1.2, and section 4.2.1 does not have much information without the repeated text.
Response: The repeated text was deleted.

90. **Comment:** Section 4.4: If extensive site characterization comes after the preliminary design, at least a basic site characterization should be included in this section.
Response: Section 4 was modified to reflect the revised design process.

91. **Comment:** Page 4-9; Section 4.5: Using/evaluating data from other sites should be a separate section, and at the end of the section.
Response: Agreed.

92. **Comment:** Page 4-10; Section 4.5.1: Last 4 paragraphs at the bottom of the page do not pertain to soil or volume characterization.
Response: Agreed. The first and last paragraph was deleted, and the remaining paragraphs were moved to the section on preliminary soil volume.

93. **Comment:** Page 4-11; Section 4.5.1.1: Table has a confusing format. Separate the two halves of the table into two tables.
Response: Table was split.

94. **Comment:** Section 4.5.1.2: Text below the table should be in the same order as the items listed in the table (may be easier to rearrange the table items). Last half of the last sentence of item once sounds like its not that important, and should be deleted.
Response: Done.

95. **Comment:** Page 4-12: Items 3 and 4 have incorrect references (Zornberg & Chadwick).
Response: Corrected.

96. **Comment:** Page 4-13; Item 7: Delete Figure 4-3 & 7. This is not an important engineering parameter and doesn't fit with the rest of the section. There is no Zornberg et al. 2001 reference.
Response: See Response 21.

97. **Comment:** Page 4-14: Item 10: The GLBD paper should be cited and referenced. Item 12: Need to include at least a brief description. Section 4.5.2: Section should be moved to the preliminary characterization section.
Response: Added at section 5.3.1.

98. **Comment:** Page 4-16; Section 4.5.3: Item 4: Reference the ASTM test number.
Response: See table 4-1 for all ASTM numbers

99. **Comment:** Page 4-21; Section 4.7.1: How does growth rate affect surface runoff? How does growth rate affect biomass production and in turn affect runoff? Should "substantial" be replaced with "significant"?
Response: Text will be rewritten, and relative impacts of parameters were discussed in Section 4.5.4.

100. **Comment:** Page 4-22: Figures 4-4 and 5. The figures need a legend to explain the different curves. Are the two storms sequential or separate?
Response: Section was rewritten, and figures were deleted.

101. **Comment:** Page 4-27; Section 4.8.1: RCRA became effective November 18, 1980. What is the reference to 1990.

Response: Clarified that 199 is Subtitle and 1992 is Subtitle C.

102. **Comment:** Page 4-42; Section 4.10.3: Last paragraph belongs in another section.
Response: Text was moved to Section 4.5.4 surface water control.

103. **Comment:** Page 5-2; Section 5.1 (last Para): "…. infiltration water, ~~or~~ making water available to plants, or inhibiting root development (or plant growth),and as a result cause the AFC to fail."
Response: Agreed.

104. **Comment:** Page 5-3; Table 5-1: What about Proctors, Ksat, and moisture retention data?
Response: Table was revised as noted and is now Table 4-1.

105. **Comment:** Page 5-5; Section 5.2.1.2: Delete the first 4 paragraphs as they are only a partial reiteration of the previous table. Do not need to discuss pH, sodium, etc. as they aren't that important.
Response: Table and text were split intentionally based on comments and input from other team members. Other team members specifically requested this information be included.

106. **Comment:** Page 5-6; Table: Consider this table with Table 5-1, and adding Proctors, etc.
Response: Table moved to Section 4 (design). Proctor is included in method D698.

107. **Comment:** Page 5-11; Section 5.3.1.1; First Para. …. And loosening the soils after placement is not a good idea. How do you loosen to full depth without deep ripping?
Response: Text referencing deep ripping was eliminated. Preference is for initial placement of the material in the specified loose condition. However, some loosening of soils after placement was acceptable to the team.

108. **Comment:** Page 5-13; Section 5.3.3: Vegetation should be a separate section (i.e., not part of construction methods).
Response: Some of the vegetation text was relocated to design, but the remainder will be kept as located.

109. **Comment:** Page 5-18: Insert Figures.
Response: Figures deleted.

110. **Comment:** Page 5-19; Section 5.3.4.2: What is the reference for 15%.
Response: The 15% value was deleted.

111. **Comment:** Page 5-20; Section 5.3.5.1: This section is oddly specific. It seems too prescriptive for this document.
Response: The text was generalized for broader application.

