Chapter 3
Alternative Design Concepts and Materials

3.1 Introduction

As previously mentioned in Section 1.3, RCRA and CERCLA regulatory requirements provide flexibility for innovation and alternatives in cover system design. The regulatory mechanism for approval of an alternative design or material typically includes a demonstration of technical equivalence. The alternative must perform in a manner that is equivalent or superior to the design or material it replaces. Depending on the function of the proposed cover system alternative, the demonstration of technical equivalence may include an evaluation of water percolation through the cover system, gas emission rate, erosion potential, and/or long-term performance (e.g., ability to accommodate foundation settlements, service life). Some of the alternative design concepts and materials discussed in this chapter have met this equivalency criterion on a project-specific basis and have been employed in cover systems for a limited number of landfills and contamination source areas.

The two alternative cover system design concepts discussed in this chapter (with a performance goal of preventing precipitation from percolating through the cover system) are based on either: (i) the evapotranspiration (ET) barrier principle; or (ii) the capillary barrier principle. Cover systems with an ET or capillary barrier are generally best suited for semi-arid and arid climates with minimal snowpack, and capitalize on the naturally occurring low precipitation rates and high potential evapotranspiration (PET) rates in these climates. Arid sites generally receive less than 250 mm of annual rainfall with evaporation exceeding rainfall and sparse vegetation, and semi-arid sites have a mean annual precipitation between 250 and 500 mm and are typically vegetated with grasses (Lincoln et al., 1982). The extent of arid and semi-arid lands in the U.S. is shown in Figure 3-1. In wetter climates, these alternative cover system design concepts are generally not as effective as designs with hydraulic barriers since the fine-grained soil layers used to store infiltrating water in the alternative designs would have to be relatively thick to provide adequate water storage capacity, and water migrating into the lower regions of these soil layers may not be easily removed by ET. The alternative design concepts differ from designs with hydraulic barriers alone in that they are intended to emphasize the following:

- unsaturated hydraulic conductivities of the soil components;
- low hydraulic conductivity of fine-grained soil layer(s), even at high degrees of soil saturation;
- relatively high water storage capacity of fine-grained soil layer(s) with eventual removal of stored water primarily by ET;
- increased transpiration through the use of diverse native vegetative; and
- ease of construction and/or substantial cost savings through the use of locally-available materials.

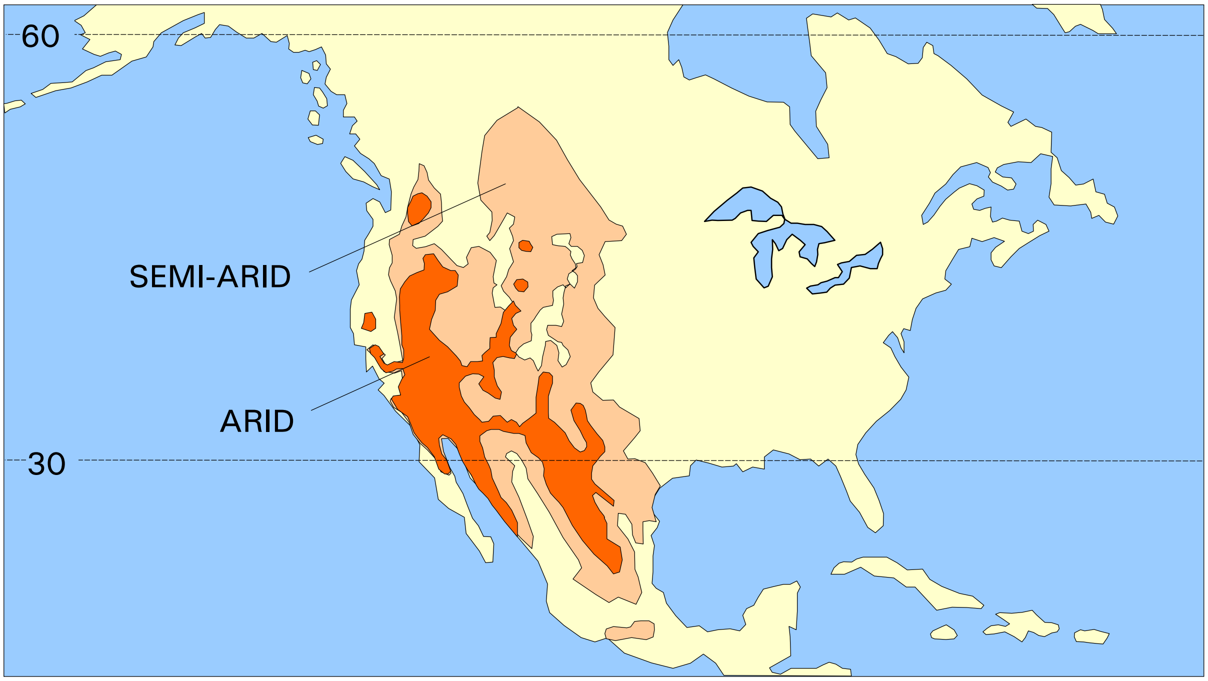


Figure 3-1. Semi-Arid and Arid Areas in the U.S. (modified from Meigs, 1953).

Because the soil layers in the alternative designs are relatively dry, they often have moderate to high gas permeabilities and, therefore, may not provide an effective barrier to gases, if any, generated within the landfill or contamination source area. It is important that the potential for gas generation and the need to collect and manage gases be considered when developing an alternative cover system design. If gas generation may occur, the collection, transmission, and, potentially, treatment of these gases should be considered. If the facility is a MSW landfill subject to EPA's gas collection and treatment regulations or if gas emissions through the cover system are a concern, the facility should incorporate appropriate gas containment components. The effect of seasonal freezing of near surface soils on lateral and downward gas migration also needs to be addressed.

In some areas in the southwest, regulatory agencies are promoting the use of alternative cover system designs to EPA performance criteria and guidance for MSW landfills. There is a concern that the CCL component of a GM/CCL composite barrier in a cover system may desiccate and crack over time, especially in semi-arid and arid climates (EPA, 1989; EPA, 1991; Suter et al., 1993), providing little value to the cover system. As an example, in southern California, regulators are currently allowing use of cover systems with ET barriers to close MSW landfills constructed without a Subtitle D liner system. The cross section of an ET barrier cover system constructed at such a landfill is shown in Figure 3-2.

The design of ET and capillary barriers is discussed in more detail below. Additional design and construction considerations for these cover systems are presented in "*Technical and Regulatory Guidance for Design, Installation, and Monitoring of Alternative Final Covers"* (ITRC, 2003). These designs should be carefully reviewed by a person knowledgeable and experienced in unsaturated soil moisture modeling and the design of such cover systems. Because there are uncertainties in the design assumptions and methods and field performance data for alternative cover system designs are limited, EPA is presenting a conservative design approach herein. Furthermore, EPA recommends that field monitoring of these cover systems be conducted to verify that the design assumptions and methods are appropriate. With these data, design procedures may be refined for a given geographic area. This is already occurring in southern California, where a more unified approach to the modeling and field monitoring of ET barriers is evolving.

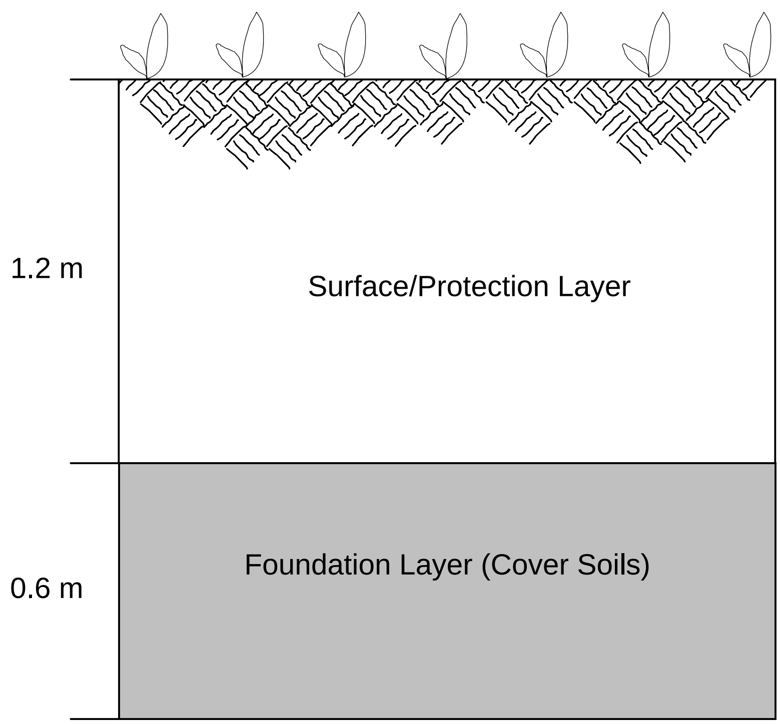


Figure 3-2. Cross Section of ET Cover System Used for a MSW Landfill in Southern California.

Chapter 3 also discusses emerging alternative materials that can be used in lieu of the various materials traditionally used in cover systems and described in Chapter 2. The considered alternative materials are geofoam, shredded tires, sprayed elastomers, and paper mill sludges.

