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Cover System Design Guidance and Requirements Document

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EXECUTIVE SUMMARY

The Cover System Design Guidance and Requirements Document outlines the earthen cover system to be deployed as a final closure remedy for selected sites within LANL, operated by LANS, LLC. These closures shall adhere to the Compliance Order on Consent (the Consent Order) signed by the New Mexico Environment Department (NMED), the U.S. Department of Energy (DOE), and the University of California on behalf of LANL. In addition, these closures will be subject to regulation for any units containing hazardous waste under the Resource Conservation and Recovery Act (RCRA) and radioactive waste management units regulated by DOE under the Atomic Energy Act (AEA). An overview of the regulatory compliance requirements is provided in section 1.

The typical LANL cover will be a monolithic soil cover referred to as an Evapotranspiration (ET) Cover described in section 2. This cover is designed to store infiltrated water until it is removed by the combination of plant transpiration and surface evaporation (collectively referred to as ET). The cover system will use locally available soils and native vegetation to create a long-lasting cover that has a performance and design life commensurate with the projected hazardous life of the contained wastes. The design steps are summarized in section 3.

This guidance describes the design considerations, requirements, and options to be incorporated into the cover system. Vegetation establishment, biointrusion considerations and design options, gas issues, soil pedology, and geomorphology requirements are described in section 4. Additionally, engineering requirements and considerations are included (e.g., cover soils to be used, erosion, surface water management controls, slope stability, and settlement concerns) and described in detail in section 5.

Acceptable modeling techniques and software are summarized in section 6. Specifically, only Richards Equation-based unsaturated flow models are acceptable to estimate the water balance in an ET cover system. Determination of RCRA-equivalence compliance is described using relevant field data and modeling techniques in section 7.

The inherent risk of the sites as well as certain performance objectives that must be adhered to will generally dictate much of the cover systems design. These performance goals are provided in section 8. Flux through a cover must be less than or equal to that determined to reduce the risk of contaminant transport to an acceptable level as determined by subsurface fate and transport (F&T) modeling. Per current regulations and standards, erosion is to be minimized and in no circumstance to exceed 2 tons/acre/year. Radioactive dose limits, including radon gas emissions, as described in governing DOE Orders shall apply where applicable. To ensure compliance, sites may include performance monitoring for such processes as erosion, flux, and gas emissions. The preferred monitoring systems are described in section 8.

Quality assurance (QA) requirements are discussed for design and construction of these cover systems in section 9. All covers shall comply with LANL QA policies as outlined in The Quality Assurance Plan (QAP) for Environmental Remediation and Support Services (ERSS) (LA-UR-06-4108). This document ensures compliance with requirements outlined from DOE, the Consent Order, and LANL management.

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Acronyms

ACAP	Alternative Cover Assessment Program
ACZ	Acceptable Compaction Zone
AEA	Atomic Energy Act
ALARA	As Low As Reasonably Achievable
ALCD	Alternative Landfill Cover Demonstration
ANSI	American National Standards Institute
AOC	area of concern
ARAR	applicable or relevant and appropriate requirement
ARS	Agricultural Research Service
ASME	American Society of Mechanical Engineers
ASQ	American Society of Quality
ASTM	American Society for Testing and Materials

Bq	becquerel
Ca	calcium
$CaCO_3$	calcium carbonate
CEC	cation exchange capacity
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFA	Central Facilities Area
CFR	Code of Federal Regulations
cfs	cubic feet per second
CME	corrective measures evaluation
CMI	Corrective Measures Implementation
the Consent Order	Compliance Order on Consent
CQA	construction quality assurance
Cs	cesium
CSI	Campbell Scientific, Inc.
DOE	U.S. Department of Energy
EBTF	Engineered Barrier Test Facility
EC	electrical conductivity
EPA	U.S. Environmental Protection Agency
EPD	Environmental Programs Directorate
ERS	Environmental Remediation and Surveillance
ERSS	Environmental Remediation and Support Services
ESP	exchangeable sodium percentage
ET	evapotranspiration
FAIRA	Federal Agriculture Improvement and Reform Act of 1996
FDR	frequency domain reflectometry
FLTF	Field Lysimeter Test Facility
FS	factor of safety
F&T	fate and transport

GCL	Geosynthetic Clay Liner
GM	geomembrane
GPS	global positioning system
ha	hectare
HELP	Hydrologic Evaluation of Landfill Performance
HI	hazard index
IBC	International Building Code
INEEL	Idaho National Engineering and Environmental Laboratory
K	potassium
LAI	leaf area index
LANL or the Laboratory	Los Alamos National Laboratory
LANS	Los Alamos National Security
LLW	low-level waste
MDA	material disposal area
MDD	maximum dry density
Mg	magnesium
mrem	millirem
mSv	millisievert
Na	sodium
NMED	New Mexico Environment Department
NRC	Nuclear Regulatory Commission
NRCS	Natural Resources Conservation Service
NRF	Naval Reactor Facility
OII	Operating Industries, Inc.
P	phosphorus
PCBE	Protective Cap/Biobarrier Experiment
pcf	pounds per cubic foot
pCi	picocuries

PET	potential evapotranspiration
PLS	Pure Live Seed
PMF	probable maximum flood
PMP	probable maximum precipitation
the Program	Environmental Remediation and Surveillance Program
QA	quality assurance
QAP	Quality Assurance Plan
QC	quality control
Ra	radium
RCRA	Resource Conservation and Recovery Act
RLD	root length density
RMA	Rocky Mountain Arsenal
Rn	radon
RUSLE	revised universal soil loss equation
S	sulfur
SAR	sodium absorption ratio
SCS	Soil Conservation Service
Sr	strontium
SRS	Savannah River Site
SWMU	solid waste management unit
TA	Technical Area
TDR	time domain reflectometry
TRU	transuranic
U	uranium
UMTRA	Uranium Mill Tailings Remedial Action
USDA	U.S. Department of Agriculture
USLE	universal soil loss equation
VOC	volatile organic chemical

WEPP	Water Erosion Prediction Project
WEQ	wind erosion equation

1.0 INTRODUCTION

The Los Alamos National Laboratory (LANL or the Laboratory) was founded in 1943 as part of the Manhattan Project to develop the first atomic weapon. During the early years of LANL, the disposal of hazardous chemical and radioactive wastes was not regulated. Unfortunately, many hazardous or potentially hazardous materials were disposed of in ways that do not meet current requirements.

LANL's Environmental Remediation and Surveillance (ERS) Program (the Program) was established in 1989 as part of a DOE nationwide program.

The Program's goals are to:

- protect human health and the environment from exposure to hazardous, radioactive, and mixed wastes from past treatment, storage, and disposal practices; and
- meet the conditions in the recent (March 2005) Consent Order signed by NMED, DOE, and the Regents of the University of California.

The Program's purpose is to investigate where hazardous chemicals and/or radioactive wastes are present as a result of past LANL operations and to clean up and restore such sites as necessary to protect human health and the environment.

These sites are called solid waste management units (SWMUs) and areas of concern (AOCs). SWMUs are defined as sites whereby solid waste was disposed of. AOCs are areas that warrant investigation or possible remediation. Contamination originated from septic tanks and lines, chemical storage areas, wastewater outfalls (the area below a pipe that drains wastewater), material disposal areas (MDAs) (landfills), incinerators, firing ranges and their impact areas, surface spills, and electric transformers. SWMUs and AOCs are found on mesa tops, in canyons, and in a few areas within the Los Alamos townsite.

Cover systems will play a major role in completing the Program. Some SWMUs and AOCs, including MDAs, will likely require a cover system to effectively close these sites. This Guidance Document describes requirements and considerations to be included in the design of such a cover system.

1.1 Los Alamos Hydrogeologic and Ecological Overview

(Newman and Robinson 2005)

LANL is located on the Pajarito Plateau along the western portion of the Espanola Basin, which is part of the Rio Grande Rift system. The plateau consists of a series of east-sloping fingering mesas separated by deep canyons containing ephemeral and intermittent streams that run from west to east. The plateau is bounded on the west by the Jemez Mountains and on the east by the White Rock Canyon. The mesa tops range in elevation from about 2377 m near the Jemez Mountains to about 1890 m toward the Rio Grande. The eastern margin of the plateau stands 91–274 m above the Rio Grande. The Rio Grande is the primary river in north-central New Mexico. All surface water drainage and groundwater discharge from the plateau ultimately arrives at the Rio Grande (DOE 1979).

Because of the 1524-m elevation gradient from the Rio Grande on the east to the Jemez Mountains 19 km to the west, there are significant precipitation and vegetation gradients on the plateau. Los Alamos has a semiarid, temperate climate. The area receives 33–50 cm of precipitation annually depending on elevation, with higher precipitation rates on the western side of the plateau. Approximately 35–40% of the annual precipitation normally falls during thunderstorms in July and August. Winter precipitation falls primarily as snow, with accumulations of 130 cm annually. Summers are generally sunny, with moderate,

warm days and cool nights. Maximum daily temperatures in summer are usually below 32°C. Brief “monsoonal” afternoon and evening thunderstorms are common, especially in July and August (Bowen 1990). The elevation and precipitation gradients coupled with the mesa canyon topography make the Pajarito Plateau a biologically diverse area. There are five major vegetation zones on the plateau (LANL 2000). From east to west (lowest to highest elevation/precipitation), these include juniper-savannah, piñon-juniper, ponderosa pine, mixed conifer, and spruce fir. The juniper-savannah community is found along the Rio Grande on the eastern border of the plateau and extends upward on the south-facing sides of the canyons, at elevations between 1706 and 1890 m. The piñon-juniper community, generally in the 1890–2103-m elevation range, covers large portions of the mesa tops and north-facing slopes at lower elevations. Ponderosa pines are found in the western portion of the plateau on the 2103–2286-m elevation range. The piñon-juniper and ponderosa pine cover types are present over most of the Laboratory. The mixed conifer cover type, at an elevation of 2286–2896 m, overlaps the ponderosa pine community in the deeper canyons and on the north slopes and extends from the higher mesas onto the slopes of the Jemez Mountains. Based on ongoing surveys, at least four federally protected animal species—the American peregrine falcon (endangered), the bald eagle (endangered), the Mexican spotted owl (threatened), and the southwestern willow flycatcher (endangered)—have been recorded in Los Alamos County (LANL 2000).

1.2 Regulatory Compliance

LANL’s Environmental Programs Directorate (EPD) implements the corrective action program pursuant to the conditions of the Consent Order signed by NMED, DOE, and the Regents of the University of California on March 1, 2005. In addition, the EPD will be responsible for closure of some hazardous waste disposal units regulated under RCRA and radioactive waste management units regulated by DOE under the authority of AEA.

LANL has several identified SWMUs and AOCs, including MDAs, where materials were buried during the operations of the Laboratory. The buried waste was placed in unlined trenches, shafts, and/or absorption beds. Many of the sites have interim soil covers, while a few have asphaltic covers. The types of wastes vary from solid waste such as construction debris to various hazardous wastes to radioactive waste generally produced from weapon operations. The radioactive waste varies from low level to Class C radioactive waste with some transuranic (TRU) waste. In some instances the waste forms have been treated or fixed prior to or during disposal. While most of the wastes were placed in solid form, there was also substantial liquid waste disposal in a number of the shafts and absorption beds. In most cases the liquids have dispersed into the surrounding geologic media, although there are containerized liquids at some disposal sites.

The underlying objective behind the closure of SWMUs, AOCs, and other waste disposal units is to protect human health and the environment. In some cases, this objective will be met by isolating the contaminants so they no longer pose a risk. The state of New Mexico and U.S. federal government have outlined requirements to help ensure this objective is met. These requirements are summarized below.

1.2.1 SWMUs and AOCs Subject to Consent Order

Unlike RCRA, the Consent Order does not contain prescriptive requirements for closure of inactive waste sites. Instead, the Consent Order establishes broad cleanup goals that the site cannot pose an excess cancer risk greater than 10^{-5} due to carcinogenic contaminants or present a hazard index (HI) greater than 1 for noncarcinogenic contaminants. For those sites requiring corrective measures, LANL will be required to perform a corrective measures evaluation (CME) to evaluate various corrective measure alternatives capable of meeting these cleanup goals. In most cases, the alternatives evaluated are expected to include waste removal, waste containment, in situ waste treatment, or some combination of

these approaches. The Consent Order specifies the factors that are to be considered in evaluating corrective measure alternatives. All alternatives must be able to meet the following four threshold criteria:

1. Be protective of human health and the environment;
2. Attain media cleanup standards;
3. Control the source or sources of releases so as to reduce or eliminate, to the extent possible, further releases of contaminants that may pose a threat to human health and the environment; and
4. Comply with applicable standards for management of wastes.

Alternatives that meet these four criteria are then given a comparative evaluation against the following five balancing criteria to recommend a preferred alternative:

1. long-term reliability and effectiveness;
2. reduction of contaminant toxicity, mobility, or volume;
3. short-term effectiveness;
4. implementability; and
5. cost.

NMED will then review the CME report and select a corrective measure that may or may not be the same as that recommended by LANL.

The corrective measure selected for some waste disposal units is expected to be waste containment, which will involve some type of cover system. The Consent Order does not contain specific design requirements for covers. Rather, LANL will need to develop design requirements capable of meeting the overall cleanup goals (i.e., less than 10^{-5} cancer risk, HI less than 1), which compare favorably to other alternatives such as waste removal.

1.2.2 Sites Containing RCRA Waste

Hazardous waste management statutes for the state of New Mexico are codified in the New Mexico Hazardous Waste Act enacted in 1985, and regulations governing hazardous waste management are set forth in Title 20 NMAC 4.1, which incorporates Title 40 Code of Federal Regulations (CFR) Parts 264 and 265.

The RCRA regulations for final hazardous waste landfill covers are found in Title 40 CFR Parts 264 and 265. Specifically, 40 CFR § 264.310 Subpart G establishes the closure requirements for the landfill cover, and 40 CFR 264 Subpart N includes requirements for hazardous waste landfills. Most applicable to LANL SWMU remedies are the regulatory requirements (40 CFR §264.310) for the design and performance of a final cover system, and the need for the cover to limit infiltration into the underlying wastes:

40 CFR §264.310 Closure and post-closure care.

A. At final closure of the landfill or upon closure of any cell, the owner or operator must cover the landfill or cell with a final cover designed and constructed to

1. provide long-term minimization of migration of liquids through the closed landfill,
2. function with minimum maintenance,
3. promote drainage and minimize erosion or abrasion of the cover,
4. accommodate settling and subsidence so that the cover's integrity is maintained, and
5. have permeability less than or equal to the permeability of any bottom liner system or natural subsoils present.

B. After final closure, the owner or operator must comply with all post-closure requirements contained in 40 CFR §§264.117 through 264.120 which include maintenance and monitoring throughout the post-closure care period. Section 264.117 specifies:

The owner or operator must

1. maintain the integrity and effectiveness of the final cover, including making repairs to the cover as necessary to correct the effects of settling, subsidence, erosion, or other events;
2. continue to operate the leachate collection and removal system (if such a system exists) until leachate is no longer detected;
3. maintain and monitor the leak detection system (if such a system exists) in accordance with 40 CFR §264.301(c)(3)(iv) and (4) and 40 CFR §264.303(c), and comply with all other applicable leak detection system requirements of this part;
4. maintain and monitor the ground-water monitoring system and comply with all other applicable requirements of subpart F of this part;
5. prevent run-on and runoff from eroding or otherwise damaging the final cover; and
6. protect and maintain surveyed benchmarks used in complying with 40 CFR §264.309.

1.2.3 Sites Containing Radioactive Waste

For sites that contain radioactive waste, the basis for analyzing and addressing the impacts of radioactive materials is contained in DOE Orders 5400.5, “Radiation Protection of the Public and the Environment,” and 435.1, “Radioactive Waste Management,” and in the National Nuclear Security Administration Service Center/Albuquerque’s “Procedure for the Release of Residual Radioactive Material from Real Property” (DOE 2000, 67153). The management of radioactive waste is regulated under the AEA, and management of waste consisting of source, special nuclear, or byproduct materials is specifically excluded from regulation under RCRA. However, if sites contain mixed waste (RCRA-governed waste and radioactive waste), the RCRA waste must still meet RCRA requirements for closure while the site must conform to standards outlined in DOE Orders 5400.5 and 435.1 at a minimum. Any waste containing polychlorinated biphenyls, asbestos, or other regulated toxic components shall be managed in accordance with requirements derived from the Toxic Substances Control Act [40 CFR 700-799].

DOE Order 5400.5 generally governs the dose limits imposed on the site waste, and outlines the limits of potential release that may enter a public drinking water supply or the atmosphere. The goal of any closure is to reduce the potential exposure to As Low As Reasonably Achievable (ALARA). Specifically, the effective annual dose equivalent to a potential member of the public from wastes contained at a given site is 100 millirem (mrem) (1 millisievert [mSv]). However, higher dose limits may be authorized. Compliance

is based on calculations made from monitoring and surveillance programs. The compliance with maximum airborne dose releases is described in 40 CFR Part 61, Subpart H. DOE Order 5400.5 also states that drinking water standards described in 40 CFR Part 141 must be complied with. No radioactive waste site shall contribute leached contaminants into a public drinking water supply whereby potential persons consuming the water would receive an effective annual dose equivalent greater than 4 mrem (0.04 mSv). Combined radium (Ra)-226 and Ra-228 shall not exceed 5×10^{-9} μCi/ml, and gross alpha activity (including Ra-226 but excluding radon [Rn] and uranium [U]) shall not exceed 1.5×10^{-8} μCi/ml.