112. **Comment:** Page 5-23; Section 5.4: CQC should go before vegetation. CQA does not incorporate CQC. They are separate. Need definition of quality assurance. Need to differentiate CQC and CQA.

Response: Text was clarified as to the intent of the discussion in the document.

113. **Comment:** Page 5-24; Section 5.4: Stop writing CQA and CQC. Table 5-5: Is the referenced engineer the CQC engineer?
Response: See 112.

114. **Comment:** Page 5-25; Table 5-6: This is all mixed up CQC vs. CQA.
Response: See 112.

115. **Comment:** Page 5-26; Section 5.4.2.1: Delete down to 3rd paragraph, because it is redundant of earlier text and does not fit in this location.
Response: Text was extensively revised to for clarification.

116. **Comment:** Page 5-27: Replace "rationale for using" with "use of." This paragraph sounds like the USDA methods are best. Must be reworded to include the USCS option. A list of the construction tests should be in this section (e.g., nuclear gage, Proctor, Atterburg, etc.)
Response: Rationale for using is no longer in the text. Additional text was added indicating the use of the USCS system with AFCs.

117. **Comment:** Page 5-29; Section 5.4.2.2: What about adding additional material to account for erosion?
Response: At this time sacrificial layers are not discussed in the document. The addition of sacrificial soil thickness, if necessary, would be a site specific design consideration.

118. **Comment:** Page 5-32; Section 5.5.1: CQC approves the material.
Response: See 112.

119. **Comment:** Page 6-2; Section 6.2.1: Replace "predicted levels" with "predicted or allowable levels." Replace "of suitable flux" with "of consistent suitable flux."
Response: Agreed.

120. **Comment:** Page 6-4; Section 6.3.1; Table 6-1: Delete clipboard, permanent black marker, and pen; as these should be obvious. The identified items do not need to be a table, and may not be needed at all. Third paragraph following the table starting with "the purpose of the site inspection" was mentioned earlier.
Response: See Response 41.

121. **Comment:** Page 6-7; Section 6.3.3: The first and second paragraphs go into too much detail for this document.
Response: The text was retained for informational purposes

122. **Comment:** Page 6-8; Section 6.4: Replace title with LEACHATE MANAGEMENT FOR SOLID WASTE LANDFILLS.
Response: The text was added.

123. **Comment:** Section 6.4.1: Very 1991 data for passage promulgation data of Subtitle D.
Response: Subtitle D is 1992.

124. **Comment:** Section 6.4.2: Is it required to quote a page of regulations in this section. If yes, what about RCRA Subtitle C?
Response: The subtitle D regulations quote was maintained as the title of Section 6.4 was change to reflect leachate management at solid waste landfills.

125. **Comment:** Page 6-10; Section 6.4.3: How does this text relate to AFCs. Who does this text impact, and how?
Response: This information was provided to inform practitioners about trends in leachate quality. It is up to each to satisfy the regulatory requirements while negotiating post-closure care programs. Several team members were interested in the information because it may help them understand potential failure indicators.

126. **Comment:** Page 6-15; Section 6.6.1: This section should be at the front of the post-closure care section. What is R.258 and R.264?
Response: The cited text has been eliminated

127. **Comment:** Page 6-18; Prevention of animal intrusion: Most AFCs do not have a barrier.
Response: The use of an animal intrusion layer can be incorporated into an AFC cover system

128. **Comment:** Page 6-21; Section 6.6.3.1: This should be considered with Section 6.6.2.3 since they are the same elements.
Response: The text was retained as Section 6.6.2.3 was intended to discuss goals, and 6.6.3.1 was intended to discuss the resulting plan.

129. **Comment:** Page 6-24; Section 6.6.4.2: Replace "engineering of the soils" with "components".
Response: Agreed.

130. **Comment:** Appendix B: An appendix for USCS should also be included.
Response: ASTM testing methodology are called out in Table 4-1

131. **Comment**: Section 1.1: Add the following at the end of Par 1. "Landfill covers are considered here as integral parts of landfill systems."
Response: Comment accepted and incorporated into the text.