3.2 ET Barrier Design

3.2.1 Overview

As discussed in Section 1.1.2 and illustrated in Figure 1-4, ET barriers consist of a thick layer of relatively fine-grained soil. The barrier may be overlain by a topsoil layer or surface treatment to promote vegetative growth and reduce the potential for erosion by water or wind. Soil types used for construction of ET barriers include fine-grained soils such as silty sands, silts, and clayey silts. In general, the greater the percentage of fines in a soil, the greater the water storage capacity and thus the thinner the barrier required to store a given amount of water. As discussed in Section 2.3.2.2.3, soils with a large fraction of clay are typically not used due to the potential for desiccation cracking of the clay. Cracks provide preferential pathways for infiltrating water to bypass the clay matrix and thereby bypass storage. In addition, there is somewhat less available water for plants in clays than in silty soils (Figure 2-11).

Previous research has shown that a simple ET barrier can be effective at limiting percolation and erosion, particularly in dry environments (Nyhan et al., 1990; Hauser et al., 1994; Nyhan et al., 1997; Dwyer, 1998; Dwyer, 2001). The thickness of the barrier is selected, based on the barrier soil's water storage capacity (Eq. 2.5) to retain infiltrating water until it can be removed by ET. Saturated flow in the near surface, when it does occur, is primarily downward as the hydraulic gradient is largely due to gravitational potential differences. Water movement deeper in the soil profile generally occurs under an unsaturated condition. Under this condition, the hydraulic gradient is comprised of a gravitational potential component (acting downward) and a matric potential component (which can act either upward or downward) (see Eq. 4.11). Matric potential gradients can be many orders of magnitude greater than the gravitational potential gradient. Water flows in response to the total potential gradient. Since the total potential gradient is the sum of the matric potential gradient, gravitational potential gradient, and other gradient components (e.g., solute potential gradient) which are generally less significant and are not considered in this guidance document, both upward and downward water movement is possible in the unsaturated soil of an ET barrier.

As previously mentioned, ET provides the mechanism to remove stored water from the ET barrier. Evaporation of water from the soil surface decreases the soil water content and, thus, matric potential in the upper portion of the barrier. This results in an upward matric potential gradient and upward flow. Plant transpiration also relies upon water potential gradients (matric and osmotic) to remove water from the ET barrier. Figure 3-3 shows a typical variation in water potential in the soil-plant-atmosphere system. In arid climates, the total water potential difference between soil moisture and atmospheric humidity can exceed 100 MPa (10,000 m of water) (Hillel, 1998). The largest portion of this overall potential difference occurs between the leaves and the atmosphere. The larger the soil-plant-atmospheric potential gradient, the more effective is the ET barrier. For this reason, well-vegetated ET barriers can be very effective in semi-arid and arid regions. These regions are characterized by large potential evapotranspiration (PET) compared to precipitation.

PET is an index that essentially represents the atmospheric "demand" for water. PET can be calculated using a form of Penman's equation (Penman, 1948). The total calculated PET for Tucson, Arizona from January 1987 through December 1999 was 25.71 m while the actual precipitation during this period was only 3.61 m (http://ag.arizona.edu/azmet/). This equates to a greater than 7:1 PET to precipitation ratio (i.e., there is a much greater demand for water by the atmosphere and plants than can be supplied to the soil by precipitation). A monthly comparison of PET versus precipitation for 1999 is shown graphically in Figure 3-4.

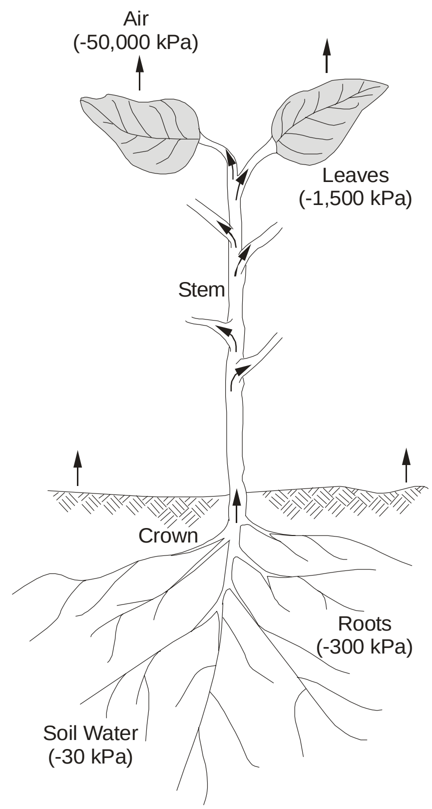


Figure 3-3. Typical Soil-Plant-Atmosphere Water Potential Variation (modified from Hillel, 1998).

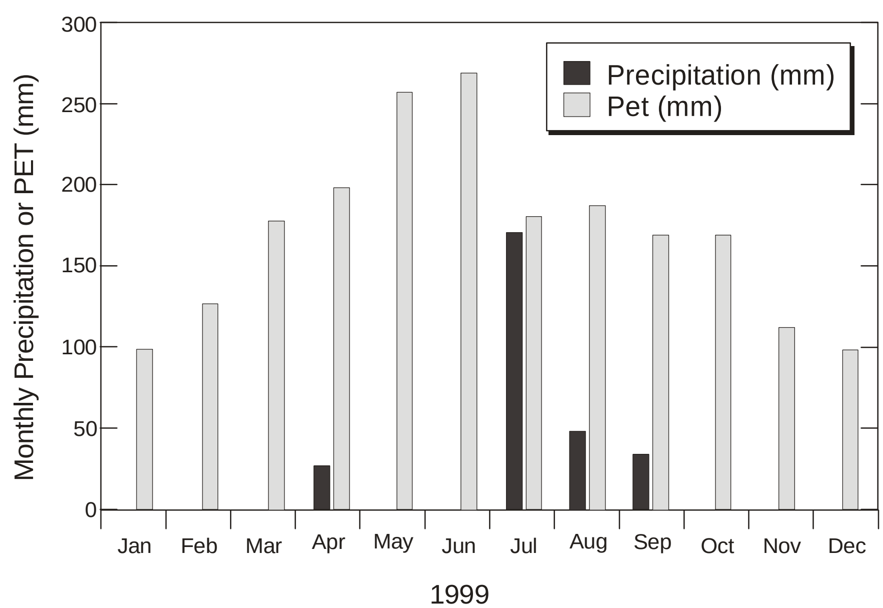


Figure 3-4. Monthly Precipitation and PET in 1999 for Tucson, Arizona.

3.2.2 General Issues

A number of the same general issues that were mentioned in Sections 2.2.1 and 2.3.1 for surface and protection layers, respectively, also apply to ET barriers. Important issues are water storage capacity and erosion potential, since excessive erosion can cause the cover to be ineffective.

3.2.3 Elements of Design

Important questions to be addressed when designing an ET barrier include the following:

- What materials should be used to construct the barrier?
- How thick should the barrier be to store the required amount of water?
- Are materials uniform and have appropriate placement methods been determined to minimize preferential pathways for percolation?
- What surface treatments should be applied to control erosion?
- Which plants should be established to promote transpiration and stabilize the cover surface?
- How and at what frequency should the barrier be maintained?
- What type and frequency of monitoring should be employed?

3.2.4 Design Concept

The ET barrier design concept can be summarized in the following steps:

1. Identify the critical infiltration event(s) that may result in percolation. This generally involves identifying the design precipitation event or series of events. Khire et al. (2000) recommend that the meteorological record for the site be reviewed to define critical time periods where PET less precipitation is near zero or negative. This condition should normally occur outside the growing season (Khire et al., 2000).
2. Calculate the depth of water that must be stored in the ET barrier based on the design infiltration event(s). For simplicity, it can be assumed that the barrier must hold all of the precipitation occurring during the critical infiltration event(s), i.e., there is no runoff or ET (Khire et al., 2000).
3. Characterize the unsaturated hydraulic properties of the considered fine-grained barrier soil and calculate its water storage capacity using Eq. 2.5.
4. Calculate the minimum soil thickness required for the fine-grained soil as described in Section 3.2.5.
5. Establish the vegetation (seed mix) to be used and any surface treatment (i.e., gravel veneer, gravel admixture, soil nutrient supplements) to be employed. Cover system vegetation is discussed in Sections 1.6.6 and 2.2.3. Surface treatments are described in Section 2.2.2.2.
6. Assess the need for optional layers (i.e., gas vent layer, biointrusion layer). Optional layers are described in Chapter 2.

7. Establish the adequacy of the design based on:
   - predictive computer modeling (Section 3.4.2),
   - field data to evaluate short-term performance (Section 3.4.3), and
   - natural analogs to predict long-term performance (Section 3.4.4).

3.2.5 Soil Thickness

An estimate of the required thickness of the ET barrier can be made based on the required depth of water to be stored in the soil and the water storage capacity of the soil. The design strategy for an ET barrier is to ensure that the storage capacity is sufficient to store the "worst-case" infiltration quantity resulting from the critical infiltration event(s), with an appropriate factor of safety, until the infiltration can be removed via ET.