DOE Order 435.1, Radioactive Waste Management, provides guidance on DOE management and requirements applicable to DOE radioactive waste types, including high-level TRU waste and low-level waste (LLW) requirements. Specific to closure of a site containing radioactive waste, a closure plan must include

- closure methodology,
- schedules and assumptions,
- site or location closure standards/performance objectives,
- allocation of closure standard/performance objective budgets to individual facilities/sites,
- assessment (preliminary) of the projected performance of each unit to be closed relative to the allocated performance objectives,
- assessment (preliminary) of the projected composite performance of all units to be closed at the site,
- alternatives (if any),
- waste characterization data,
- closure control plans, and
- stakeholder concerns.

DOE Order 435.1 identifies performance requirements for LLW disposal facilities for waste disposed of after September 26, 1988:

1. Dose to representative members of the public shall not exceed 25 mrem (0.25 mSv) total annual effective dose equivalent from all exposure pathways, excluding the dose from Rn and its progeny air.
2. Dose to representative members of the public via the air pathway shall not exceed 10 mrem (0.10 mSv) in a year total effective dose equivalent, excluding the dose form Rn and its progeny.
3. Release of Rn shall be less than an average flux of 20 picocuries (pCi)/m^2/s (0.74 becquerel [Bq] /m^2/s) at the surface of the disposal facility. Alternatively, a limit of 0.5 pCi/l (0.0185 Bq/l) of air may be applied at the boundary of the facility.

DOE Order 435.1 states that for LLW disposal facilities a closure plan shall include

1. a description of how the disposal facility will be closed to achieve long-term stability and minimize the need for active maintenance following closure and to ensure compliance with the requirements of DOE 5400.5, Radiation Protection of the Public and the Environment;

2. the total expected inventory of wastes to be disposed of during the operational life of the facility shall be prepared and incorporated in the performance assessment;

3. the performance assessment shall determine the aspects of the types of monitoring to be performed and types of radionuclides to be evaluated; and

4. the monitoring plan shall be capable of detecting early changing trends prior to exceeding performance objectives outlined.

DOE Order 435.1 states that a performance assessment shall be prepared and maintained for DOE LLW disposed of after September 26, 1988. The performance assessment shall include calculations for a 1000-year period after closure of potential doses to representative future members of the public and potential releases from the facility to provide a reasonable expectation that the performance objectives identified are not exceeded as a result of operation and closure of the facility. The performance assessment shall include a demonstration that projected releases of radionuclides to the environment shall be maintained ALARA. The point of compliance is determined to be a 100-meter buffer zone surrounding the disposed waste. Additionally, the closure must be capable of deterring an inadvertent intruder for at least 100 years following closure. This assumption relies on the design of this feature into the closure or institutional control of the site for a minimum of 100 years. It is assumed there is no institutional control 100 years after closure of the site.

The closure requirements applicable to sites containing TRU wastes depend on the date of disposal of the wastes. TRU wastes disposed of before May 1, 1970 were not subject to regulation by DOE Orders. Historically, DOE’s intent has been to address closure and long-term care of these sites in accordance with the requirements of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). Sites disposing of TRU wastes after November 17, 1985 are subject to regulation under 40 CFR Part 191, “Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes.” Requirements applicable to TRU wastes disposed of between May 1, 1970 and November 17, 1985 are less certain. DOE Order 435.1 recommends that 40 CFR Part 191 requirements be applied to such wastes as a good management practice, but this is not a requirement.

Requirements under 40 CFR Part 191 for TRU disposal facilities include

1. containment to limit the amount of radionuclides that may be released to the accessible environment for 10,000 years;

2. institutional controls, markers, or other controls to prevent inadvertent intrusion into disposed wastes;

3. limits on the dose to members of the general public from disposed wastes over 10,000 years; and

4. groundwater protection requirements to prevent radionuclides from exceeding 40 CFR Part 141 drinking water standards over 10,000 years.

Compliance with the containment requirements is to be demonstrated through a performance assessment that will evaluate release of radionuclides from the facility for a period of 10,000 years after closure.

Another requirement that may apply to closure of LANL sites is contained in 10 CFR Part 61, “Licensing Requirements for Disposal of Radioactive Waste.” 10 CFR Part 61 provides guidelines for closure of sites containing Nuclear Regulatory Commission (NRC) radioactive waste. Presently, these requirements do not apply to any LANL SWMUs, AOCs, or MDAs since these sites are not subject to NRC licensing. In the event that any LANL sites were deemed to be subject to remedial actions under CERCLA, however, it is possible that 10 CFR Part 61 could be found to be an applicable or relevant and appropriate requirement (ARAR) under CERCLA. Unique to this regulation is the requirement that a cover must include a minimum of 5 m of soil over the top of the waste to provide for protection against inadvertent human intrusion. An alternative to the 5 m of soil would include an intrusion prevention layer that would prevent inadvertent human intrusion for a minimum of 500 years after closure of the site.

Additionally, the amount and type of radioactive material contained in a given site, as evaluated per DOE-STD1027, dictates whether 10 CFR Part 830, “Nuclear Safety Management,” applies to closure activities. 10 CFR Part 830 Subpart A describes the quality requirements, while Subpart B describes the associated safety basis requirements.

2.0 COVER DESIGN

There are primarily two types of covers commonly used to close landfills and designated sites. The first type, referred to as a “resistive” cover, attempts to block or resist the downward movement of water typically with low permeability soil barrier layers and/or geosynthetic materials such as high density polyethylene membranes. These "resistive"-type barriers are considered *prescriptive* covers. The second type of cover is referred to as a “store and release” cover. These are alternative earthen covers designed to take advantage of site-specific conditions such as dry climates and soils with high water storage capacities. These cover types are designed to store infiltrated water until that water can be removed by evaporation from the surface of the soil profile or through plant transpiration. The combination of evaporation and transpiration is termed ET.

2.1 Prescriptive Cover

Land disposal of waste is primarily governed under RCRA. Consequently, regulatory agencies commonly refer to cover designs developed for RCRA sites as prescriptive for *all* closures, including those containing radioactive waste. Sites containing radioactive waste often take the closure requirements developed for RCRA Subtitle C facilities and extrapolate the design for an increased design life requirement due to the nature of the waste.

A RCRA Subtitle C disposal facility contains hazardous solid waste, while a RCRA Subtitle D disposal facility contains municipal solid waste. The regulations for Subtitle C facilities (40 CFR 264 and 265) state that a design should attempt to minimize percolation of water through the cover into the underlying waste, thus minimizing the creation of leachate that can in turn leak from the landfill and potentially harm the surrounding environment. These regulations also state that erosion of the final cover is to be kept to a minimum; however, the terms “minimize” and “minimum” are not defined quantitatively.

In an attempt to clarify this vagueness, the U.S. Environmental Protection Agency (EPA) published a design guidance document (EPA 1991). This design guidance document recommended that landfill closures for RCRA Subtitle C and/or CERCLA facilities incorporate the following layers (Figure 2.1-1) in a cover profile:

1. <u>Composite Barrier Layer.</u> Consists of a low hydraulic conductivity geomembrane(GM)/soil layer. This is the first layer encountered above the landfill material. It consists of a 60-cm layer of compacted natural or amended soil with a maximum saturated hydraulic conductivity of 1×10^{-7} cm/sec in intimate contact with an overlying 0.5-mm (20-mil) thick (minimum) GM liner. The function of this composite barrier layer is to limit downward moisture movement.

2. <u>Drainage Layer.</u> Consists of a minimum 30-cm soil layer having a minimum hydraulic conductivity of 1×10^{-2} cm/sec, or a layer of geosynthetic material having equivalent characteristics. This layer exists directly above the composite barrier layer. The drainage layer’s purpose is to minimize the time the infiltrated water is in contact with the composite barrier layer and hence lessen the potential for the water to reach the waste.

3. <u>Topsoil Vegetation Layer.</u> A top layer with vegetation (or an armored top surface) and a minimum of 60 cm of soil graded at a slope between 3% and 5%. This layer shall be capable of sustaining nonwoody plants, have an adequate water-holding capacity, and be sufficiently deep to allow for expected, long-term erosion losses as well as protect the underlying soil barrier layer from damage due to freeze/thaw cycles. This is the uppermost surface layer of the landfill cover.

4. <u>Optional Layers.</u> Optional layers include gas vent, Rn barrier (compacted clay layer can serve as the Rn barrier), and biointrusion layers.

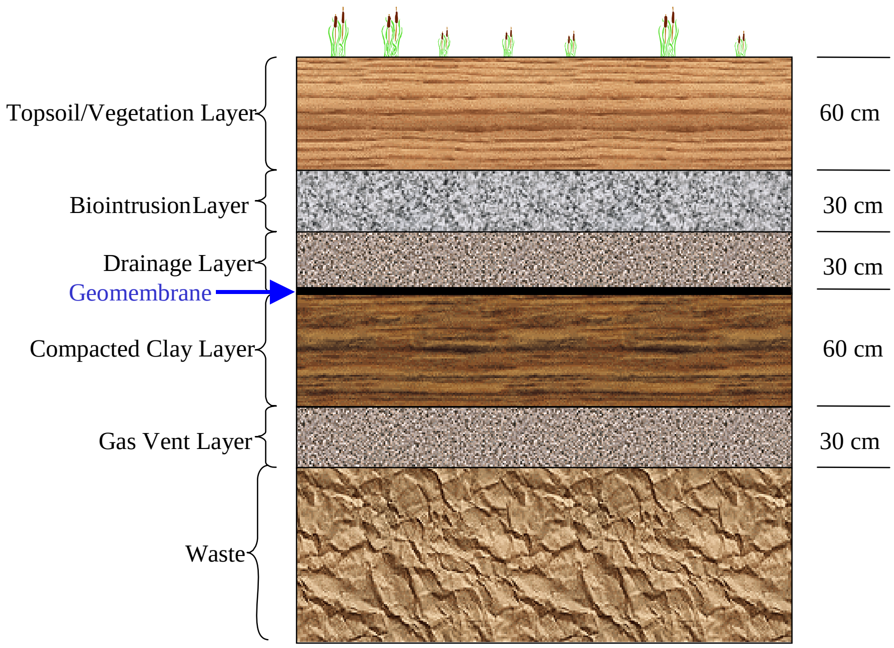


Figure 2.1-1. RCRA Subtitle C compacted clay cover (EPA 1991)

The 1991 EPA RCRA/CERCLA design guidance is in the process of being updated to include alternative earthen covers and is available in draft form on the internet (<u>http://hq.environmental.usace.army.mil/epasuperfund/geotech/index.html</u>).

2.2 ET Cover Concept

In the Los Alamos, New Mexico area, the climate's demand for water, referred to as potential evapotranspiration (PET), is more than three times greater than the actual supply of water (precipitation) (Figure 2.2-1). Consequently, "store and release" type covers designed to take advantage of large variances between the demand for water and actual supply of that water, such as ET covers, are well suited for these climates.

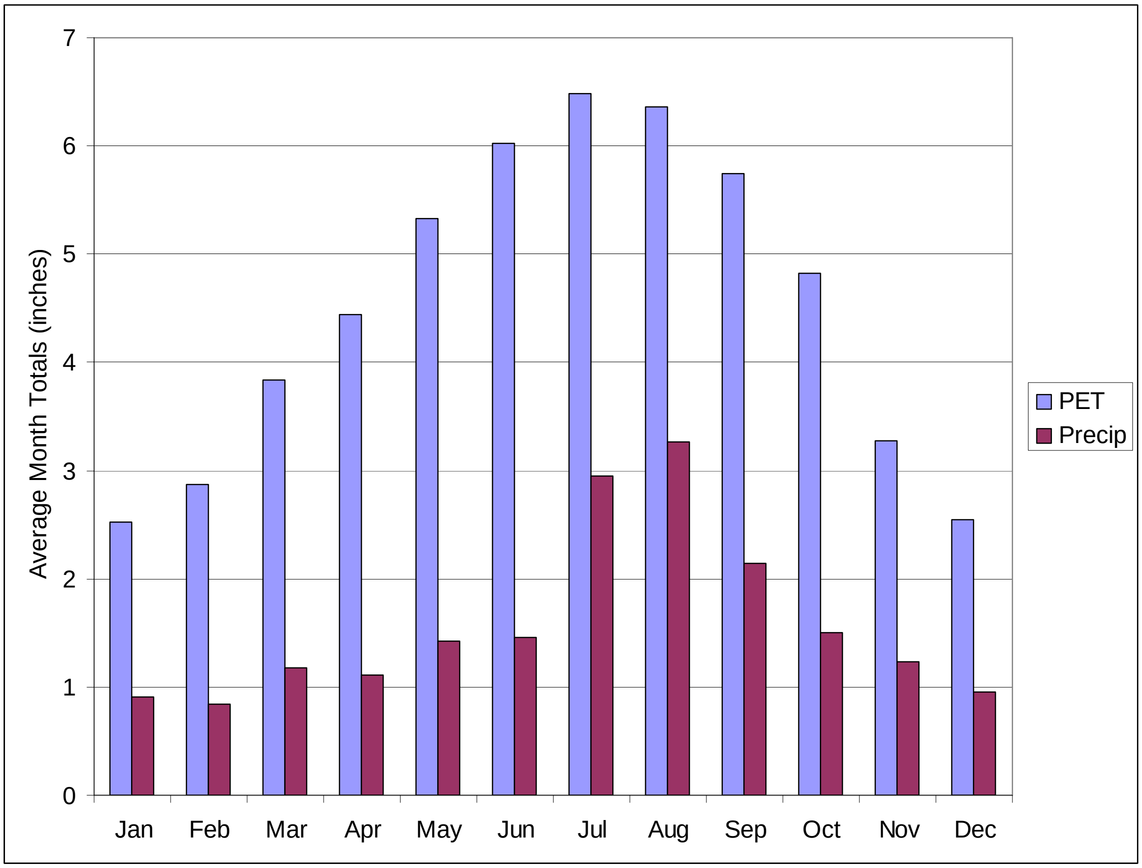


Figure 2.2-1. Climate's demand for water (PET) vs. supply of water (precipitation) for Los Alamos, NM

The ET cover consists of a single, vegetated soil layer constructed to represent an optimum mix of soil texture, soil thickness, and vegetation cover (Dwyer 1997). The ET cover is a monolithic soil layer that has adequate soil-water storage capacity to retain any infiltrated water until it can be removed via ET (Figure 2.2-2). EPA maintains a fact sheet on ET covers that is available on the internet (http://www.clu-in.org/download/remed/epa542f03015.pdf).

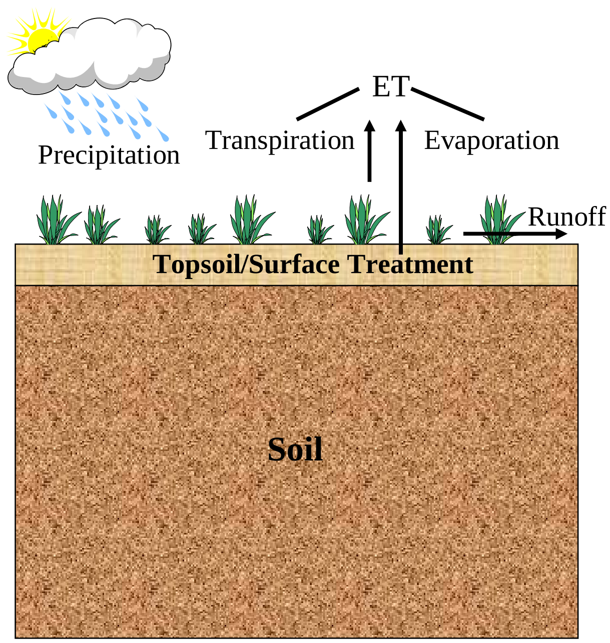


Figure 2.2-2. Typical ET cover profile

The “store and release” or 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 (Nyhan et al. 1990b, Hauser et al. 1994, Hakonson et al. 1994, Dwyer 1997, Nyhan et al. 1997, Khire et al. 1997, Chadwick et al. 1999, Dwyer 2001, Scanlon et al. 2002, Dwyer 2003, Nyhan 2005).

ET provides the mechanism to remove stored water from the cover soil layer. Water can move upward in response to matric potential gradients induced from evaporation drying the upper portion of the cover soil layer. Matric potential gradients can be many orders of magnitude greater than the gradient component due to gravity. Evaporation from the surface will decrease the water content and thus increasing the matric potential of the soil, 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 2.2-3 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 largest portion of this overall potential difference occurs between the leaves and the atmosphere (Figure 2.2-3). The larger the soil-plant-atmospheric potential gradient, the more effective an ET cover system can be. For this reason, well-vegetated cover systems are very effective in arid and semiarid regions because these regions are characterized by large PET compared to precipitation.