132. **Comment**: Section 1.1 paragraph two should be reworded as follows. "This document focuses on a class of landfill final covers ("alternative" covers) that differ in both design and operational theory from those designs described in RCRA regulations as minimum recommended designs. Several primary types of alternative landfill covers have been proposed by solid, hazardous, and mixed waste landfills . In addition, alternative covers have been constructed and are fully operational at industrial waste, construction debris, municipal solid waste, and hazardous waste landfills. Alternative final covers (AFCs) may be used on bioreactors landfill, conventional landfills, or other types of landfills. Types of AFCs may

include, but not limited to, asphalt covers, concrete covers, capillary barrier covers and evapotranspiration (ET) covers. This document focuses on ET covers and the decisions associated with their successful design, construction, and long-term care. Therefore the AFC discussed in this document are assumed to be ET covers including an integrated vegetation cover system unless specifically stated otherwise.

Response: Comment accepted plus additional language from previous comments will be added.

133. **Comment**: Section 1.2.1, Add the following to the end of paragraph 7. "Despite the simplicity of the design, proper performance of an ET cover depends on careful analysis of the site variables and a thorough design procedure."

Response: Comment accepted with language modifications.

134. **Comment**: Section 1.2.1, Change the wording of the 8th paragraph to the following "A variation of the ET cover concept involves addition of a capillary barrier (Stormont 1997, Kavazanjian 2001). This design consists of a coarser-grained layer placed under a finer-grained soil. The name is derived from the break in pore structure that results at the interface of the two soil types. Soil water is held in the fine-grained layer by capillary forces and will not move into the coarse-grained layer until the fine-grained layer approaches saturation near the interface. (Stormont 1997, Jury et al. 1991). Quality control in constructing a capillary break layer may be particularly important to prevent mixing of the coarse-grained and fine-grained layers, and to ensure that flaws in the capillary break do not cause failure (Morel-Seytoux, 1996). The consequences and potential for lateral flow in the fine-grained soil above a capillary break should also be considered (Stormont 1997 and Morel-Seytoux 1996). Laboratory and field-scale testing of covers incorporating capillary breaks have demonstrated their potential viability, but included some failures (Stormont 1997 and Dwyer 2001).

Response: Comment accepted.

135. **Comment**: Section 1.3 Note on this section: In some circles, the term "barrier" refers to a low-permeability layer within the cover. The only design here that employs such a layer is the asphalt design. Capillary barrier designs don't employ this type of "barrier." I suggest not classifying them as "barrier-type" and "nonbarrier-type" and just putting them all together in the same section. Start with the ET design as it is the most common. Also, the vegetative, compacted soil drawing is not described in the text. Compacted soil layers are sometimes added as a low-perm layer and then they start to look like a compacted clay design. Also, Fig 1-1 should be re-drawn in MSWord to make a smaller file size.

Response: Accepted.

136. **Comment**: Section 1.3.3, par 4: Note: This statement can be misleading because it points to the size of the event as being most critical. The real issue is to conduct a comprehensive site analysis including not only precip quantities but timing of precip relative to storage and transpiration capacity.

Response: The information regarding climate, timing of precipitation event and site characterization has been revised to address these issues.

137. **Comment**: Section 1.3.3, Par 6 Note: If we are going to list failure factors we better have a fairly comprehensive list. The most critical is adequate site characterization followed by

understanding of the ecological factors that influence storage and transpiration. This list warrants a little discussion.

Response: Text was added to section 1.2 to acknowledge ecological aspects of failure. This is also addressed in section 6.

138. **Comment**: Section 1.3.4 Note: there is some useful information in the following section, but it is organized in a way that is not readily useful to someone not familiar with the topic. Also, the primary topics of interest to landfill cover designers are not clearly presented. I could rewrite but not without agreement that it is needed.

Response: This paragraph has been rewritten.

139. **Comment**: Section 1.3.4 Second par, add as second sentence. Note: all water held in the soil above the water table(s) is at negative pressure.

Response: See Comment 138.

140. **Comment:** Section 1.3.4, Second Par. change 30 atmospheres to 65 atmospheres.

Response: See comment 138.