As discussed in Section 2.3.2.2.7, the depth of water, H_w, that can be stored in a soil layer is the product of the water storage capacity, θ_{sc}, of the soil and the layer thickness, H_s. The storage capacity, in turn, is a function of the soil's field capacity and permanent wilting point. Representative values of θ_{sc} for different soil textures were presented in Table 2-6.

In dry environments, plants commonly reduce the water content of a near-surface soil to the permanent wilting point during every growing season (Anderson et al., 1993), making the soil's entire storage capacity available for subsequent precipitation when ET is low and plants are dormant. Thus, one potential scenario of the required amount of infiltration that an ET barrier has to store annually is the total precipitation input during the dormant period(s). Another scenario might be that created by spring snowmelt or summer thunderstorms. Both of these design scenarios should be considered.

ET-barrier type cover systems located in temperate climates have been vegetated with perennial, fast-growing, and deep-rooted hybrid poplar trees (Licht et al., 2001). Hybrid poplar trees have been used for phytoremediation and have been considered for cover system applications (i.e., phytocaps) because they exhibit relatively high water uptake rates (e.g., 810 to 1,070 mm/yr for tree plantations) and growth rates (e.g., 1 to 3 m/yr), develop deep root systems (2 to 3 m deep), are easily propagated, and can be planted economically. Two cover systems with ET cover systems vegetated with hybrid poplars are being monitored under the Alternative Cover Assessment Program (ACAP), which is discussed in Section 3.4.3.

Generally, there is a need to incorporate a factor of safety into the design of an alternative barrier to help offset some of the uncertainties associated with weather, in-place soil properties, and vegetation growth. Reasonable values for these parameters should be used and a factor of safety should be applied, at a minimum, to the required amount of water to be stored. Since there are few field performance data available for alternative cover systems, EPA believes that the minimum thickness of an ET barrier should be the larger of 1.25 H_s (i.e., a factor of safety of 1.25 applied to the calculated cover soil layer thickness) and 0.9 m. This factor of safety and minimum thickness not only account for uncertainities in precipitation, modeling, and material properties, but also allow for the possibility of long-term erosion of the surface soil. This level of conservatism may be reduced somewhat when the performance of the alternative barrier is modeled using an unsaturated flow code and site-specific parameters, if the cover system is monitored (see Chapter 8), or if a GM is used beneath the ET barrier. The latter case may apply when an ET/GM composite barrier is used in lieu of a GM/CCL composite barrier.

As an example, during 1987 to 1999 Tucson, Arizona received from about 5.1 to 236.0 mm of precipitation annually during December and January, when plants are typically dormant. The average precipitation during this time period was 58.2 mm. Dividing the worst-case precipitation value of 236.0 mm by a storage capacity of 0.15 for a silty loam soil yields a required ET barrier thickness of 1.7 m. Applying a factor of safety of 1.25 to this thickness yields a design thickness of 2.125 m. The above calculation method is simple, but conservative, and doesn't take into account runoff or evaporation. When the above scenario was simulated using an unsaturated flow model with historical weather data and assuming the silty loam soil was initially at its wilting point, the required barrier thickness to limit percolation to less than 0.5 mm/yr during the simulation period was calculated to be approximately 0.8 m. Applying a factor of safety of 1.25 to this thickness yields a design thickness of 1.0 m.

3.3 Capillary Barrier Design

3.3.1 Overview

As discussed in Section 1.1.2 and illustrated in Figure 1-5, capillary barriers consist of one or more layers of finer-grained soil overlying one or more layers of coarser-grained soil. Like the ET barrier, a capillary barrier may have a topsoil layer or surface treatment to promote vegetative growth and reduce the potential for erosion. The finer-grained soil in a capillary barrier has similar characteristics to the fine-grained soil used to construct an ET barrier: it is generally a silty soil, as described in Section 3.2.1. Soil types used for construction of the coarser-grained component range from coarse sand to cobbles.

The capillary barrier design concept relies on the differences in pore size distribution between the upper finer-grained soil and the lower coarser-grained soil to promote retention of water in the finer-grained soil under unsaturated flow conditions, as long as the contrast in unsaturated properties (e.g., soil-moisture characteristics and unsaturated hydraulic conductivities) of the two soils is sufficiently large. This can be explained as follows: at a given matric potential, a coarser-grained soil tends to have a much lower water content than a finer-grained soil. The hydraulic conductivities of unsaturated soils decrease exponentially with decreasing water content because flow paths through thin films of water coating the soil particles in dry soil are extremely tortuous. Thus, dry gravel is actually much less permeable to water than moist silty sand. If the soils remain unsaturated, the finer-grained soil tends to retain nearly all the soil water and the underlying layer serves as a barrier due to its dryness. The matric potential in the finer-grained soil layer typically must approach a value near zero (i.e., saturated conditions) before any appreciable flow occurs into the coarser-grained layer (Figure 1-5).

In contrast to ET barriers, which experience primarily vertical water flow, the primary direction of water flow (i.e., vertical or lateral) in capillary barriers depends on whether or not the capillary barrier is sloped. The water balance for non-sloped capillary barriers is similar to that for ET barriers. Thus, water is removed from the finer-grained soil component of a non-sloped capillary barrier by ET or percolation (breakthrough) into the coarser-grained soil layer. For sloping capillary barriers (most common scenario), lateral diversion of infiltrating water provides an additional means of removing soil water from the finer-grained soil layer. Lateral diversion is essentially gravity-driven unsaturated drainage within the finer-grained layer. Because the water content in the finer-grained layer is usually greatest near its interface with the underlying coarser-grained soil layer, and the hydraulic conductivity of an unsaturated soil increases with increasing water content, lateral diversion is concentrated near this interface. Laterally diverted water causes the water content in the finer-grained soil to increase in the downdip direction. The diversion length is the distance that water is diverted along the interface between the soil layers before there is appreciable breakthrough into the coarser-grained layer. To avoid significant breakthrough, the cover system slope length should be less than the diversion length (Figure 3-5). Therefore, if a capillary barrier is sloped, the two-dimensional (lateral and vertical) effects of soil-water movement must be taken into account in design of the barrier.

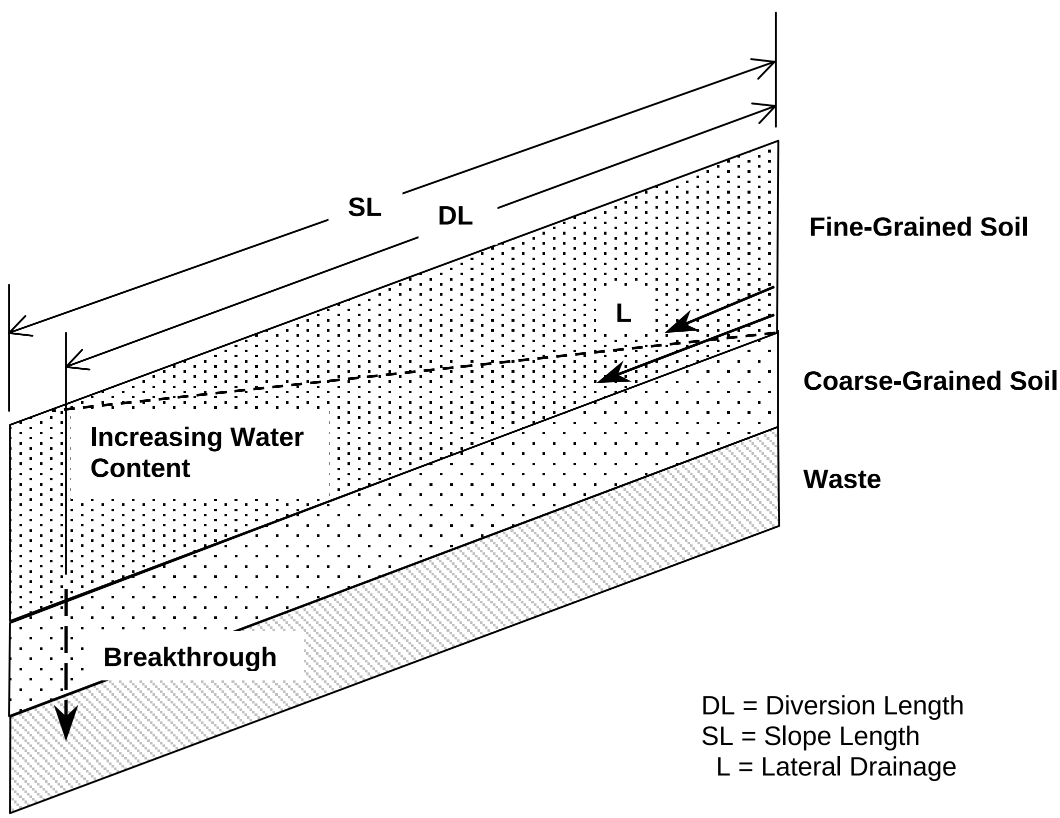


Figure 3-5. Problem Where Diversion Length is Less than Cover Slope Length on a Capillary Barrier.