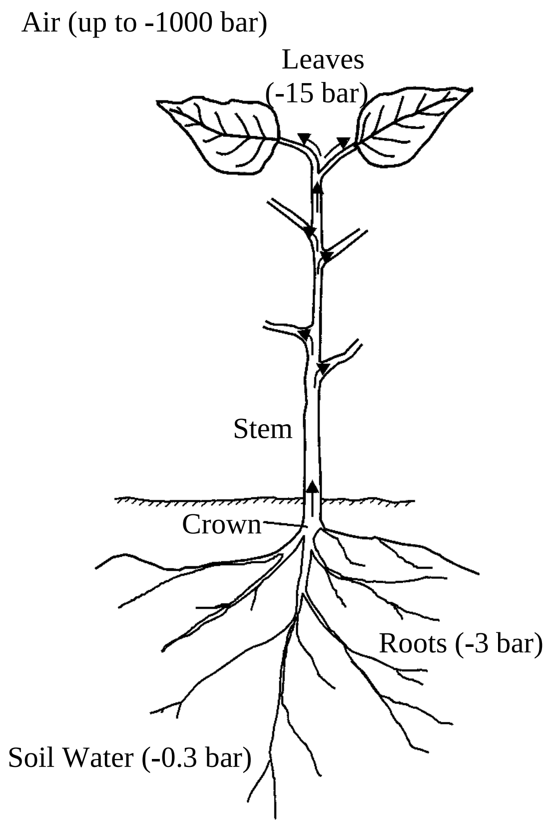


Figure 2.2-3. Typical soil-plant-atmosphere water potential variation (Hillel 1998)

Advantages of an ET cover system over its prescriptive counterpart include: (1) they are significantly less expensive to construct (Dwyer 1998); (2) require less maintenance; (3) relatively easy to repair; (4) construction is easier and thus more reliable (Dwyer 2000); (5) requires less QA during construction (Dwyer 1998); (6) performance is better than prescriptive covers (Dwyer 2003); and (7) because they are composed of natural soils and mimic nature, they shall have excellent performance for indefinite periods of time. Figures 2.2-4 through 2.2-5 show recent deployments of ET covers. Refer to Appendix B - Field Data for examples of more alternative earthen cover deployments and field data obtained to date.

Figure 2.2-4. ET cover under construction on Kirtland Air Force Base, Albuquerque, NM

Figure 2.2-5. OII Landfill: ET cover in southern California

3.0 TYPICAL LANL COVER DESIGN

This design 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 3.0-1 describes the typical cover profile to be used for all sites at LANL unless site specifics dictate a variance. Any variance from this design must be approved by appropriate LANL personnel in concurrence with the applicable regulator(s).

Figure 3.0-1. Typical LANL ET cover profile

The LANL cover prototype will be an ET cover with optional layers as required. The source material or waste to be covered dictates the regulatory drivers and thus the design life. Each site is currently covered with an interim cover. Each interim cover is to be characterized by depth and soil properties to be included in design modeling efforts for the final cover system. The overall cover depth must be determined during the design process.

The following cover components are to be included with each LANL cover system:

1. **Vegetation.** Native vegetation shall 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. Vegetation requirements are described in section 4.1.

2. **Surface treatment layer.** An admixture composed of soil and rock 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 shall not be compacted to allow for better plant establishment and initial growth. Design of this layer is described in section 5.2.3.

3. **Cover soil.** This layer is composed of quality soil with adequate water storage capacity, described in more detail in section 5.1. The soil shall possess adequate levels of plant-essential nutrients to encourage the establishment and productivity of non-woody indigenous plants (primarily grasses and forbs). 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.

4. **Interim cover.** This is the existing soil cover. The interim cover soil layer can be considered as part of the final cover system profile provided it is adequately characterized.

The following cover components are to be included with a LANL cover system as required:

Bio-barrier. A layer to control or eliminate the intrusion of flora and/or fauna. There are many options described later in section 4.2 that can be included to serve as a bio-barrier. Examples of protection from biointrusion include the overall cover depth that may provide adequate protection or possibly the inclusion of a cobble layer, among other options. If a coarse soil layer (such as cobble) is chosen to be used as a bio-barrier and this layer is placed beneath the ET cover's fine soil layer it will create a capillary barrier. If a capillary barrier is created by inclusion of one of the bio-barrier choices, the criteria and design considerations specific to a capillary barrier must be followed. If a sloped capillary barrier is introduced, the lateral diversion effects must also be considered.

Gas control layer. In general, common landfill gases such as carbon dioxide and methane are not a concern at LANL. However, Rn and tritium are of concern at some sites and must be controlled. An optional gas control layer may be warranted to control these gases. Refer to section 4.3.

Figure 3.0-2 describes the design process involved. This guidance document deals only with the final design processes and documentation needed to ensure a complete design package.

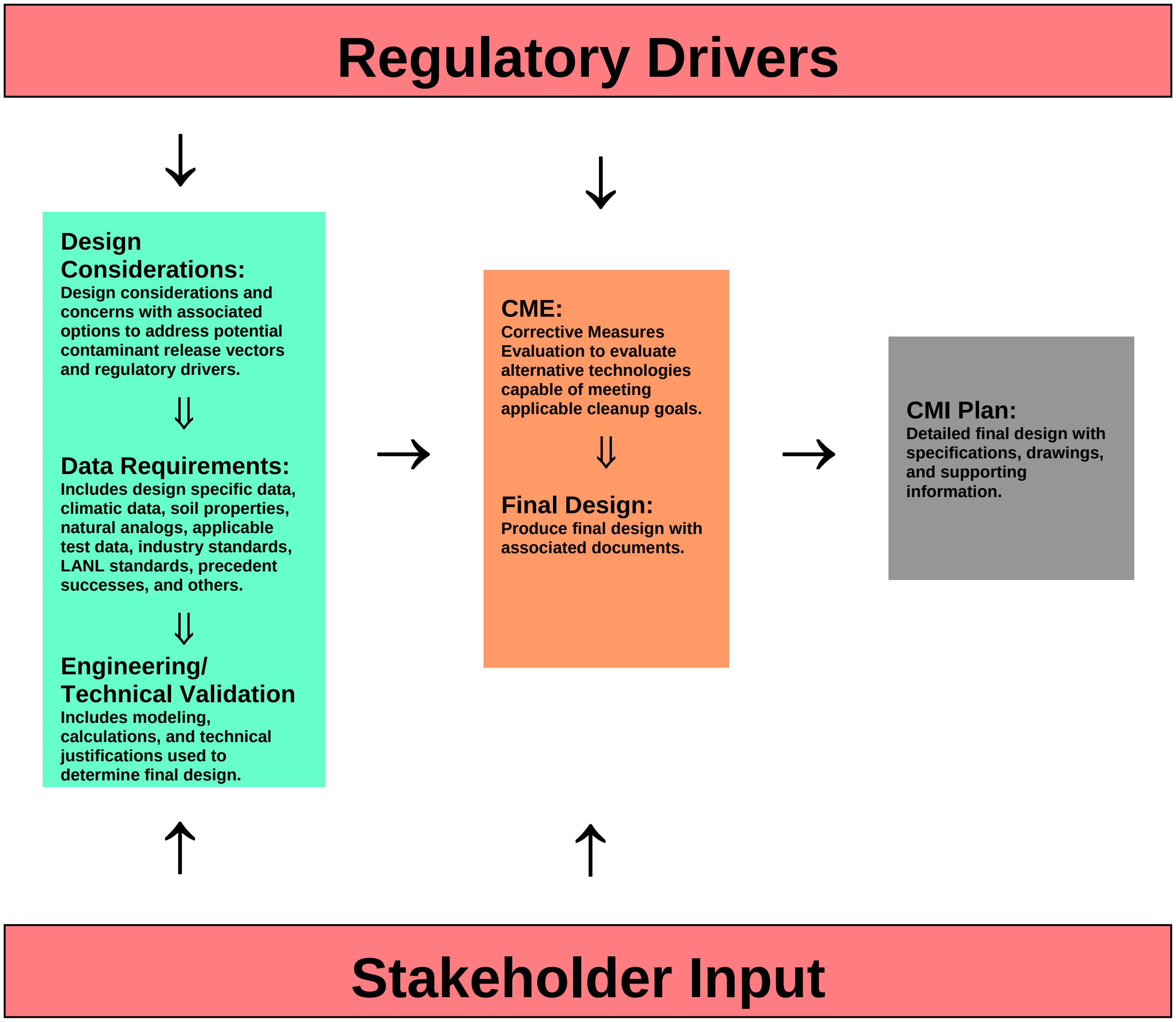


Figure 3.0-2. Design process

3.1 LANL Cover Design Steps

The following steps shall be considered when designing a cover system to meet determined performance and/or risk objectives of each specific LANL site. These steps are briefly described below, followed by reference to enhanced descriptions of each step and its location within this guidance document.

1. 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.

2. Determine the regulatory drivers for closure of each specific site (section 1.2).

3. Determine the design life of the cover system to be deployed based on the applicable regulations and encapsulated waste. RCRA closures require a minimum 30-year post-closure monitoring period to ensure the cover system is working as intended, while DOE Order 435.1 requires that a

closure be accompanied by a performance assessment that provides confidence the closure system (of which the cover is one part) will provide a 1000-year protective period for the public from any radioactive dose releases above allowable limits and ideally reduce any potential hazards to ALARA. Should 40 CFR 191 apply to a site, this will extend this performance period to 10,000 years. The Consent Order does not specify a design life for corrective measures. Those corrective measures where wastes are left in place (e.g., capping) will be required to include long-term monitoring to assure the corrective measure remains protective of human health and the environment. Technically, the cover system shall be designed to protect human health and the environment until the encapsulated waste no longer poses a significant threat (section 1.2).

4. Determine performance objectives of the cover system. Review, assess, and determine (during the CME) additional data needs, and design documentation to support final design. To the extent practical, use assessments performed during the CME process as design inputs to the Final Design. Performance objectives include, but are not limited to:

    - Risk (section 1.2). Sites subject to the Consent Order must not pose a long-term excess cancer risk greater than 10^{-5} or a HI greater than 1. These risk goals will determine the allowable long-term contaminant release rates for various exposure pathways (e.g., migration to groundwater). The cover system must be designed to control contaminant release rates so that the long-term risk goals are met.

    - Radiation dose limits. DOE Orders 5400 and 435.1 dictate allowable human receptor dose limits, as does 40 CFR 191 if it applies (section 1.2). To meet these dose limits, a cover system may require minimization of flux to prevent migration into groundwater, control of gases including Rn, minimization of erosion, and control of biointrusion, among other potential issues.

    - Flux through the cover system (sections 7 and 8). Each LANL site will require a F&T modeling effort to assess that site's influence on groundwater. The upper boundary condition (cover flux) must be less than that which will produce an adverse risk to groundwater. Sites containing RCRA waste must show the cover meets RCRA-equivalence standards (section 7).

    - Erosion of the cover system (section 5.2). 40 CFR 264 dictates that a cover system must be designed to minimize erosion. As a minimum, all cover systems shall be designed so that the calculated sheet erosion rate does not exceed 2 tons/acre/year (4.5 tonnes/ha/year) (EPA 1991). Erosion effects due to both wind and water must be taken into account. Because a significant number of closures at LANL will be long-term (1000-year), the cover systems must be designed to minimize erosion over this period of time.

    - Gas emissions must be controlled where applicable (section 4.3). Typical landfill closures are designed to control methane and carbon dioxide produced as a result of organic waste decomposition. However, LANL sites have minimal organics and consequently will produce minimal methane and/or carbon dioxide. Depending on the site, emissions of most concern at LANL include Rn, tritium, and volatile organic chemicals (VOCs).

    - Control biointrusion (section 4.2 and Appendix C). 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 whereby contaminants can be brought to

the surface or allow for increased flux and thus increased potential for groundwater contamination.

- Access control (section 4.7). A closure system may require limited access to the site. Access controls can provide an excellent means to control waste migration from shorter-term design life closures such as RCRA-governed sites and even sites containing tritium, since this half-life is about 12 years and DOE Order 435.1 states that institutional controls may be utilized for up to 100 years. Sites subject to the Consent Order will be required to meet risk goals based on current and reasonably foreseeable future land use. These sites will be required to have institutional controls to ensure the land use remains consistent with the land use scenarios used to develop cleanup levels. In general, unrestricted access will not be allowed for sites closed with wastes left in place.

- Aesthetic considerations (section 4.8). Although not a regulatory requirement, a cover system shall be designed to blend into a dynamic ecosystem. Closed sites may require the cover system to be aesthetically appealing to nearby communities.

- Future use considerations. The future use of each site will involve industrial use by LANL or remain vacant.

5. Determine site-specific issues that will affect the design of the cover system—these relate to those identified in step 4, 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 (sections 4 and 5).

6. Determine the cover type to be deployed (sections 2 and 3). It has been decided due to climatic and waste considerations that alternative earthen covers (specifically ET covers) shall be universally deployed for site closures at LANL. An ET cover consists of a single, vegetated soil layer constructed to represent an optimum mix of soil texture, soil thickness, and vegetation cover (Dwyer 1997). 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.

7. Identify an acceptable borrow soil (section 5.1). Borrow sources have been identified for use as cover material. The borrow source at Technical Area (TA)-61 is assumed to be a primary source for cover soil. This borrow source is estimated to have over 3 million cubic yards of available soil and is economically and practically viable. Other soil with adequate fines and plant nutrients shall also be used. These other soils with adequate fines content shall be mixed with TA-61 tuff soils to enhance the ability of that soil to maintain native vegetation and to act as a binder for the tuff soil.

8. Ensure that the cover soil will maintain the desired native vegetation (sections 4.1 and 5.1). The soil should not have excessive salts. The soil shall adhere to the soil requirements summarized in Table 5.1-1. Soil nutrients shall adhere to requirements summarized in Table 5.1-2.

9. Determine the required cover soil depth (sections 3, 6, 7, and 8).

   - Determine the in situ density of the undisturbed borrow soils to be used (sections 3 and 5.1). Recent studies (Dwyer 2003, Benson et al. in press) have shown that hydraulic properties of soil can change with time due to pedogenesis. The tuff soils at LANL present a unique problem in that it is difficult to determine where the long-term hydraulic properties of the soil

will reside. Natural analogs may be required at LANL to determine an in situ density (section 4.4).

- Nearby, native soils shall be used because local vegetation is adapted to them (section 5.1). Soils shall have adequate water storage capacity. Loams tend to have the best storage capacity (Figure 3.1-1) and generally minimize the potential for desiccation cracking that can lead to preferential flow.

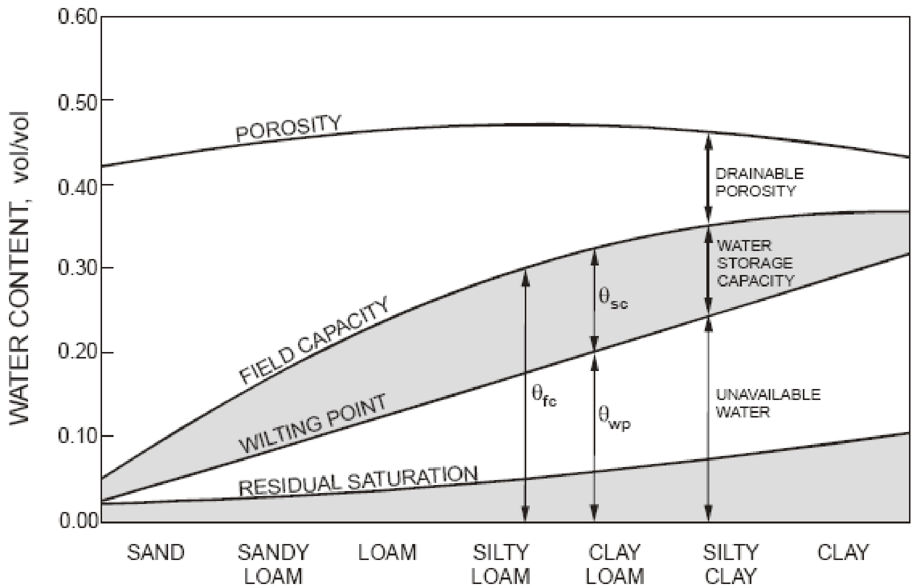


Figure 3.1-1. Relation between moisture retention parameter and soil texture class (modified from Schroeder et al. 1994)

- Test the borrow soil to be used at a remolded density similar to its undisturbed in situ density. The hydraulic properties shall be obtained at this density.

- Soil properties such as strength characteristics shall be determined if required (i.e., slope stability concerns with steep side slopes). Soil properties shall also be obtained, such as grain size distribution and Atterberg limits. These properties can be used in a Construction Quality Assurance (CQA) Plan to distinguish acceptable soils from those deemed unacceptable (section 9).

- Determine an estimate of required soil depth based on an approximated net storage capacity of the borrow soil to be used against an approximated design infiltration event (e.g., spring snowmelt) (sections 3, 5.1, 6, 7, and 8).

- Model the cover system given desired vegetation characteristics and determined climatic conditions (section 6). 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. 1999 (sections 6 and 7).

10. The acceptable density and moisture range produced during construction activities is referred to as the Acceptable Compaction Zone (ACZ) (Dwyer et al. 1999). Determine the ACZ for

placement of cover soils. The ACZ is defined as the acceptable density and moisture range at which the cover soil will be installed. Cover soil shall be placed within the ACZ (Figure 3.1-2) specific to the soil used. After the cover soil has been placed, the upper six inches (15 cm) shall be scarified or disced prior to seeding to increase the potential for establishment of vegetation. The final slope and slope tolerances described in the design shall be maintained. Positive drainage shall be maintained at all times during installation of the cover systems.