141. **Comment:** Section 3.1.3, Paragraph 1, Change the wording to "This goal is stated in RCRA as a minimum technical requirement under both Subtitles C and D regulations. The Subtitle D requirement also states that the permeability must be no greater than 1×10^{-5} cm/sec. The intent of this regulation is to reduce amount of water migrating through the cover through the use of low-permeability materials resulting in a decrease or elimination of leachate migrating through the waste. Alternative landfill covers perform differently than conventional covers. Since AFCs are designed to reduce percolation into the waste through storage of infiltration and subsequent transpiration, and not through the use of low-permeability materials, this goal is not achieved in the strictest sense by AFC designs. Properly designed and constructed AFCs can adequately reduce the flux of water through the cover. Essentially, the evaluations conducted under Sections 3.2.2.1 and 3.2.2.2 should result in compliance with this goal. EPA states in their draft 2002 EPA Technical Guidance for RCRA/CERCLA Final Covers that their recommended percolation ranges for MSW landfill cover systems (0.1 to 1 mm/yr) is likely conservative with respect to preventing the "bathtub" effect since MSW generally has the capacity to absorb a substantial amount of water. However, the EPA also states that hazardous waste cover systems may require a higher level of performance to prevent the "bathtub" effect.

Response: Comment accepted with modification. Change completed. See comment 13.

142. **Comment:** Section 4.1.2 last paragraph Delete entire paragraph.

Response: See previous comment.

143. **Comment**: Section 4-2 par 4, change as follows "As stated above, the first step in evaluating a site to determine the kind of landfill cover required should be a quick and inexpensive assessment of the regional climate. Such an assessment provides a simple and low-cost determination of the potential for an alternative AFC at the site. The water balance is an accounting of all water entering and leaving an AFC—a mass balance (see Figure 4-2). The source for infiltration is both precipitation and irrigation, if applied. ET moves the

majority of the incoming water back to the atmosphere. The second largest loss of water is typically by surface runoff. Over an annual cycle , the sum of soil water storage change and lateral soil water movement tends toward zero for an AFC. The remaining quantity, deep percolation, depends on climate, soil, and plant growth, as well as their interactions at the site. Where the water table is near or in the waste and there is no landfill liner, capillary rise from the water table and possible change in groundwater storage may be important components of the water balance; normally, these components do not apply or are very small for AFCs. Evaluation and design of an AFC requires assessment of possible deep percolation below the root zone; as it is an important part of the water balance.

Response: Site screening is addressed in section 4.2.1. Shallow water table issues should be evaluated during site characterization.

144. **Comment**: Section 4.2 par 6 should read as follows. “Transpiration is greatest when the plant mass is the greatest. The maximum rate of infiltration of water into the cover may or may not impact a site during the period of maximum transpiration. As a screening tool to evaluate the effectiveness of an AFC; the cover should be evaluated during its maximum stress conditions (i.e., during the period of minimum evapotranspiration, or during a spring snow-melt event). The maximum stress event, critical event, will need to be negotiated with the regulators. The design may be based on estimated future extreme events predicted from models or extrapolated from available records. However, some regulators have chosen other criteria than the critical event as a design basis. As an example some regulators may wish to determine the impact of a long-duration low-intensity storm where precipitation does not exceed the rate of infiltration. This scenario may not present a deleterious erosional impact on the cover, but could place the maximum amount of stress on the cover by causing the greatest amount of water to percolate into the cover materials. This situation could create a significant potential for precipitation to percolate through the cover. A similar situation may be created by snowmelt. It is critical to note that the design event for any individual cover may be a period as long as a season and may be as short as a several-day storm or snow melt event.

Response: The critical event is to be discussed with regulators, as is stated in several locations in the text. The changes were made, and the site screening information was incorporated into the Section 4.2.1 Design Concepts section.

145. **Comment**; Section 4.2 immediately following paragraph 6, Note: the following paragraph is much too simplistic for me. First, ET estimates are typically poor. We shouldn’t suggest that an ET cover will be successful based on these data. Second, even if infiltration exceeds ET if the cover is designed correctly it may be able to handle the inflow. This simple analysis is likely to give some designers and regulators an expectation of success (or failure) where that is not warranted.

Response: This has been handled in previous comments.

146. **Comment**: Section 4.2 last paragraph. This paragraph largely repeats the previous paragraph.

Response: See previous comment.

147. **Comment** Section 4.4 Move last paragraph and make it the first paragraph. "For practical reasons of cost, the initial preliminary design can be achieved without extensive site characterization. With knowledge of the water-storage capacity of the available borrow soils and a regulatory agreement concerning how much water storage will be required, a design engineer can easily calculate a preliminary estimate of the depth of soil that will be required. This process is briefly outlined below. If economic reasons allow further consideration of an AFC, design personnel should proceed with extensive site characterization. The design should be refined through numerical simulation using characterization data to evaluate changes in performance to both changes in the cover design and environmental factors.

Response: Comment accepted and in the revised design process.