Some advantages of incorporating a capillary barrier rather than an ET barrier alone in a cover system include:

- The finer-grained soil layer of a capillary barrier stores more water than a comparable layer without the capillary break (i.e., a free-draining layer). Compared to an ET barrier, the additional storage capacity either serves to reduce overall percolation, or reduce the total thickness required for the finer-grained soil to yield the same degree of percolation inhibition.
- The additional water stored within a capillary barrier tends to encourage the establishment and development of the surface vegetation. The increased vegetative cover, in turn, removes more soil water due to greater ET. Furthermore, plants serve an important function in reducing surface erosion.
- In addition to providing the capillary break, the coarser-grained layer of the capillary barrier can serve as a biointrusion barrier and/or possibly a gas collection layer if small amounts of gas are generated. (If gas emissions through the cover system are a concern, gas containment components should be incorporated into the cover system design.)

Potential disadvantages of a capillary barrier compared to an ET barrier include the need to specify and construct two different material types, the potential difficulties in constructing the interface between the different materials (to form the capillary break), and minimizing differential settlement.

3.3.2 General Issues

A number of the same general issues that were mentioned in Sections 2.2.1 and 2.3.1 for surface and protection layers, respectively, also apply to the capillary barrier. Important issues are water storage capacity and erosion potential, since excessive erosion can cause the cover to be ineffective. In addition, it is particularly important to construct smooth and unmixed interfaces between adjacent soil layers, as discussed in Section 3.5.2. Good CQA/CQC of these interfaces is essential.

Two issues specific to capillary barriers were described by Koerner and Daniel (1997) and are as follows: (i) the finer-grained soil must not be allowed to migrate over time into the underlying coarser-grained soil; and (ii) over periods of extremely high precipitation, the capillary barrier may cease to function, at least temporarily, as the coarser-grained soil becomes moist and more permeable than the finer-grained soil. The former issue is discussed in more detail in Section 3.3.6. The latter issue is addressed by incorporating an appropriate factor of safety in design, as discussed in Section 3.3.4.

3.3.3 Elements of Design

Important questions to be addressed when designing a capillary barrier include the following:

- How should the barrier be sloped?
- What materials should be used to construct the barrier?

- How thick should the different layers be to store the required amount of water, wick away infiltrating water, and create a capillary break?
- What surface treatments should be applied to control erosion?
- Which plants should be established to promote transpiration and stabilize the cover surface?
- How and at what frequency should the barrier be maintained?
- What type and frequency of monitoring should be employed?

3.3.4 Design Concept

The design concept for the finer-grained soil component of the capillary barrier is essentially the same as that presented for the ET barrier in Sections 3.2.4 and 3.2.5. The required minimum thickness, however, can be less for a non-sloped capillary barrier than for an ET barrier. In general, the capillary barrier increases the apparent field capacity of the finer-grained soil component, thereby increasing the water storage capacity of this component. Consequently, the finer-grained soil layer in a capillary barrier may not need to be as thick as the same layer used alone in an ET barrier. In fact, the non-sloped capillary barrier may be preferred if the finer-grained soil layer is required to be relatively thick. If this layer is too thick, all of the stored water may not be removed by subsequent ET.

The apparent field capacity, θ_{afc}, of the finer-grained soil component of a capillary barrier can be estimated using a measured or modeled water content at which drainage from the capillary barrier occurs (Stormont and Morris, 1998). This water content is greater than the soil's field capacity due to the effects of the capillary break and can be calculated as:

$$\theta_{afc} = 1/L\int_0^L \theta\left(z + h_z^*\right)dz \qquad \text{(Eq. 3.1)}$$

where: θ = volumetric water content; L = thickness of the finer-grained soil layer; z = distance above the finer-coarser interface; and h_z^* = minimum head at which flow into the coarser-grained layer first occurs.

The texture of the finer-grained soil is important in determining the additional water storage capacity achieved with a capillary barrier. Stormont (1996) described a field-scale (14 m^2 surface area) water balance experiment conducted to measure the water storage capacity of a capillary barrier. The barrier was comprised of a 900-mm thick layer of silty sand placed over uniform gravel (0.6 mm). The barrier was installed at a 10% grade. The water content in the finer layer, measured as added water, was increased at a constant rate of about 10 mm/day. Breakthrough into the coarser layer was detected by collecting water that drained from the coarser layer. The volumetric water content in the finer-grained layer at breakthrough was about 0.40 near its interface with the coarser-grained layer. Stormont (1996) estimated the total amount of water stored in the capillary barrier at breakthrough by integrating the measured water content over the thickness of the finer-grained layer. Expressed as a normalized quantity with respect to area (volume of water divided by surface area), the capillary barrier stored 285 mm of water at breakthrough, which corresponds to an average apparent field capacity of approximately 0.32. The storage capacity of the capillary barrier can be compared to that estimated for a simple ET barrier. Without the capillary break, water will drain approximately to the soil's field capacity. The field capacity for the same soil (silty sand) can be estimated at 0.19, based on the data for representative soils presented in Table 2-6. By integrating this water content over the same 900 mm thickness, the silty sand in an ET barrier configuration would be expected to store about 170 mm of water before drainage commenced. Thus, an additional 115 mm of water storage was gained by the capillary break for the same cover soil thickness. In other words, a simple ET barrier would need to be about 1510 mm thick to store the same amount of water as 900 mm of the same soil in the considered capillary barrier configuration.

The texture of the coarser-grained soil is also important in assessing the water storage capacity of a capillary barrier (Khire et al., 2000). For example, if the coarser soil becomes more broadly graded, h_z^* in Eqn. 3-1 will decrease and θ_{afc} will decrease. In contrast, if coarser soil becomes more uniformly graded or if the average particle size of the coarser soil is reduced, h_z^* will increase and θ_{afc} will increase.

The design of a sloped capillary barrier also includes the selection of the slope gradient and the distance between lateral drainage outlets to minimize the percolation of water through the coarser-grained soil. These parameters can be assessed using a two-dimensional or three-dimensional unsaturated flow computer model, such as HYDRUS-2D or VS2D-T. These models are briefly described in Chapter 4. In general, layer thickness, diversion length, and slope gradient requirements depend on climatological information for the specific site (e.g., precipitation, temperature, humidity) and the characteristics of the soils used in the cover (e.g., water storage capacity, hydraulic conductivity, texture). Other factors that should be taken into consideration include slope stability, vegetation characteristics, and potential for desiccation (Dwyer, 1997).

The lateral diversion capacity of the finer-grained layer is dependent in large part on the hydraulic conductivity of the layer. In general, the hydraulic conductivities of silts and loams are too low to permit appreciable lateral diversion. Field tests of capillary barriers with homogeneous finer-grained layers indicate that the effective diversion lengths are less than 10 m (Nyhan et al., 1990; Hakonson et al., 1994; Stormont, 1995; Stormont, 1996; Nyhan et al., 1997). These short diversion lengths are a consequence of the relatively low hydraulic conductivity of the finer-grained soils compared to the infiltration rate during stressful periods when the soil is relatively wet (e.g., spring snowmelt). Thus, soils that are often preferred as a rooting medium and for their water storage capacity (e.g., loams, silts) may not be conductive enough to substantially divert soil water laterally.

Utilizing "transport layers" or "unsaturated drainage layers" within the finer-grained layer (Stormont, 1995) that allow water to drain laterally and outlet (e.g., in a swale) can increase the diversion capacity of capillary barriers. Transport layers are one or more relatively conductive layer(s) that drain water laterally within the cover's finer soil layer while remaining unsaturated. Because soil water tends to accumulate near the interface between the finer and coarser layers and unsaturated hydraulic conductivity increases with water content, a transport layer near the interface is most effective in laterally diverting water. An effective transport layer, for example, could consist of a 300-mm thick relatively fine-grained, uniform sand that has a relatively high hydraulic conductivity under moderate to high matric potentials. The lateral diversion afforded by a transport layer complements the water storage function of the overlying soil, expanding the conditions and climate for which a capillary barrier could be effective.

3.3.5 Coarser-Grained Soil Layer

The primary function of the coarser layer is to form a capillary break, but it may also serve as a biointrusion barrier or, possibly, a gas collection layer.

Capillary break - The movement of water from the overlying finer-grained layer into the underlying coarser-grained layer is controlled by the water entry potential of the coarser-grained layer. The water entry potential is the potential associated with the movement of water into the smallest pores that form a continuous network. Water will not move from an overlying moist layer into an initially dry underlying layer at potentials less than the water entry potential suction of the underlying layer. Using a coarser-grained soil with a higher water entry potential delays the movement of water from the finer-grained soil layer into the coarser layer, permitting more water to be stored in the finer layer near the interface (Figure 1-5). The suction head corresponding to the water entry potential can be roughly approximated by the height of capillary rise within a soil (Hillel and Baker, 1988). Thus, the water entry potential is expected to be high for a uniform coarse-grained soil and decrease as the amount of fines in the soil increase.