- Cover soil shall be placed at the goal density. The goal density is best determined from the borrow soil's in situ density. That is, over an extended period of time, a given soil will move toward its "natural" density state. Therefore, it is the goal of the soil installation to place the soil at a density that is as close to that "goal" density as possible from the onset.
- Measure the in situ density of the borrow soil used. This may be done by means of American Society for Testing and Materials (ASTM) D 1556-90 Test Method for Density of Soil in Place by the Sand-Cone Method or ASTM D 3017-88 Standard Test Method for Water Content of Soil and Rock in Place by Nuclear Methods (Shallow Depth).
- Determine a proctor curve for each borrow soil used per ASTM D 698, Test Method for Laboratory Compaction Characteristics of Soil Using Standard Effort, to obtain the respective maximum dry density (MDD) and optimum moisture content.
- It is understood that for tuff or tuff amended with other soils it will be difficult to determine a goal density. For amended soil or soil where the in situ density is not available, 90% of the MDD as determined from ASTM D 698 for that soil can be assumed to be the goal density.
- The allowable dry unit weight or soil density during construction shall then be the goal density plus or minus 5 pounds per cubic foot (pcf) (metric units).
- The cover soils shall be placed as dry as possible not to exceed the optimum moisture content per ASTM D 698 derived for each borrow soil used. Only moisture to control dust during placement shall be utilized. Installing soil dry will provide for a maximum initial water storage capacity in the cover and minimize the potential for desiccation cracking. This is particularly important when using clays (Suter et al. 1993, Dwyer 2003). This moisture content is applicable for all soils in the cover system, including the interim cover's upper foot (31 cm).

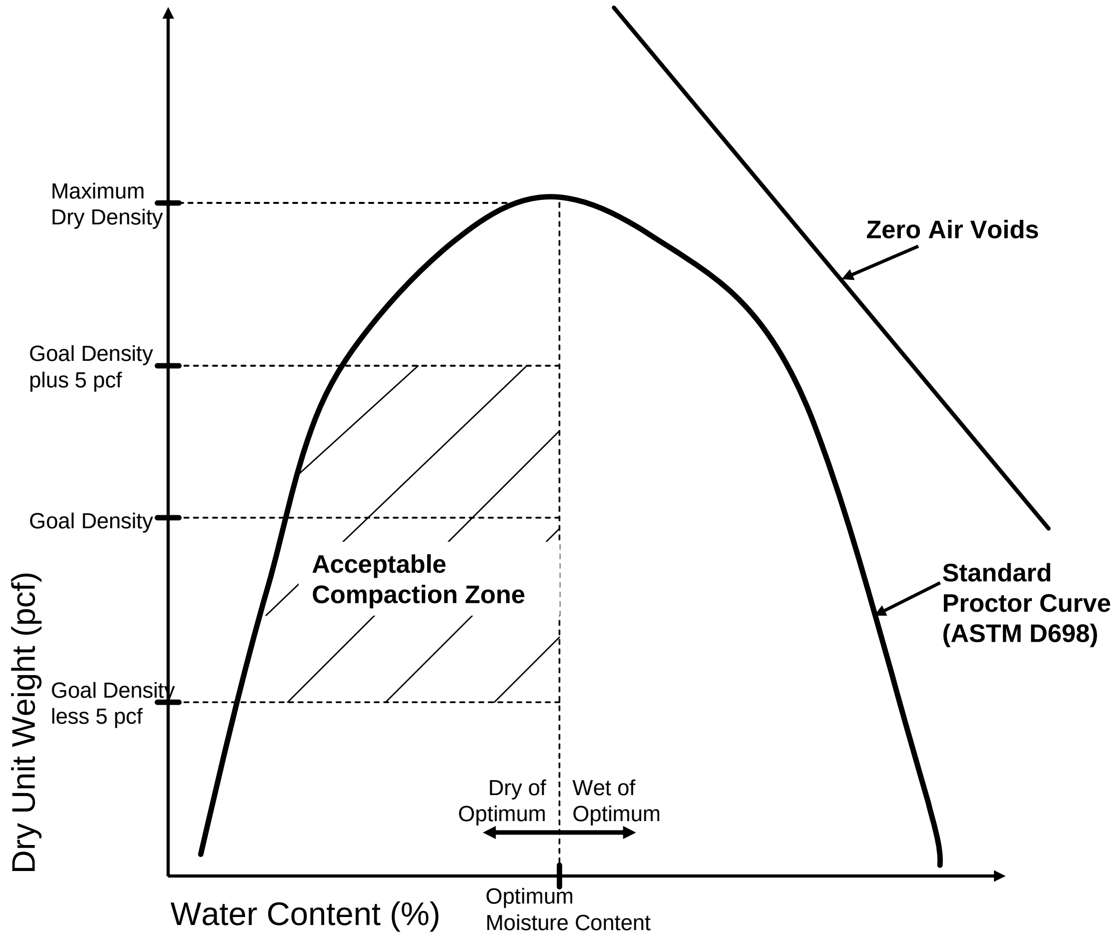


Figure 3.1-2. ACZ for soil placement

11. Another important aspect of cover soil density is that it not exceed the root limiting bulk density of the applicable native vegetation to be utilized (Table 3.1-1). The borrow soil investigation performed (Shaw 2006, Appendix C) includes soil dry bulk densities that those soils were tested at to determine their hydraulic properties. The soils in TA-61 were generally classified as a sandy loam. The 90% suggested density value in the absence of a determined in situ density as described above in step C is less than the 1.75 g/cm^3 listed in Table 3.1-1. Therefore, the root limiting bulk density criterion is not expected to be an issue with LANL cover systems.

Table 3.1-1
Minimum Soil Bulk Density At Which a Root Restricting Condition May Occur (Natural Resources Conservation Service [NRCS] 1996)

Soil Texture	Bulk Density[1] (g/cm^3)
Coarse, medium, and fine sand and loamy sands other than loamy very fine sand	1.80
Very fine sand, loamy very fine sand	1.77
Sandy loam	1.75
Loam, sandy clay loam	1.70
Clay loam	1.65
Sandy clay	1.60
Silt, silt loam	1.55
Silty clay loam	1.50
Silty clay	1.45
Clay	1.40

[1] These are general values determined from agricultural crops (e.g., corn, soybean) and may not apply to native vegetation that are more opportunistic with regard to water and less affected by higher densities.

12. Determine the vegetation mix to be utilized on the cover system (section 4.1).

13. Identify the design infiltration event(s). This is dependent on design life. Shorter-duration design lives such as RCRA-specific closures can solely rely on existing climatic data compiled at LANL weather stations (http://www.weather.lanl.gov/). For example, it can be as simple as trying to simulate a spring snowmelt event where PET is low and infiltration is potentially high, or it can be wet years with high summer thunderstorms. However, for long-duration design lives (1000-year) required for sites with radioactive waste, natural analogs shall be utilized to help predict future climate scenarios and subsequent vegetation variations. Other studies examining biota interactions and soil pedogenesis must also be considered. This generally involves identifying the design precipitation event or series of events. A climate scenario for a long-term cover system has not been determined as of the release of this document.

14. Determine the minimum required depth of cover soil required to minimize flux. 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:

$$NSC = (FC - PWP)\, b \qquad \textbf{Equation 3.1}$$

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.

15. A more detailed method to determine the minimum cover soil depth required to minimize flux utilizes an accepted unsaturated flow software package such as UNSAT-H or HYDRUS; both are based on the Richards' Equation (section 6). The Dwyer Point of Diminishing Returns Method (Dwyer et al. 1999) shall be utilized (section 7). 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 3.1-3) is determined to be the point of diminishing return for soil depth. A cover profile shall be modeled with the expected design layers included. The monolithic soil-water storage from the ET cover shall 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. It does not infer the minimum overall depth of the cover system. Soil loss due to erosion, biointrusion, or radon mitigation are a few considerations that could require a thicker cover system.

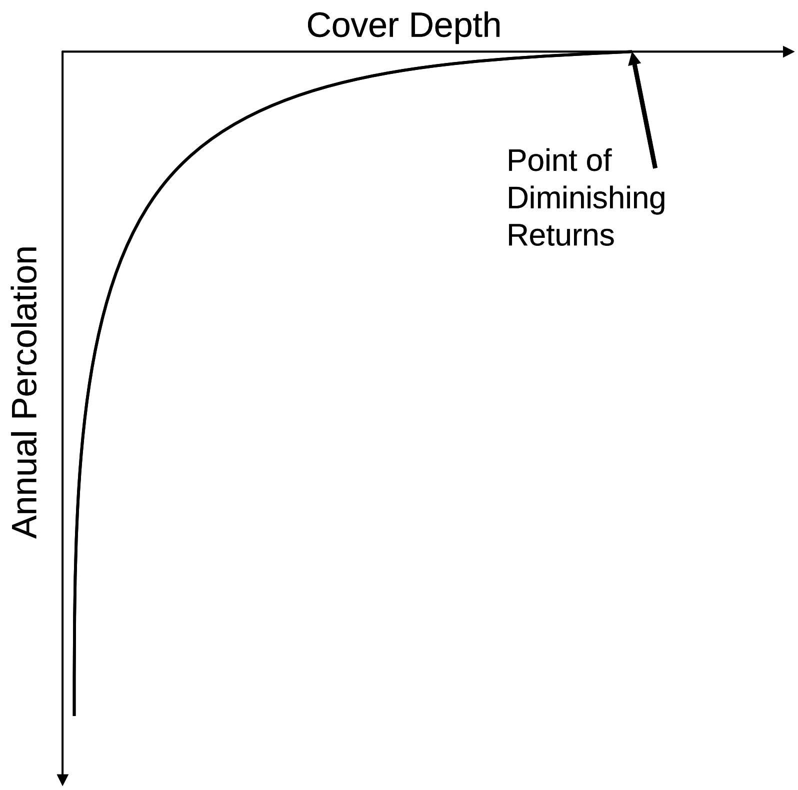


Figure 3.1-3. Cover depth vs. annual percolation

16. If a capillary barrier is introduced into the cover profile resulting from inclusion of layers such as a bio-barrier, all capillary barriers' considerations and restraints shall be evaluated and adhered to (Appendix D). A capillary barrier is only to be used as a consequence of additional layers (e.g., bio-barrier) or existing conditions. The upper fine-soil layer of a capillary barrier works similar to an ET cover. Capillary barriers consist of fine-over-coarse soil layers. Differences in pore size distribution between two soil layers cause infiltrated water to be retained in the upper soil layer under unsaturated flow conditions, as long as the contrast in unsaturated properties (e.g., soil-moisture characteristics and unsaturated hydraulic conductivities) of the soils in the two soil layers is sufficiently large. In general, the upper soil layer must consist of a soil exhibiting a significantly greater retention (matric potential) than the lower soil layer at the same water content. Thus a capillary barrier effect results when a "relatively fine-grained soil" overlies a "relatively coarse-grained soil." The capillary pressure head in the fine-grained upper soil layer typically must approach a value near zero (i.e., saturated conditions) before any appreciable flow occurs into the lower coarse-grained layer.

17. Perform sensitivity modeling of the cover profile as required during the final design process (section 6). 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 Rn flux layers.

18. Perform analyses to predict soil loss due to both surface water and wind erosion (section 5.2). Each cover is required to have a surface treatment composed of a rock/soil admixture to minimize

soil loss due to erosion (section 5.2.3). Any predicted soil loss due to erosion is to be added to the overall cover depth in addition to the minimum depth estimated in step 15.

19. Determine other layers or enhancements to the cover system as required based on performance and/or risk assessment(s) performed such as those outlined in steps 3 and 4. These may include a bio-barrier, gas control layer, Rn protection layer, subgrade structural support layer, or a lateral drainage layer (sections 4 and 5).

20. Evaluate the available field data of similar climatic and soil textural classifications to determine whether the design is feasible (Appendix B). 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. For sites subject to the Consent Order, the detailed design, specifications, and supporting materials will be included in the Corrective Measures Implementation (CMI) Plan to be submitted to NMED.

21. 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 (section 4.4). Natural analogs will be utilized as part of the final design report or CMI Plan and provide long-term data that will help justify that the design will perform as intended. At the date this document went to press, applicable natural analogs for long-term cover designs had not been identified at LANL.

22. Adjust the unsaturated modeling to include the final cover system profile as well as the upper portion of the subgrade and waste layers to determine that the flux requirements are still adequate. Include this information in the final design report or CMI Plan to help justify that the design will perform as intended (section 6).

23. Determine the installation requirements (e.g., such as the ACZ for construction of the fine-soil layer of the cover system), to ensure performance of the cover delivers that desired per the design (section 9). This will be included in the construction documents (design drawings and specifications).

24. Determine the method to be used to ensure that acceptable materials and construction methods are used to build the cover systems (section 9). This will be included in the CQA documentation.

25. Determine the monitoring equipment, methods and frequencies to be employed to verify design objectives are met (section 8). This will be included in the post-closure monitoring plan. For sites subject to the Consent Order, the monitoring plan will be included as part of the CMI Plan.

26. Determine maintenance monitoring criteria, methods and frequencies to be performed to ensure that cover systems are not degrading (section 8). This will be included in the cover system maintenance plan. For sites subject to the Consent Order, the maintenance plan will be included as part of the CMI Plan.

4.0 DESIGN CONSIDERATIONS, OPTIONS, AND REQUIREMENTS

Each cover design must take into account the site-specific characteristics such as flora and fauna, climate, waste, potential contaminant release vectors, and existing conditions. These design considerations vary from site to site and consequently so will the design considerations.

4.1 Vegetation Requirements

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 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).

Conventional engineering approaches for designing landfill covers often fail to fully consider ecological processes. The ultimate goal is to design a maintenance-free landfill cover. Some degree of maintenance or post-construction refinement may be necessary until the cover reaches a state of equilibrium with its inherent environment. A cover shall be stabilized with vegetation comprising plant communities that closely emulate a selected local “climax” (Reith and Caldwell 1993). A “climax” community, in ecological terms, is the type of plant community one finds in an area that has long been undisturbed and is in equilibrium with all other environmental parameters (e.g., climate, soil, and landscape properties; fauna; and other flora). Central to the concept of “climax” is the community’s relative stability in the existing environment (Whittaker 1975). A diverse mixture of native plants on the cover will maximize water removal through ET (Link et al. 1994). The cover will then be more resilient to natural and man-induced catastrophes and fluctuations in environments. Similarly, biological diversity in cover vegetation will be important to community stability and resilience given variable and unpredictable changes in the environment resulting from pest outbreaks, disturbances (overgrazing, fires, etc.), and climatic fluctuations. Local native species that have been selected over thousands of years are best adapted to disturbances and climatic changes (Waugh 1994). In contrast, plantings of non-native species common on waste sites are genetically and structurally monotonous (Harper 1987) and are therefore more vulnerable to disturbances. Pedogenic processes will gradually change the physical and hydraulic properties of earthen material used to construct covers (Hillel 1980). Plant communities inhabiting the cover will also change in response to these changes in soil properties.

An engineered cover that is to last until the waste it covers is deemed harmless must be designed as an evolving component of a larger dynamic ecosystem. Cover components initially designed for a specific purpose such as a barrier or drainage layer will not function independent of one another and shall therefore be designed as a system (linked assemblage of components) rather than as individual components. Inevitable changes in physical and biological conditions shall be taken into account to help

ensure the long-term effectiveness of the cover system. For resistant waste forms with long resident time, man-made materials of unknown durability shall not be relied upon to effectively maintain waste isolation.

Revegetation goals (Waugh et al. 2002) for LANL closure sites include establishment of plant communities that

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

Seeding of monocultures or low-diversity mixtures on engineered covers is common; however, on LANL closure sites, the revegetation goal is to emulate the structure, function, diversity, and dynamics of native plant communities in the area. 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 shall be selected.
- The plants shall survive drought and temperature extremes.
- The plants shall 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 shall be capable of thriving with minimal addition of nutrients.

- The plant population shall be sufficiently diverse to provide erosion protection under a variety of conditions.
- The plants shall not be an attractant to burrowing wildlife.
- The vegetative cover shall be capable of surviving and functioning with little or no maintenance (e.g., without irrigation other than for initial plant establishment, fertilization, and mowing).

Guidance on selection of vegetative materials is found in Wright (1976), Thornburg (1979), Lee et al. (1984), and EPA (1985). These references provide information about plant species, seeding rate, time of seeding, and areas of adaptation. Growth information for a number of plant species is available in the U.S. Department of Agriculture (USDA) plant database at http://plants.usda.gov/.

4.1.1 LANL-Specific Seeding Requirements

4.1.1.1. Native Seed

Seeding of covers and disturbed areas shall at a minimum include native grasses. These grasses have well-developed root systems with long, very thin roots that are excellent in stabilizing soil against erosion. These types of roots are less likely to lead to preferential flow paths compared to the larger woody roots of a pine tree. The root system for blue grama grass (Boutloua gracilis) is an excellent example of this as seen in Figure 4.1-1.