148. **Comment**: Section 4.5.1 par 7, "We need to make sure that we aren't advocating deep plowing. The consequences of ponding are severe.

Response: See previous response 71.

149. **Comment**: Section 4.5.1.2 bullet 6, second paragraph should read. "Determination of the unsaturated hydraulic conductivity (typically inferred by measuring the soil water characteristic curve and saturated hydraulic conductivity) is needed for computer modeling with those models that use Richards' equation. Unsaturated hydraulic conductivity of a soil is directly related to the water content of the soil which, in turn, is a function of the tension under which the remaining water is held. A saturated soil (a degree of saturation of 100 percent, or a volumetric moisture content equal to the porosity—another geotechnical property) has a suction of zero (not strictly correct). The relationship between suction and water content is not unique, it may exhibit hysteretic behavior (i.e. different drying and wetting paths). Flow of water takes place under unsaturated conditions, but the hydraulic conductivity decreases significantly as the soil dries. Hydraulic conductivity relationships (also known as k-functions) differ greatly among soils. They are sensitive to the soil density, particle size distribution, soil structure, and the wetting history of the soil. In unsaturated soils of an ET landfill cover, hydraulic conductivity values may vary over several orders of magnitude.

Response: See response 20.

150. **Comment** Section 4.8 par 4 should read as follows "There are currently two broad categories of models available for use in landfill cover simulation. The categories reflect the origins and intended applications of the models: (1) those used by practitioners of the physical sciences (geologists, hydrologists, soil physicists) to predict the movement of water under saturated conditions, and (2) those models used by agronomists in agricultural applications (including crop yield, fertilizer requirements, soil leaching). It has been said that there currently is no one model that adequately predicts performance of all cover designs in all environments. Within these two categories there are model the use the water balance approach to determining the flux through the AFC, and those that use the Richard's Equation approach to determining the flux through the cover. There are strong advocates for each approach."

Response: Thank you. Accepted.

151. **Comment:** Section 4.8.2 par 1 4th sentence add at the end “with accuracy sufficient for regulatory application.”

Response: Comment accepted with modifications and completed.

152. **Comment: Section 4.8.4.1 at end of section “**Note: all of the following factors, except geosynthetic properties and hysteresis, will have major influence on modeled results.” I suggest lumping them all together into “Important Factors” and not breaking out into first and second order importance.

Response: See previous comment.

153. **Comment:** Section 4.8.5 “Seems this should be later in the section.

Response: Text has been revised.

154. **Comment:** Section 4.8.10 bullet 12: I don’t think we should say anything that encourages use of reference values for anything other than preliminary modeling.

Response: Bullet 12 is deleted from the text.

155. **Comment:** That there is a lot of excellent data in the document, but it could be packaged much better. The document is not written in a cohesive manner and doesn’t flow, making it hard to follow. It seems to have been written by multiple authors and that there was not an editor. We would rather take additional time to get the document to a quality format, even if it means delaying release further.

Response: Thank you we have restructured to document to be more cohesive.

156. **Comment:** That AFC are well suited for the South West US and may not be suitable for all locations without allowing significant infiltration.

Response: Given applicable performance expectations, effective AFCs can be designed and constructed in all locations, but may be limited by material and economic considerations.

157. We believe statements like the text box on Page 85 stating, “Some regulatory agencies have required AFCs to achieve their design goals absent a vegetative cover, however the vegetative cover-rapidly and efficiently removes water from the entire soil cover, & controls wind and water erosion.” Without further explanation, a regulator may interpret this to mean that other agencies consider the benefits of vegetation as a factor of safety. Where in fact without accounting for vegetation benefits few sites would work.

Response: Based on information provided by regulators from the state of California, nonvegetative AFCs have been designed constructed and found effective.

158. **Comment**: The document has numerous typographical errors throughout the document. In addition, the alternative landfill covers are referred to differently throughout the document. The document uses “alternative covers,” “alternative final covers,” “alternative landfill covers.” The document should only use one term when referring to alternative covers. These discrepancies need to be corrected prior to publication of the final version.

Response: We appreciate your comments and have attempted to make the terminology consistent; however, the industry is not consistent, so we added language showing interchangeable terminology.

