CLOSING SMALL TRIBAL LANDFILLS AND OPEN DUMPS

How to Design Environmentally Safe Covers

Including additional design guidance for arid regions

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Cover Photo: An Evapotranspiration cover system at the Rocky Mountain Arsenal site near Denver, Colorado. September 2010.

EXECUTIVE SUMMARY

The purpose of this guidance is to help tribal public works managers, and environmental managers, and tribal leadership determine an appropriate final cover profile for closing small landfills and open dump sites on tribal lands. This document includes updated information from previous guidance documents for closing small landfills and open dump sites within arid regions on tribal lands.

This document presents design and operation considerations for the closure of small landfills and open dump sites, that while not recognized as landfills under the federal regulations in 40 CFR Part 258, should consider additional environmental safeguards. This document further provides guidance and a recommended design methodology for a final cover profile to close open dumps and solid waste landfills that meet the requirements set forth in 40 CFR 258.1(f). More specifically, this applies to small municipal solid waste landfills and open dumps that satisfy criteria summarized in the Decision Tree contained in Section 1.0 of this Guidance. This document is intended for facilities on trust land within Indian Country.

GLOSSARY

ASTM is the acronym for the American Society for Testing and Materials. An ASTM testing method defines the way a test is performed and the precision of the result.

Biodegradation is the chemical dissolution of organic waste material by bacteria or other biological means.

Biointrusion is the intrusion into the underlying waste through the final cover profile by flora and/or fauna.

Bulk Density is defined as the mass of soil divided by the total volume it occupies.

CFR is the acronym for the Code of Federal Regulations, the codification of the general and permanent rules published in the Federal Register by the federal government. ***40 CFR 258*** covers criteria for municipal solid waste landfills.

Desiccation Cracking is defined as the polygonal-shaped cracking that develops in clay or mud which has dried out.

ET Cover or evapotranspiration cover is a cover profile composed of soil with native vegetation.

Evapotranspiration (ET) is a term that represents the removal of water from a soil profile by the combination of evaporation from the soil surface and transpiration by the available plant community.

Flux is the percolation rate through a cover profile.

Geomembrane is a kind of geosynthetic material made up of an impermeable membrane. Geomembranes are made of various materials; most commonly low-density polyethylene (LDPE), high-density polyethylene (HDPE), or polyvinyl chloride (PVC).

Hydraulic Conductivity is a property of vascular plants, soil or rock, which describes the ease with which water can move through pore spaces or fractures. It depends on the intrinsic permeability of the material and on the degree of saturation. Saturated hydraulic conductivity describes water movement through saturated media.

Infiltration is the process by which water on the ground surface enters the soil.

Landfill is a site for the disposal of waste materials by burial and is the oldest form of waste treatment.

Matric Potential is also referred to as soil suction. It is that component of the *water potential of plants and soils that is due to capillary forces. Thus the water potential of cell walls and intercellular spaces is largely due to matric potential.

Municipal Solid Waste (MSW) commonly known as trash or garbage, is a **waste type** consisting of everyday items we consume and discard. It predominantly includes food wastes, yard wastes, containers and product packaging, and other miscellaneous inorganic wastes from residential, commercial, institutional, and industrial sources.

Open Dump An uncovered site used for disposal of waste without environmental controls. It includes any facility or site where solid waste is disposed of which is not a sanitary landfill which meets the criteria promulgated under section 4004 of the Solid Waste Disposal Act (42 U.S.C. 6944) and which is not a facility for disposal of hazardous waste.

Percolation is water that infiltrates into and through a cover profile into the underlying. The rate of water percolating through the cover is referred to as the cover‘s flux.

Permeability is the property of a porous material to permit a liquid or gas to pass through. Permeability is often interchangeably used with the term saturated hydraulic conductivity.

Plant Transpiration is a process similar to evaporation. It is a part of the water cycle, and it is the loss of water vapor from parts of plants (similar to sweating), especially in leaves but also in stems, flowers and roots.

Potential 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. It is commonly referred to as the climate‘s demand for water.

Prescriptive Cover is a cover profile that is specifically described by regulatory statue. For federal application it is described in 40 CFR Part 258. It may also be described in state regions.

RCRA is the acronym for the Resource Conservation and Recovery Act. RCRA was enacted in 1976 and is the public law that creates the framework for the proper management of non-hazardous and hazardous solid waste.

Resistive Cover is a cover profile that is designed to minimize percolation by restricting or ‗resisting‘ the movement of water through it by the inclusion of a barrier layer with a low saturated hydraulic conductivity.

Sole Source Aquifer is a sole or principal source aquifer as one which supplies at least fifty percent (50%) of the drinking water consumed in the area overlying the aquifer. These areas can have no alternative drinking water source(s) which could physically, legally, and economically supply all those who depend upon the aquifer for drinking water. For convenience, all designated sole or principal source aquifers are referred to as "sole source aquifers" (SSA).

Store and Release Cover, also referred to as an ET Cover, is cover profile that is designed to store any infiltrated water within its profile until that water can be removed via ET.

1.0 APPLICATION OF DESIGN GUIDANCE

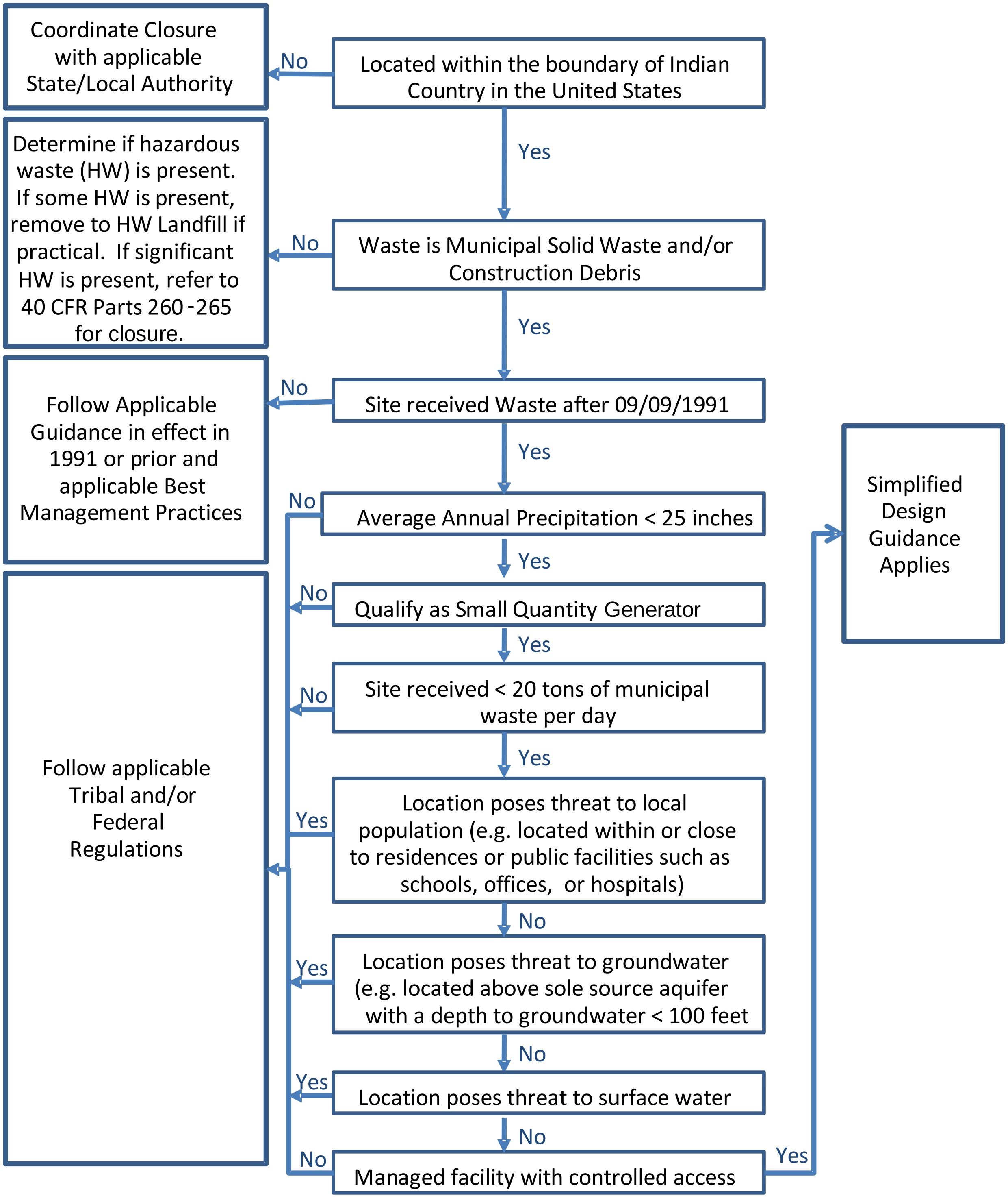
Use the Decision Tree on page 8 to determine if the Closure Design Guidance in Section 4 (and the Appendices) applies to each site under consideration. Note that this design guidance applies only to arid sites where annual precipitation is less than 25 inches.

For sites that do not meet the criteria in the Decision Tree, a prescriptive cover summarized in Section 2.2 may be an option. An alternative cover such as the recommended cover profile may still be an option; however it should be evaluated based on site-specific conditions.

This guidance is intended for municipal solid waste landfills and open dump sites that are not specifically covered by 40 CFR Part 258 and are located on Indian Country (may include all Federal Lands). A recommended cover profile for managed landfills or open dumps that meet the criteria summarized in the following Decision Tree is described in Section 4.

DECISION TREE: Simplified Cover Design Guidance for Closure of Small Landfills/Open Dumps In Indian Country

CRITERIA



1.1 INTRODUCTION

This Guidance is intended to assist and *simplify* the design and construction of a final cover system for closure of managed small landfills and open dumps that pose limited risk to human health and the environment. Limited risk is summarized in Section 1.2 (below) while the recommended criteria intended to limit the use of this Guidance is outlined in the Decision Tree on page 8. This Guidance recommends the use of an Evapotranspiration (ET) Cover for sites that meet this limited risk criterion. The ET Cover concept is described in Section 2.1 with a recommended cover provided in Section 4.0. If the criteria outlined in the Decision Tree are not satisfied and unacceptable risks are present at the site, that site may warrant further considerations including the possible use of a prescriptive cover as detailed in 40 CFR Part 258 and summarized in Section 2.2. The use of a prescriptive cover at a higher risk site does not mean that a prescriptive cover is a superior cover; only that the use of an alternative cover system at such a site may not be acceptable under federal regulations.

Design steps for the ET cover profile are described in Section 2.5. Other design considerations beyond minimization of water intrusion through the cover and establishment of vegetation include mitigating soil loss due to erosion and controlling surface water. These issues are discussed in Section 2.3 and 2.4, respectively.

Design steps for a prescriptive cover system can be found in EPA Publication EPA/625/R-94/008: Design, Operation, and Closure of Municipal Solid Waste Landfills. Prescriptive requirements are described in 40 CFR Part 258.

A good design is critical to the successful deployment of a final cover system. Just as important to the long-term success is the quality of the construction of this cover system. Construction considerations are described in Section 3.0.

1.2 CLOSURE DESIGN RISK

Controlling risk is a primary goal for environmental remediation efforts. Landfill and large open dump closures are no exception. Risk, as it relates to solid waste disposal sites, is defined as the actual or potential threat of adverse effects on human health and the environment by effluents**,** emissions**,** wastes**,** resource depletion**,** etc., arising from the landfill‘s encapsulated waste. Within the realm of environmental risk, this process involves a multi-staged analysis characterized by a ―risk assessment", ―risk characterization" and ―risk management". A risk assessment is ―the evaluation of scientific information on the hazardous properties of environmental agents, the dose-response relationship, and the extent of human exposure to those agents". In essence a pollutant is identified and its possible effects on those exposed are described. The result of this analysis ―is a statement regarding the probability that populations or individuals so exposed will be harmed and to what degree," also known as a risk characterization. Once risk has been assessed and characterized, ―political, social, economic and engineering implications together with risk-related information" are gathered ―in order to develop, analyze and compare management options and select the appropriate managerial response to a potential chronic health hazard". This process is called risk management. Together these steps comprise the scientific approach to risk.

The number of variables to be considered are generally site-specific and too numerous to list all. However, some common variables to consider when assessing the site's human and environmental health risks include:

- Proximity to shallow sole source aquifers: considerations should include whether the site is directly above a sole source aquifer; the depth to groundwater; and the potential of leachate from the site (quantity and quality) that could adversely affect groundwater.
- Proximity to residences and public facilities: Is there the possibility of growth of nearby communities toward the site or the possibility of future construction on the site? Risks associated with this issue include the potential for methane migration into nearby structures.
- Type of waste: Considerations should include whether the site contains municipal or hazardous waste; are there any medical or other wastes such as asbestos; is the waste biodegradable – byproducts of biodegradation include carbon dioxide and methane gas as well as potential differential settlement. Obviously hazardous waste will create more risk than waste such as construction debris like broken concrete and wood.
- The size and shape of the trench, pit, or excavated area can determine the potential for future differential settlement. Differential settlement can result in the creation of significant surface cracks that allow water flow down through the cover and into the underlying waste while also allowing the upward escape of methane gas. Additionally, differential settlement may create surface depressions or low spots that allow for ponding of surface water and thus increased percolation into the waste. This in turn can lead to increased methane generation along with the potential for increased leachate production and thus an increased potential groundwater contamination.
- Site location: considerations include whether the site is susceptible to flooding; earthquakes; is the site susceptible to substantial erosion due to its shape, slope, etc.; is the site subject to intrusion by burrowing animals and plant roots that may harm the effectiveness of the cover system or bring waste to the surface?
- Site climate: considerations can include does the site have excessive precipitation; is there significant snow; are there high intensity storm events that can create excessive erosion?
- Soil type: considerations can include - does the underlying soil beneath the waste have a low permeability such as silt or clay or a high permeability such as sand or gravel; does the cover soil have adequate storage capacity; is the cover soil capable of maintaining a quality stand of native vegetation?
- Waste placement: considerations should include - was the waste compacted as it was placed; was the waste placed dry or wet; was the waste placed in a manner that would lead to future differential settlement?

2.0 COVER DESIGN

A final cover system for a solid waste landfill is intended to isolate the underlying waste and thus reduce its inherent risk to human health and the environment. The final cover may be composed of a single monolithic soil layer or multiple layers acting as a system. The cover profile should be designed to address each of the site-specific potential release vectors from the landfill or open dump. A release vector is a potential pathway for harmful encapsulated waste to be released into the environment. Examples include:

a. Flux: Water that infiltrates into and through a cover profile to the underlying waste is referred to as percolation. Percolation rate is referred to as flux. Excessive flux can lead to significant leachate generation that can potentially escape a landfill and carry harmful contaminants to groundwater, polluting drinking water supplies.

b. Erosion: Excessive erosion can remove the protective cover or reduce its effectiveness to isolate the underlying waste. Some erosion can be planned for and taken into account in the cover design. However, excessive erosion, particularly rill and gully formation should be avoided.

c. Surface Water: Surface water must be controlled to minimize erosion and potential release of harmful contaminants. Surface water controls can include controlling the speed, direction, and volume of water. They can also control surface water generated upstream of the site from running onto the site and/or running off of the site.

d. Biointrusion: Excessive or unwanted intrusion into the underlying waste through the final cover profile by flora and/or fauna can be a release vector. A layer of rock such as cobble can be added as part of the cover, or the cover can simply be made thicker.

e. Gas: Carbon dioxide and methane are the primary gases created during biodegradation of buried municipal solid waste. Inclusion of a gas collection layer is a common solution for this issue. A major concern related to methane generation and transport is the potential accumulation of gas in nearby structures. Methane gas can accumulate within an enclosed structure and create an explosive threat. If structures exist near a landfill or large open dump, it is a good idea to monitor for methane within these structures.

Two types of covers are discussed in this guidance. The first type of cover is referred to as a ‗store and release' cover. That is, the cover is designed to store infiltrated water within its profile until it can be released to the atmosphere via evapotranspiration (ET). The combination of evaporation from the cover soil surface or through plant transpiration is termed *ET*. These are alternative earthen covers designed to take advantage of site-specific conditions such as climates where the demand for water referred to as potential evapotranspiration (PET) significantly exceeds the supply of water (precipitation). This is further discussed in Section 2.1.1. The second type of cover, referred to as a ‗resistive' cover, attempts to block or resist the downward movement of water typically with low permeable soil barrier layers and/or geosynthetic materials such as high density polyethylene membranes. These ‗resistive'-type barriers are considered *prescriptive* covers as detailed in 40CFR258. The prescriptive cover is further discussed in section 2.2.