Biointrusion Barrier - As discussed in Sections 2.3.2.2.4 and 2.3.2.2.5, plants and animals penetrating the cover system can create conduits for water to move downward into the waste, and may even transport waste to the surface. Plant roots will generally not grow in soils with water contents below the wilting point. Because coarse materials drain to low water contents, typically below the wilting point, they can serve as barriers to root penetration. To be effective as a root barrier, fines must be kept out of the coarse soil layer. This suggests that the particle-size of the coarse layer material either has to be fine enough such that the overlying fines do not penetrate into it, or an intermediate layer or a geotextile (GT) must be used to retain the overlying soil, as discussed in Section 3.3.6. One design approach deterring animal invasion is to use cobble-size particles that are too heavy for the animals to displace, as discussed in Section 2.3.2.2.5. Another approach is to use a dry, cohesionless uniform material that does not form a stable burrow or tunnel.

Gas Collection Layer - For wastes that produce gas, it may be necessary to collect, transmit, and potentially treat this gas as it is emitted from the buried waste. The coarser layer of the capillary barrier may potentially be used for gas collection and transmission. If the facility is a landfill subject to EPA's gas collection and treatment regulations or if gas emissions through the cover system are a concern, the cover system should incorporate a gas barrier over the coarser layer. While these alternative designs may be adequate for hydraulic control, they should generally not be used without gas containment components at MSW landfill sites where landfill gas collection and treatment is required.

3.3.6 Internal Stability

In general, the greater the contrast in texture or particle-size distribution of the fine and coarse-grained soil components of a capillary barrier, the greater the effectiveness of the capillary break (Stormont, 1997). There is concern, however, that finer soil particles will move into the pores of the coarser soil, degrading the interface and reducing the effectiveness of the capillary break. The conventional approach for evaluating the internal stability of the capillary barrier is to ensure the soils satisfy a soil retention criterion. The retention criterion establishes the relationship of grain sizes of adjacent materials necessary for the coarser material to retain the finer material. The retention criteria for soil and geotextile filters are discussed in for detail in Section 4.7.

From conventional filter criteria, interface stability is favored by soils having similar particle-size distributions, apparently in conflict with maximizing the effectiveness of a capillary break. Conventional criteria, however, have been developed using high hydraulic gradients for applications such as dams. In contrast, capillary barriers would only rarely, if ever, experience positive pore pressures, and the associated hydraulic gradients would be small. Furthermore, capillary barriers will be subjected to cycles of wetting and drying in response to climatic conditions. Thus, interface stability should be considered under dry conditions, as well as, under relatively small positive water pressures. The biggest risk to internal stability of a capillary barrier may occur during barrier construction. For example, vibratory compaction could cause a large number of finer particles to move into the coarser particles.

Koerner and Daniel (1997) recommend that a GT separator be considered at the capillary barrier interface. They indicate that for extremely long service times (e.g., hundreds of years) fiberglass GTs have been considered for this application. It is noted, however, that with a GT at the capillary barrier interface, the capillary break may occur between the finer-grained soil and GT rather than between the finer- and coarser-grained soils (Stormont et al., 1997). This effect reduces the water storage capacity of the finer-grained soil. The GT could also function as a lateral drainage layer. If it is necessary to use a GT separator, the effects (reduced water storage capacity and lateral drainage) associated with use of the GT should be considered and addressed in the final capillary barrier design..

3.4 Alternate Design Performance Evaluation

3.4.1 Introduction

The preceding sections highlighted how the water storage and lateral diversion characteristics of ET and capillary barriers are affected by factors such as soil type and thickness and slope of the interface. In addition to the influence of material properties and configuration, the “stress” provided by the climate will have a major impact on the performance of these types of barriers. To accommodate these factors into the development of designs and estimating the performance of ET and capillary barriers, numerical simulations can be used. However, numerical simulations have two challenging aspects that must be addressed to enable reasonable representation of actual field conditions. First, for near-surface applications it is necessary to account for the effect of time- and climate-dependent processes, including precipitation, soil water evaporation, and plant transpiration. The second aspect, specific to capillary barriers, is that water movement within the near-surface soils and near the interface is transient, unsaturated flow involving materials of widely varying properties. Accuracy and stability of numerical solutions involving these types of flow behavior can be difficult to achieve.

As previously discussed in Section 1.2.3, EPA recommends that a cover system be designed to minimize percolation to prevent the bathtub effect, with a specific value selected based on the nature of the contained waste, the hydrogeological vulnerability of the site, and other factors. The Agency considers this performance criterion to apply over a considered performance period (e.g., maximum rate over at least a 30-year post-closure simulation).

Numerical modeling should be used to design a cover system that meets this performance criterion. Natural analogs may be used to help predict long-term cover performance, and field monitoring may be required, depending on site-specific percolation criteria.

3.4.2 Numerical Modeling

Computer numerical simulations can be used to predict the water balance performance of a cover system. Computer simulations are only as good as the input data provided and the system modeled. Much of the difficulty comes in obtaining good and accurate input data to correctly predict a cover system's water balance performance. It is advised that a realistic set of input parameters be developed for the simulations based on measurements from the actual soil to be used (at the anticipated installed density and moisture content), values from the literature, and expert opinion. Generally, input properties include unsaturated soil properties (i.e., moisture characteristic curves - matric potential versus moisture content) and hydraulic conductivity. There are a number of practitioners who believe that even a near perfect set of input data and a well-designed computer model will still not yield reliable results. Because of this limitation, it may be prudent in critical applications to not rely solely on the results of one set of computer model predictions and/or to use a larger factor of safety. It is suggested that for critical applications, two different computer models be employed and the results of the simulations compared.

The EPA HELP computer model (Schroeder et al., 1994a,b) is at present the industry standard for conducting water balance analyses for conventional hydraulic-barrier cover systems. This model is discussed in more detail in Section 4.2.3.2. Field applications of the model are discussed in Section 4.3. The HELP model incorporates a number of simplifying assumptions and does not solve the unsaturated flow equations. Thus, it is not considered particularly good for evaluating ET barriers and it is not recommended for evaluating capillary barriers. Unfortunately, there are no public-domain water balance models currently available that are as user friendly as HELP and that properly model unsaturated flow within the cover system soil layers.

A model that may be used for the analysis of ET and capillary barriers is UNSAT-H (Fayer and Jones, 1990), a one-dimensional finite-difference computer program to solve for water and heat flow in soils. This model is discussed in more detail in Section 4.2.8. Field applications of the model are discussed in Section 4.3. The UNSAT-H code solves Richard's partial differential equation (Richards, 1931) and can be used to simulate the water balance for evapotranspirative or non-sloped capillary barriers. However, the vegetation options in the model were developed for the DOE Hanford site near Richland, Washington and may not be applicable to other areas of the country. The model user either assumes that: (i) the vegetation is similar to cheatgrass; or (ii) vegetation quantity is based on a daily leaf area indices input by the user. The vegetation is required to start germinating from a seed before Julian day 91 or after day 273 and to stop transpiring between Julian days 151 to 243. In some areas of the southwest, Tucson, Arizona, for instance, relatively high precipitation and plant transpiration is still occurring after Julian day 243.

Other models that may be considered and that are discussed in this guidance document are LEACHM (Section 4.2.3.3.), SoilCover (Section 4.2.3.5), and, for sloping capillary barriers, HYDRUS-2D (Section 4.2.3.6). All of the models have their specific advantages and disadvantages, some of which are listed in Table 4-1.

3.4.3 Performance Monitoring

Because of design and construction quality control uncertainties, performance monitoring is recommended for alternative covers. Field performance data provide perhaps the most reliable information for assessing whether cover systems are performing as designed. It is recommended that a project specific monitoring system be utilized to monitor the performance of an ET or capillary barrier throughout the life of the cover system. As an example, a lysimeter used by the ACAP program for monitoring landfill cover performance is shown in Figure 3-6. Additional performance monitoring techniques are discussed in more detail in Chapter 8.

Examples of performance monitoring of alternative cover systems are highlighted below:

- **Albuquerque, New Mexico** The Alternative Landfill Cover Demonstration (ALCD) is a large-scale field test at Sandia National Laboratories located on Kirtland Air Force Base in Albuquerque, New Mexico (Dwyer 1997, Dwyer 1998, Dwyer 2001). Six landfill cover profiles are installed with automated retrieval of water balance data (runoff, lateral drainage, percolation, soil moisture chances within the covers, and precipitation). The covers are periodically stress tested by adding precipitation to the covers through sprinkler systems to simulate worst case infiltration events at various locations in arid and semi-arid climates. Four alternative covers (ET Cover, 2 different Capillary Barrier Designs, and a cover featuring a GCL) are installed next to two prescriptive covers (RCRA Subtitle D - similar to Figure 1-6(a) and RCRA Subtitle C - similar to Figure 1-7) for direct water balance performance comparison. The project's intent is to compare and document the performance of alternative landfill cover technologies of various costs and complexities for interim stabilization and/or final closure of landfills in arid and semi-arid environments. The test covers are constructed side-by-side for comparison based on their performance, cost and ease of construction. The ALCD is not intended to showcase any one particular cover system. The focus of this project is to provide the necessary tools; i.e., cost, construction and performance data, to the public and regulatory agencies so that design engineers can have less expensive, regulatory acceptable alternatives to the conventional cover designs. This project has been extensively reviewed by regulators from across the country as well as by panels from the National Academy of Science and the Department of Energy. Results from this project have shown properly designed alternative covers such as ET Covers and