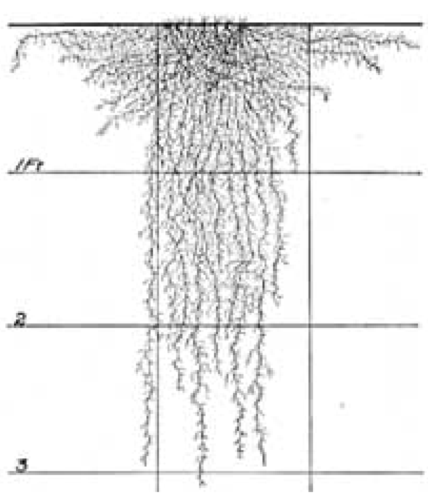


Figure 4.1-1. Blue grama grass root system

Any seed or live plant used to revegetate disturbed areas at LANL shall be native to the Los Alamos vicinity. Foxx and Tierney (1985) describe the status of all flora native to this area. Tierney and Foxx (1982) describe the floristic composition and plant succession on a near-surface radioactive waste disposal site at LANL. Careful consideration shall be given to the root systems of plants chosen for revegetation. Biointrusion and contaminant uptake by plants are of concern at some LANL MDAs with near-surface radioactive wastes. Foxx et al. (1984) describes the various root depths and characteristics of native plants at LANL. The following is a recommended seed mix to be employed for LANL MDA closure sites (Table 4.1-1).

Table 4.1-1
Suggested General Seed Mix

Common Name	Scientific Name	% of mix	PLS (lbs/acre)
Sideoats grama	Bouteloua curtipendula	15%	3.75
Blue grama	Bouteloua gracilis	15%	3.75
Indian ricegrass	Oryzopsis hymenoides	10%	2.5
Western wheatgrass	Agropyron smithii	15%	3.75
Sand dropseed	Sporobolus cryptandrus	10%	2.5
Sheep fescue	Festuca ovina	20%	5
Firewheel	Gaillardia pulchella	3%	.75
Western yarrow	Achillea millefoium	2%	.5
Prairie coneflower	Ratibida columnifera	4%	1
Blue flax	Linum perenne lewisii	6%	1.5
TOTAL			**25 (drilled)**

4.1.1.2. Seed Application

Seeding or planting of native vegetation on cover systems shall ideally be done in the spring, after the last frost of the season and prior to the arrival of the summer rains that typically occur in July and August. Seeding shall not be done August 1 to September 30 to avoid germination too close to the first frost, as this can kill the new seedlings.

There are a number of seed application methods that can be utilized to seed the cover systems and adjacent disturbed areas. The preferred method is drill seeding. Drilling introduces seed directly into the prepared seedbed by machine. Broadcast seeding by machine or hand may be appropriate for small or confined areas. Hydraulic seeding uses a slurry composed of water and some or all of the following: seed, fertilizer, mulch, and tackifier. The slurry is then sprayed onto the prepared seedbed.

Revegetation shall be done by first preparing the soil by tilling and applying fertilizer. Care must be taken to ensure the rock/soil surface treatment maintains the desired ratio during this activity. Care must also be taken to ensure the rock/soil surface treatment layer is not mixed further into the cover profile. Slow-release organic fertilizers shall be applied as necessary to eliminate any deficiencies of the topsoil. Bio-Sol or similar fertilizer shall be applied at up to 1500 lbs/acre. Prior analyses of the cover soils used will dictate the actual fertilizer rate required. Granular humate can be applied at 400-500 lbs/acre if in a hydroseeding slurry and up to 1800 lbs/acre if it is incorporated into the top 4 inches of the soil. Application rates of composted manure vary depending on the source (chicken, horse, etc.) and the type of materials (wood chips, paper, soil, etc.) used to compost. If composted manure is to be applied, nutrient content shall be tested and interpreted before it is used.

Seeding shall be performed by drilling at a minimum rate of 25 Pure Live Seed (PLS) pounds per acre. In areas that limit equipment access, broadcast seeding may be used at a rate of 40 PLS pounds per acre. In areas to be seeded with high visibility, additional wildflowers shall be included in the seed mix. A

variety of species shall be used (including cool and warm season species) in the seed mix to ensure growth in areas of differing conditions.

For small areas where drilling equipment cannot easily access, broadcast seeding may be used. However, if broadcast seeding is used, the planting rates shall be multiplied by 1.5 to a minimum of 40 PLS pounds per acre. Sloped areas will require a higher seeding rate than flatter areas. As a general rule, slopes 3:1 and steeper shall be seeded at two times the seeding rate. Disturbed areas that are particularly prone to erosion or are in an environmentally sensitive area may require higher seeding rates to protect the ground from erosive forces of water.

4.1.1.3. Temporary Erosion Protection and Maintenance After Seeding

Maintenance (i.e., watering, fertilizing, and weeding) of a seeded area after initial installation will directly affect the results of the project. When optimum conditions exist over a period of time, at least 60 days, a higher percentage of seed will germinate. Design specifications shall include instructions to the contractor to include supplemental water to ensure vegetation establishment during the first 60 days after planting. Furthermore, it is recommended that a fertilizer be applied as required to ensure adequate nutrients for germination and continued plant establishment. Use a slow-release fertilizer such as Bio-Sol or approved equal at a rate of ~1500 pounds per acre.

A temporary soil retention blanket or similar temporary erosion measure will be used for slopes of 3:1 and steeper. In flatter areas hay mulch will be applied and crimped. Mulch shall consist of clean cereal grain straw, grass hay, long fiber wood cellulose, or commercial materials developed for this purpose. Anchor the mulch as required with crimping equipment, soil-anchored mulch, tackifiers, or netting materials. Straw or hay mulches shall be free of weed seeds. If hay-mulched areas cannot be anchored by crimping, use hydraulic mulch wood fibers with tackifier.

Use soil retention blankets of a uniform web of interlocking excelsior wood fibers or weed-free straw, or a combination of straw and coconut fibers. For 3:1 slopes or gentler, use single netted blankets such as Greenfix America WS05 or similar product. For slopes greater than 3:1, double-netted blankets shall be used such as Greenfix America WS072 or similar product. For 3:1 slopes and steeper when two growing seasons of protection is desired, use straw/coconut blend blankets such Greenfix America CFS072R or similar product.

4.1.2 Soil and Organic Properties

Nutrient and salinity levels significantly affect the ability of the soil to support vegetation. The soil layers need to be capable of providing nutrients to promote vegetation growth and maintain the vegetation system. Low nutrient or high salinity levels can be detrimental to vegetation growth, and, if present, supplemental nutrients may need to be added to promote vegetation growth. For example, at Fort Carson, Colorado, biosolids were added to a monolithic ET cover to increase organic matter and provide a slow release of nitrogen to enhance vegetation growth. In addition, topsoil promotes growth of vegetation and reduces erosion. For ET covers, the topsoil layer is generally a minimum of six inches thick (McGuire et al. 2001). Refer to section 5.1 for salt limitations and nutrient requirements in cover soil.

4.1.3 Water Storage Capacity in Rooting Medium Soils

A cover system must include a rooting medium composed of soils with adequate water storage to maintain the desired native vegetation. An example of the effects of inadequate water storage in the upper soil layer of a cover is seen in the contrast between Figures 4.1-2 and 4.1-3 (Dwyer 2003). Figure 4.1-2 is a test plot composed of a multiple-layered cover system designed with a thin topsoil layer. It was

installed in 1995. The vegetation appeared well developed until a severe drought was experienced in 1998. 1996 and 1997 were wetter than average years due to El Nino. The cover profile was a 1-ft topsoil layer over a sand layer. This relatively thin upper soil layer had inadequate water storage capacity to maintain the native vegetation through this drought period, while the test plot cover shown in Figure 4.1-3 had 3.5 times more storage capacity because of its available depth (3.5-ft deep soil profile), resulting in a very dense vegetation surface.

Figure 4.1-2. Multilayered cover with a thin (1-ft-thick) top soil layer

Figure 4.1-3. ET cover – 3.5-ft-thick soil layer

Monitoring for both the establishment of vegetation and its continued success is important. Refer to section 8 for post-construction monitoring requirements and success determination.

4.2 Biointrusion

Biointrusion in a landfill cover system refers to the flora and fauna (including insects) interactions or intrusion into the cover system. Biointrusion is important in that it can represent a mechanism leading to vertical transport of contaminants to the ground surface via plant root uptake or soil excavation by burrowing animals and insects. Furthermore, biointrusion can lead to increased infiltration and preferential flow of surface water through the cover system as well as contribute to the change in the soil layer's hydraulic properties, as described below. However, the increased soil moisture resulting from burrowing effects on infiltration can actually stimulate increased plant growth, leading to an increase in plant transpiration (Hakonson 2000, Gonzales et al. 1995) and a resulting net decrease in flux.

Vertical transport by biota may be small over a short time scale; however, over many decades these processes may become dominant in mobilizing buried waste (Hakonson 1998). Burrowing by animals and insects have the potential to access buried waste several meters below ground surface, which may lead to chemical and radiation exposures to organisms and physical transport of waste upward in the soil profile to ground surface, to biota, and across the landfill surface to offsite areas. These processes are enhanced by erosion (wind/water), transport of animals moving on/off the landfill, deposition of soil particles on biological surfaces from rain splash and wind re-suspension, and wind transport of senescent vegetation to offsite areas.

4.2.1 Criteria for Inclusion of a Bio-Barrier in a Cover System

A design engineer must have an understanding of the site-specific flora and fauna at LANL and its potential impact on the waste in conjunction with potential contaminant release vectors to make informed decisions regarding bio-barriers. That is, how biointrusion can access and spread contaminants must be understood. Much of the available literature including research performed at LANL is summarized in Appendix C. Ideally, the performance assessment for the site should dictate whether biointrusion is a concern or not and, if it is, what type of biointrusion is to be minimized. In general, inclusion of a biointrusion layer or bio-barrier component in a cover system is recommended for waste sites with the following characteristics (this is a partial list of concerns only):

- Sites that expect significant disturbance to the cover system from burrowing animals.
- Sites with waste that require complete isolation from the surrounding ecology, including flora and fauna.
- Sites that contain soil with contaminant concentrations that may cause radiological surface control limits to be exceeded due to accumulation in plant material based on contaminant-specific plant concentration factors.
- Sites with documented near-surface unplanned liquid radioactive waste releases.
- Sites that have documented occurrences of contaminated vegetation.
- Sites that are concerned with waste transport to the surface via burrowing animals or insects.
- Sites that are concerned with excessive animal burrowing that can lead to increased erosion.
- Sites where inadvertent human intrusion is believed to be a potential problem. 10 CFR 61 suggests that a depth of 15 feet will prevent inadvertent human intrusion into a waste cell. It is believed that intentional human intrusion cannot be stopped; however, inadvertent human intrusion can be given sufficient warning that danger is present below.

4.2.2 Bio-Barrier Options

As discussed above, biointrusion can have a significant impact on cover systems. There are a number of bio-barriers that can be employed to prevent or reduce the effect of biointrusion on a cover system.

A bio-barrier as recommended by the EPA (1991) has historically been a thin (30-cm) sand or gravel layer located just below the topsoil layer (Figure 4.2-1). The purpose of the sand/gravel layer was to provide a layer that offered minimal water storage capacity, thus discouraging plants from entering it, and a cohesionless layer whereby burrowing animals or insects will not penetrate. It was thought that the cohesionless nature of sands and gravels would not allow for a burrow hole and thus the burrowing

animal or insect would not penetrate this layer. To design an effective biointrusion layer as part of a landfill cover system, one must understand the site's ecosystem and how the landfill cover design will affect this ecosystem. There are many ways to prevent or minimize biointrusion. You can block it with large heavy cobble, discourage it with cohesionless layers such as gravel or sand, use manufactured items such as herbicide mats to stop root penetration, or you can alter the design of the profile to minimize it.

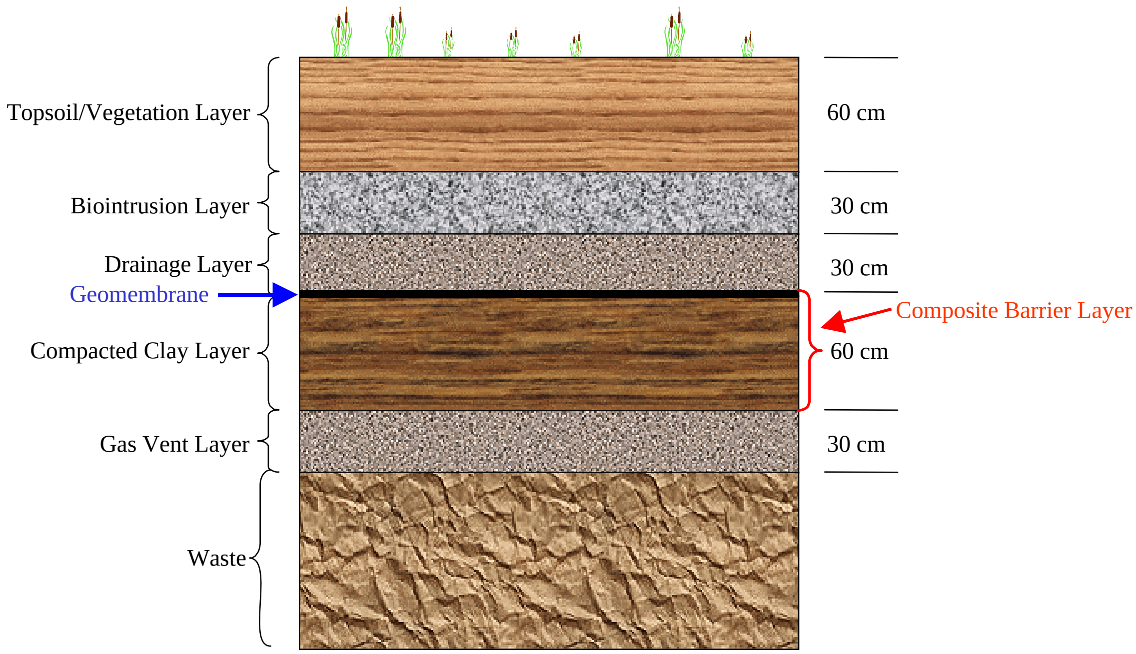


Figure 4.2-1. Typical prescriptive RCRA Subtitle C cover profile (modified from EPA 1991)

The specifics of the site shall dictate the type of bio-barrier used. Examples of bio-barriers include the following:

1. Rock/cobble layer. A cobble layer placed beneath the ET cover soil comprised of cobbles at least 1.5 times the body weight of the target burrowing animal.
2. Capillary barrier. The coarse soil layer within a capillary barrier can serve as a bio-barrier to both burrowing animals and root intrusion.
3. Cobble/soil admixture. Cobble a minimum of 1.5 times the weight of the target animal mixed with cover soil.
4. Depth of cover system. Cover system thick enough that it is unlikely a biointruder of concern will penetrate beneath it.
5. Rock/soil admixture surface treatment. A rock/soil admixture designed to reduce erosion has been shown to also reduce small mammal intrusion.

For cover systems with shorter-term design lives (i.e., no radionuclides present), the following bio-barriers can be considered:

6. Buried fencing. Metal fencing buried horizontally beneath the surface to prevent burrowing animals.
7. Root control bio-barrier. A geotextile laced with a herbicide designed to prevent root growth is strategically placed within a cover profile to keep plant roots from penetrating deeper within the profile.

NOTE: Rock or concrete used in a bio-barrier layer buried within the cover profile that is not expected to be exposed to the elements during the lifetime of the cover do not need to meet the durability requirements set forth in section 5.2.6. The rock and/or concrete need only be “sound” rock or concrete. Enhanced descriptions of the bio-barrier examples are provided in sections 4.2.2.1 through 4.2.1.8.

4.2.2.1 Rock/Cobble Layer

Rock or cobble bio-barriers have been demonstrated to prevent plant root and burrowing animal intrusion through landfill covers (Hakonson 1986, Cline et al. 1976); unfortunately, these were relatively short-term studies. Within an ET cover, a rock or cobble layer can be placed beneath the cover soil layer (Figure 4.2-2). This layer is designed to physically prevent or discourage burrowing animals from penetrating through it into the underlying waste or contaminated soils. The bio-barrier also discourages the intrusion of roots. The cobbles shall be a minimum of 1.5 times the body weight of the animal of concern. At LANL, the pocket gopher is likely to be this animal.

A filter layer composed of sand and/or gravel is placed above the bio-barrier: this layer is designed to prevent fine soil from entering the cobble layer. The filter layer’s grain size distribution must adhere to the filter criteria discussed in Appendix D. For shorter design lives such as RCRA-equivalent cover systems, a geotextile can be used above the bio-barrier in lieu of the filter soil layer. Geotextiles are not used for long-term closures due to their limited useful life. A geotextile is often placed on the soil beneath a cobble bio-barrier prior to placement of the cobble to prevent the mixing of the underlying fine soil into the cobble.

Because a capillary barrier will be formed by inclusion of a rock/cobble bio-barrier layer similar to that shown in figure 4.2-2, design considerations summarized in Appendix D shall be adhered to. Furthermore, the durability of the rock/cobble used shall be “sound” rock/cobble as determined by engineering judgment for covers governed by DOE 435.1.