2.1. ET COVER CONCEPT

The ET Cover also referred to as a ‗Store and Release' Cover is an excellent cover system if
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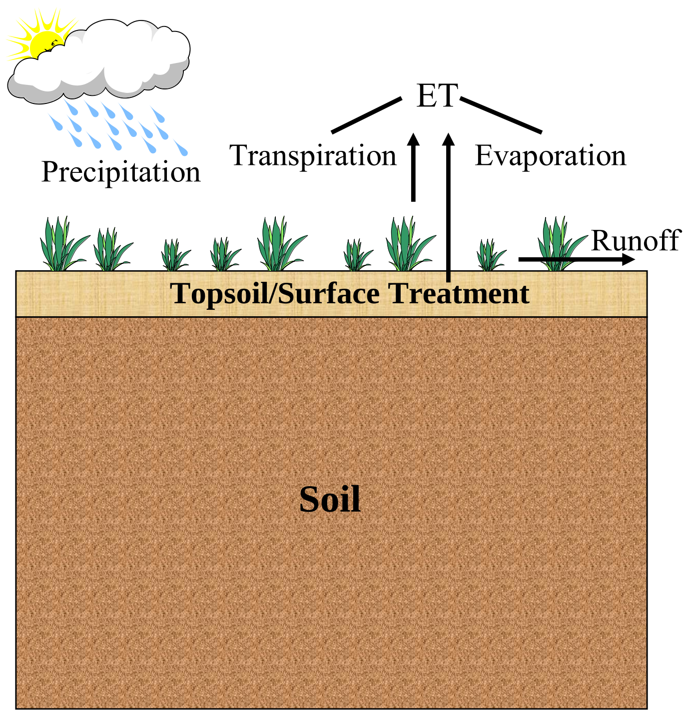

Figure 1. Typical ET cover profile

The ET cover concept relies on the cover soil to act like a sponge. Infiltrated water is held in this ‗sponge' until it can be removed via ET. Previous research has shown that a simple ET cover can be very effective at minimizing percolation and erosion, particularly in dry environments (Hauser et al. 1994, Hakonson et al. 1994, Nyhan et al. 1997, Khire et al. 1997, Dwyer 2001, Dwyer 2003, Albright et al 2004, Nyhan 2005).

ET provides the mechanism to remove stored water from the cover soil layer. Water can move upward because of evaporation drying the upper portion of the cover soil layer. Evaporation from the surface will decrease the water content and thus increasing the matric potential of the soil, (soil suction) resulting in an upward matric potential gradient and inducing upward flow.

Plant transpiration also relies upon matric potential gradients to remove water from the cover soil layer. Figure 2 shows the large matric potential difference between the soil and atmosphere. In dry environments, the total potential difference between soil moisture and atmospheric humidity can be up to 1000 atmospheres (bars) (Hillel 1998). The larger the soil-plant-atmospheric potential gradient, the more effective an ET cover system can be.

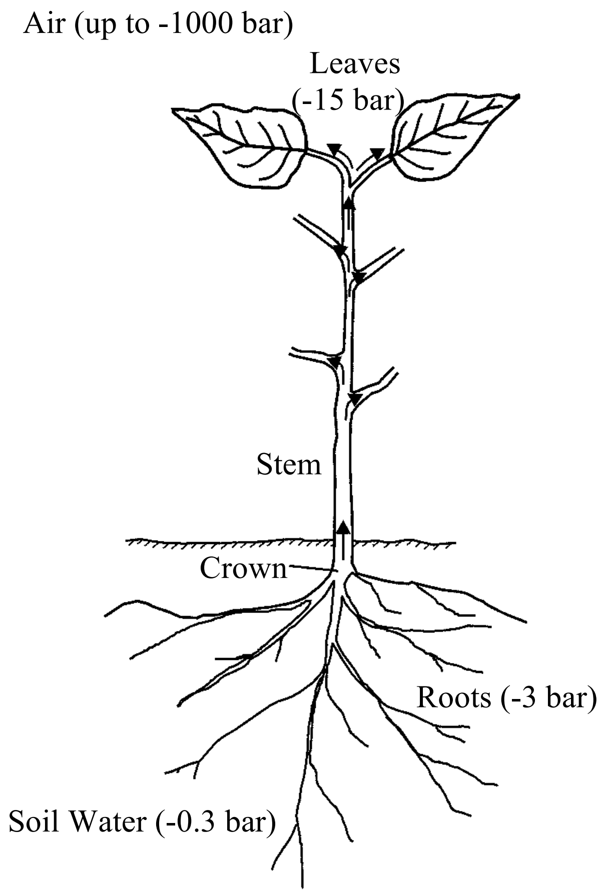

Figure 2. Typical Soil-Plant-Atmosphere Water Potential Variation (Hillel 1998)

2.1.1 CLIMATES WELL SUITED FOR ET COVERS

Sites well suited for an ET Cover include climates where the demand for water or potential evapotranspiration (PET) is significantly greater than the supply of water or precipitation. One of the criteria included in the Decision Tree in Section 1.0 applies to climates with 25-in of annual precipitation or less (Figure 3).

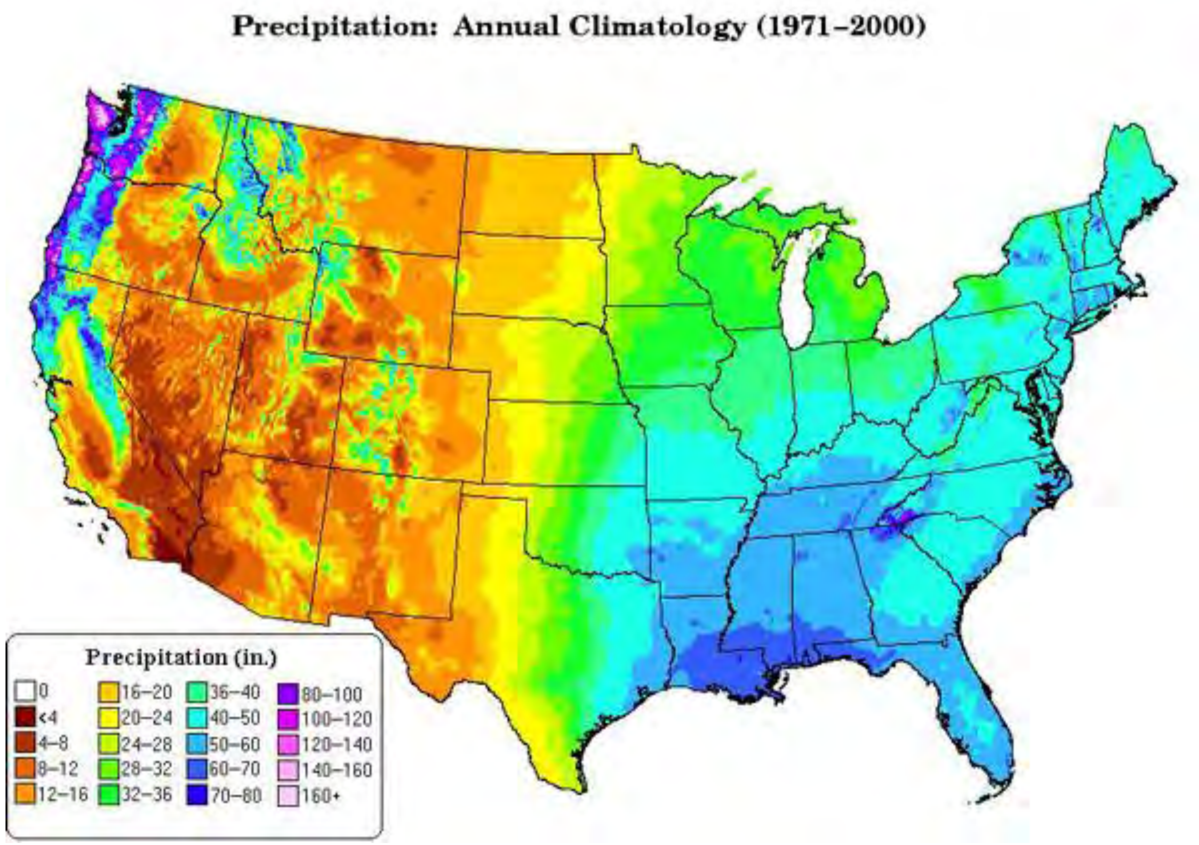

Figure 3. United States Climate Map (Natural Resources Conservation Service http://www.wcc.nrcs.usda.gov/climate/prism.html)

However, more important than the annual precipitation is the ratio of the demand for water or PET to the climate supply of water. As long as this ratio is significantly large enough, an ET Cover should be able to minimize flux. Typical climates that extend across much of the United States where the majority of precipitation occurs during the summer months when PET is at its peak while precipitation during the winter months is lower also while PET is lower are generally suited for store and release covers given the average PET is greater than precipitation for each month of the year. An acceptable ratio of PET: precipitation should be based on site-specific conditions and risk.

An example of a typical environment well suited for an ET Cover is Albuquerque, NM. The PET far exceeds the precipitation for each month of the year (Figure 4) and thus a well designed ET Cover should provide adequate storage capacity to minimize flux.

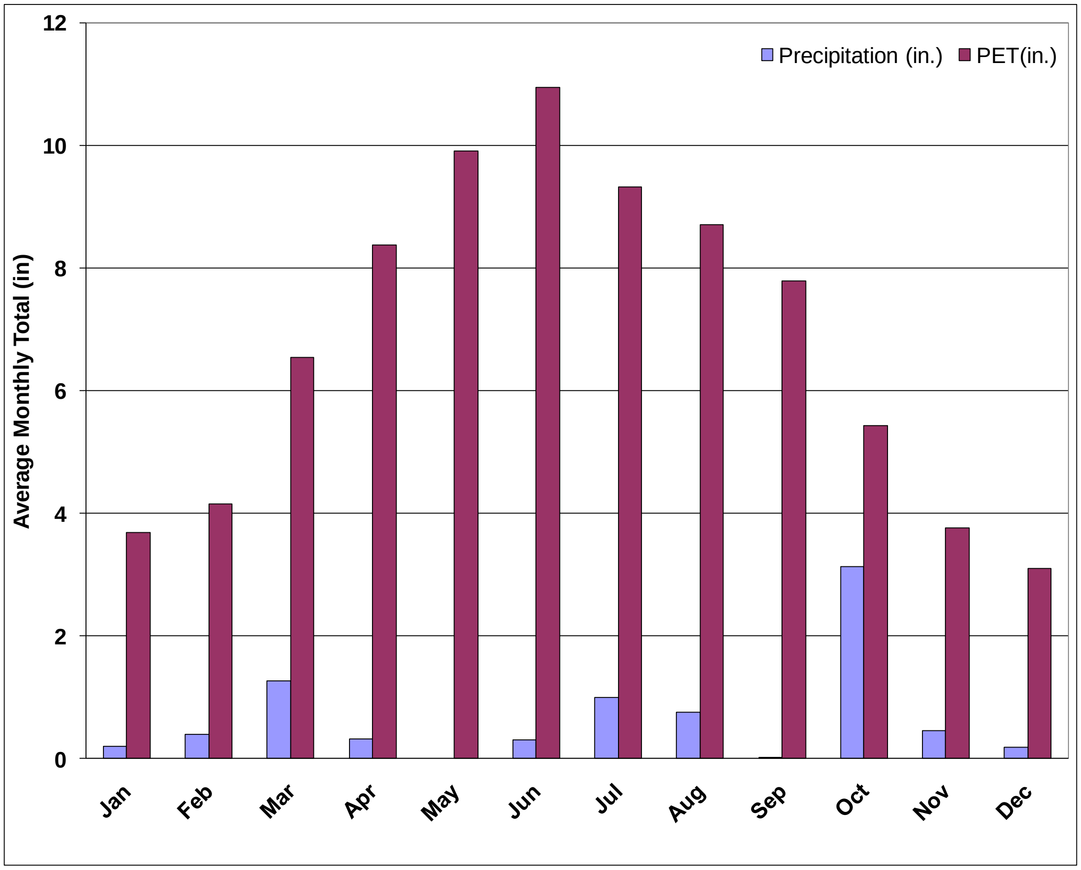

Figure 4. Climate's demand for water (PET) vs. supply of water (precipitation) Albuquerque, NM (1998)

An example of a non-typical climate also well suited for an ET Cover includes Livermore, California, just east of San Francisco. The weather in this area is different than many areas of the country. It is hot and dry in the summer with much of the vegetation dormant during this period due to lack of precipitation. The area receives most of its precipitation during the winter months while the PET for the area is at its lowest levels. Despite this weather pattern, the average PET exceeds the precipitation for the area for every month of the year (Figure 5).

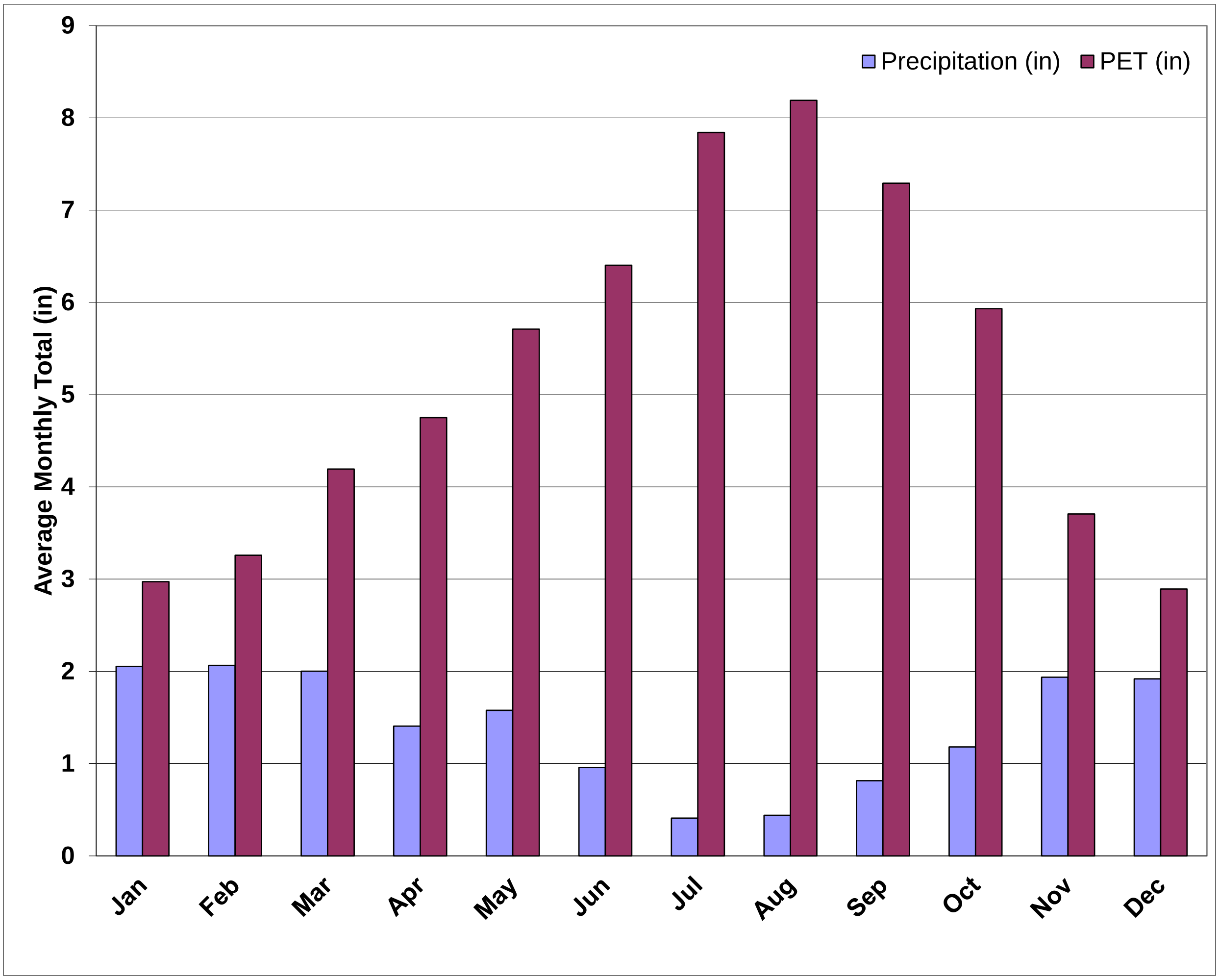

Figure 5. Climate's demand for water vs. supply of water Livermore, CA

2.1.2 CONSIDERATIONS FOR ET COVER

Emphasis during the design and construction of a cover system is placed on achieving the designated performance goals. Two primary performance goals for a cover system include minimization of flux through the cover and minimization of soil loss due to erosion. Performance goals can also include controlling the release of gas and/or biointrusion. For an ET Cover to successfully minimize flux and erosion, a moderate density in the cover soil should be achieved. Covers placed too loosely will allow infiltrated water to quickly move down and potentially through the soil profile not allowing the cover to store the water until the moisture is removed via ET. Placing the cover too densely subjects the profile to preferential flow resulting from desiccation cracking described in section 2.2.1 and can adversely affect the establishment of vegetation. Therefore, the cover soil should be placed with moderate compaction that closely mimics the natural or ‗in-situ' density of the soil in its undisturbed state. Generally, this is about 90% of the maximum dry density using the standard proctor method (ASTM D698). Other considerations should include limiting the amount of salts in the soil that can adversely affect the vegetation establishment as well as increase the erodibility of the soil (Appendix B). Adequate plant nutrients are also important, but cover soil can be amended to increase available plant nutrients.