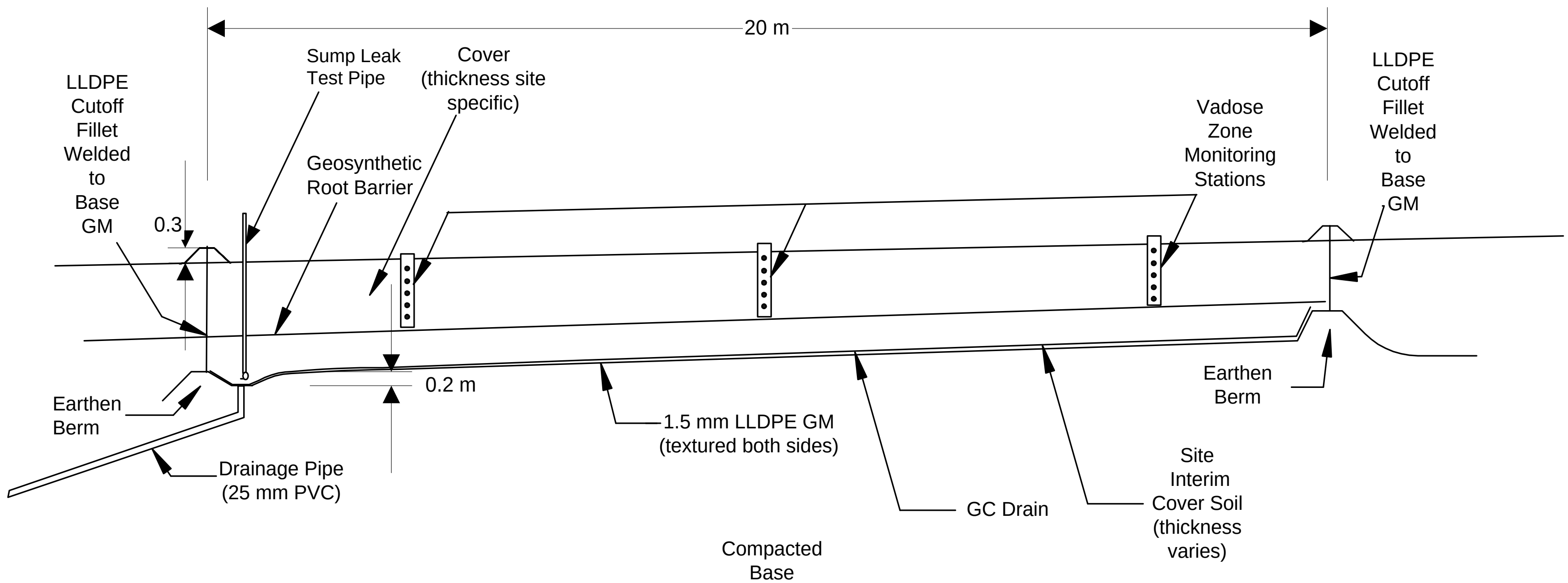
Capillary Barriers are as good as or better than their prescriptive counterparts. Results from this demonstration have been used by a number of regulatory agencies to approve permits for the use of an alternative landfill cover in lieu of a prescriptive cover (Dwyer 2001).

- **EPA's Alternative Cover Assessment Program (ACAP):** (http://www.acap.dri.edu/)
- **Sierra Blanca, Texas** (http://www.beg.utexas.edu/environqlty/vadose/index.htm)

3.4.4 Natural Analogs

Conventional engineering approaches for designing landfill covers often fail to fully consider ecological processes. Natural ecosystems effective at capturing and or redistributing materials in the environment have evolved over millions of years. Consequently, when contaminants are introduced into the environment, ecosystem processes begin to influence the distribution and transport of these materials, just as they influence the distribution and transport of nutrients that occur naturally in ecosystems (Hakonson et al., 1992). As described in Section 1.5.6, as the ecological status of the cover changes, so will performance factors such as water infiltration, water retention, ET, soil erosion, gas diffusion, and biointrusion (Caldwell and Reith, 1993). An important objective for an effective cover system is to design it so that subsequent ecological change will enhance and preserve system performance. Consideration of natural analogs can enhance a cover system design by disclosing what properties are effective in a given environment or what processes may lead to possible modes of failure. These factors can in turn be avoided during the design and construction phases. Natural analog studies provide clues from past environments as to possible long-term changes in engineered covers. Analog studies involve the use of logical analogy to investigate natural and archaeological occurrences of materials, conditions, or processes that are similar to those known or predicted to occur in some part of the engineered cover system (Waugh, 1995).

One possible analog might be observed by trenching adjacent to the site in an undisturbed area and measuring the depth of plant roots (Dwyer et al 1999). This will reveal the general depth of infiltration. Another method for assessing the average long-term depth of water penetration (or infiltration depth) is to trench adjacent to the site in an undisturbed area to observe the depth of calcium carbonate ($CaCO_3$) deposits or formation of a caliche layer. Soils in semiarid and arid regions commonly have carbonate-rich horizons at some depth below the surface. The position of the $CaCO_3$ bearing horizon is therefore, related to depth of leaching, which, in turn, is related to climate (Birkeland, 1984).



Notes:
1. Base shall be approved fill (fines > 30%) compacted to >95% of max. dry unit weight based on ASTM D 698 and dry of optimum water content.
2. Smooth base before placing GM. Eliminate all ridges, depressions, etc. > 25 mm in height. Remove all stones, etc. larger than 10 mm.
3. Place GM in early mornining and ensure good contact with all surfaces. No gaps shall exist between base and GM.
4. Vertical cutoff sheets shall be fillet welded to base GM.
5. GC drain is GN with non-woven GT heat bonded to both sides. Install using rub sheet.
6. Interim cover soil shall be placed on GC drain from the edges. No equipment can travel on GM or GC drain. Once spread in 450 mm loose lift, compact to >85% of max. dry unit weight based on ASTM D 698.
7. Vadose zone monitoring stations instrumented with TDRs to measure soil water content and heat dissipation sensors to monitor soil water pressure and temperature.

Figure 3-6. Test Plot Design Used at ACAP Sites.

The origin of carbonate horizons involves carbonate-bicarbonate equilibria (Birkeland, 1984), as shown by the following reactions:

$$\underset{g}{CO_2} + \underset{l}{H_2O}$$

$$\downarrow$$

$$\underset{s}{CaCO_3} + \underset{aq}{H_2CO_3} \leftrightarrow \underset{aq}{Ca^{2+}} + \underset{aq}{2HCO_3^-}$$

Carbon dioxide partial pressures in soil air are 10 to more than 100 times that in the atmosphere; this decreases the pH, which, in turn, increases $CaCO_3$ solubility. The partial pressure of CO_2 is high as a result of CO_2 produced by root and microorganism respiration and organic matter decomposition. Thus, one would expect the highest CO_2 partial pressure to be associated with the A horizon located near the surface, with values diminishing down to the base of the zone of roots. In arid and semi-arid regions, the quantity of water leaching through the soil is also generally greater near the surface than at depth. Thus, as the water moves vertically through the soil, the Ca^+ and HCO_3^- content might increase to the point of saturation after which further dissolution of $CaCO_3$ is not possible. Combining the effects of high CO_2 partial pressure and downward-percolating water, the formation of $CaCO_3$-rich horizons may be understood as follows. In the upper zone of the soil, Ca^{2+} may already be present or may be derived by weathering of calcium-bearing minerals. Due to plant growth and biological activity, CO_2 partial pressure is high and forms HCO_3^- upon contact with water. Water leaching through the profile carries Ca^{2+} and HCO_3^- downward in the profile. Precipitation of $CaCO_3$ to form a caliche horizon takes place by a combination of decreasing CO_2 partial pressure below the zone of rooting and major biological activity and the progressive increase in Ca^{2+} and HCO^{3-} concentrations with depth in the soil solution as the water percolates downward and water is lost by evapotranspiration. The position (depth) of the $CaCO_3$ bearing horizon is therefore related to depth of leaching, which, in turn, is related to the climate.

As more alternative cover systems are installed and demonstrate successful performance, confidence for their use at other sites will grow. A number of experiments and field-scale demonstrations throughout the country are currently producing field data to document the short-term performance of alternative cover technologies (Dwyer, 1997; Dwyer, 1999; Dwyer, 2001; Benson, 1997). As with any emerging technology, longer-term performance data are lacking. Natural analogs can be used to deduce how a system may perform over a longer period (Waugh, 1995). Computer modeling can be used to predict long-term performance and compare alternative designs (Khire, 1995; Morris and Stormont, 1997a, b). Until long-term performance data have been obtained, the combination of computer model predictions, field data, and natural analog studies forms the basis for evaluating long-term alternative cover system designs.

3.5 Construction of Alternative Designs

ET covers may often be easier to build and require a lesser amount of quality assurance (QA)/QC during construction than conventional designs with hydraulic barriers. This is due to the fact that the ET cover may only involve placement of two soil types, a topsoil layer and the relatively fine-grained ET barrier, and no geosynthetics or soils that must be compacted to meet strict hydraulic conductivity criteria. The complexity of construction of a capillary barrier increases with the number of layers in the system, including layers for soil water storage, internal drainage, biointrusion resistance, and/or gas transmission.