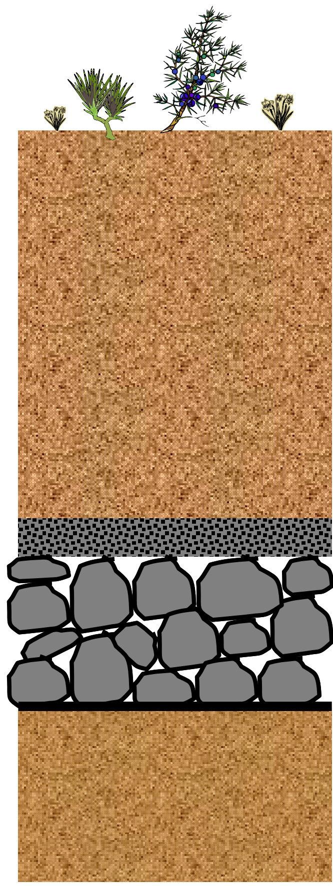


Figure 4.2-2. ET cover profile with a bio-barrier

A cover system deployed at DOE's Fernald, Ohio, site contained a bio-barrier within it composed of cobble (Figure 4.2-3). This site closure included the construction of a landfill where much of the waste generated during decontamination and decommissioning activities was placed (http://www.fernald.gov/vimages/PhotoTour/2003/Aug03/pages/6319D-4149.htm). The final cover on the On-Site Disposal Facility is nearly nine feet thick (2.74 m) and includes a biointrusion layer of minimum six-inch (15 cm) cobble. The three-foot-thick layer (31 cm) of cobble was designed to prevent vegetation and burrowing animals from establishing themselves on the cell.

Figure 4-2.3. Installing cobble bio-barrier in cover system at Fernald, Ohio

A more recent example is the closure of multiple sites at the Rocky Mountain Arsenal (RMA) in Denver, Colorado. RMA was once considered the most contaminated site in the world. The U.S. Army and Shell produced biological and chemical weapons at this site for years prior to its decommissioning. The site's future use is intended to be a wildlife refuge. Part of the remediation of the site includes the placement of cover systems over contaminated sites. A key feature of these cover systems is the inclusion of a bio-barrier that will prevent burrowing animals or root intrusion into the contaminated soils. RMA is located adjacent to Denver's Stapleton Airport, which was closed when the new Denver International Airport was opened east of Denver. Stapleton Airport's land was planned for redevelopment. As such, the runways required removal, and it was decided the rubblized concrete runways would be used as the bio-barrier (Figure 4.2-4). The design was similar to that shown in Figure 4.2-2.

Figure 4.2-4. Biointrusion layer at RMA in Denver, Colorado

4.2.2.2 Capillary Barrier

The inclusion of a rock/cobble layer to serve as a bio-barrier can introduce a capillary barrier into the cover system. If a capillary barrier is created due to the inclusion of a bio-barrier or other layer (e.g., gas vent layer or drainage layer), all design considerations associated with a capillary barrier shall be included as described in Appendix D.

4.2.2.3 Cobble/Soil Admixture

Another bio-barrier that utilizes cobble involves placing cobble within the soil layer of an ET cover rather than beneath it. This layer will allow for water storage and root intrusion yet prevent animal intrusion. The cobble can be placed within the entire soil profile or at specified locations within the profile. The cobble is placed within the soil layer at a soil to gravel ratio (greater than 50% cobble to soil) that disallows burrowing animals from tunneling though it. An example of such a system was deployed in a landfill cover design at the Monticello, Utah uranium mill tailings pile closure (Figure 4.2-5).

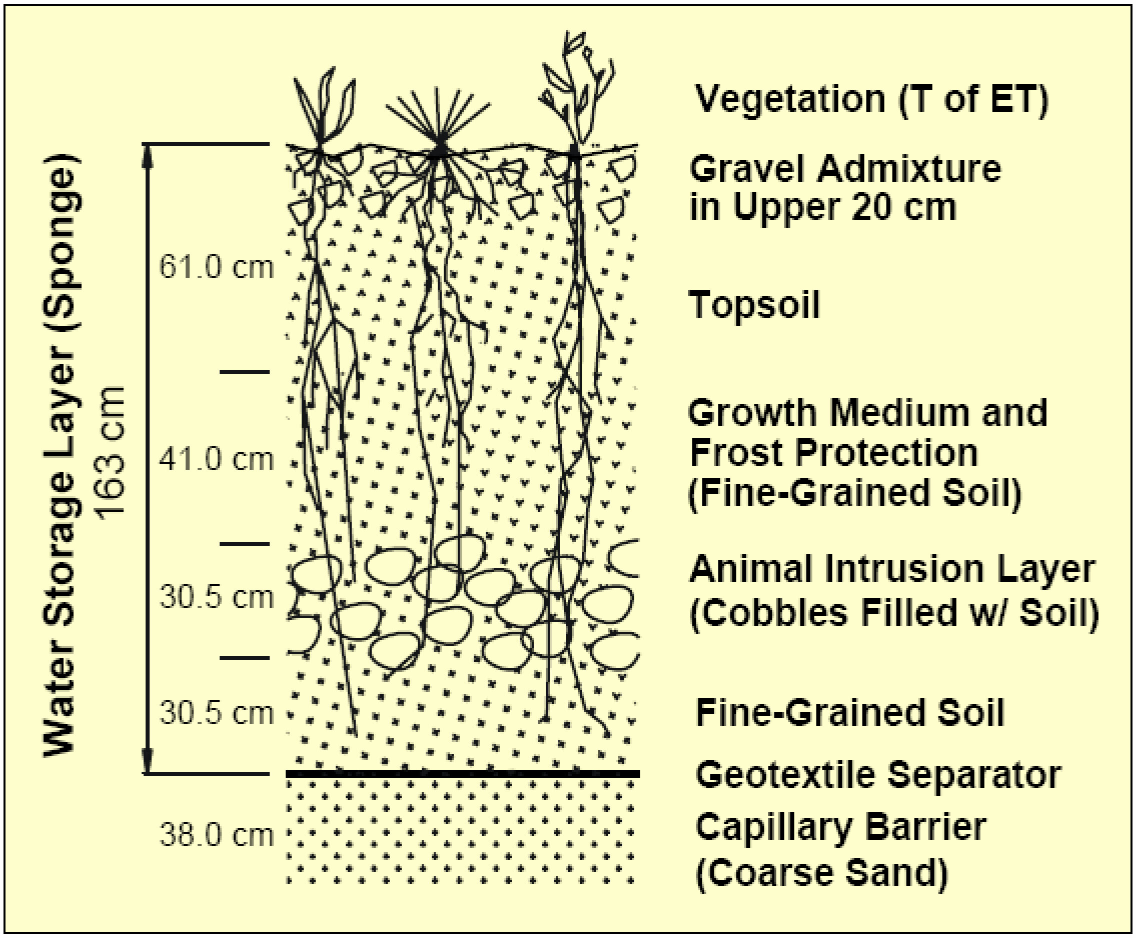


Figure 4.2-5. Monticello, Utah landfill cover profile

4.2.2.4 Depth of Cover System

The total depth of a cover system can actually be a bio-barrier. That is, the overall depth of the cover system may be thick enough that it is unlikely either burrowing animals/insects or plant roots will penetrate it. For example, 40 CFR Part 61 suggests that a cover thickness of at least 5 m will prevent accidental human intrusion. Furthermore, the cover depth may be thicker than burrowing animals or roots will likely penetrate.

4.2.2.5 Rock/Soil Admixture Surface Treatment

A surface treatment like the rock/soil admixture described in section 5.2.3 has been shown to prevent the burrowing of small mammals such as field mice. Observations made by Dwyer (2006) at a Superfund closure near Farmington, New Mexico noted that field mice burrowing is common near the site. There were widespread burrow holes observed on the site prior to placement of the cover system with the rock/soil admixture. These holes continue adjacent to the site; however, since installation of the cover system, there has been minimal observed burrowing on the cover system to date, believed to be the result of the rock mixed into the topsoil layer of the cover system (Figure 4.2-6).

Figure 4.2-6. Rock/soil admixture surface treatment at Superfund closure, Farmington, NM

4.2.2.6 Buried Fencing

For shorter design lives (i.e., no radionuclides present at the site), the horizontal placement of a metal fence may best stop the burrowing of animals nearer the surface so that an abandoned hole will not serve as a preferential path. Galvanized wire mesh placed at a shallow depth parallel with the surface will stop most small animals from burrowing below it (Dwyer et al. 1999). The fencing allows for root penetration and has no other impact on the cover system. The size of the wire mesh is dependent on the animal intruder of concern. Treatment of the metal, such as galvanizing the fence, is recommended to prevent rusting (Figure 4.2-7).

Figure 4.2-7. Placing wire mesh biointrusion layer

4.2.2.7 Root Control Bio-Barrier

Another bio-barrier option for shorter design life cover systems includes the use of a geotextile laced with a herbicide. Textile mats laced with an herbicide such as trifluralin have been used at sites to prevent root intrusion below a specified point. The mat is installed at a specified depth within the cover profile, and is designed to stop the growth of roots once in contact with it. The manufacturers of these products generally suggest their design life is less than 20 years. These root control bio-barriers have also been used above lysimeters used in research projects and cover system monitoring programs to prevent the intrusion of roots into the lysimeter.

Bio-barrier® Root Control System and Bio-barrier® II Weed Control System (http://www.geo-synthetics.com/pdf/products/Bio-barrier/Bio-barrierApplicationManual.pdf) are made of a durable, nonwoven, polypropylene geotextile fabric with permanently attached nodules containing trifluralin. Trifluralin prevents root tip cells from dividing, which is the method by which roots grow. The nodules are engineered to slowly release the trifluralin, creating a zone where root growth is inhibited. The geotextile fabric is porous to allow air, nutrients, and water through it. Bio-barrier® is installed vertically around any type of structure, creating a narrow protection zone in which roots will not grow. Bio-barrier® II is installed horizontally and will inhibit the growth of roots vertically below it. This product is generally only useful for a few years, however.

The technology was developed at the DOE-funded Pacific Northwest Laboratory, then tested at the Savannah River Ecology Laboratory and marketed by Reemay Inc. of Old Hickory, Tennessee. Vegetation can grow in the overlying soil, but not through Bio-barrier®. Limited root mass is the herbicide's only adverse effect on the plant. Research conducted so far at the Savannah River Ecology Laboratory, located on the Savannah River Site (SRS), indicates that Bio-barrier® may be effective for at least 15 years under SRS conditions. Continued study at SRS will show if Bio-barrier® is effective for its estimated lifespan of 30 years or more (http://www.uga.edu/srel/biobar.htm). The release of the herbicide is temperature sensitive. The climate and sandy soils of the Upper Coastal Plain make the herbicide

conducive to fast release, so Bio-barrier® might not last as long in this region. Bio-barrier® is not yet used in the hazardous waste industry. The industry is taking a conservative approach because the product is expensive—it costs an estimated $60,000 an acre. There are similar products made by other manufacturers.

4.2.2.8 Other Bio-Barriers

Other possibilities include miscellaneous items such as cast stone, a product that was developed for waste stabilization at Hanford. Cast stone would be useful as a bio-barrier. For this application, it would be prepared from Portland cement (Type I, II), Type F fly ash, Grade 120 blast furnace slag, and water. The material would be prepared in a manner similar to concrete, producing a slurry of approximately 6% Portland cement, 32% fly ash, 34% blast furnace slag, and 28% water. The slurry would be poured in place to form a barrier of the desired thickness. The slurry would cure rapidly to form a barrier with desirable properties. Specifically, the barrier would have excellent physical strength; a compressive strength of 3,000 to 4,000 psi, or possibly higher, would be expected. Volume change during curing would be negligible, minimizing the tendency to crack during this process. These attributes, high strength and resistance to cracking, would make the material an excellent barrier, resistant to penetration by burrowing animals and by plant roots. The barrier would be impermeable to fluid flow; the hydraulic conductivity has been determined experimentally to be negligible. The material itself would be non-toxic, passing Toxicity Characteristic Leaching Procedure and American National Standards Institute/American Nuclear Society 16.1 tests. It is anticipated that readily available concrete preparation equipment could be used to prepare cast stone. A local batch plant might be used, or mixing equipment could be brought to the site. Cost estimates for a six-inch-thick barrier is about $3 per square foot.

Shredded tires have also been used as a bio-barrier.

4.3 Gas Issues

Because it is unlikely gas vent layers will be incorporated in cover systems at LANL, the actual design of the layer is outside the scope of this document. However, issues related to gas produced by various waste must be understood by the design engineer to properly assess the site. Waste buried at LANL contains VOCs, radioactive contaminants, and other hazardous constituents. Transport-mechanism-controlling redistribution of these contaminants depends largely on the partitioning between solid, liquid, and gaseous phases. For many contaminants, transport in the gas phase may be as great as or much greater than transport in the aqueous phase. While gas transport causes movement of contaminants upward toward the soil surface, and downward toward the water table, the proximity of the source term near the land surface indicates that gaseous transport to the atmosphere can be significant. Design of a cover for an applicable LANL site must either accommodate or minimize gas transport within the cover. To illustrate the importance of designing the cover with due consideration for gas transport, we review in this section the impact of gaseous transport on some of the primary contaminants of concern at LANL.

Common VOCs include carbon tetrachloride, chloroform, trichloroethylene, tetrachloroethylene, and 1,1,1-trichloroethane. Numerical modeling studies can help indicate whether VOCs released from a LANL site will vent to the atmosphere. Some activated metals disposed of in disposal sites release radioactivity as they corrode. While some of the radioactive corrosion byproducts, such as Cl-36, are subject only to aqueous transport, a significant fraction of the released radioactivity is transported in the gas phase. Tritiated water and C-14 can release from beryllium reflector blocks, for example, and are transported both in aqueous and gaseous phase. The need to properly assess the relative rates of transport via liquid and gas movement is warranted. The importance of gas transport in the redistribution of C-14 and tritium must be well understood. If significant gases are being released, a venting system to remove such things as VOCs and C-14 from beneath the cover may be required. Installation of a cover over an emanating

site without a venting system would reduce the fraction of gas that is presently vented to the atmosphere through the soil surface. The cover soil would reduce the surface flux and result in higher gaseous concentration in the waste zone. These gaseous contaminants would be both vented around the cover to the surface and transported deeper into the subsurface. However, the transport of gas is a complex process that includes distance from the source to the boundary of interest, soil moisture content, gas-aqueous partitioning, water flux, solid-aqueous partitioning, soil-gas diffusion coefficients, and barometric pressure variations. In summary, before the final design of a cover can be completed, a careful analysis of the effects on gas transport from the given site should be made.

4.3.1 Heat Issues

Both biological degradation of organic waste and radionuclide decay produce heat within a landfill. Chemical reaction rates and transport of contaminants are functions of the temperature. Microbial degradation of organic matter, corrosion rates of metals, and chemical transport in the subsurface are often accelerated at elevated temperatures. An analysis of the amount of heat produced at a given LANL site should be evaluated.

4.3.2 Biological

An effort to estimate the amount of heat produced from the degradation of organic waste in a given LANL site should be made. One potential source of heat generation is from subsurface biological degradation of organic wastes. Heat is generated through aerobic and anaerobic metabolism. Elevated temperatures are common in landfills and composting. Factors affecting microbially driven temperature increase include moisture content, bulk density, and heat capacity of the waste materials and waste material composition. Increased CO_2 evolution is often used as evidence of aerobic biodegradation of organic contaminants in soil.

4.3.3 Radionuclide Heat Generation

The total amount of heat generation from the decay of radionuclides and its distribution should be understood.

4.3.4 Rn Attenuation

Some radioactive wastes emit Rn-222 in the form of a heavier-than-air gas. Inhalation of Rn gas at sufficient concentrations is a human health hazard. Federal regulations limiting Rn releases to the atmosphere are contained in DOE Order 435.1 Section IV.P(1)(c). The regulations are also typically applied as an ARAR to DOE sites undergoing remediation. These regulations require that release of Rn-222 to the atmosphere not exceed: (1) an average release rate of 20 picocuries per square meter per second or (2) increase the annual average concentration of Rn-222 in the air at or above any location outside of the disposal site by more than one-half picocurie per liter. To attenuate the release of Rn to the environment, the cover system may need to incorporate a Rn gas barrier. This barrier may be composed of the soil in the cover system or possibly the use of a geosynthetic material such as a GM. While the half-life of Rn-222 is short (3.8 days), Rn is a part of the U-238 decay series. U-238 has a half-life of about 4.5 billion years. Given this long half-life, there has been some concern about the longevity of GM barriers used for Rn control. Although GMs will not last forever, a properly selected and appropriately formulated GM, adequately protected by design, can last for a timeframe measured in hundreds of years. However, even with this best case scenario for the longevity of a GM, the GM will still not provide adequate protection, given significant Rn gas emissions, to be protective for a 1000-year performance period. Therefore, a GM shall not be used to control Rn at LANL. Consequently, only soil depth shall best be relied on for protection against Rn gases at applicable sites.