2.2 PRESCRIPTIVE COVER CONCEPT

A prescriptive cover also referred to as a ‗resistive cover' is designed to limit percolation by incorporating a barrier layer within its profile. The barrier layer is typically a clay layer with a low saturated hydraulic conductivity or a geomembrane or a combination of the two. The intent of the low permeable barrier layer is to ‗resist' the movement of water into and thus through it. Federal prescriptive standards for this profile are described in 40 CFR Part 258 (see below). Many states have the authority to regulate the closure of landfills and as such have their own unique prescriptive standards for the cover profile or may have directly adopted the federal standard.

Regulations for the final cover of a RCRA Subtitle ―D" facility are prescriptive. Specifically, these minimum prescriptive requirements for the final cover system include:

1) have a permeability or saturated hydraulic conductivity less than or equal to that of the bottom liner or natural subsoils present, or no greater than 1 x 10^{-5} cm/sec, whichever is less [40 CFR 258.60(a)(1)];
2) minimize infiltration through the closed Municipal Solid Waste Landfill (MSWL) by the use of an infiltration layer containing a minimum 45 cm (18-in) of earthen material [40 CFR 258.60(a)(2); and
3) minimize erosion of the final cover by the use of an erosion layer containing a minimum 15 cm (6-in) of earthen material that is capable of sustaining native plant growth [40CFR258.60(a)(3)].

These requirements are summarized in a cover profile shown in Figure 6.

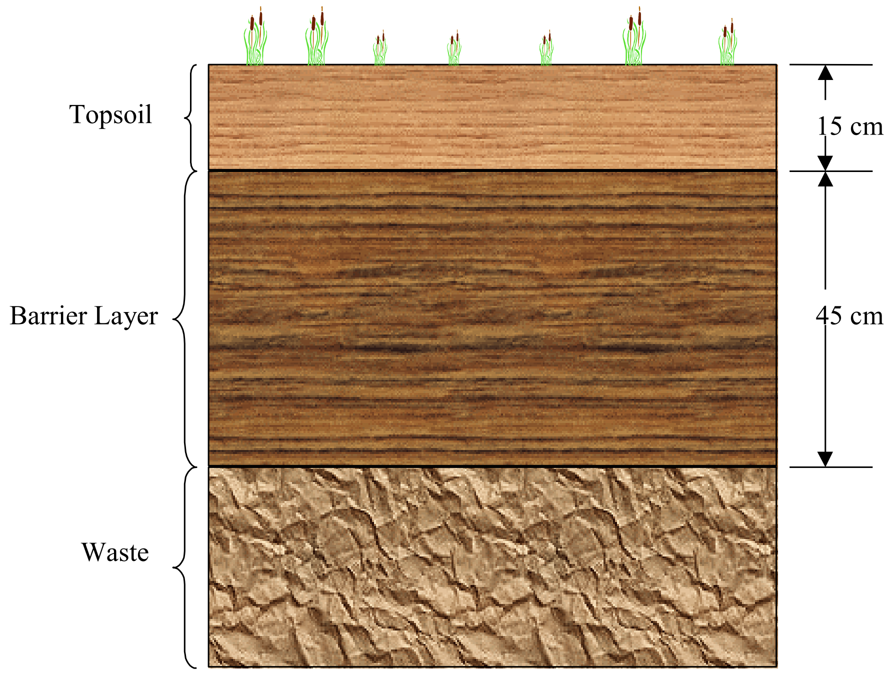

Figure 6. RCRA Subtitle D Minimum Cover Profile

Many state and local regulatory authorities have modified the minimum cover requirements set forth in 40CFR258; generally making the requirements more stringent. Some have altered the barrier soil layer requirements by requiring a lower saturated hydraulic conductivity requirement, for example requiring a maximum of 1 x 10^{-6} cm/sec instead of 1 x 10^{-5} cm/sec. Others have required a composite barrier layer comprised of both a clay barrier layer and a synthetic geomembrane. Local environmental regulations should be consulted for minimum cover profile requirements.

2.2.1 CONSIDERATIONS FOR PRESCRIPTIVE COVER PROFILES

As previously discussed, the emphasis of the prescriptive cover profile is to minimize flux by resisting the movement of water vertically downward. This is achieved via a low saturated hydraulic conductivity in the barrier layer. There are some drawbacks to using the minimum profile described in 40CFR258. To achieve the lower saturated hydraulic conductivity in the barrier layer, the soil is typically installed in a moist condition (generally wet of the optimum moisture content per ASTM D698) and heavily compacted to achieve a higher density. This allows for the clay particles to be remolded and lower the initial or ‗as-built' saturated hydraulic conductivity of the soil layer. Experience has shown these clay barrier layers to be vulnerable to such things as near-surface desiccation cracking (Figure 7), especially in drier environments (Suter et al. 1993, Dwyer 2003).

Figure 7. Desiccation Cracking in Clay Barrier Layer

Desiccation cracking can provide easy pathways for water migration downward and *defeats the purpose* of trying to install a relatively impermeable (low saturated hydraulic conductivity) barrier layer. An EPA design guidance document (EPA 1991) for final landfill covers states: *"In arid regions, a barrier layer composed of clay (natural soil) and a geomembrane is not very effective. Since the soil is compacted „wet of optimum', the layer will dry and crack"*. Further, some soil textures cannot meet the low saturated hydraulic conductivity without amendments (e.g. mixed with bentonite). These amendments significantly increase the cost of construction.

2.3 EROSION

The minimization of flux through a cover is often the primary concern during the design process of a final cover system. However, the minimization of erosion has proved to be of significant concern especially in dry environments. Annual soil loss should be limited to 2 tons/acre/year (EPA 1991). Perhaps more important, the formation of rills and gullies (Figure 8) in the cover system should be avoided. The recommended cover profile described in section 4.0 utilizes a gravel/soil admixture for the surface of the cover to minimize erosion and mitigate the formation of rills/gullies. Refer to Appendix A for a recommended design methodology for the upper layer of the cover to minimize erosion.

A cover system's susceptibility to erosion is a function of a number of factors, including slope angle and length, surface soil characteristics, rainfall intensity and duration, and vegetation (Figure 8). Vegetation will assist to minimize erosion, however in dry climates; native vegetation is commonly sparse and unable to form a continuous blanket to completely limit erosion. Consequently, each cover design should address how to assist vegetation in minimizing both short and long-term erosion.

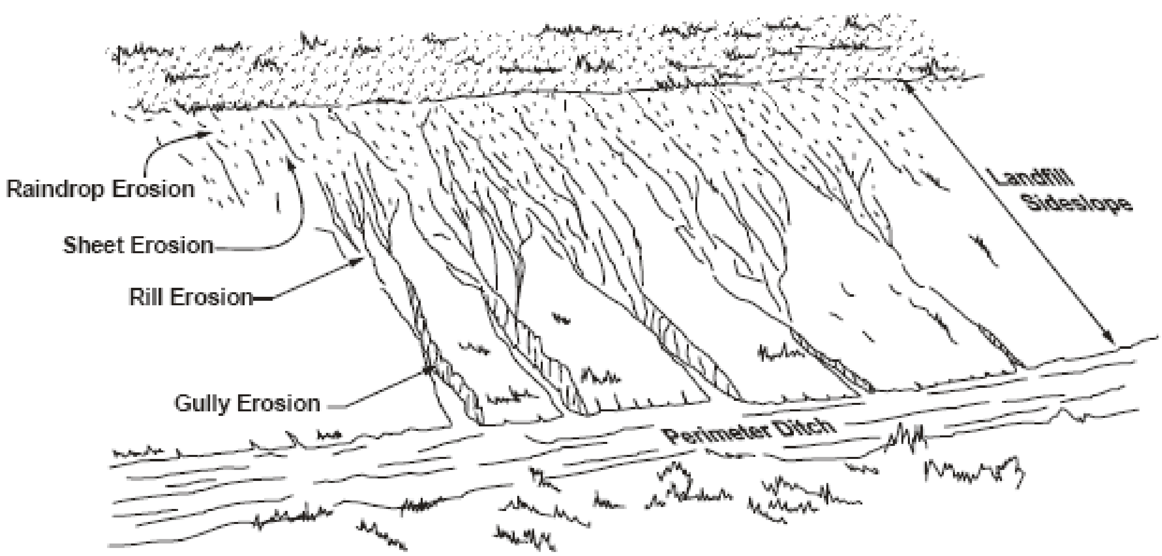

Figure 8. Types of Water Erosion That May Occur on a Cover System

Cover top slopes are generally influenced by the topography of the site. Engineering concerns such as erosion, settlement, shedding surface water, and final aesthetics all play a role in the determination of the final cover top slope(s). Side slopes should be minimized and must meet applicable slope stability requirements.

The determination of the final cover slope can be a balancing act between maximizing slope to increase runoff and thus decrease infiltration or minimize slope to decrease erosion.

Unfortunately, erosion and infiltration are inversely related when compared against slope and slope length (Figure 9).

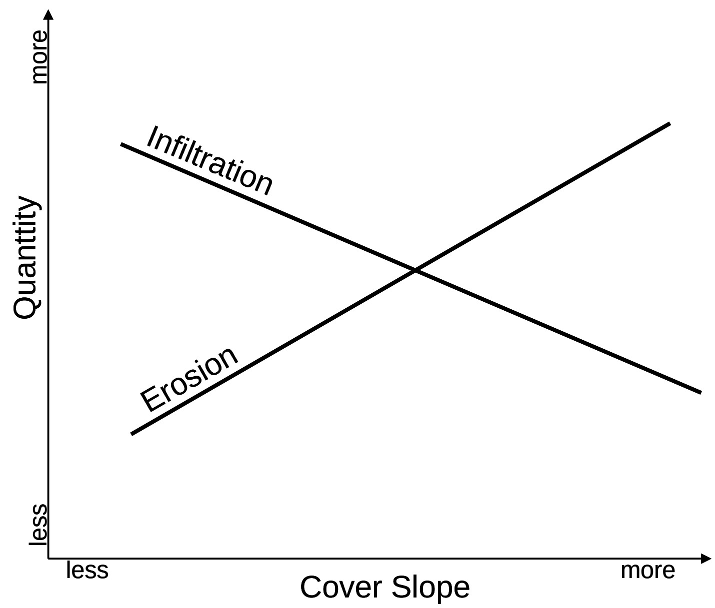

Figure 9. Infiltration / Erosion vs. Cover Slope

2.4 SURFACE WATER MANAGMENT

Control of surface water runoff at a landfill disposal facility is necessary in order to minimize the potential for environmental damage to ground and surface waters by direct and indirect effects. Direct surface water contamination can result from solid waste and other dissolved or suspended contaminants carried by surface runoff. Uncontrolled surface runoff can also contribute to leachate and gas generation, thereby increasing the potential for both surface- and ground water contamination. Surface water courses should be diverted from the landfill and there should be no uncontrolled hydraulic connection between the landfill and standing or flowing surface water.

2.5 DESIGN STEPS FOR COVER SYSTEM

A set of recommended design steps for a cover system are described in this section. The following steps should be formally or informally considered when designing a cover system to meet determined performance and/or risk objectives at each site. These steps are briefly described below.

Note: Throughout this document, a cover system is referred to instead of merely a cover because it is very important that the design of a final cover be designed as a system rather than merely as a group of individual components comprising a cover.

1. Determine the regulatory drivers for closure of each specific site.
2. Determine the design life of the cover system to be deployed based on the applicable regulations and encapsulated waste. Subtitle D municipal solid waste landfills as defined

by RCRA typically require a minimum 30-year post-closure monitoring period to ensure the cover system is working as intended. Sites that are not considered municipal solid waste landfills under RCRA should determine the length of closure based on site-specific parameters. See the Decision Tree in Section 1.0 for additional guidance.

3. Determine performance objectives of the cover system. Review, assess, and determine additional data needs, and design documentation to support the final design. Performance objectives can include, but are not limited to:

    a. Risk. The cover system must be designed to control risks associated with each specific site.

    b. The cover flux (moisture that has moved vertically down through the cover profile) must be less than that which will produce an adverse risk to groundwater. Generally, flux should be minimized.

    c. Erosion of the cover system. As a minimum, all cover systems should be designed so that the calculated sheet erosion rate does not exceed 2 tons/acre/year (EPA 1991). Erosion effects due to both wind and water should be taken into account. Refer to Appendix A.

    d. Gas emissions should be taken into account and be controlled where applicable.

    e. Control biointrusion if warranted. Biointrusion in a landfill cover system refers to the flora and fauna interactions or intrusion into the cover system. Uncontrolled biointrusion may increase contaminant release from a closed site via such things as burrowing animals and/or insects and root intrusion from plants or grasses whereby contaminants can be brought to the surface or allow for increased flux and thus increased potential for groundwater contamination.

    f. Access control. A closure system may require limited access to the site. A typical control is the installation of a fence around the site with a locked gate.

    g. Aesthetic considerations. Closed sites may require the cover system to be aesthetically appealing to nearby communities.

    h. Future use considerations. A cover system should take into account the potential future use of the site.

4. Determine site-specific issues that will affect the design of the cover system—these relate to those identified in step 3, as well as differential settlement, subgrade considerations, extent of subsurface contamination, size, slopes, seismic, adjacent facilities, existing complications such as underground utilities, and surface water management issues.

5. Determine the cover type to be deployed whether it is a prescriptive cover such as the summarized in section 2.2 or an alternative cover such as an ET Cover. This document emphasizes the use of an ET Cover. The ET cover is a monolithic soil layer that has adequate soil-water storage capacity to retain any infiltrated water from the determined design precipitation event(s) until it can be removed via ET.

6. Identify an acceptable borrow soil to be used in the cover system.

    a. *For an ET Cover*, the soil should have adequate water storage capacity while having the capability to support native vegetation (refer to Appendix B). The borrow soil can be excavated soil from a nearby area or purchased off-site and transported on-site. Nearby, native soils are ideal for use in an ET Cover for economic reasons and because local vegetation is adapted to them. Refer to Appendix C to assist in determining whether these soils have adequate water storage capacity. Loams tend to have good storage capacity and generally minimize the potential for desiccation cracking that can enable preferential flow (Figure 10).