Specific construction and maintenance considerations for alternative cover system designs are discussed below.

3.5.1 Compaction Requirements

CCL hydraulic barriers in conventional cover system designs are compacted so to attain a very low saturated hydraulic conductivity. As discussed in Section 2.5.4 of this document, this generally requires compacting the soil lifts 'wet of optimum' to remold the soil and produce high soil densities. Compacting the soil wet of optimum increases the potential for desiccation cracking and reduces the initial water storage capacity since the CCL is generally at a degree of saturation of at least 85%.

The alternative cover system designs outlined in this chapter are designed to function under unsaturated conditions; consequently obtaining very low saturated hydraulic conductivity is not a priority. Because a very low initial saturated hydraulic conductivity is not the objective when placing finer-textured soils in an alternative cover system, compaction "dry of optimum" is usually desired to reduce the potential for desiccation cracking. This compaction alternative also allows for additional initial water storage capacity and a structure that is less restrictive to plant roots. Compaction density requirements for the finer-grained soils should be based on consideration of the water content-unsaturated hydraulic conductivity relationship for the soil, erosion resistance, and plant rooting requirements. Generally, compaction for the ET barrier is performed in an attempt to mimic the naturally occurring in-situ soil density for a particular borrow material. Ideally, target densities for constructed ET cover soils should be within +/- 5% of the in-situ borrow soil density. In addition, this target in-situ soil density should be used for any subsequent laboratory testing and for input parameters in computer water balance models. It should be noted that unsaturated soil properties and saturated hydraulic conductivity are very sensitive to the soil's density. Uniformity of compaction is critical.

3.5.2 Capillary Barrier Soil Interfaces

During the emplacement of a capillary barrier, special care must be taken during the placement and compaction of the first lift of fine-grained soil on the underlying uncompacted coarse-grained soil. The interface between these two materials should remain smooth and continuous and the materials should not be mixed together.

Heavy compaction, especially if a vibratory compactor is used, will tend to cause finer soil migration into the coarser layer, a situation to be avoided. Conversely, however, a lack of compaction will leave the finer soil near the interface in a loose condition. This finer soil could be more prone to internal erosion under the action of seepage forces should gravity-driven water percolation develop at the interface. Small wide-tracked bulldozers have been used to construct this interface. The steel tracks help distribute the weight of the bulldozer over a greater surface area, thus reducing its contact pressure. Kneading compaction is not recommended for the first lift of fine-grained soil; rather a smooth drum roller should be used. This will help minimize the potential for mixing of fine and coarse soils at their interface. The design process for capillary barriers should include an evaluation of appropriate procedures for soil compaction.

3.6 Maintenance and Monitoring of Alternative Designs

3.6.1 Maintenance

Maintenance is discussed in Chapter 9. The most important maintenance activities for the alternative designs involve maintaining the intended vegetative cover and the erosion control measures, repairing erosion gullies, surface depressions caused by localized settlement, surface cracks, and, as an associated activity, maintaining and repairing surface-water management structures.

Maintaining the surface layer and repairing cracks and erosion gullies in alternative cover systems is generally even more critical than maintaining the surface and protection layers in conventional cover systems that have a drainage layer and a GM barrier. A crack in an alternative cover system may allow short circuiting of water through the cover system and impair cover system performance. If differential settlement of an ET barrier occurs, the barrier can simply be repaired by applying more soil to the surface to bring the cover system back to its original grade. For a capillary barrier, the repair is more complex. The finer-grained soil first should be excavated to expose the coarser-grained soil, and the depression in the coarser-grained soil should be filled with the coarser soil so that the interface between the finer and coarser-grained soils is brought back in-line with that adjacent to it. The finer-grained soil at the repair location should then be blended in with (e.g., stair-stepped into) the surrounding finer-grained soil to reduce the potential for preferential pathways for infiltrating water.

3.6.2 Monitoring

Monitoring is discussed in Chapter 9. Alternative cover systems should be monitored to identify problems with excessive erosion, excessive differential settlement, excessive cracking, or slope instability, assess the health of the vegetative cover, and evaluate gas emissions, if gases are a concern. If the cover system water balance is being assessed, the soil moisture content or matric potential, percolation through the cover system, and surface-water runoff may also be monitored.

3.7 Alternative Materials

3.7.1 Geofoam

As described by Horvath (1995a), geofoam refers to any manufactured material created by some internal expansion process that results in a material with a texture of numerous, closed, gas-filled cells. The cell walls are solid, although generally relatively thin and permeable to gases. Currently, the most common geofoam material is expanded polystyrene (EPS), a white foam that is also used for non-geofoam applications, like beverage cups and packaging. It is noted that EPS, along with extruded polystyrene (XPS), another geofoam material, are both referred to by ASTM as rigid cellular polystrene (RCPS) in below-grade applications (Horvath, 1995a). This lightweight material of a density between 10 and 20 kg/m^3 has unique engineering properties. White (1995) presents the following data as typical of EPS:

- water absorption is very low, e.g., 2% (maximum) by volume;
- low temperatures, under-water or wet environments, and exposure to freeze-thaw cycling do not adversely impact mechanical properties;
- EPS is a very efficient thermal insulator (because it is approximately 98 to 99% gas by volume), and this feature has been capitalized upon in several landfill applications; and
- the mechanical properties of elastic modulus, Poisson's ratio, and compressive strength are readily assessed by either static or cyclic loading tests.

According to Horvath (1995a), the only concern with using EPS and XPS geofoams is that they may degrade when in contact with certain chemicals (i.e., petroleum hydrocarbons and, possibly the plasticizer in PVC GMs.

Geofoam has been used above the drainage layer and barrier of a cover system for insulation and because of its lightweight properties (Gasper, 1990). It has also been used as a spray for daily landfill cover (Gasper, 1990), beneath a GM as a smooth protection layer over steep slopes in an abandoned quarry (Horvath, 1995b), and to promote methane and radon gas venting (White, 1995 b).

3.7.2 Shredded Tires

Scrap automobile and truck tires represent a large quantity of waste material that can be used in select construction, operations, and closure applications for waste containment facilities. In the U.S., an estimated 280 million scrap tires are generated annually. When cut into pieces, typically ranging from 50 to 300 mm in length, shredded tires may be used in cover systems as the gas collection layer, the drainage layer, the protection layer, or a component of the foundation layer (GeoSyntec Consultants, 1998a,b,c).

Modern tires are composed of a combination of natural rubber and synthetic rubber elastomers derived from oil and gas. Multiple carbon blacks, extender oils, waxes, antioxidants, and other materials are added to enhance performance characteristics and manufacturing efficiency. Tires contain a bundle of high tensile strength steel wires surrounded by rubber that forms the bead of a tire to provide a firm contact with the rim. The individual wires that compose this bundle can be up to 3 mm in diameter and are relatively stiff. Most tires also contain steel belt wire in the tread and sidewall areas. This wire is much smaller diameter than bead wire and is therefore more flexible.

Metal wires protruding from tire shreds may scratch or puncture GMs and GCLs used in a cover system. Therefore, whenever tire shreds are used in a cover system, careful consideration should be given to the design of adequate protection (e.g., a geotextile or a soil layer between the tire chips and GM) for the cover system geosynthetics. To minimize the potential for bead wires to pucture a GM or GCL, the bead wire protrusions from the tire shreds should be limited (to less than 10 mm for example) and a GT or soil cushion layer should be considered. Project-specific laboratory or field testing is recommended. Tire shreds containing bead wire should not be placed in contact with geosynthetics: either the bead wire needs to be removed or a soil layer needs to be placed between the tire chips and the geosynthetics. Belt wire can also be problematic. The results of a field test program (GeoSyntec, 1998b) show that belt wires in direct contact with a GM can create some minor damage (i.e., indentations, scratched, dents). To reduce the potential for GM damage by protruding or loose belt wire, the GM should be separated from the tire chips by a GT or soil layer. The wires exposed at the cut edges of tire shreds can also be a hazard to personnel walking on the shreds, and can puncture the tires of vehicles trafficking over them. Track mounted or steel-wheeled equipment should be used when practical to mitigate the latter problem.

The exposed metal in tire shreds may also leach metals when exposed to water; however, with exceptions of iron and manganese, the metal concentrations are anticipated to be below their primary or secondary drinking water standards (Duffy, 1996; Humphrey et al., 1997).
Tire shreds are combustible at temperatures above 322 ˚C. Combustion generally requires an external ignition source (e.g., lightening), although there have been several fires in tire-shred fills used for highway embankment fills that seem to be associated with spontaneous combustion due to self-heating. Humphrey (1996) describes three fires that occurred during 1995 in tire shred fills that were at least 6 m deep. Two of these fills are located in Washington, and one is located in Colorado. Humphrey gave several potential mechanisms for ignition of the tire shreds, with the most likely mechanism being oxidation of exposed steel wires. To reduce the potential for future tire fires, Humphrey recommends minimizing the amount of steel belt exposed at the cut edges of tire shreds, minimizing the amount of crumb rubber in the shred material, covering the shreds with at least 1.2 m of soil to limit contact of the shreds with oxygen, not placing organic materials (e.g., topsoil) directly over the shreds, and preventing contact between the shreds and fertilizer. These recommendations may be appropriate for relatively deep fills, but appear to be very conservative for applications where tire shreds are used in a cover system drainage layer or gas collection layer.