159. **Comment:** The response to AFCEE's review comment number 64 on page 173 regarding use of a ratio of potential evapotranspiration (PET) to annual precipitation (PRCP) to screen a site was not satisfactorily addressed in the Draft Final document. AFCEE-published guidance documents use a PET/PRCP ratio greater than 1.2 as a conservative first estimate to determine if an ET cover may be appropriate for a site. In all cases, a more detailed evaluation with data from the site is required to verify the assumptions associated with the "Site Screening" estimate. Therefore, the Air Force will continue to use this ratio for preliminary screening at a site.

Response: See page 26.

160. **Comment:** The main AFCEE concern is the Draft Final document requirements for regulatory agreements/negotiations before design begins. Some statements in the Draft Final would appear to presume that the stakeholders know the correct outcome of engineering design before it is accomplished. In each case, these statements require "negotiations" between the Air Force, the design engineer, and the regulators regarding an issue of ET landfill cover design. The common element of concern is that it is accepted engineering practice that the design by a design engineer can only be accomplished after evaluation of the site data. The Draft Final document is worded in such a way that in each case, the reader is left with the impression that each stakeholder will be expected to reach design engineer decisions without studying the site data first. Thus, the approach suggested by the Draft Final implies that all the stakeholders know parameters of the final design even before design begins.

Below are examples of text in the guidance document regarding regulatory agreement and/or negotiation component and the reason we have concerns.

a. Section 1.2.3, Paragraph 1, lines 3-4, and 7-8 (page 4)

Text: *"The quantity of precipitation to be considered in ET cover design is not defined by technical analysis but, rather, is a topic for* ***regulatory negotiation****. … The decision to use average or extreme event precipitation data for that period should be discussed between design engineer and regulator."*

Reason: Historical climatic records for the site determine the quantity of precipitation of importance to ET landfill cover design; it should not be changed or set by "negotiation." Decisions of whether to use extreme event or an average value of precipitation to meet requirements for a landfill cover can not be determined until after site-specific design estimates. This text will require a complete site-specific design before discussion with all stakeholders about site requirements.

b. Section 4.1, Paragraph 2, lines 2-4 (page 28); and Section 4.3, Paragraph 1, lines 2-4 (page 30)

Text (repeated in two sections): *"With knowledge of the water-storage capacity of the available borrow soils and a* ***regulatory agreement*** *concerning how much water storage will be required; a design engineer can readily calculate a preliminary estimate of the depth of soil that will be required."*

Reason: This concern was raised as AFCEE's review comment number 66 on page 174, and comment 68 on pages 174 and 175 of the Draft Final. The central issue in this text is the calculation of a preliminary estimate of soil depth. A preliminary estimate requires evaluation of available site-specific data and calculation. Anyone who provides an estimate of the required water storage before the design is complete may agree to an inadequate landfill cover—it is not possible to know how much water must be stored in the soil before evaluation of the interacting effects of soil properties, plant properties, and site-specific climate. During the early stages of design, a preliminary estimate of the required soil thickness for the cover is obtained at low cost with the EPIC or similar model from suitable measured soil and plant parameters that are available from publications of the USDA, NRCS, and may be used in conjunction with site-specific, daily measurements of climate data. After complete site-measured soils data are available, the design engineer can then determine the soil thickness required to meet goals for the cover.

c. **Section 4.4.1, Paragraph 6, lines 6-7 and 10-11 (page 32)**
Text: *"The maximum stress event, critical event, will need to be **negotiated with the regulators**. … As an example some regulators may wish to determine the impact of a long-duration low-intensity storm where precipitation does not exceed the rate of infiltration."*
Reason: Section 4.4 focuses on site characteristics and this subsection focuses on site climatic impacts. The interaction between site climate, soils, and plants will determine the nature of the maximum stress event. At the beginning of design of the ET cover, the nature of the maximum event is unknown. This is not a parameter that can be open to "negotiation" at this stage. The design engineer should estimate the maximum stress event, then work cooperatively with all stakeholders in the design process.

d. Section 4.6.1, Paragraph 2, lines 1-2, 6-7, and 13-14 (page 49)
Text: *"The type of storm that is used to help design the AFC should be **negotiated** with the regulatory authority prior to engaging in a significant design effort. ….. Some regulatory agencies now predicate the approved AFC design on longer duration low intensity storm (slow soakers). ….. The type of analysis performed to estimate runoff might differ depending on the type of stress event that is agreed upon with the approving regulatory agency."*
Reason: This section of the draft final contains a discussion of surface runoff estimates. At most sites, it will be virtually impossible for stakeholders to know the "type of storm" that is of most importance to the design, before the design is complete. Therefore, the statement "negotiation prior to design" has the potential to create a stalemate on the part of the stakeholders in their desire to come to agreement. The logic flow is straightforward – (1) a major factor in estimating surface runoff is the soil, (2) the soil in all ET landfill covers will be a new mixture and unlike any existing and natural soil, (3) the properties of the new soil created in the cover, control the type of storm/surface runoff relationship and thus, (4) one simply can not adequately describe surface runoff prior to site-specific design. Also, the very type of storm producing critical events useful to cover design will be revealed by modeling or similar activities utilizing site-specific climatic, soil, and plant data.