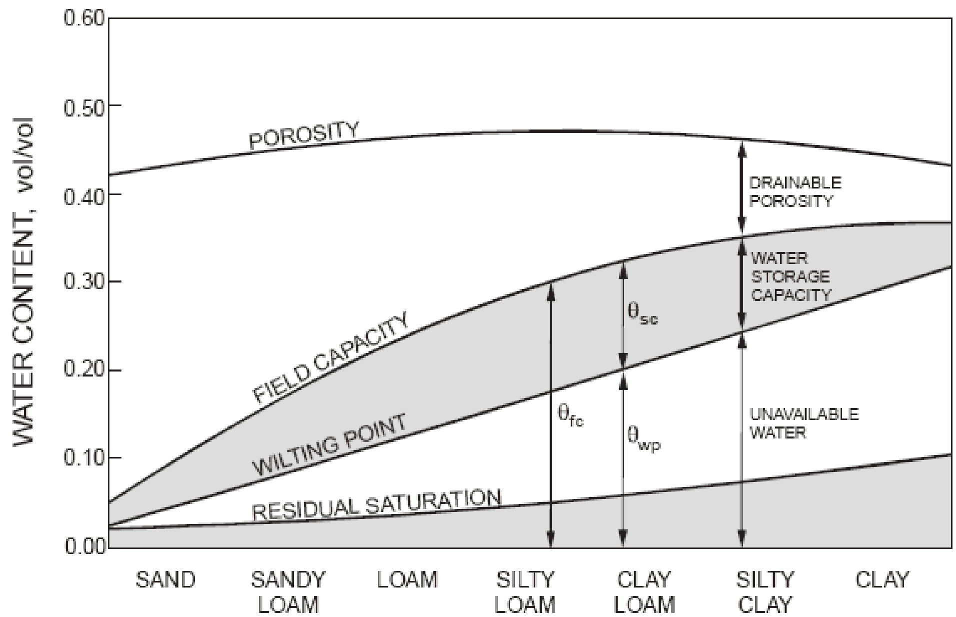

Figure 10. Relation between moisture retention parameter & soil texture class (Schroeder et al. 1994)

b. *For a Prescriptive Cover* similar to that shown in Figure 6, the topsoil properties should provide an effective rooting medium for native vegetation. However, the key to the barrier layer soil properties are such that the saturated hydraulic conductivity is less than the regulatory mandated minimum. To achieve the low permeability criterion, the soil must have limited rock content and have an adequate volume of fines – preferably clay. Generally, the higher the clay content, the lower the soil's saturated hydraulic conductivity. Furthermore, the soil barrier layer is typically placed ‗wet of its optimum' moisture content (ASTM D698) and heavily compacted in an effort to remold the soil and ultimately lower the initial saturated hydraulic conductivity of the layer. Refer to section 2.2.1 for pitfalls related to this construction process and soil texture.

If laboratory testing of the soil is to be performed for design analysis, the following considerations for this testing are offered (Refer to Appendix C):

- If the potential cover soil is to be modeled, it is common to test for the soil's hydraulic properties. It is recommended to test the borrow soil at a remolded density similar to the intended installation density. That is, any laboratory testing of the soil to be used in the cover system should be tested at a density similar to the intended constructed density of the cover. A soil's hydraulic properties are sensitive to the soil's density and thus any modeling performed should be done based on hydraulic properties derived at the intended soil density.

- Other soil properties that may be tested for include strength characteristics (i.e., if slope stability is a concern with steep side slopes) or particle size analysis if erosion is a concern.

7. Cover soil placement density. The density of the cover soil should meet the performance requirements. If low permeability is required, such as the soil barrier layer of a prescriptive cover, the soil density will be higher and thus heavy compaction is generally warranted. The upper topsoil layer in Figure 6, is generally placed without compaction. If it becomes too dense during the construction process, it is advised that it be disced prior to seeding to enhance the vegetation establishment. The recommended density for an ET Cover referred to as the goal density is intended to mimic the natural conditions of the borrow soil in an undisturbed setting (i.e. *in-situ* density) because soils tend to migrate toward this density in the long-term. Furthermore, the density needs to be dense enough to slow water infiltration to the point where ET can remove the water while not adversely affecting the water storage capacity of the cover profile. It is recommended to determine this *in-situ* density of the undisturbed borrow soils to be used and set this as the goal density for placement of the cover soil. A tolerance of +/- 5 pounds per cubic foot is common for this constructed density.

8. Determine the cover profile required layers and depth. *For a prescriptive cover*, the minimum requirements are shown in Figure 6. *For an ET Cover*, determine the minimum required depth of cover soil required to minimize flux (Appendix C). For a site that meets the criteria outlined in Section 1.0 that utilizes the recommended cover profile described in Section 4.0, this step is assumed to be unnecessary. That is, the cover soil has an adequate quantify of fines and thus has adequate storage capacity for the relatively dry environment and low risk site. However, a technique is described in Appendix C that allows for a technical justification for the depth of cover to be deployed to minimize flux should this analysis be warranted.

9. Perform an analysis to predict soil loss due to both surface water and wind erosion as required. Any predicted soil loss due to erosion is to be added to the overall cover depth in addition to the minimum depth estimated in previous steps. Refer to Appendix A.

10. Determine other layers or enhancements to the cover system as required based on performance and/or risk assessment(s) performed. These may include a bio-barrier, gas control layer, subgrade structural support layer, or a lateral drainage layer.

11. Determine the vegetation mix to be utilized on the cover system.

12. Evaluate the available field data of similar climatic and soil textural classifications to determine whether the design is feasible. Compile this data as supporting documentation in the final design report to be submitted to regulators for final approval and permitting. This field data will provide short-term data that will justify that the design will perform as intended.

13. Evaluate applicable natural analogs for all parts of the cover systems such as the hydraulic storage capacity, as well as for such things as biointrusion, climate scenarios, erosion control, and vegetation. In this case, natural analog can be defined as an

occurrence of materials or processes which resemble those expected in the proposed geological waste repository. Natural analogs can help evaluate the long-term performance of a cover system.

14. Determine the installation requirements, to ensure performance of the cover delivers that desired per the design. This will be included in the construction documents (design drawings and specifications).
15. Determine the method to be used to ensure that acceptable materials and construction methods are used to build the cover system. This should be included in the Quality Assurance (QA) documentation. Refer to Appendix D.
16. Determine maintenance monitoring criteria (if any), methods and frequencies to be performed to ensure that cover systems are not degrading. This will be included in the cover system maintenance plan.
17. After the various design considerations have been evaluated and applicable options selected, the cover system must be engineered to produce the final cover system details. Besides selecting the required cover profile described above, the appropriate soils must be used or amended. Erosion must be minimized. Surface water run-on must be avoided while surface runoff must be controlled. Cover slopes should be designed to minimize erosion while shedding surface water. For steeper slopes, stability issues may be of concern.

3.0 COVER CONSTRUCTION

The quality of construction and materials used is critical to achieving design objectives and criteria. The borrow source used for cover soil should be well characterized prior to its acceptance for adequate volume, quality of material, and uniformity of material. A description of some of the important issues related to cover soil is located in Appendix B.

3.1 SOIL PLACEMENT

An important aspect involved with the construction of a soil cover system is that the soils are placed at a uniform density. This will help limit preferential flow through the cover. Preferential flow cannot be avoided, but necessary precautions should be employed to ensure it is minimized.

Cover soils should be placed within an acceptable density range. When possible, cover soil (water storage layer and surface treatment layers only) should come from the same borrow source. If there is not adequate borrow soil available from a single source, then soils imported from multiple borrow sources should all be well characterized and placed within respective specified ranges.

The upper rock/soil admixture layer should be placed in a loose state without compaction. If this soil layer becomes compacted or is determined to be too density after its installation, but prior to seeding, it should be loosened prior to seeding. Care should be taken to ensure the rock to soil ratio is maintained. The final slope and slope tolerances described in the design should be maintained. Positive drainage should be maintained at all times during installation of the cover systems.

3.2 Quality Assurance (QA)

Quality Assurance (QA) of both the construction process and materials used is critical to the successful installation of a cover system. Paramount to this success is the assignment of a person or team to ensure that adequate QA is applied to the project. The QA engineer should understand the design and the ultimate goal for success of the project and help ensure that the constructed product meets the goal.

A QA Plan specific for the project should be written. This should include any QA testing to be performed, success or failure criteria for the testing, frequency of testing, equipment or materials to be used in testing along with applicable ASTM standards. The QA Plan should identify what documentation is to be completed during the construction process and what individuals or companies should retain the documented QA process.

Refer to Appendix D for recommendations of information to be included in the QA Plan including examples of QA testing/frequency/criteria.

4.0 RECOMMENDED COVER PROFILE

This guidance document serves to provide technical assistance in the closure of sites that have been determined to meet acceptable risk and regulatory requirements by applying a well designed cover system over them. Figure 11 describes a recommended cover profile for sites that satisfy the criteria outlined in Section 1.0.

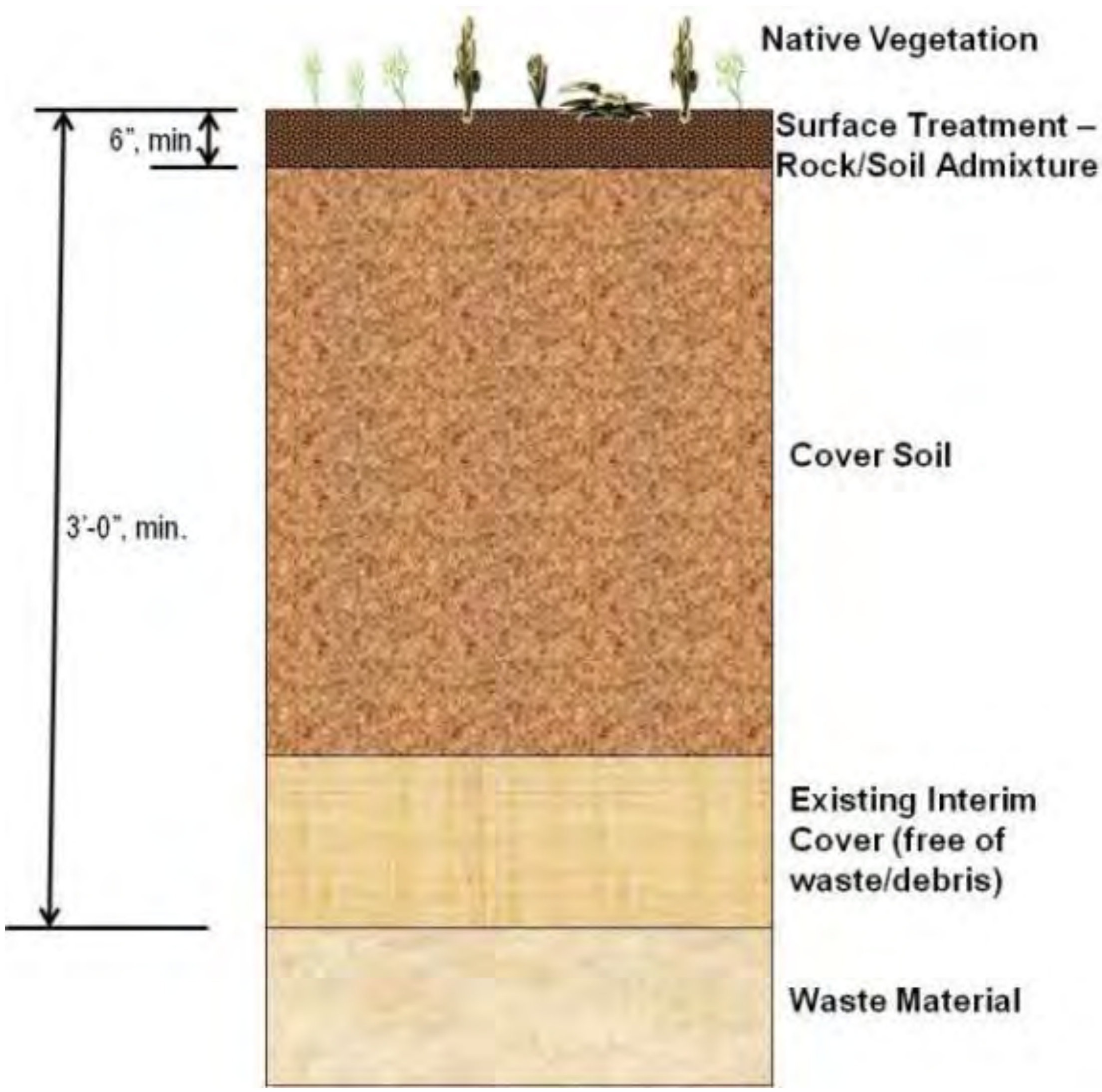

Figure 11. Recommended Cover Profile

The basic recommended cover is an ET Cover. The elements of this cover system are described below:

1. **Vegetation.** Native vegetation should be established on the cover. Plant cover reduces the harmful effects of surface erosion resulting from both runoff and wind. It provides for the removal of infiltrated water through transpiration.

2. **Surface treatment layer.** An admixture composed of soil and rock is designed to resist erosion due to both surface water runoff and wind. The admixture also enhances the vegetation establishment. The soil is to be composed of quality topsoil capable of sustaining native vegetation. This layer should *not be compacted* to allow for better plant establishment and initial growth. A typical mix is 25% rock (nominally ½" to 2" diameter) to 75% topsoil by volume. The mixture should be well mixed prior to final placement. The rock should be a quality durable rock. Refer to Appendix A for a design methodology.

3. **Cover soil.** This layer is composed of quality soil with adequate water storage capacity. The soil should possess adequate levels of plant-essential nutrients to encourage the establishment and productivity of non-woody indigenous plants (primarily grasses and forbs). The amount of slat in the soil should also be limited (Appendix B). Amendments may be required to achieve this. The soil is to serve as a rooting medium and provide for storage of infiltrated water until removed via ET. If there is substantial depth to an interim cover system that contains quality soil and is free of waste and debris, this soil depth can be included in the final cover depth. The interim cover should be well characterized prior to its inclusion in the final cover profile. All soil in the final cover profile should be placed as dry as possible while maintaining dust control and no wetter than the optimum moisture content for the given soil. This will allow for an increased initial soil storage capacity and mitigate the potential for desiccation cracking. Refer to Appendix B for soil quality issues and Appendix C for storage capacity and minimum cover thickness issues.

4. **Subgrade.** The subgrade soil for a final cover system should be heavily compacted to provide a stable foundation for the final cover profile. The upper foot of the subgrade is also recommended to be dry of its optimum moisture content (ASTM D698). This will help maintain the initial storage capacity of the cover system.

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APPENDIX A

EROSION

A.1 SHORT-TERM AND LONG-TERM EROSION

The cover system design should address the potential for short-term erosion (i.e., before a good stand of vegetation is established), and make use of temporary erosion-control measures as necessary. The design should also address long-term erosion after vegetation has been established. Erosion can be damaging not only to the cover system but also to areas into which eroded soil is deposited. Erosion can spread waste and contaminants. Furthermore, it is important that constructed erosion-control measures be properly installed and maintained.

The timing for completion of cover system construction can impact the potential for early vegetation establishment and thus affect the severity of erosion. Ideally the conclusion of cover construction should be scheduled to allow vegetation to become established as soon as practicable and before the end of the growing season, if at all possible. Short-term erosion control materials may be needed to protect the surface layer until vegetation is adequately established. The design specifications should be written to ensure optimization of vegetation establishment based on that site's climate seeding and/or planting of native vegetation.

The construction contractor is often made responsible for maintaining temporary erosion control measures and repairing damage due to erosion during and shortly after construction. However, the general contractor may only have limited expertise in soil erosion control. Furthermore, the contractor may not be privy to design decisions that affect the potential for severe short-term erosion. Thus, caution should be exercised in placing responsibility upon the contractor, who may be ill-equipped to make informed decisions about appropriate erosion control measures. The design engineer should consider the potential for and consequences of short-term erosion and be proactive in specifying appropriate control measures (e.g., silt fences, rolled erosion control materials, sediment traps, hay bales, etc.) in the construction documents.

The Natural Resources Conservation Service (NRCS) (2000) makes the following recommendations to limit short-term erosion during construction:

- cover disturbed soils as soon as possible with vegetation or other materials (e.g. mulch) to reduce erosion potential;
- divert water from disturbed areas;
- control concentrated flow and runoff to reduce the volume and velocity of water and prevent formation of rills and gullies;
- minimize the length and steepness of slopes (e.g., use benches);
- prevent off-site sediment transport;
- inspect and maintain any structural control measures;
- where wind erosion is a concern, plan and install windbreaks;
- avoid soil compaction by restricting the use of trucks and heavy equipment to limited areas after seeding of the cover system; and
- scarify or disc the upper 6-inches (15 cm) of cover soil that may have been compacted during construction activities prior to vegetating or placing sod.

Long-term erosion is an important consideration in the design of the cover's surface layer. In spite of the admittedly approximate nature of predictive equations for erosion control, most cover systems will require an analysis of long-term and, sometimes, short-term erosion. Typical design criteria are as follows:

- The design sheet and rill erosion rate should not be exceeded. Although it is advisable to select allowable rates of soil erosion on a project-specific basis, all covers should be designed so that the sheet erosion rates not exceed 2 tons/acre/year (EPA, 1991). This maximum allowable rate is a result of both wind and runoff erosion rates.
- Using the sheet and rill erosion rate from this calculation, the thickness of cover soil at the end of the design life should be calculated to verify that there is adequate thickness remaining and that sheet and rill erosion has not progressed through the cover soil and into the underlying layers. There should also be sufficient soil thickness to support vegetation and provide for adequate water storage capacity.
- The surface layer should resist gully formation under the tractive forces of runoff from the site-specific design storm(s).
- Wind erosion should also be evaluated.