Physical characteristics of tire shreds are dependent upon the shred size (gradation), uniformity, exposed wire content, and whether the shreds have been mixed with soils. Compared to natural materials (i.e., sands and gravels) typically used as drainage layer materials, tire shreds have a much larger size. If the tire shreds are used as a drainage or gas collection material, soil or GT filter or separation layers are often required between the shreds and the adjacent materials.

Based on data complied from Ahmed (1993), Humphrey et al. (1993), and Cecich et al. (1996), loosely dumped tire shreds typically exhibit dry densities between 4.0 and 4.8 kN/m^3; the density of compacted tire shreds is typically between 5.5 and 7.5 kN/m^3.

Tire shreds are relatively compressible. Laboratory tests on compacted tire shreds less than 75 mm in length indicate that tire shreds may exhibit vertical strains of up to approximately 20% under low vertical stresses up to approximately 25 kPa (Ahmed, 1993; Nickels, 1995). Tire shred compressibility under the anticipated overburden stress should be accounted for when specifying the minimum thickness of the as-compacted tire shred layer. Because they are so compressible, construction of CCLs over tire shreds may be difficult. GeoSyntec Consultants (1998a) showed that construction of a CCL directly over 300 mm of foundation soil underlain by 300 mm of tire shreds resulted in the development of numerous cracks in the CCL as the tire shreds compressed. Such a relatively thin soil layer over the tire chips made it difficult to obtain the required compaction density in the overlying CCL. Additionally, the weight of a sheepsfoot roller or similar equipment used for compaction of a CCL could cause deflections of the tire shreds in the foundation layer that would be large enough to introduce cracks into the CCL, thereby increasing its hydraulic conductivity. When the foundation layer was modified to a 450-mm thick soil layer over a 150-mm thick tire shred layer, the foundation was adequate for construction of a CCL with a hydraulic conductivity of 1×10^{-6} cm/s or less. These results are dependent on the size of the tire shreds and the thickness of the tire shred layer. All other things being equal, smaller shred size and a thinner shred layer will provide more constructible conditions than if these parameters were reversed. A field test program may be considered when assessing the feasibility of constructing a CCL on top of a tire chip layer. The compressibility of tire shreds may also preclude placement of GM directly over a tire shred layer. This is mostly a problem during construction when construction equipment imposes stresses on the GM. For example, the deformation imposed by a low-ground pressure dozer spreading a 0.3-m thick soil layer over the GM may be sufficient to tear welded seams. Moreover, the compressibility of the shreds directly under the GM may complicate placement of the GM itself (i.e., it may be difficult to unroll the GM and the weight of field personnel may cause deformations that are sufficient to complicate field welding). In the absence of a field test program to investigate this issue, GeoSyntec Consultants (1998b) has recommended that at least 0.3 m of soils be placed over the tire shreds to allow construction of the GM and overlying soil layers.

When comprising a gas collection or drainage layer, tire shreds must be able to provide the required flow capacity under the applied normal stress. This is typically not a problem given the relatively low stresses in cover system applications; however, at higher normal stresses, tire shred compression and hydraulic conductivity reduction may be significant. Various tests have indicated the hydraulic conductivity of 12 to 75 mm long tire shreds to be on the order of 0.006 to 0.79 m/s (Edil et al., 1992; Glade et al., 1993; Duffy, 1996) under relatively low normal stresses. The lower end of this range corresponds to smaller tire shreds. High variability in hydraulic conductivity values are due to differences in shred size, initial density, hydraulic gradients, and confining pressures under study conditions.

Available published data on the shear strength of tire shreds indicate a wide range of shear strength properties for tire shreds and tire shred/soil mixtures. The data are from varying test types and test conditions. Humphrey et al. (1993) present data from large-scale direct shear tests conducted on tire chips with three different gradations. At normal stresses ranging from 14 to 68 kPa, the reported failure envelopes (i.e., friction angle and cohesion intercept) ranged from 19˚ and 11.5 kPa to 26˚ and 4.3kPa. At the lower end of the normal stress range (i.e., 14 to 17 kPa), these measured shear strengths yield equivalent secant friction angles of 38 to 45˚.

3.7.3 Sprayed Elastomers

Although sprayed elastomers, such as polyurethane and polyurea, have been used for waterproofing secondary containment systems, concrete water tanks, tunnels, roofs, and other structures, there has been limited application of these materials to waste containment or remediation sites. Sprayed elastomers could potentially function as gas and/or hydraulic barriers in cover systems at these sites. These materials are typically easier and faster to apply than other cover system barriers materials. Sprayed elastomer barriers would also usually have fewer seams than GM barriers. However, these materials have not yet been used in a full-scale cover system application, and the installation quality control and quality assurance procedures for such an application are still being developed.

An elastomer barrier can be installed by heating an elastomer, pressurizing it, and spraying it onto a surface. The material can be applied directly to a prepared soil subgrade. However, it may be difficult to achieve a continuous barrier with a uniform finish using this installation practice, especially if the subgrade surface has cracks. Therefore, in a cover system barrier application it may be more appropriate to spray the elastomer onto a lightweight nonwoven heatbonded GT placed without wrinkles or folds on a soil subgrade.

Laboratory testing has been conducted on factory-sprayed and field-sprayed polyurea elastomer samples. Factory-sprayed samples were obtained from the material supplier, and field-sprayed samples were collected from a 30 m x 30 m test plot installed in 1993 at a landfill in Michigan. As described by Miller et al. (1997), the test plot included subplots with elastomer sprayed over a prepared soil subgrade with some cracks, over a moist prepared soil subgrade with less cracks, over a lightweight nonwoven heatbonded GT placed on a prepared soil subgrade, and over a woven GT placed on a prepared soil subgrade. Half of the sprayed area on each subplot was covered with approximately 150 mm of soil and the other half was left exposed. The results of mechanical and hydraulic tests conducted on the factory-sprayed elastomer samples and interface direct shear tests conducted on the field-sprayed elastomer samples are presented by Cheng et al. (1994). According to Miller et al. (1997), the elastomer sprayed over the nonwoven GT appeared to provide the best barrier installation. Field samples have been removed from this barrier at periodic intervals to assess long-term performance. No significant degradation or deterioration in the mechanical or hydraulic properties of the barrier samples has been observed (Miller et al., 1997).

It should be recognized that sprayed elastomers have not yet been used in a full-scale cover system application. While this type of application holds some promise, additional research and development is necessary.

3.7.4 Paper Mill Sludges

Paper mill sludges have been shown to have properties similar to those of clays and, as a consequence, have been used as the hydraulic barrier material for some landfill cover systems in, at least, Maine, Wisconsin, and Massachusetts (Zimmie and Moo-Young, 1995). From the limited engineering properties data available for paper mill sludges, the properties vary considerably among the sludges depending on the manufacturing process, water content, organic content, sludge age, degree of consolidation, and other factors. Since the sludges are degradable, their properties are time dependent. The degradation processes also generate gases, which must be managed.

Zimmie and Moo-Young (1995) performed laboratory tests to evaluate the water content, organic content, specific gravity, permeability, compaction, consolidation, and strength characteristics of seven paper mill sludges of various ages. They found that the sludges had a high initial water content ranging from 150 to 268%, an initial solids content of 27 to 40%, and an initial hydraulic conductivity ranging from about 5×10^{-10} to 5×10^{-8} m/s, and behaved similarly to highly organic soil.

Zimmie and Moo-Young (1995) also performed laboratory tests on six undisturbed samples of a sludge used as the cover system barrier material for a MSW landfill in Massachusetts. Three samples of the sludge were obtained shortly after construction and the other three samples were taken at 9, 18, and 24 months after construction. The results of the laboratory tests on these samples indicated that the water content and hydraulic conductivity of the sludge decreased somewhat over time, presumably as the sludge consolidated and biodegraded (i.e., it mineralized to become more like a kaolin clay).

Moo-Young and Zimmie (1996) evaluated how freeze-thaw affects the hydraulic conductivity of paper mill sludges through a series of laboratory tests on sludge samples and by monitoring the depth of frost penetration in the sludge barrier for the previously-mentioned MSW landfill in Massachusetts. Based on the results of their laboratory tests, performed over a range of water contents, if a sludge barrier is subjected to freezing and thawing cycles, the hydraulic conductivity of the sludge may increase by one to two orders of magnitude. Over the several year field study, the frost layer had not penetrated into the sludge barrier due to the protection provided by the overlying soil layers and the high water content of the sludge.

When using paper mill sludge in a cover system application, the chemical characteristics of the sludge need to be considered. Water percolating through the sludge may mobilize volatile organic compounds and heavy metals contained in the sludge. To keep certain chemicals from leaving the site (e.g., as runoff), paper mill sludge may be required to be the barrier or be located below the barrier. Depending on its chemical properties, it may not be suitable for use as a protection layer.