e. Section 4.7, Paragraph 1, lines 5-6 (page 51)
Text: *"Ultimately, which model is selected and how it is used will be **negotiated** between the regulators, and the facility owner and operator."*

Reason: The model chosen for design use will ultimately be determined by site conditions, requirements for the ET cover, availability of models, and familiarity by the design engineer with the use of the models available. All stakeholders will be involved in the decision making process, but the design engineer will have his/her Professional Engineer (PE) stamp "on the line" and thus is ultimately responsible for the model used in the design.

Response: It is highly recommended that discussions with regulators begin early to establish performance expectation for the landfill cover systems. This will prevent delays and in turn additional costs.

161. **Comment:** The document has not convinced us that the alternative cover systems described will cause the leachate percolation into the waste to decrease or remain the same as with the currently required final covers. The document seems to, at times, acknowledge that the alternative caps will perform worse in this area, but will make up for it in other areas (such as future use of the site, cost, etc.). In other parts, the document appears to claim that the percolation into the waste will be the same or less, but no scientific evidence has been provided. In order for a site to have one of these caps over a municipal solid waste landfill, the operator must demonstrate that the alternative cap is no more permeable than the bottom liner, or else they must petition for an adjusted standard in Illinois from the Illinois pollution Control Board. Based upon evidence provided, the Illinois EPA does not envision landfill operators being able to demonstrate the cap is not more permeable than the bottom liner and thus operators would not be able to demonstrate compliance with RCRA Subtitle D, as it is currently written.

Response: Please see the introduction of the document describing the intent of this guidance. Information relating to AFC performance can be found in the Team's Case Study Document Published in 2003 and USEPA ACAP Reports. AFC design process in this guidance document will determine if a specific design is compatible with specific performance requirements.

162. **Comment:** Computer modeling for these types of covers is certainly problematic. The document acknowledges that there are no perfect models for this type of system. Some are appropriate with respect to agricultural issues, and some are appropriate for soil and hydraulic conductivity issues. But none of the models yet take both factors into account. The report claims that no models are entirely accurate, because they are models and not reality. However, if no model can be accurate for this type of system, the Illinois EPA does not see the opportunity for an adequate review of the system. The permit reviewer would not be able to accurately determine if the percolation into the waste would be reduced, particularly with respect to the groundwater impact.

Response: The document is intended to document the model capabilities and emphasize the ITRC team opinion that models are most useful for design sensitivity analysis.

163. **Comment:** In the system proposed, the soil to be used must be porous and able to hold water, so the vegetation can "pump" it out through evapotranspiration. While this may work for keeping water out of the waste, it would likely increase the probability that gas migration into the surrounding areas would occur. Not only would gas migrate more easily through the cover due to increased permeability, but it would seem that the porous nature of the cover would hinder attempts at containing problems, since any number of pathways would likely exist. The document notes that gas may escape through the cover, but only notes that

additional management will be required. Although gas pressure in the fill is also a problem, migration off-site would seem to be far more damaging, in that a far more potential to have disastrous outcomes in the worst-case scenarios.

Response: The use of an alternative cover does not preclude the construction of a gas collection system if such a system is desired or necessary. Research is under way to evaluate the oxidation of methane as it passes through the soil column of a cover.

164. **Comment:** Finally, landfill gas can, and often does, have a high methane content and methane is a much more powerful greenhouse gas than carbon dioxide. Phytocaps, that readily allow gas to pass through them, would seem to preclude the use of gas extraction systems that convert the methane into carbon dioxide—and many times beneficially use the energy that is released. Instead, with a phytocap the methane in landfill gas would apparently be discharged into the atmosphere. The document does not acknowledge these drawbacks and should consider solutions.

Response: Please see response to 163.

APPENDIX G

ITRC Contacts, Fact Sheet, and Product List

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