A.2 EROSION ANALYSIS TOOLS

Some of the more common methods for calculating sheet and rill erosion, gully formation, and wind erosion are briefly described below.

A.2.1 SHEET AND RILL EROSION DUE TO SURFACE RUNOFF

The Natural Resources Conservation Service (NRCS) in 7 CFR Part 610 describes erosion measures suggested for highly erodible soils. Specifically, subpart 610.11 sets forth the equations and rules for utilizing the equations that are used to predict soil erosion due to water and wind. Section 301 of the Federal Agriculture Improvement and Reform Act of 1996 (FAIRA) and the Food Security Act, as amended, 16 U.S.C. 3801-3813 specified that the Secretary would publish the universal soil loss equation (USLE) and wind erosion equation (WEQ) used by the Department within 60 days of the enactment of FAIRA. This subpart sets forth the equations, definition of factors, and provides the rules under which NRCS will utilize the USLE, the revised universal soil loss equation (RUSLE), and the WEQ.

A.2.1.1 REVISED UNIVERSAL SOIL LOSS EQUATION (RUSLE)

RUSLE represents a revision of the USLE technology in how the factor values in the equation are determined. RUSLE is explained in the U.S. Department of Agriculture Handbook 703, ‗Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE).'' The RUSLE is expressed as:

$$A_S = R_e \times K \times LS \times C \times P_c \qquad \text{Equation A.1}$$

Where:

A_S = average annual soil loss by sheet and rill erosion in tons per acre caused by sheet and rill erosion;

R_e = rainfall energy/erosivity factor (dimensionless) and is a measure of rainfall energy and intensity rather than just rainfall amount;

K = soil erodibility factor (dimensionless), is a measure of the relative resistance of a soil to detachment and transport by water, and varies based on seasonal temperature and rainfall (adjusts it bi-monthly for the effects of freezing and thawing, and soil moisture);

LS = slope length and steepness factor (dimensionless). It accounts for the effect of length and steepness of slope on erosion based on the relationship of rill to interrill erosion;

C = vegetative cover and management factor (dimensionless) and is the ratio of soil loss from land cropped under the specified conditions to the corresponding loss from clean-tilled, continuous fallow. Estimates the soil loss ratio at one-half month intervals throughout the year, accounting for the individual effects of prior land use, crop canopy, surface cover, surface roughness, and soil moisture.; and

P_C = conservation support practice factor (dimensionless) and is the ratio of soil loss with a specific support practice (such as cross-slope farming, strip cropping, buffer strips, and terraces) to the corresponding soil loss with uphill and downhill tillage.

Input values for RUSLE are developed using site-specific information and the database that is part of the RUSLE computer program. A free Windows based version of RUSLE, Version 2 can be downloaded from **http://www.ars.usda.gov/Research/docs.htm?docid=6010**. Using A_s computed from Equation A.1, the thickness of cover soil at the end of the cover system design life can be calculated to verify that there is sufficient cover soil remaining.

A.2.1.2 WATER EROSION PREDICTION PROJECT (WEPP) MODEL

The WEPP erosion model computes soil loss along a slope and sediment yield at the end of a hillslope (USDA 1995). Interrill and rill erosion processes are considered. Interrill erosion is described as a process of soil detachment by raindrop impact, transport by shallow sheet flow, and sediment delivery to rill channels. Sediment delivery rate to rill flow areas is assumed to be proportional to the product of rainfall intensity and interrill runoff rate. Rill erosion is described as a function of the flow's ability to detach sediment, sediment transport capacity, and the existing sediment load in the flow.

The appropriate scales for application are tens of meters for hillslope profiles, and up to hundreds of meters for small watersheds. For scales greater than 100 meters, a watershed representation is necessary to prevent erosion predictions from becoming excessively large.

Overland flow processes are conceptualized as a mixture of broad sheet flow occurring in interrill areas and concentrated flow in rill areas. Broad sheet flow on an idealized surface is assumed for overland flow routing and hydrograph development. Overland flow routing procedures include both an analytical solution to the kinematic wave equations and regression equations derived from the kinematic approximation for a range of slope steepness and lengths, friction factors (surface roughness coefficients), soil textural classes, and rainfall distributions. Because the solution to the kinematic wave equations is restricted to an upper boundary condition of zero depth, the routing process for strip cropping (cascading planes) uses the concept of the equivalent plane. Once the peak runoff rate and the duration of runoff have been determined from the overland flow routing, or by solving the regression equations to approximate the peak runoff and duration, steady-state conditions are assumed at the peak runoff rate for erosion calculations. Runoff duration is calculated so as to maintain conservation of mass for total runoff volume.

The erosion equations are normalized to the discharge of water and flow shear stress at the end of a uniform slope and are then used to calculate sediment detachment, transport, and deposition at all points along the hillslope profile. Net detachment in a rill segment is considered to occur when hydraulic shear stress of flow exceeds the critical shear stress of the soil and when sediment load in the rill is less than sediment transport capacity. Net deposition in a rill segment occurs whenever the existing sediment load in the flow exceeds the sediment transport capacity.

In watershed applications, detachment of soil in a channel is predicted to occur if the channel flow shear stress exceeds a critical value and the sediment load in the flow is below the sediment transport capacity. Deposition is predicted to occur if channel sediment load is above the flow sediment transport capacity. Flow shear stress in channels is computed using regression equations that approximate the spatially-varied flow equations. Channel erosion to a nonerodible layer and subsequent channel widening can also be simulated. Deposition within and sediment discharge from impoundments is modeled using conservation of mass and overflow rate concepts.

The WEPP model was developed in the 1980‘s when an increasing need for improved erosion prediction technology was recognized by the major research and action agencies of the United States Department of Agriculture and Interior, including the Agricultural Research Service (ARS), Natural Resource Conservation Service (NRCS), Forest Service (FS), and Bureau of Land Management (BLM). In 1985, these agencies embarked on a 10-year research and development effort to replace the Revised Universal Soil Loss Equation. Some of the differences between the WEPP model and the RUSLE are as follows:

- The RUSLE equation is based on undisturbed agricultural and rangeland top soil conditions, whereas any kind of soil can be described with WEPP. Thus, WEPP is well suited to describe a landfill cover, which is a disturbed condition.
- The WEPP model is capable of predicting erosion and deposition in more complex situations, such as when berms are involved. WEPP can predict the erosion on a cover as well as the deposition in berm channels in the watershed mode. The WEPP model‘s ability to determine runoff and channel flow can also aid in determining stability issues with berms, such as overtopping. RUSLE can only predict the upland erosion between berms.
- RUSLE can only predict average annual upland erosion. WEPP‘s climate generator includes stochastically generated events. *This is an important point in arid environments where there are very few precipitation events annually, but when they occur, they are often torrential events that have major impacts on the site*. Thus, a landfill in an arid

climate is unlikely to fail in an average year, whereas, it is very likely to fail in a year when a major storm event has occurred. WEPP can predict the impacts from a major storm event, but RUSLE cannot.

The windows based version of the WEPP software is available along with additional information regarding the WEPP model, software, and documentation at: **http://www.ars.usda.gov/Research/docs.htm?docid=6010**.

A.2.2 TRACTIVE FORCE METHOD

The concentration of runoff under many circumstances encourages the formation of rills, which, if unchecked, grow into gullies (Figure A-1). This can be the most severe type of erosion of cover systems soils at landfill and waste remediation sites.

Figure A-1. Gully Formation Measured Over Six-Feet Deep in Albuquerque, NM

The dynamics of gully formation are complex and not completely understood. Gully growth patterns are cyclic, steady, or spasmodic and can result in the formation of continuous or discontinuous channels. Gully advance rates have been obtained by periodic surveys, measurements to steel reference stakes or concrete-filled auger holes, examination of gully changes from small-scale maps, or from aerial photographs. Studies are producing quantitative information and some procedures that combine empirically- and physically-based methods have been advanced. Vanoni (1975) presented six methods used for prediction of gully growth and/or gully head advance. They all follow some type of multiplicative or power law and are replete with empirical constants that are generally site specific. McCuen (1998) updated and further described gully erosion prediction equations with the observation that five factors underlie the relevant variables of the process: land use, watershed size, gully size, soil type, and runoff momentum. Having investigated the relevant factors, however, McCuen found that none of the equations treat all terms. Better methods of evaluating gully formation that are more physically based are needed. Consequently, all covers should be designed to mitigate gully formation.

The potential for gully development in vegetated soil surface layers has been assessed at landfill sites using the tractive force method described by Temple et al. (1987) and DOE (1989) and developed for channel flow. The tractive force method (Temple et al., 1987; DOE, 1989) can be used to calculate the allowable shear stress of a vegetated surface layer as:

$$\tau_a = \tau_{ab} \times C_e^2 \geq 0.9kPa$$ **Equation A.2**

Where:

τ_{ab} = allowable shear stress for the surface layer with bare soil (kPa); and

C_e = void ratio correction factor (dimensionless).

Temple et al. (1987) and DOE (1989) provide graphs for both τ_{ab} and C_e values.

The allowable shear stress ($\tau_1 a$) (Equation A.3) must be equal to or greater than the effective shear stress ($\tau_1 e$) applied to the surface layer by the flowing water:

$$\tau_a \geq \tau_e = \gamma_w \times D \times S(1 - C_F)\left(\frac{n_s}{n}\right)^2$$ **Equation A.3**

Where:

γ_w = unit weight of water (kN/m^3);

D = flow depth (m);

S = slope inclination (dimensionless);

C_F = vegetal cover factor (dimensionless);

n = Manning's roughness coefficient for the considered vegetative cover (dimensionless); and

n_s = Manning's roughness coefficient for the bare soil (dimensionless).

Guidance on the selection of values for the vegetal cover factor and the Manning's coefficients is provided by Temple et al. (1987) and DOE (1989).

The depth of flow can be calculated using the Manning's equation (Equation A.4) (DOE, 1989):

$$D = \left(\frac{q \times n}{S^{0.5}}\right)^{0.6}$$ **Equation A.4**

Where:

q = peak rate of runoff (mP3P/s/m) from the Rational Formula (and incorporating the flow concentration factor);

n = Manning's roughness coefficient for the considered vegetative cover (dimensionless);

S = slope inclination (dimensionless);

A.2.3 WIND EROSION EQUATION (WEQ)

Wind erosion physically removes the lighter, less dense soil constituents such as organic matter, clays, and silts (Figure A-2). Thus it removes the most fertile part of the soil and lowers soil productivity (Lyles, 1975). During the 1930's, a prolonged drought culminated in dust storms and soil destruction of disastrous proportions. The Wind Erosion Equation (WEQ) (Equation A.5) for predicting soil loss due to wind erosion is:

Figure A-2. Wind Erosion in Arid Climate

$$E = f(I\ K\ C\ L\ V)$$ **Equation A.5**

Where:

E = the estimation of average annual soil loss in tons per acre.

f indicates the equation includes functional relationships that are not straight-line mathematical calculations.

I = the soil erodibility index.

K = the ridge roughness factor.

C = the climatic factor. All climatic factor values are expressed as a percentage of the value established at Garden City, Kansas. Garden City, Kansas was the location of early research in the WEQ and established the standard for climatic factors against which the other locations are measured.

L = the unsheltered distance across an erodible field, measured along the prevailing wind erosion direction.

V = the vegetative cover factor.

A.3 ROCK/SOIL ADMIXTURE

The erosion analysis tools described above, as well as similar others, are all best suited for farmlands or uniform watersheds with frequent and average rainfall. They are much less applicable to desert or dry climates where infrequent storms are the rule. The models are also better suited for finer grained soils like clay and silt and less so for coarser loams. They are best suited for larger areas and less accurate for smaller areas. They all state that they can deal with minor rill development but none can deal with gully formation other than the tractive force method that estimates the potential for gully erosion. *In arid and semi-arid climates, soil loss due to gully erosion can be orders of magnitude greater than sheet flow erosion.* In order to overcome these shortcomings Anderson and Dwyer (Dwyer et al 1999) developed a gravel/soil admixture designed to mitigate soil loss on landfill covers. This design was later modified by Dwyer (et al 2007).

Gravel/soil admixtures provide excellent means to minimize erosion while allowing for vegetation establishment without a significant reduction in evaporation (Waugh et al 1994, Dwyer 2003). Erosion (Ligotke 1994) and water balance studies (Waugh 1994) suggest that moderate amounts of gravel mixed into the cover topsoil will control both water and wind erosion. As wind and water pass over the landfill cover surface, some winnowing of fines from the admixture is expected, creating a vegetated erosion-resistant surface sometimes referred to as a ―desert pavement". Figure A-3 shows the results of wind erosion in northwestern New Mexico on the Navajo Reservation where a prescriptive landfill cover had been installed. The local native soils were generally a coarser loam material, but to comply with prescriptive regulations – a soil was imported that contained a significant amount of fines (silt and clay). This soil was installed to meet the low saturated hydraulic conductivity requirement for a prescriptive barrier layer. Severe winds eroded the newly installed fine cover soils leaving behind some desiccated clay and minimal fines stabilized by sparse vegetation roots. Of the two-feet of soil originally installed as the cover, less than a foot remained after a year.

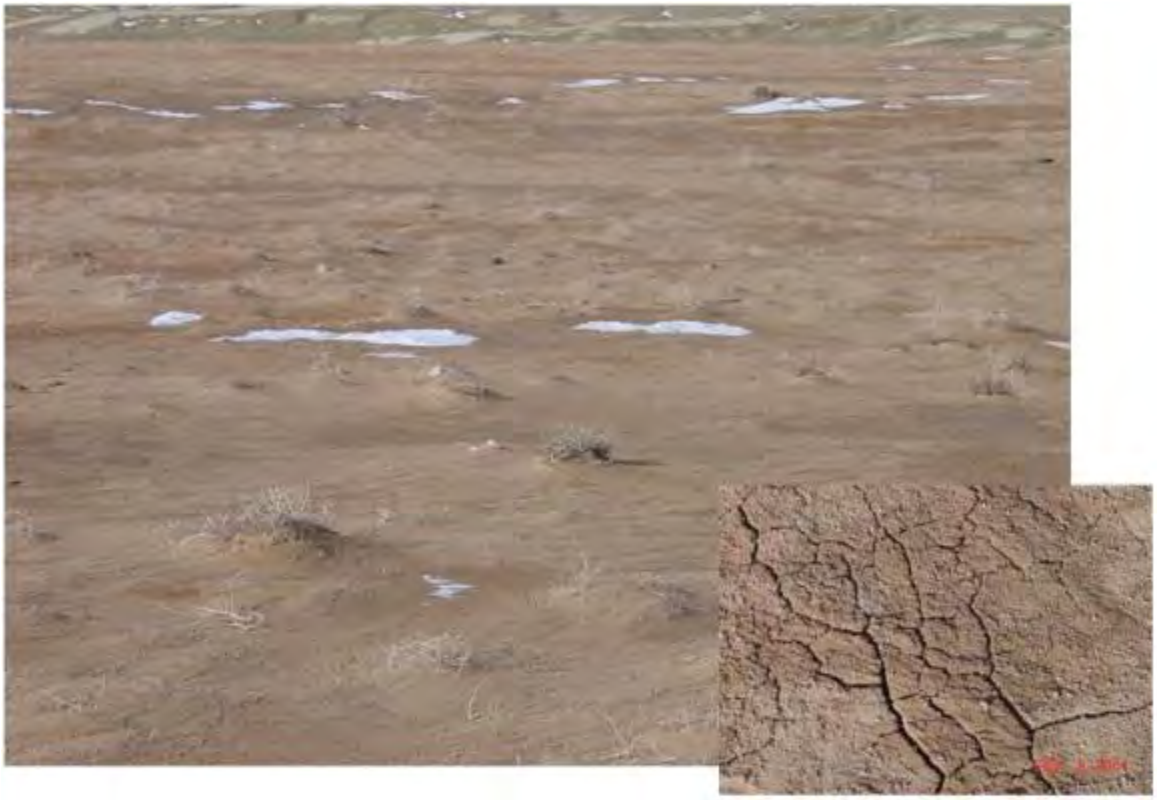

Figure A-3. Landfill Cover Located on the Navajo Reservation that experienced significant Wind Erosion

The design of a gravel admixture layer should be based on the need to protect the soil cover from water and wind erosion. A gravel admixture can effectively protect a cover from long-term wind erosion. The protection from water erosion will depend on the depth, velocity, and duration of water flowing across the landfill cover. These flow values can be established from the physical properties of the cover (slope, convex or concave grading, slope uniformity, and length of flow paths) and the intensity of the precipitation water (precipitation rates, infiltration vs. runoff relationships, snowmelt and off-site flows).