For a soil layer to function as an effective barrier to gas diffusion, air-filled voids in the soil have to be discontinuous. Gas diffuses very slowly through wet soils that contain only occasional, unconnected air bubbles. Relatively thick layers of clay-rich soil are typically employed when protection from Rn emissions is needed. For clayey soils to function effectively as gas barriers, they must be at a high degree of saturation and free of cracks. Over a design life of hundreds of years, maintaining a wet, undesiccated layer of clayey soil under natural conditions is not practical (Suter et al. 1993, Dwyer 2003). One design methodology documented by DOE (1989) involves determining the allowable Rn emission, estimating the Rn diffusion coefficient through the soil, and sizing the thickness of the soil layer based on the calculated diffusive flux. Additional information on Rn attenuation through cover systems is presented in NRC publications (Rogers and Associates 1984, Yu and Chen 1993).

A quick and easy way to determine the Rn flux through a soil or multiple-layered cover system can be found on the internet (http://www.wise-uranium.org/ctb.html). This site provides a calculator that determines the Rn fluxes through cover systems. It can also be used to optimize the cover thickness to satisfy a given flux constraint. The calculator is a clone of the Radiation Attenuation Effectiveness and Cover Optimization with Moisture Effects code, as described in Rogers and Associates (1984). It performs one-dimensional, steady-state Rn diffusion calculations for a multilayer system. In addition, the calculator optionally estimates the long-term moisture contents in each layer based on rainfall and evaporation, and adjusts the diffusion coefficients correspondingly.

4.4 Natural Analogs

Conventional engineering approaches for designing landfill covers often fail to fully consider ecological processes. Natural ecosystems effective at capturing and or redistributing materials in the environment have evolved over millions of years. Consequently, when contaminants are introduced into the environment, ecosystem processes begin to influence the distribution and transport of these materials, just as they influence the distribution and transport of nutrients that occur naturally in ecosystems (Hakonson et al. 1992). As the ecological status of the cover changes, so will performance factors such as water infiltration, water retention, ET, soil erosion, gas diffusion, and biointrusion. The objective in constructing an effective landfill is to design the cover so that subsequent ecological change will enhance and preserve the encapsulating system. Consideration of natural analogs can enhance a cover design by disclosing what properties are effective in a given environment or what processes may lead to possible modes of failure. These factors can in turn be avoided during the design and construction phases. Natural analog studies provide clues from past environments as to possible long-term changes in engineered covers. Analog studies involve the use of logical analogy to investigate natural and archaeological occurrences of materials, conditions, or processes that are similar to those known or predicted to occur in some part of the engineered cover system (Waugh 1994).

An objective for designing the covers at LANL, given the longevity requirements, is to accommodate long-term environmental processes with the goal of sustaining performance with as little maintenance as possible. The performance of the LANL covers will change in the long term as the environmental setting inevitably evolves in response to natural processes. Understanding how environmental conditions may change is crucial to designing, constructing, and maintaining long-term cover systems (Clarke et al. 2004). Effective modeling and performance assessment will require scenarios based on both current and possible future environmental settings. Natural analog studies help identify and evaluate likely changes in environmental processes that may influence the performance of engineered covers, processes that cannot be addressed with short-term field tests or existing numerical models (Waugh et al. 1994). Natural analog information is needed to

1. engineer cover systems that mimic favorable natural systems,

2. bound possible future conditions for input to predictive models and field tests, and
3. provide clues about the possible evolution of engineered covers as a basis for monitoring leading indicators of change.

Natural analogs also help demonstrate to the public that numerical predictions have real-world complements. Evidence from natural analogs can improve our understanding of

1. meteorological variability associated with possible long-term changes in climate;
2. vegetation responses to climate change and disturbances;
3. effects of vegetation dynamics on ET, soil permeability, soil erosion, and animal burrowing;
4. effects of soil development processes on water storage and permeability; and
5. site ecology.

Some investigation will be necessary to determine the landfill's waste contents and their relative harmful life expectancy. Materials such as radioactive waste can be harmful for a very long time. A natural analog is warranted to determine the cover system's performance over this length of time.

4.4.1 Examples of Natural Analogs

One application for analog studies (Suter et al. 1993, Mulder and Haven 1995, Dwyer 1997, Waugh and Smith 1997) is to assess the effectiveness of deployed prescriptive landfill covers. Another use is to look at the potential effectiveness of alternative covers. Refer to Appendix A for discussion of problems associated with prescriptive covers.

Climate data are required for design and performance evaluations of engineered covers. Evaluations may require projections of long-term extreme events and shifts in climate states over hundreds and thousands of years, as well as annual and decadal variability in meteorological parameters. There have been a few demonstrated methods based on global change models and paleoecological evidence to establish a first approximation of possible future climatic states at other sagebrush steppe sites, including Hanford (Waugh et al. 1994) and Monticello (Waugh and Petersen 1995).A preliminary analysis of paleoclimate data for Monticello yielded average annual temperature and precipitation ranges of 2–10°C and 80–60 cm, respectively, corresponding to late glacial and mid-Holocene periods. Instrumental records for regional stations were then used as a basis for selecting soil and vegetation analog sites that span a reasonable range of future climate states. Pedogenic (soil development) processes will change soil physical and hydraulic properties that are fundamental to the performance of engineered covers. Pedogenesis includes processes such as (1) formation of macropores for preferential flow associated with root growth, animal holes, and soil structural development; (2) secondary mineralization, deposition, and illuviation of fines, colloids, soluble salts, and oxides that can alter water storage and movement; and (3) soil mixing caused by freeze-thaw activity, animal burrows, and the shrink-swell action of expansive clays (Chadwick and Graham 2000). There have also been measured key soil physical and hydraulic properties in natural and archaeological soil profiles at climate analog sites to infer possible future pedogenic effects on the performance of the Monticello cover (Waugh et al. 2003). Other studies have conducted similar investigations at eastern disposal sites (Benson et al. 2005). Plant communities will establish and change on soil covers, whether intended or not, in response to climate, to soil development, and to disturbances such as fire, grazing, or noxious plant invasion. Changes in plant abundance, ET rates, root penetration, and animal burrowing may alter the soil-water balance and stability of a cover. Still more studies have attempted to quantify evidence of possible future ecological changes from

successional chronosequences. For example, at the Lakeview, Oregon, disposal site, possible future responses of plant community composition and leaf area index (LAI) to fire were evaluated using a nearby fire chronosequence (Waugh 2004). In addition, possible vegetation responses to climate change scenarios were evaluated at regional climate-change analog sites. LAI, as an index of plant transpiration, ranged from 0.15–1.28 for the fire chronosequence and from 0.43–1.62 for dry and wet climate analog sites.

Trenching adjacent to the site in an undisturbed area and determining the depth of plant roots may derive a simplistic analog. This can reveal the general depth of infiltration. Another method of determining the average long-term depth of water penetration (or infiltration depth) is to trench adjacent to the site in an undisturbed area to determine the depth of calcium carbonate ($CaCO_3$) deposits or formation of a caliche layer (Figure 4.4-1). Soils in semiarid and arid regions commonly have carbonate-rich horizons at some depth below the surface. The position of the $CaCO_3$-bearing horizon is therefore related to depth of leaching, which, in turn, is related to climate (Birkeland 1984).

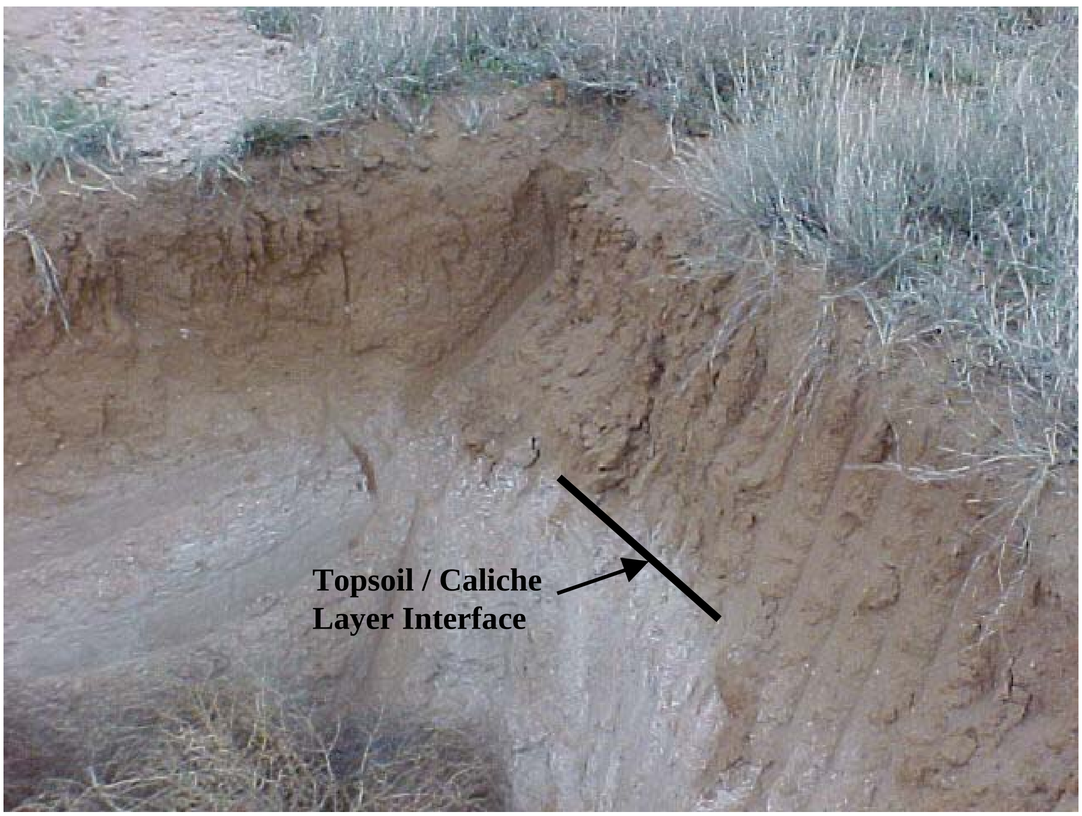


Figure 4.4-1. $CaCO_3$/soil interface at shallow depth

An example of a side slope natural analog is described here. Vegetated rocky side slopes are ubiquitous in semiarid and arid environments. A preliminary study of a vegetated rocky side slope was conducted in a semiarid area south of Grand Junction, Colorado (Smith et al. 1997). This slope flanks the Beaver Gulch drainage located at the Delta County–Mesa County boundary. Results of the investigation revealed the slope had an average gradient identical to disposal cell design guidance of 20%. Geomorphic and pedological evidence indicate this slope had been erosionally stable for more than 1000 years. Moisture infiltration was limited by transpiration to approximately 2 feet, as shown by the development of a thick

caliche layer at that depth. Surface erosional stability was provided by vegetation consisting of approximately 54% plants and litter cover; 37% rock cover consisting of coarse sand, gravel, and cobbles; and the remainder bare soil. Successful imitation of a side slope cover design like this analog slope would allow wastes to be placed beneath side slopes with the assurance of erosional infiltration control.

The natural analog of gravel covers for erosion control on landfill caps was developed from studies located in Nevada and Arizona (Simanton et al. 1986, Nyhan et al. 1990b, Hakonson et al.1990). Much of the ground surface in the Northern Mojave and Chihuahuan deserts is covered by erosion pavement (i.e., desert pavement), a natural layering of stones that has developed over thousands of years in many of the world's deserts. This natural stone covering has a very profound effect on water balance in these arid ecosystems by decoupling runoff from erosion and by greatly enhancing infiltration and plant-available moisture. The enhanced soil moisture results in increased plant biomass (Lane et al. 1986).

Age dating water within the mesas at LANL could also serve as a valuable natural analog.

4.5 Pedology Considerations

Soil formation is also known as pedogenesis (from the Greek words pedon, for "ground," and genesis, meaning "birth" or "origin"). Pedogenesis is the changes in soil structure caused by physical-chemical weathering and biointrusion. Soil formation is an ongoing process that proceeds through the combined effects of five soil-forming factors: parent material, climate, living organisms, topography, and time. Each combination of the five factors produces a unique type of soil that can be identified by its characteristic layers, called horizons.

A large number of processes are responsible for the formation of soils. This fact is evident by the large number of different types of soils that have been classified. However, at the macro-scale level, there are five main principal pedogenic processes acting on soils. These processes are laterization, podzolization, calcification, salinization, and gleization (Pidwirny 2006).

Laterization is a pedogenic process common to soils found in tropical and subtropical environments. High temperatures and heavy precipitation result in the rapid weathering of rocks and minerals. Movements of large amounts of water through the soil cause eluviation and leaching to occur. Almost all of the byproducts of weathering, very simple small compounds or nutrient ions, are translocated out of the soil profile by leaching if not taken up by plants for nutrition. The two exceptions to this process are iron and aluminum compounds. Iron oxides give tropical soils their unique reddish coloring. Heavy leaching also causes these soils to have an acidic pH because of the net loss of base cations.

Podzolization is associated with humid cold mid-latitude climates and coniferous vegetation. Decomposition of coniferous litter and heavy summer precipitation create a soil solution that is strongly acidic. This acidic soil solution enhances the processes of eluviation and leaching, causing the removal of soluble base cations and aluminum and iron compounds from the A horizon. This process creates a sub-layer in the A horizon that is white to gray in color and composed of silica sand.

Calcification occurs when ET exceeds precipitation, causing the upward movement of dissolved alkaline salts from the groundwater. At the same time, the movement of rainwater causes a downward movement of the salts. The net result is the deposition of the translocated cations in the B horizon. In some cases, these deposits can form a hard layer called caliche. The most common substance involved in this process is $CaCO_3$. Calcification is common in the prairie grasslands.

Salinization is a process that functions in a similar way to calcification. It differs from calcification in that the salt deposits occur at or very near the soil surface. Salinization also takes place in much drier climates.

Gleization is a pedogenic process associated with poor drainage. This process involves the accumulations of organic matter in the upper layers of the soil. In lower horizons, mineral layers are stained blue-gray because of the chemical reduction of iron.

Past practices have largely neglected pedogenic effects in the design of landfill covers. EPA (1991) and specific landfill cover regulations such as those described in 40 CFR 258 suggest that the effectiveness of a cover system is a result of a very low “as-built” saturated hydraulic conductivity value in a soil barrier layer. However, dynamic pedogenic effects on this barrier layer will change the installed saturated hydraulic conductivity of this soil barrier layer beginning shortly after construction (Suter et al. 1993, Dwyer 2003, Benson et al. in press). Consequently, many early assumptions regarding landfill closures were flawed as described in Appendix A. Typical processes that occur after the construction of a cover system, such as freezing and thawing, wetting and drying, root growth and death, and burrowing of worms and insects, can form larger pores in cover soils (Hillel 1998), thus altering the hydraulic properties of that soil and the hydrology of the cover system (Suter et al. 1993, Benson and Othman 1993, Chamberlain et al. 1994, DOE 1989, Albrecht and Benson 2001, Dwyer 2003.

Time-dependent changes in cover soil properties caused by pedogenesis (changes in soil structure due to processes such as weathering and biota intrusion) confound quantitative assessments based on water-content measurements. For example, Benson et al. (2005b) showed that, within five years from the end of construction, the saturated hydraulic conductivity of cover soils can increase by a factor of more than 1000, van Genuchten’s α parameter can increase by a factor of 100, and the saturated volumetric water content can increase as much as 1.5 times. Changes of this magnitude can have a large effect on interpretations based on water contents unless a new threshold water content is regularly defined in accordance with the level of pedogenesis that has occurred.

Cracking due to frost can increase the layers’ saturated hydraulic conductivity, in some cases by as much as four orders of magnitude (Benson et al. 1995). Desiccation can create cracks and thus create preferential flow paths (Montgomery and Parsons 1990, Suter et al. 1993, Benson et al. 1994b). Shallow excavation of a soil barrier layer revealed extensive cracking in the barrier layer (Dwyer 2003). Furthermore, root intrusion into the barrier layer can increase the saturated hydraulic conductivity by as many as three orders of magnitude (Dwyer 2003, Waugh et al. 1999).

Because there is adequate evidence that pedogenic properties do alter a soil’s hydraulic properties, it is best practice to attempt to install the cover soils at properties they will migrate toward long-term. That is, soil may be placed at higher or lower densities, but long-term tendency for a given soil is to move toward an equilibrium dry bulk density. This density can be determined by measuring the in situ density of a given borrow soil in an undisturbed location to measure where that soil density will move toward. Similar measurements may be made with regard to unsaturated hydraulic conductivity. See section 3 for detailed descriptions and design recommendations.

4.6 Geomorphology

Geomorphology is the basis of soil formation. Applicable and appropriate geomorphology studies shall be utilized for all LANL sites that contain long-lived radioactive waste. DOE (1989) outlines the purpose and approach of such studies. Many of these studies have previously been performed at LANL. Reneau (1995) is an excellent example of applicable geomorphology studies performed at LANL. This study discusses the possibility of steep mesa edges retreating up to 50 feet during the potential lifetime of a

cover system governed by DOE 435.1. Consequently, an evaluation of each MDA closure shall be made of the potential for mesa edge retreat and its potential consequence on the site. Furthermore, Reneau (1995) concludes that sediment transport is the largest threat for contaminant transport. Therefore, special attention is to be given to the cover system design for each MDA site to ensure that erosion due to both wind and surface runoff is mitigated to an acceptable level.