Erosion is greatly affected by rainfall intensity. As the intensity increases, the velocity of subsequent run-off also increases. Thus the erosive energy of the flowing water increases as the square of the velocity. Consequently, the amount of erosion can increase significantly as the rainfall intensity increases. Anderson and Stormont (1997) estimated that a single 6-hr, 100-year storm produces more than ten times the annual average erosion quantity. In response to intense rainfall, erosion does not occur as a uniform lowering of the surface, but by the formation of rills that turn into gullies. When run-off is channeled into the developing gullies, the velocity increases, and thus erosion increases (Figure A-1). *For a cover surface, gully formation is particularly problematic because it can compromise the function of the cover system to isolate the underlying waste.*

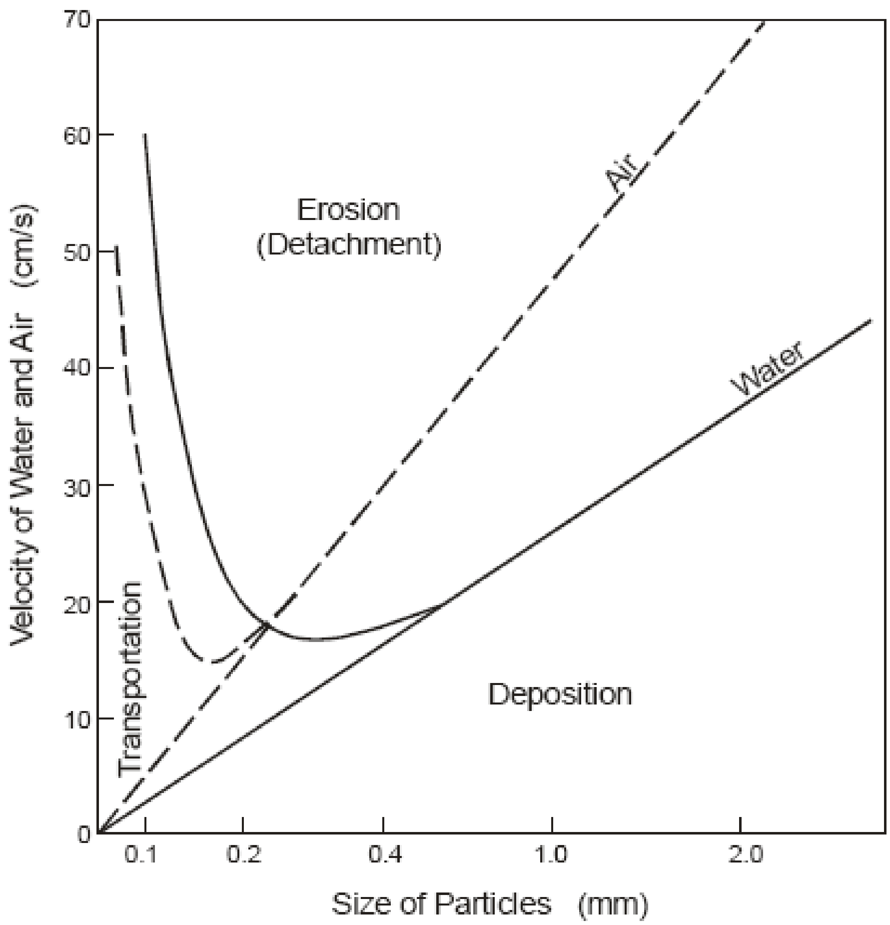

Figure A-4. Relationship Between Erosion Mechanism (Air or Water), Particle Size and Fluid Velocity (Garrels, 1951 as referenced by Mitchell, 1993).

Erodibility of soils increases as particle size decreases (Figure A-4). Clay particles, while small, can possess cohesive strength that resists erosion until they become nearly saturated whereby their cohesion approaches zero. Silts are generally the most erosive soils. Surface soils have been modified by the addition of larger particles, e.g. gravel, to increase their resistance to erosion (Ligotke 1994, Waugh et al 1994, Dwyer et al 1999, Dwyer 2003, Dwyer et al 2007). As the finer portions of the soil are removed by erosive forces, the larger particles remain behind and form an ―armored” surface sometimes referred to as a ―desert pavement”. This surface is much more stable and resistant to surface erosion due to both surface water run-off and wind erosion.

A.3.1 SOIL /GRAVEL ADMIXTURE DESIGN METHODOLOGY

An approach to design a soil/gravel admixture to serve as a surface ―armor” or ―desert pavement” (Figure A-5) was developed that combines analytical and empirical relationships in a step-by-step process (Dwyer et al, 1999, Dwyer et al 2007).

Figure A-5. Gravel recently installed on Superfund closure in Farmington, NM

The following steps are involved in the design methodology:

1. Estimate the design rainfall event;
2. Predict run-off for the given slope characteristics, including slope angle and length;
3. Estimate the channel (gully) geometry in response to estimated run-off;
4. Calculate the particle size that will be displaced by the channel; velocity;
5. Determine the depth of scouring and remaining armored layer.

A.3.1.1 DESIGN RAINFALL EVENT

Use a design rainfall return period that makes sense for the site and the waste encapsulated. A common design event used is a 100-year return period. Local hydrology requirements should be met.

A.3.1.2 RUN-OFF PREDICTION

The ―rational method" is one of the simplest and best-known analysis methods routinely applied in urban hydrology for smaller areas. The rational method (Equation A.6) is based on the assumption that rainfall occurs uniformly over the watershed and at a constant intensity for duration equal to the time of concentration. This method is commonly used for areas under 40 hectares in size.

The peak rate of runoff, (Q) in cfs (runoff is actually in acre-inches/hour but is rounded to equate to cfs), is given by the following expression:

$$Q =- C\,I\,A \qquad \textbf{Equation A.6}$$

Where:

C = Run-off coefficient (dimensionless)

I = Rainfall intensity (in/hr)

A = Surface area that contributes to run-off (acres)

The appropriate value for ‗I' in this case where erosional processes are being evaluated is the peak intensity. The duration of the peak rainfall intensity is often derived from the ―time of concentration," which represents the time for run-off from the most remote portion of the contributory watershed to exit that watershed. This time of duration is dependent on the slope angle and length and the surface described by the value ‗C'. Common values for ‗C' are listed in table A1.

Table A1. Runoff coefficient values (modified from Barfield et al., 1983).

Vegetation and Slope Conditions	Soil Texture		
	Open sandy loam	Clay and silty loam	Tight clay
Woodland			
Flat, 0-5% slope	0.10	0.30	0.40
Rolling, 5-10% slope	0.25	0.35	0.50
Hilly, 10-30% slope	0.30	0.50	0.60
Pasture			
Flat, 0-5% slope	0.10	0.30	0.40
Rolling, 5-10% slope	0.16	0.36	0.55
Hilly, 10-30% slope	0.22	0.42	0.60
Cultivated			
Flat, 0-5% slope	0.30	0.50	0.60
Rolling, 5-10% slope	0.40	0.60	0.70
Hilly, 10-30% slope	0.52	0.72	0.82

The assumed contributory area is found from the following figure A-5.

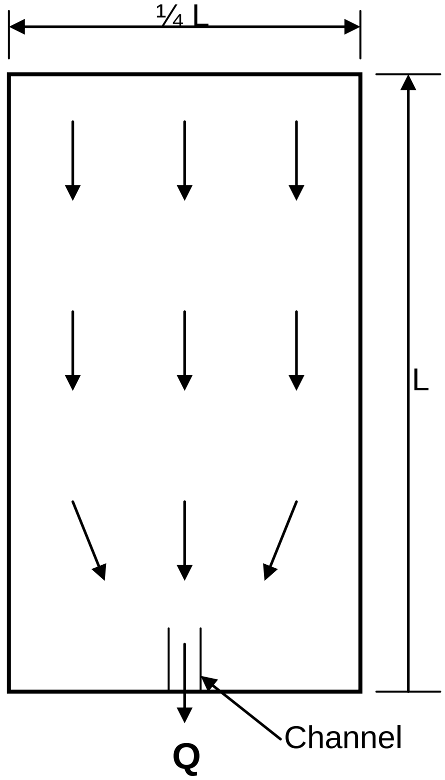

Figure A-5. Contributory Area for Gully Formation

The contributory area on a landfill can generally be assumed to be the slope length multiplied by the width that contributes to the formation of gullies, that is, the lateral gully spacing. The slope width is assumed to about one quarter that of the slope length based on professional experience and consultation with experts. Consequently, ‗A‘ is equal to ¼L^2.

A.3.1.3 CHANNEL GEOMETRY

The channel geometry shown in figure A-6 is that assumed for the gully formation.

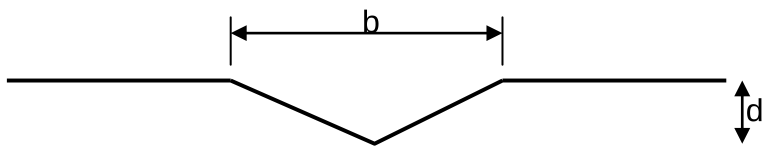

Figure A-6. Channel Geometry

The geometry of the channel that forms is based on regression equations developed from analysis of a large number of channels (Simons, Li & Assoc., 1982). The channel width is given by:

$$b = 37\left({Q_m}^{0.38} / M^{0.39} \right)$$

Equation A.7

Where:

b = width of flow (ft)

Q_m = mean annual flow (cfs)

M = percentage of silts and clays in soils

The mean annual flow (Q_m) is assumed to be between 10 to 20% of the peak rate of run-off (Q) (Dwyer et al, 1999).

For the given discharge point of geometry, the hydraulic depth (d_h) defined as the flow cross-sectional area divided by the width of water surface is half of the gully depth (d).

For flows at the critical slope:

$$b = 0.5 \times F^{0.6} \times F_t^{-0.4} \times Q^{0.4}$$ **Equation A.8**

Where:

F = width to depth ration = b/d_h

F_t = Froude Number ≈ 1.0

These equations can be solved simultaneously to yield the channel width and depth for a given peak flow rate and percentage of silt and clay. With the channel dimensions, the velocity in the channel can be found.

A.3.1.4 INCIPIENT PARTICLE SIZE

The incipient particle size is the particle that is on the brink of movement at the assumed conditions. Any increase in the erosional forces acting on the particle, due to an increase in velocity or slope, for example, will cause its movement. This incipient particle size (D_c) can be calculated using the Shield's Equation:

$$D_c = {}^{\tau}/_{F_s(\gamma_s - \gamma)}$$ **Equation A.9**

Where:

τ = total average shear stress (pcf)

F_s = Shield's dimensionless shear stress = 0.047

γ_s = specific weight of soil (pcf)

γ = water density = 62.4 pcf

The total average shear stress is given by:

$$\tau = \gamma \times d_h \times S$$ **Equation A.10**

Where:

S = slope (ft/ft)

A.3.1.5 DEPTH OF SCOUR AND ARMOURING REQUIRED

The incipient particle size defines the maximum size of particle that will be eroded for a given set of conditions. The material larger than the incipient particle size will not be displaced or eroded and can form an armoring that will protect the channel from further erosion from similar or lesser storm events.

The depth of scour (Ys) (Figure A-7) to establish an armor layer is given by (Pemberton and Lara, 1984):

$$Y_s = Y_a\left[\frac{1}{P_c} - 1\right]$$ **Equation A.11**

Where:

Y_s = scour depth

Y_a = armor layer thickness

P_c = decimal fraction of material coarser than the incipient particle size.

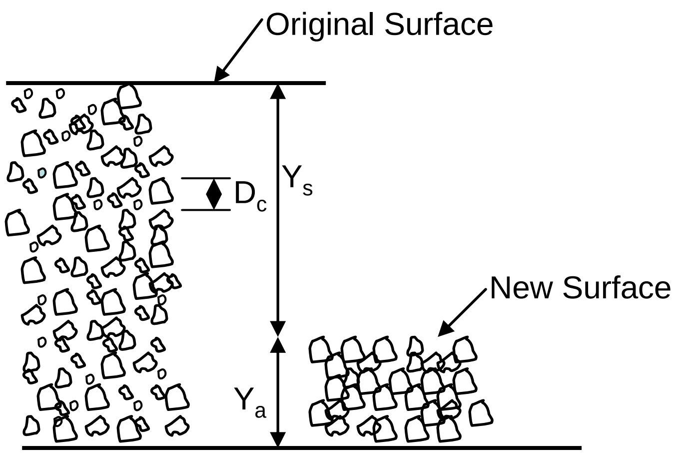

Figure A-7. Armor Layer Development

Other considerations that should be included in the rock/soil admixture design include:

- Rock mixed into the soil/rock admixture on the top slope and side slope should be durable.
- The hydraulic properties of interstitial soil would match the underlying water storage soil layer.

51. The interstitial soil would be live topsoil with favorable fertility, microbiology, propagules, and nominal phytotoxicity.

APPENDIX B

COVER SOIL and VEGETATION RECOMMENDATIONS

B.1 SALT CONTENT IN SOILS

Excessive soil salts can prevent the establishment of vegetation, as well as, precipitate out on the surface creating a surface crust that reduces or prevents the infiltration of water. Saline soils are susceptible to concentrated surface water flow and thus gully erosion. It is understood that a primary goal of a cover system is to limit flux through the cover into the underlying waste. However, infiltration of water into the cover system is required to maintain the integrity of the cover's vegetation. Vegetation is essential to ensure the long term integrity of the cover system by stabilizing the soil and minimizing erosion while removing moisture via transpiration. The lack of vegetation and/or surface crust increases runoff that can lead to increased erosion as seen in figure B-1.

Figure B-1. Excessive Gully Erosion on Shallow Slope

Soluble salts in a cover soil can go into solution following a precipitation event or series of events. As the soil dries, moisture is moved upward by matric potential gradients where the salts in solution precipitate out at or near the ground surface as the water evaporates. These precipitated salts, in conjunction with the existing salts present in the upper soil layer, promote the formation of a brittle surface crust (Figure B-2). Soil water salinity can negatively affect soil physical properties by promoting the binding of fine mineral particles into larger aggregates. This process may promote the formation of surface crusts. Surface crusts are essentially impermeable to water when dry. The reduced permeability promotes higher surface runoff volumes due to decreased water infiltration into the landfill cover soil. In turn, the higher surface runoff volumes increase the erosion of the landfill cover.

Figure B-2. Surface Crack in Brittle Cover Soil

Infiltration in the cover soil is compromised by salt-induced soil dispersion. High salt contents induce dispersion of soil particles and the dispersed particles plug pores within the soil surface by two means. First, dispersed soil particles plug underlying pores in the soil thereby constricting avenues (channels and pores) for water and roots to move through the soil. Secondly, soil structure promoting favorable water infiltration is disrupted because of this dispersion and a cement-like surface layer is formed when the soil dries. The hardened upper layer, or surface crust, further restricts water infiltration and plant establishment on the cover soil.

As described above, excessive salt concentrations of soil in the rooting medium can adversely affect vegetation that in turn increases erosion. Soil dispersion disrupts natural soil structure and hardens the soil and blocks water infiltration. Under these conditions, it is difficult for plants to get established and grow. Saline soils are a problem because high salt concentrations prevent plant roots from effectively utilizing soil water. Plant roots absorb water from the soil through the process of osmosis. Osmosis is the process whereby water is moved from an area of lower salt (higher water) concentration to an area of higher salt (lower water) concentration. The salt concentration inside a normal plant cell (approximately 1.5%) is relatively high compared to normally dilute salt concentrations in soil water. Therefore, under ―normal" soil water salinity levels water will move into root cells from the surrounding soil. However, under high saline soil conditions, the concentration of salts in the soil water can rise above 1.5% and may inhibit the movement of water from the surrounding soil to the plant roots. High salt concentrations in the soil can in fact cause water to move out of plant roots, thereby dehydrating the plant. High salt contents in the soil may also induce nutrient deficiencies in existing plants since plants take up nutrients from the surrounding soil via water intake.

Cover soil can be characterized by the following agronomic characteristic ranges that include: pH, electrical conductivity (EC), sodium absorption ratio (SAR), exchangeable sodium percentage (ESP), calcium carbonate equivalent, cation exchange capacity (CEC), percent organic matter, nitrogen (N), phosphorous (P), and potassium (K).

Electrical conductivity (EC) estimates the amount of total dissolved salts (TDS), or the total amount of dissolved ions in the water. EC is measured in micro Siemens/cm or micromhos per centimeter (1µS/cm = 1 µmho/cm). The Sodium Adsorption Ratio (SAR) is the proportion of sodium (Na) ions compared to the concentration of calcium (Ca) plus magnesium (Mg). An SAR value of 15 or greater indicates an excess of sodium will be adsorbed by the soil clay particles. Excess sodium can cause soil to be hard and cloddy when dry, to crust badly, and to take water very slowly. Cation Exchange Capacity (CEC) is a calculated value that is an estimate of the soils ability to attract, retain, and exchange cation elements. It is reported in millequivalents per 100 grams of soil (meq/100g). The exchangeable sodium percentage (ESP) refers to the concentration of sodium ions on cation exchange (CEC) sites. An ESP of more than 15 percent is considered the threshold value for a soil classified as sodic. This means that sodium occupies more than 15 percent of the soil's CEC. Be aware that sensitive plants may show injury or poor growth at even lower levels of sodium. Table B-1 summarizes the tests that evaluate the salt content in soils with recommended limits for each test.

Table B-1. Soil Requirements to Limit excess Salts

Test	Limits
EC	Less than 8 µS/cm
SAR	Less than 6
ESP	Less than 15% (g/g)
$CaCO_3$	Less than 10% (g/g)

B.1.1 CALCIUM CARBONATE CONTENT IN COVER SOILS

The aforementioned discussion on salt content in soils centered on soluble salts. Less soluble salts such as calcium carbonate ($CaCO_3$) are also harmful to cover soils in excess. Figure B-3 reveals the difference in vegetation establishment on cover soils based on $CaCO_3$ content. *$CaCO_3$ is prevalent in soils in the southwestern United States*.

Soils with Higher than 10% $CaCO_3$ by Weight

Soils with Lower than 10% $CaCO_3$ Content by Weight

Figure B-3. Negative Impact of High Salt Content on Vegetation on a Cover System (Dwyer 2003)

$CaCO_3$ is a salt that can be formed by the reaction of carbon dioxide (an acid-forming oxide), and calcium oxide (a base-forming oxide). Carbon dioxide produced by root (and soil microorganism) respiration, in the presence of water, forms H_2CO_3 (carbonic acid) (Birkland 1974). This formation tends to be most active in the upper soil where biological activity is highest. Calcium cations from weathering of primary minerals, or from windblown dust, or even entering the soil in rainwater, tend to stay dissociated in the upper soil where pH tends to be lower and water tends to be more abundant (Birkland 1974; Jones and Suarez 1985; Monger and Gallegos 2000). As soil solutions pass to greater depth in the soil, increased pH and less abundant water drive the equilibrium toward precipitation of $CaCO_3$ (Birkeland 1974; Harden 1991; Pal et. al. 2000; Monger and Gallegos 2000). As this process continues over time, $CaCO_3$ accumulates in the lower soil. Soil that contains $CaCO_3$ is called calcareous soil. Secondary accumulations of $CaCO_3$ in the subsoil are referred to as calcic horizons. They may exist either as cemented layers, accretions, or concentrated horizons in lower soil profiles. These features are often colloquially but incorrectly termed caliche. Caliche (a geologic feature) forms on or very near the surface of soil in arid and semiarid regions), typically as a result of capillary rise and evaporation of $CaCO_3$-charged ground water.

Calcic soil horizons, by comparison, are a phenomenon of downward leaching. To a certain extent, the depth to calcic soil horizons depends on the amount of rainfall. Typically, as rainfall increases, so too does the depth to a calcic soil horizon. When annual rainfall exceeds 100 centimeters (~39 inches), calcic soil horizons disappear from the soil profile (Blatt et al. 1980).

One of the primary means by which $CaCO_3$ affects plant growth is by inhibiting the ability of plants to absorb nutrients from the soil. $CaCO_3$ affects plant uptake of both macronutrients (e.g., nitrogen and phosphorus) and micronutrients (e.g., zinc and boron).

The macronutrient most affected by the presence of $CaCO_3$ is phosphorus. Phosphorous is absorbed by plants in two forms: $H_2PO_4^-$, and HPO_4^{2-}. Of these, $H_2PO_4^-$ is most readily available to plants, whereas plants do not readily absorb HPO_4^{2-}. In fact, McGeorge (1933) considered the monovalent form the only form of phosphorus that influenced plant growth and nutrition. In order for phosphorus to be absorbed by the root, the solution or film around the root must have a pH of 7.6, which is more difficult to attain in higher pH soil (McGeorge 1933). The abundance of these forms of phosphorous available to plants depends upon the pH of the soil (McGeorge 1933). In low pH (acidic) soil $H_2PO_4^-$ is most abundant, whereas HPO_4^{2-} is most abundant in high pH (alkaline) soil. The presence of $H_2PO_4^-$ is greatly reduced in calcareous soil with pH between 8.0 and 8.5 (McGeorge 1933; Sharma et al. 2001). In addition, phosphorus can react with $CaCO_3$ in soil to form calcium carbonate phosphate (McGeorge 1933; Dominguez 2001), a form unavailable to plants.

The uptake of micronutrients by plants is also affected by the presence of $CaCO_3$. The micronutrients whose absorption by plants is most affected by the presence of $CaCO_3$ are boron, zinc, iron, copper, and manganese (Brady and Weil 1994; Jones and Woltz 1996; Abdal et al. 2000). Reactions with $CaCO_3$, water, and carbon dioxide in soil can transform these micronutrients into forms unavailable for plants (Muramoto et al. 1991; Wang and Tzou 1995; Jones and Woltz 1996). One of the most common micronutrient deficiencies in plants is boron (Brady and Weil 1994). In calcareous soil, boron is fixed or bound by soil colloids (Brady and Weil 1994; Rahmatullah et al. 1998). For example, a study on sunflowers found that, as soil concentrations of $CaCO_3$ increased, the dry weight of sunflower shoots decreased, and correlated with decreasing concentrations of boron in the plant tissue (Rahmatullah et al. 1998).

Concentrated $CaCO_3$ in soil also increases the potential for crusting, thereby reducing water infiltration and inhibiting root penetration (West et al. 1988; Abdal et al. 2000; Dominguez et al. 2001; Sharma et al. 2001). In other words, *physical changes of the soil caused by higher concentrations of* $CaCO_3$ *can cause reductions in plant production.*

In addition to inhibiting plant growth, increasing $CaCO_3$ concentrations in soil have also been linked to decreases in soil microfauna populations (Sharma et al. 2001). The affected microfauna include fungi, bacteria and actinomycetes, and azotobacter (Sharma et al. 2001). Microfauna are critical to the conversion of soil nitrogen into forms available to plants. Mycorrhizal associations (a symbiotic relationship between the root and fungi) can be critical for plants to increase uptake and harvesting of nutrients, especially phosphorus, and water.

The maximum allowable calcium content levels for cover soil in the rooting zone (upper 3-feet [91 cm]) should be less than 10% by weight (Dwyer 2003).

B.2 SOIL NUTRIENT REQUIRMENTS

Just as important to limit the amount of salts in a cover soil is that the soil used have adequate nutrients to allow for a quality stand of native vegetation. Adequate soil nutrients must be available to adequately establish native vegetation on the cover surface. The parameters considered for acceptable nutrients for a given borrow soil are: cation exchange capacity (CEC), percent organic matter, nitrogen (N), phosphorus (P), and potassium (K+). The following soil nutrients values are required in the upper 3-feet (91 cm) of all cover soil installed. Table B-2 summarizes the recommended tests to be performed on soils to determine the appropriate nutrients levels with their recommended acceptable ranges.

Table B-2. Soil Nutrient Requirements for Covers

Test	Limits
CEC	Greater than 15
Percent organic matter	Greater than 2% (g/g)
N	Greater than 6 parts per million (ppm)
P	4 to 7ppm
K	61 to 120 ppm

The disadvantages of a low CEC obviously include the limited availability of mineral nutrients to the plant and the soil's inefficient ability to hold applied nutrients.

Organic matter makes up only a small part of the soil. Even in small amounts, organic matter is very important. Soil organic matter has several parts: The living microbes in the soil (like bacteria and fungi), which break down very rapidly when they die. Partially decayed plant material and microbes, for instance, plant material you mix in or manure. The stable material formed from decomposed plants and microbes. This material is called humus, and is broken down very slowly.

Organic matter affects both chemical and physical properties of the soil:

> Chemical Effects: Organic matter releases many plant nutrients as it is broken down in the soil, including nitrogen (N), phosphorus (P) and sulfur (S). It is also one of two sources of CEC in the soil. (Clay is the other major source.) CEC represents the sites in the soil that can hold positively charged nutrients like calcium (Ca^{++}), magnesium (Mg^{+}) and potassium (K^{+}). If CEC is increased, the soil can hold more nutrients and release them for plant growth. To increase CEC, you have to increase organic matter.

> Physical Effects: Organic matter loosens the soil, which increases the amount of pore space. This has several important effects. The density of the soil goes down (it becomes less compacted) and the soil structure improves. This means that the sand, silt and clay particles in the soil stick together, forming aggregates or crumbs. Because there is more pore space, the soil is able to hold more water and more air. Plants grown on healthy soils won't be as stressed by drought or excess water. Water also flows into the soil from the surface more quickly. With less compaction, it is also easier for plant roots to grow through the soil.

There are many ways to add organic matter to soils. Compost and manure may add larger amounts of organic matter. Compost is very similar in composition to soil organic matter. It breaks down slowly in the soil and is very good at improving the physical condition of the soil. Manure may break down quickly, releasing nutrients for plant growth, but it may take longer to improve the soil using this material. Whatever matter is chosen to amend the soil, it should meet the environmental standards of the site.

B.3 VEGETATION

A major consideration when selecting plants for a site is provided in Executive Order 13148, which promotes the use of native species on revegetated sites. EPA defines native plants as plants that have evolved over thousands of years in a specific region and have adapted to the geography, hydrology, and climate (see http://www.epa.gov/greenacres/). Native plants found in the surrounding natural areas have the best chance of success, require the least maintenance, and are the most cost-effective in the long term. Ideally, revegetation of a site will create natural conditions that encourage re-population by native animal species and are consistent with the surrounding land. Using non-native plants located close to native plant environments could displace the native plants; therefore, it is important to check the invasive nature of the proposed plants (Executive Order 13112). Plant succession must be considered; for example, the original species planted may not survive but may attract local wildlife to the area that will disperse the seed and aid in the overall revegetation of the site.

A key element in the stability and performance of an ET cover system is vegetation. Native grasses are desired on landfill and open dump covers because they stabilize the surface soil and reduce erosion, transpire stored soil-water, and have relatively shallow thin roots that generally do not result in preferential flow paths (EPA 1991).

Landfill cover vegetation goals (Waugh et al. 2002):

- are well adapted to the engineered soil habitat,
- are capable of high transpiration rates,
- limit soil erosion, and
- are structurally and functionally resilient.

Diverse mixtures of native and naturalized plants will maximize water removal and remain more resilient given variable and unpredictable changes in the environment resulting from pathogen and pest outbreaks, disturbances (overgrazing, fire, etc.), and climatic fluctuations. Local indigenous ecotypes that have been selected over thousands of years are usually best adapted. In contrast, the exotic grass plantings common on engineered covers are genetically and structurally rigid, are more vulnerable to disturbance or eradication by single factors, and will require continual maintenance (Mattson et al. 2004).

Selection of plant species is an important consideration in the design of a vegetated surface layer. The vegetation serves several functions (Mattson et al. 2004):

- Plant leaves intercept some of the rain before it impacts the surface layer, thereby reducing the energy of the water and the potential for erosion.
- Plant vegetation also helps dissipate wind energy.
- The shallow root system of plants enhances the surface layer resistance to water and wind erosion.
- Plants promote ET of water, which increases the available water storage capacity of the cover soils and decreases drainage from these soils.
- A well-vegetated surface layer is generally considered more natural and esthetically pleasing than an unvegetated surface layer.

In selecting the appropriate vegetation for a site, the following general recommendations are offered:

- Locally-adapted, low-growing grasses and shrubs that are herbaceous or woody perennials should be selected.
- The plants should survive drought and temperature extremes.
- The plants should contain roots that will penetrate deep enough to remove moisture from beneath the surface but not so deep as to disrupt the drainage layer, hydraulic barrier, or gas collection layer.
- The plants should be capable of thriving with minimal addition of nutrients.
- The plant population should be sufficiently diverse to provide erosion protection under a variety of conditions.
- The plants should not be an attractant to burrowing wildlife.
- The vegetative cover should be capable of surviving and functioning with little or no maintenance (e.g., without irrigation other than for initial plant establishment, fertilization, and mowing).

APPENDIX C

ANALYSIS TO DETERMINE MINIMUM ET COVER THICKNESS

Determine the minimum required depth of cover soil for an ET Cover required to minimize flux. For a site that meets the criteria outlined in Section 1.0 that utilizes the recommended cover profile described in Section 4.0. this step is assumed to be unnecessary. That is, the cover soil has an adequate quantify of fines (greater than 20% pass the number 200 sieve) and thus has adequate storage capacity for the relatively dry environment and low risk site. The following steps may be performed if this is not the case.

a. Identify the design infiltration event(s). This can be dependent on design life. Utilizing average climatic conditions is often used. Other possibilities include the simulation of extreme or stress conditions such as wet years or extreme precipitation events.

b. A first-order estimate of required cover thickness can be determined from estimates of the water-holding or storage capacity of the soil and the amount of infiltrated water that has to be stored. The design strategy for an ET cover system is to ensure the storage capacity is sufficient to store the ―worst-case" infiltration quantity resulting from the design precipitation event until it can be removed via ET. The maximum water content a soil can hold after all drainage downward resulting from gravitational forces is referred to as its field capacity. Field capacity is often arbitrarily reported as the water content at about 330 cm of matric potential head (Jury et al. 1991). Below field capacity, the hydraulic conductivity is often assumed to be so low that gravity drainage becomes negligible and the soil moisture is held in place by suction or matric potential. The storage capacity of a soil layer is thus calculated by multiplying its field capacity by the soil layer thickness. This assumes a consistent field capacity. However, not all of this stored water can be removed via transpiration (by plants). Vegetation is generally assumed to reduce the soil moisture content to the permanent wilting point, which is typically defined as the water content at 15,000 cm of matric potential head (Cassel and Nielsen 1986). Evaporation from the soil surface can further reduce the soil moisture below the wilting point to the residual saturation, which is the water content ranging from below 15,000 cm to an infinite matric potential. If water is only removed by plants, Stormont and Morris (1998) reported that the net storage capacity, also referred to as the available water-holding capacity, of a soil layer can be approximated by:

$$NSC = (FC - PWP)\, b \qquad \textbf{Equation C.1}$$

where:

NSC = net storage capacity

FC = field capacity

PWP = permanent wilting point

b = soil layer thickness

For example, the water content at field capacity from a representative soil sample is estimated to be 16% while the permanent wilting point is assumed to be about 6%. Thus the net storage capacity for this soil is about 10% of its thickness.

It is important to note that the use of field capacity and permanent wilting point here is arbitrary and ignores other factors that affect the amount of moisture retained in a soil layer (e.g., Jury et al. 1991, Cassel and Nielsen 1986). Nevertheless, these are simple and commonly used concepts and are applicable for approximating the water storage capacity of a soil layer.

c. Model the cover system given desired vegetation characteristics and determined climatic conditions. Model the cover profile for a deeper than desired depth. If a unit gradient bottom boundary condition is used, place it below any significant transient soil-moisture activity. Determine the minimum depth required based on the Dwyer Pont of Diminishing Returns Method (Dwyer et al. 2007).

   A more detailed method to determine the minimum cover soil depth required to minimize flux utilizes an accepted unsaturated flow software package based on the Richards' Equation (ITRC 2003). The Dwyer Point of Diminishing Returns Method (Dwyer et al. 2007) should be utilized. This method simply determines the cover depth at which flux has been minimized. That is, the cover soil depth where an additional increment of soil will no longer decrease flux (Figure C-1) is determined to be the point of diminishing return for soil depth. A cover profile should be modeled with the expected cover and waste layers included. The monolithic soil-water storage from the ET cover should be modeled at a depth greater than the minimum expected depth. If a capillary barrier is introduced into the cover profile resulting from the addition of a bio-barrier or other underlying coarse soil layer, multiple model runs will be required to determine the minimum cover soil required for storage capacity to minimize flux. The effect of the capillary barrier on the storage capacity of the cover profile may be ignored resulting in an added factor of safety (FS) in the cover's water storage capacity. The model output of predicted percolation at various points within the cover profile is then plotted against the cover depth. Generally, in arid and semiarid climates, the point of diminishing returns is when the estimated flux approaches zero or actually produces a negative flux (upward movement of moisture). The cover soil depth that produces the minimum flux or ―point of diminishing returns" is the minimum depth required for water storage capacity ***only***.

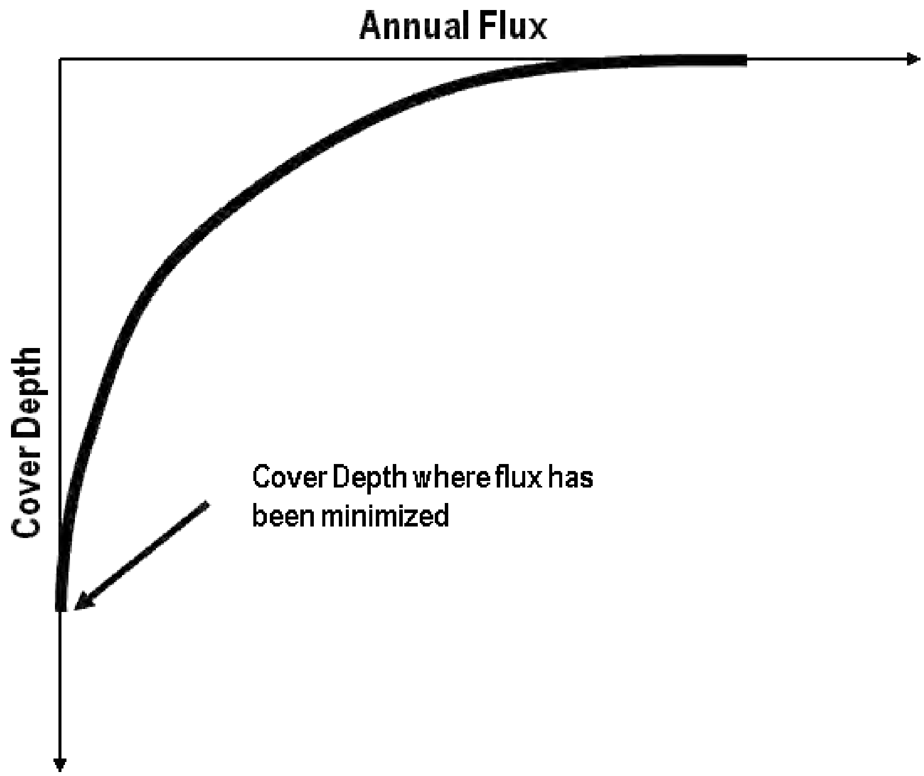

Figure C-1. Cover depth vs. annual percolation

Perform sensitivity modeling of the cover profile as required during the final design process. Examples of model sensitivities include variances in soil properties, optional layer additions, and climatic and vegetation variations. These sensitivity analyses may increase the thickness of the cover soil layer or help determine the best choice(s) for optional layers such as bio-barriers and drainage layers.

APPENDIX D

QUALITY ASSURANCE

D.1 CONSTRUCTION QUALITY ASSURANCE

Quality Assurance (QA) is a planned system of activities that provides the owner / operator and permitting agency confidence that the facility was constructed as specified in the design. QA is generally the responsibility of the owner and often designated to the design engineer(s) or other designated party. Quality control (QC) is a planned system of inspections used to directly monitor and control the quality of the construction process and materials used. QC is generally the responsibility of the contractor building the facility. Recommendations and considerations to be included in a QA Plan and in the QA process are included below. It is understood that the size and complexity of the project will dictate the extent of the QA process.

D.1.1 QA PLAN

A written QA Plan should precede any field construction activities. This plan should consider standards recommended in the EPA Technical Guidance Document ―Quality Assurance and Quality Control for Waste Containment Facilities" (EPA, 1994).

A copy of the site-specific plans and specifications, QA plan, and QA documentation reports should be retained at the facility by the QA engineer. The plans, specifications, and QA documents can be the chief means for the facility owner/operator to demonstrate to the regulatory agency that QA objectives for a project have been met.

The QA plan should include a detailed description of all QA activities to be used during materials inspection and construction to manage the installed quality of the covers and associated facilities. The QA plan should be tailored to each specific project with all important guidelines and standards integrated into the project plans and specifications.

D.1.2 PERSONNEL QUALIFICATIONS

An important factor in assessing the quality of a cover system installation is the degree to which key personnel involved in the process are qualified to perform the required tasks. QA personnel must be familiar with:

1. the project's design including plans and specifications;
2. project layout;
3. materials to be used;
4. drainage control features;
5. soil borrow materials;
6. construction procedures, complications, schedule, and equipment;
7. material placement techniques and requirements;
8. equipment to be used and its capabilities; and
9. site specific complications/concerns.

Key individuals involved in the QA process during the construction of cover systems and their minimum recommended qualifications are listed in Table D.1.

Table D.1. Minimum Personnel Qualifications (EPA, 1994)

Individual	**Minimum Qualifications**
Design Engineer(s)	Registered Professional Engineer with adequate job-specific experience.
QA Personnel/Inspector(s) - Designated Representative(s)	The individual(s) designated by the appropriate authority with knowledge of the project, and its plans, specifications, and QA documents. Employed separately from the contractor(s) building the facility.
QA Engineer –Designated Representative	The individual in charge of the daily QA process. Employed separately from the contractor(s) building the facility. Adequate experience and technical knowledge of cover system design and construction process and requirements.
QA Certifying Engineer. Representative or Designated Individual(s)	Individual with intimate knowledge of the project, and its plans, specifications, and QA documents. Employed separately from the contractor(s) building the facility.
QC Personnel	Employed by the general contractor, installation contractor, or earthwork contractor involved in the waste containment facilities; appropriately trained.
QC Officer	The individual specifically designated by the general contractor, manufacturer or fabricator in charge of quality control activities.

D.1.3 DOCUMENTATION

In addition to insuring the correct installation of the cover system, another major intent of the QA process is to provide documentation of the construction process.

D.1.3.1 DAILY INSPECTION REPORTS

Daily reporting and documentation procedures should be required. The QA engineer should prepare daily written inspection reports that are to be included in the final QA documentation. The daily reports should include information about the work accomplished, tests performed and observations made, along with descriptions of the adequacy of the work completed.

D.1.3.2 DAILY SUMMARY REPORTS

A daily written summary is to be prepared by the QA engineer. These reports provide a chronological framework for identifying and recording all other reports and aids in tracking what activities/tasks were completed and by whom. At a minimum, the daily summary reports should include the following:

- Date, project name, location, waste containment unit under construction, personnel involved in major activities, and other relevant identification information.
- Description of weather conditions, including temperature, cloud cover, and precipitation.
- Summaries of any meetings held and actions recommended or taken.
- Specific work units and locations of construction under way during that particular day.
- Equipment and personnel being utilized in each work task, including subcontractors.
- Identification of areas or units of work being inspected.
- Unique identifying sheet number of geomembranes for cross-referencing and document control.
- Description of off-site materials received, including any quality control data provided by the supplier.
- Calibrations or recalibrations of test equipment, including actions taken as a result of recalibration.
- Decisions made regarding approval (or disapproval) of units of material or of work and/or corrective actions to be taken in instances of substandard or suspect quality.
- Inspection data sheets and/or problem reporting and corrective measures used to substantiate any QA decisions described in the previous item.
- Signature of the QA engineer.
- Any other pertinent information.

D.1.3.3 INSPECTION AND TESTING REPORTS

All observations, results of field tests, and results of laboratory tests performed on- or off-site should be recorded on a data sheet. Recorded observations and test results can take the form of notes, charts, sketches, or photographs, or a combination of these.

At a minimum, the inspection data sheets should include the following information:

- Description or title of the inspection activity.
- Location of the inspection activity or location from which the sample was taken.
- Type of inspection activity and procedure used (reference to standard method when appropriate or specific method described in QA plan).
- Unique identifying geomembrane sheet number for cross-referencing and document control.
- Recorded observation or test data.
- Results of the inspection activity (pass/fail); comparison with specification requirements.
- In addition to the individual preparing the data sheet, identification of all personnel involved in the inspection.
- Signature of the QA inspector and review signature by the QA engineer.

D.1.3.4 PROBLEM IDENTIFICATION AND CORRECTIVE MEASURES REPORTS

A problem is defined as material or workmanship that does not meet the requirements of the plans, specifications, or QA plan for a project or any obvious defect in material or workmanship (even if there is conformance with plans, specifications, and the QA plan). At a minimum, problem identification and corrective measures reports contain the following information:

- Location of the problem.
- Description of the problem (in sufficient detail and with supporting sketches or photographic information where appropriate) to adequately describe the problem.
- Unique identifying geomembrane sheet number for cross-referencing and document control.
- Probable cause for the problem.
- How and when the problem was identified (reference to inspection data sheet or daily summary report by inspector).
- Where relevant, estimation of how long the problem existed.
- Any disagreement noted by the inspector between him/her-self and contractor about whether or not a problem existed or the cause of the problem.
- Suggested corrective measure(s).

- Documentation of correction, if corrective action was taken and completed prior to finalization of the problem, and completed corrective measures report (reference to inspection data sheet, where applicable).
- Where applicable, outline of suggested methods to prevent similar problems in the future.
- Signature of the QA inspector and review signature of QA engineer.

D.1.3.5 DRAWINGS OF RECORD

Drawings of record (better known as ―as-built" drawings) should be prepared to document the actual lines, grades, and conditions of each component of the covers/facilities. For the cover soil components, the record drawings should include survey data that identifies lower and upper elevations of a particular component (layer), the plan dimensions of the component, and locations of all destructive and nondestructive test sampling sites.

D.1.3.6 FINAL DOCUMENTATION AND CERTIFICATION

Upon completion of the project, the QA engineer should prepare a final documentation and certification report. This report is to include all daily inspection reports, the daily QA engineer's summary reports, inspection data sheets, problem identification and corrective measures reports, other documentation (such as quality control data provided by manufacturers or fabricators, laboratory test results, photographs, as-built drawings, internal QA memoranda or reports with data interpretation or analyses), and design changes made by the design engineer during construction. The document should be certified to be correct by the QA certifying engineer.

D.1.3.7 DOCUMENT CONTROL

The QA documents should be maintained under a document control procedure. Any modifications to the documents should be reported to and agreed upon by all parties involved. An indexing procedure should be developed for conveniently replacing pages in the QA plan when modifications became necessary; the replacement pages detail the revision status.

D.1.3.8 STORAGE OF RECORDS

During construction, the QA engineer should be responsible for all QA documents including copies of the design criteria, specifications, plan revisions, and originals of all data sheets and reports. Duplicate records should be kept at a separate location to prevent the loss of this valuable information if the originals were inadvertently destroyed.

D.1.4 MEETINGS

Pre-designated meetings included a pre-bid meeting held prior to bidding of the contract. Also, a pre-construction meeting that can be held in conjunction with a resolution meeting after the contract has been awarded, but prior to the start of construction activities.

D.1.4.1 PRE-BID MEETING

The intent of this meeting is to discuss the QA plan and to resolve differences of opinion among the various concerned parties before the project was let for bidding. Holding the pre-bid meeting before formal construction bids are prepared can allow the companies bidding on the construction to better understand the level of QA required on the project. Also, if the bidders identify problems with the QA plan, they can be corrected early on in the process.

D.1.4.2 RESOLUTION MEETING

The objectives of the resolution meeting are to establish lines of communication, review construction plans and specifications, emphasize the critical aspects of the project needed to achieve proper quality, begin planning and coordination of tasks, and identify potential factors that might cause difficulties or delays in construction. The meeting should be attended by appropriate personnel including the project‘s design engineer, representatives of the general contractor and major subcontractors, the QA engineer, and the QA certifying engineer.

The resolution meeting can cover the following activities:

- An individual should be assigned to take minutes.
- Individuals can be introduced to one another along with their project responsibilities (or potential responsibilities) can be identified.
- Copies of the project plans and specifications should be made available for group discussion.
- The QA plan can be distributed.
- Copies of any special permit restrictions that are relevant to construction or QA should be distributed.
- The plans and specifications should be described, along with unique design features (so the contractors would understand the rationale behind the general design), potential construction problems, and allow for questions from any of the parties concerning the construction.
- The QA plan should be reviewed and discussed, with the QA engineer and QA certifying engineer outlining their expectations and identifying the most critical components of their project participation.
- Procedures for Manufacturing Quality Control (MQC) and Construction Quality Control (CQC) proposed by installers and contractors should be reviewed and discussed.
- Corrective actions to resolve potential construction problems should be discussed.
- Procedures for documentation and distribution of documents should be discussed.
- Each organization‘s responsibility, authority, and lines of communication should be discussed.
- Suggested modifications to the QA plan that would improve quality management on the project should be solicited.

- Climatic variables (e.g., precipitation, wind, temperature) that might affect the construction schedule should be discussed.

Familiarizing all project participants with inspection and testing procedures and the criteria for pass/fail decisions (including the resolution of test data outliers) is a key objective of this meeting. Additionally, it is imperative that all parties understand the key problems QA personnel have identified and that each party fully understands their roles and responsibilities and the procedures regarding problem resolution.

D.1.4.3 PRE-CONSTRUCTION MEETING

The pre-construction meeting can be held in conjunction with the resolution meeting if desired. The meetings should be scheduled after the general construction contracts have been awarded and the major subcontractors and material suppliers have been established. The purpose of the pre-construction meeting is to review the details of the QA plan, to ensure that the responsibility and authority of each individual is clearly understood, to reach agreement on the established procedures to resolve construction problems, and to establish a foundation of cooperation in quality management. The pre-construction meeting should be attended by the design engineer, representatives of the general contractor and major subcontractors, the QA engineer, and the QA certifying engineer.

The pre-construction meeting should include the following activities:

- Assignment of an individual to take meeting minutes.
- Introduce parties and identify their responsibilities and authority.
- Distribute the QA plan, identify any revisions made after the resolution meeting, and answer any questions about the QA plan, procedures, or related documentation.
- Discuss lines of project communication.
- Discuss reporting procedures, distribution of documents, the schedule for routine project meetings, and resolution of construction problems.
- Review site requirements and logistics, including safety procedures.
- Review the project design, discuss the most critical construction aspects, and discuss scheduling and sequencing issues.
- Discuss MQC procedures to be employed by the fabricators contracted to the general contractor.
- Discuss CQC procedures to be employed by the installer or contractor.
- Compile a list of action items requiring resolution and assign responsibilities for these items.

D.1.4.4 PROGRESS MEETINGS

Weekly progress meetings should be held at the job site. At times, additional progress meetings can be called at the discretion of the Construction Quality Assurance engineer. Meeting attendees should be those involved in the specific issues being discussed. These meetings should be helpful in maintaining lines of communication, resolving problems soon after they are developed, identifying action items, and improving overall quality management. The QA engineer or his/her designated representative should be present at all meetings.

D.1.5 SAMPLE CUSTODY

All samples should be identified and described in the QA plan. Whenever a sample is taken, a chain of custody record should be made for that sample. If the sample is transferred to another individual or laboratory, records of the transfer should be established so that chain of custody can be traced. The purpose for the records of sample custody is to assist in tracing the cause of anomalous test results or other testing problems, and to minimize the potential for accidental sample loss.

D.1.6 WEATHER

Weather can play a significant factor on construction activities and material placement during cover installation. The contractor or installer is responsible for complying with the contract plans and specifications (along with the MQC/CQC plans for the various components of the cover system). Specifications should include restrictions on weather conditions for certain construction activities such as soil placement where dry soil placement is critical. The contractor or installer is responsible for insuring that these weather restrictions are observed during construction.

D.1.7 WORK STOPPAGES

Unexpected work stoppages can result from a variety of causes. The QA engineer should be careful during any work stoppages to determine: (1) whether in-place materials were covered and protected from damage, (2) whether partially covered materials were adequately protected, and (3) whether manufactured materials were properly stored and properly or adequately protected from the elements. In essence, the cessation of construction during work stoppages does not mean that QA inspection and documentation temporarily ceases.

EPA Region 9 Waste Management Division contact information:
Office Manager
U.S. Environmental Protection Agency
Office of Pollution Prevention and Solid Waste
75 Hawthorne Street
Mail Code WST-7
San Francisco, CA 94105

Email: **baker.michelle@epa.gov**

Webpage: **http://www.epa.gov/region9/waste/tribal/index.html**

EPA Region 9, Waste Management Division Office Receptionist
415-947-8708