The purposes of any geomorphic hazard assessment are: (1) to identify the geomorphic processes affecting the site, (2) to estimate the probability of their occurrence, and (3) to evaluate the possible magnitude of their effects during the life of the closed site. The general approach used to fulfill these purposes involves three steps: (1) identification of past geomorphic processes and estimation of their rates from the geomorphic and stratigraphic records (postglacial time, roughly 10,000 years), (2) identification of present geomorphic processes and estimation of their rates from historic records and field observations (typically less than 80 years), and (3) prediction of future geomorphic processes and rates with appropriate allowances for various uncertainties associated with such processes. This process involves the integration of data at varying scales of space (regional to single point) and time (thousands of years to instantaneous). The hazards assessments are typically qualitative in nature although some quantitative models are available.

4.7 Access Controls

Fencing is required around the perimeter of each landfill. The type and extent of fencing will depend on the existing natural vegetation and topographic features and is to be approved by the LANL designated representative. All access points are to have locking gates. The fencing standards used at LANL shall be followed (http://engstandards.lanl.gov).

4.8 Aesthetic and End Use of Final Closure Sites

Aesthetic and land use criteria are becoming more important in the design of cover systems (EPA 2004). More and more, facility owners, regulators, and the local community are sensitive to the aesthetics of closed waste management sites. Today, it is not uncommon to design aesthetic enhancements into site closure projects. Closed waste containment and remediation sites located in ecologically significant areas have been used as wildlife enhancement areas or wetlands. Both the Rocky Flats Plant and RMA in the greater Denver, Colorado area are destined for wildlife refuges upon closure.

Cover systems at LANL will not be used for any future development possibilities other than industrial use within LANL's continued control. However, cover systems shall consider aesthetics in their final design. The cover systems ideally will be designed to blend into the surrounding environment.

5.0 ENGINEERING REQUIREMENTS AND CONSIDERATIONS

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. ET cover designs ideally mimic naturally occurring conditions that take advantage of site conditions such as dry climates and soils with higher storage capacities. Consequently, the engineering performed will try to mimic applicable natural analogs in detailing the final cover system. Besides selecting the required cover profile described in section 3, 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 shall be designed to minimize erosion while shedding surface water. For steeper slopes, stability issues may be of concern. Some MDA sites will present settlement issues due to the randomness of waste placement or potential of degradation of waste containers and subsequent collapse potential.

5.1 Cover Soil

It is important to determine there are adequate soils available for the construction of any cover system. This involves ensuring that both the quantity and quality of soil is available. An ET cover consists of a single, vegetated soil layer constructed to represent an optimum mix of soil texture, soil thickness, and vegetation cover (Dwyer 1997). Consequently, the quality of soils is of utmost importance to ensure the long-term integrity of the cover system.

5.1.1 Borrow Material for Cover Soil

A borrow investigation was performed at TA-61 to help ensure there is adequate quantity of soils available for the myriad of cover systems required at LANL. Soils on the Nambe Pueblo were also evaluated. The soils have also been tested for their unsaturated hydraulic soil characteristics.

5.1.1.1 TA-61 Borrow Site

A geotechnical characterization and drilling exercise was performed (Shaw 2006) at TA-61 to identify a potential borrow source for soil to use as a cover material throughout the LANL site. The site is located on the Pajarito Plateau composed of Quaternary age ash flow and ash fall tuff. The borrow site is approximately 30 acres in size. The approximate volume of soil evaluated was 3.1 million cubic yards. It is made up of varying terrain and vegetation. The site is generally covered with ponderosa pine, scrub oak, piñon, and juniper.

The soils at TA-61 are composed of native or undisturbed surface soil and volcanic ash flow tuff. The native soils on the mesa surface tend to be relatively thin and poorly developed. The soil is more coarse and sandy near the surface while possessing more clay underneath. The soil profile tends to have higher organic content near natural drainages. The soils at depth (to a depth of about 60–70 feet) are generally non- to partially-welded ash flow tuff, also known as ignimbrite. A number of samples were laboratory tested for hydraulic and some geotechnical properties. The soils were tested at DB Stephens Laboratory in Albuquerque, New Mexico (Shaw 2006). Borrow volumes of available cover soil were estimated, as were approximate costs to excavate and transport to applicable sites. Laboratory testing included:

A. For all samples: initial soil properties (moisture content and dry bulk density), saturated hydraulic conductivity (constant head permeameter), and moisture characteristic curves (using hanging columns, pressure plates, a water activity meter, and a relative humidity box depending on the matric potential).

B. For some samples: particle size distribution (wet sieve and hydrometer), Atterberg limits, particle density, and proctor compaction (ASTM D 698).

Calculated values from tested properties included unsaturated hydraulic conductivity, porosity, ASTM and USDA classification, particle size characteristics (d_{10}, d_{50}, C_u, and C_c) and van Genuchten parameters (α, n, residual moisture content, and saturated moisture content).

The hydraulic properties were tested at densities ranging from about 75–95% of the MDD per ASTM D 698. The majority of these soils were characterized as a sandy loam. The saturated hydraulic conductivity values ranged from about 1×10^{-2} cm/sec at remolded densities in the lower density range to as low as about 1×10^{-5} cm/sec with remolded densities toward the higher end. The average saturated hydraulic conductivity was about 10^{-4} cm/sec.

5.1.1.2 Nambe Pueblo Soil

A field investigation was performed to collect samples of alluvial soil for potential use as a cover soil or for soil amendment for laboratory testing. This soil is comprised of Santa Fe Formation alluvium that is highly variable in the grain size characteristics. Based on observations, the soil was stated as possessing soil ranges (Unified Soil Classification) from plastic clay to poorly graded sand. Ten samples were collected and tested for properties as described above for TA-61 with accompanying calculated values also similar to those calculated for TA-61 soils. The hydraulic values were tested over a wide series of densities. Samples tested at densities remolded to about 82.5% of the MDD provided saturated hydraulic conductivity values between 8.1×10^{-6} and 2.7×10^{-3} cm/sec. This density range generally reflects loosely placed soils. Soils remolded to about 95% of their MDD generally decreased the saturated hydraulic conductivity, while those remolded to about 75% of MDD typically showed about an order of magnitude increase in the saturated hydraulic conductivity.

5.1.1.3 Basalt

Basalt outcrops located within LANL land limits include areas in TAs-33, -36, -70, and -71. These outcrops were identified via U.S. Geological Survey quadrangle maps. LANL owns mineral rights within its boundaries and therefore could potentially mine this material if required and determined to be economically and practically viable. The basalt could serve as material required for a bio-barrier, riprap, and/or other erosion-resistant material.

5.1.2 Salt Content in Soils

Cover soil will be characterized by the following agronomic characteristic ranges that include pH, electrical conductivity (EC), sodium absorption ratio (SAR), exchangeable sodium percentage (ESP), $CaCO_3$ equivalent, cation exchange capacity (CEC), percent organic matter, nitrogen (N), phosphorous (P), and potassium (K).

EC estimates the amount of total dissolved salts, 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 SAR is the proportion of sodium (Na) ions compared to the concentration of Ca plus magnesium (Mg). An SAR value of 15 or greater indicates an excess of Na will be adsorbed by the soil clay particles. Excess Na can cause soil to be hard and cloddy when dry, to crust badly, and to take water very slowly. CEC is a calculated value that is an estimate of the soil’s ability to attract, retain, and exchange cation elements. It is reported in millequivalents per 100 grams of soil (meq/100g). The ESP refers to the concentration of Na ions on CEC sites. An ESP of more than 15% is considered the threshold value for a soil classified as sodic. This means that Na occupies more than 15% of the soil’s CEC. Be aware that sensitive plants may

show injury or poor growth at even lower levels of Na. Table 5.1-1 summarizes the tests that evaluate the salt content in soils, with maximum allowable limits for each test.

Table 5.1-1
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 15% (g/g) – to 3-ft (91 cm) depth of cover; No limit below 3 ft (91 cm)

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 5.1-1.

Figure 5.1-1. 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 5.1-2). 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 lead to increased erosion.

Figure 5.1-2. 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 (Figure 5.1-1). 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 via water intake take up nutrients from the surrounding soil (http://interactive.usask.ca/ski/agriculture/soils/soilman/soilman_sal.html).

5.1.2.1 $CaCO_3$ Content in Cover Soils

The aforementioned discussion on salt content in soils was more related to soluble salts. Less soluble salts such as $CaCO_3$ are also harmful to cover soils in excess. Figure 5.1-3 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 5.1-3. 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) (Birkeland 1974). This formation tends to be most active in the upper soil where biological activity is highest. Ca 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 (Birkeland 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 et al. 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 groundwater.

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 cm (~39 inches), calcic soil horizons disappear from the soil profile (Blatt et al. 1980).

Formations of $CaCO_3$ horizons or accumulations in soil of arid and semiarid regions in the world are common. In India, 54% of the total geographic area has soil that is calcareous (Pal et al. 2000), and in Iowa 2.6 million acres of land are affected by $CaCO_3$ (Kiloen and Miller 1992). All the borrow areas characterized at RMA contained some soil that had a $CaCO_3$ layer at depth (the Bk horizon). Generally, at RMA, the calcic soil layer is present at depths between 4 and 13 feet below grade.

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 [P]) and micronutrients (e.g., zinc and boron).

The macronutrient most affected by the presence of $CaCO_3$ is P. P 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 P that influenced plant growth and nutrition. In order for P 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 P available to plants depends upon the pH of the soil (McGeorge 1933, Salisbury and Ross 1992). 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, P can react with $CaCO_3$ in soil to form $CaCO_3$ phosphate (McGeorge 1933, Dominguez et al. 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, 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 P, and water.

Based on research performed by Dwyer (2003) and an extensive literature review conducted by Arthur (2004) for cover systems to be installed at RMA in Denver, Colorado, the maximum allowable Ca content levels for cover soil in the rooting zone (upper 3 feet [91 cm]) shall be 10% by weight.

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.

5.1.3 Soil Nutrient Requirements

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 CEC, percent organic matter, N, P, and K. The following soil nutrient values are required in the upper 3 feet (91 cm) of all cover soil installed. Table 5.1-2 summarizes the tests to be performed on soils to determine the appropriate nutrient levels with their recommended acceptable range.

Table 5.1-2
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	Greater than 5 ppm
K	Greater than 61 ppm
pH	Between 6.0 and 8.4

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. CEC represents the sites in the soil that can hold positively charged nutrients like Ca, Mg, and K. If CEC is increased, the soil can hold more nutrients and release them for plant growth. To increase CEC, organic matter must be increased.

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: (1) the living microbes in the soil (like bacteria and fungi), which break down very rapidly when they die; (2) partially decayed plant material and microbes, for instance, plant material you mix in or manure; and (3) the stable material formed from decomposed plants and microbes. This material is called humus, which is broken down very slowly.

Organic matter affects both chemical and physical properties of the soil. Chemical effects include organic matter releases many plant nutrients as it is broken down in the soil, including N, P, and sulfur (S). It is also one of two sources of CEC in the soil. (Clay is the other major source.) Physical effects include organic matter that 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 fairly 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 must meet the environmental standards of the site.

5.1.4 Soil Placement

An important aspect involved with the construction of a soil cover system is that the soils are placed in a uniform manner. This will help limit preferential flow through the cover. Dwyer (2003) describes the impact of preferential flow in landfill covers. Preferential flow cannot be avoided, but necessary precautions shall be employed to ensure it is minimized. An important feature of the design specifications will involve determining an acceptable density range at which to install the cover soils.

The acceptable density and moisture range produced during construction activities is referred to as the ACZ (Dwyer et al. 1999). Cover soil shall be placed within the ACZ (section 3) specific to the soil used. Cover soils shall be placed within a tight density range. If there is not adequate borrow soil available from a single source, then soils imported from multiple borrow sources must be blended and placed within an ACZ specific to the newly blended soil. These blended soils must meet all requirements stated in this document.

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

5.2 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 5.2-1). Vegetation is ideal to minimize erosion; however, in dry climates such as Los Alamos, native vegetation is relatively sparse and unable to form a continuous blanket to completely limit erosion. Consequently, each cover design shall address how to assist vegetation in minimizing both short- and long-term erosion.

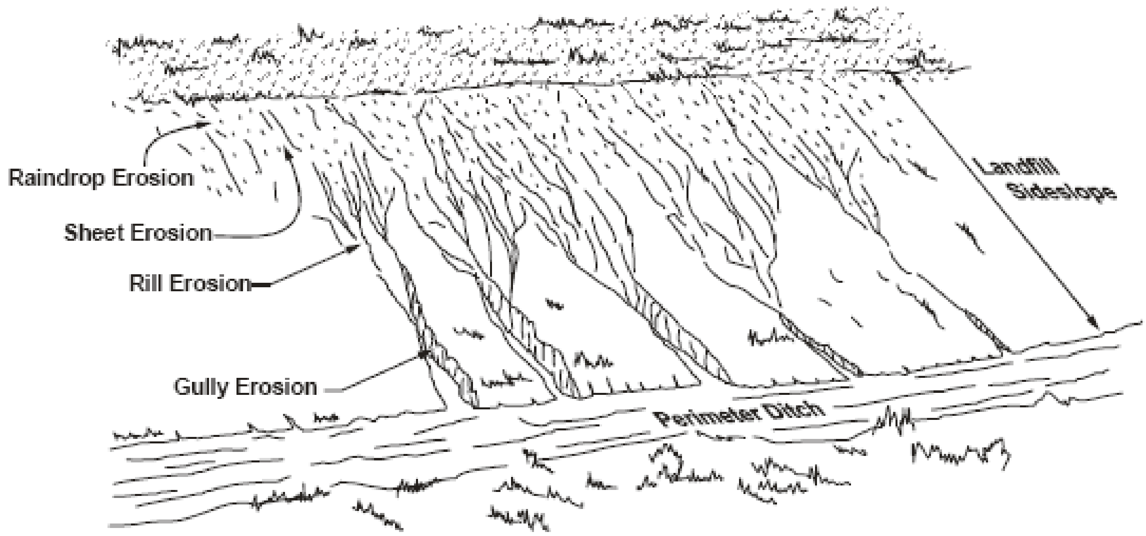


Figure 5.2-1. Types of water erosion that may occur on a cover system

5.2.1 Short-Term and Long-Term Erosion

The cover system design shall 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 shall 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 further serve to spread accumulated surface contamination. 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. The conclusion of cover construction shall 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 shall be written to ensure seeding and/or planting of native vegetation prior to the arrival of the summer rains in July and August. Furthermore, it shall be specified that supplemental irrigation will be required to ensure an adequate stand of vegetation as soon after construction as possible.

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 shall 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 shall 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 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 shall not be exceeded. Although it is advisable to select allowable rates of soil erosion on a project-specific basis, all LANL covers shall be designed so that sheet erosion rate not exceed 2 tons/acre/year (4.5 tonnes/hectares (ha)/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 shall 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 shall also be sufficient soil thickness to support vegetation and provide for adequate water storage capacity.
- The surface layer shall resist gully formation under the tractive forces of runoff from the site-specific design storm(s).
- Wind erosion shall also be evaluated.

5.2.2 Erosion Analysis Tools

The following analysis methods for sheet and rill erosion, gully formation, and wind erosion are suggested for use at LANL sites and are briefly described below.

5.2.2.1 Sheet and Rill Erosion Due To Surface Runoff

The 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 USDA within 60 days of the enactment of FAIRA. This subpart sets forth the equations and definition of factors and provides the rules under which NRCS will utilize the USLE, the revised universal soil loss equation (RUSLE), and the WEQ.

5.2.2.1.1 RUSLE

Since the publication of the USLE in 1985, additional research on erosion processes has resulted in refined technology for determining the factor values in the USLE. RUSLE represents a revision of the USLE technology in how the factor values in the equation are determined. RUSLE is explained in the USDA 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 (Equation 5.1):

$$A_s = R_e \, K \, (LS) \, C \, P_c$$ **Equation 5.1**

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) 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) 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) 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) is the ratio of soil loss with a specific support practice (such as cross-slope farming, stripcropping, 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 5.1, the thickness of cover soil at the end of the cover system design life can be calculated to verify there is sufficient cover soil remaining.

5.2.2.1.2 Water Erosion Prediction Project (WEPP) Model

The WEPP 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 m, 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 1980s, when an increasing need for improved erosion prediction technology was recognized by the major research and action agencies of the USDA and Department of the Interior, including the Agricultural Research Service (ARS), NRCS, Forest Service, and Bureau of Land Management. In 1985, these agencies embarked on a 10-year research and development effort to replace the RUSLE. Some of the differences between the WEPP model and the RUSLE are as follows:

- The RUSLE 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.

5.2.2.2 Landscape Evolution Modeling

Landscape evolution and long-term erosion analysis have been conceptually performed at LANL for MDA G (Wilson et al. 2005) using a software package named SIBERIA (Wilgoose 2000). SIBERIA was developed for large mine sites in Australia where optimization of large tailings piles can be regulated over a 1000-year period. Referring to case studies, SIBERIA is generally not used by practitioners to predict erosion rates, but rather to predict a long-term evolving landscape (Landloch 2004, Ayres et al. 2005). In these case studies, WEPP or RUSLE were generally used to actually predict and design for erosion minimization. SIBERIA was used to optimize the shape of the large piles.

5.2.2.2.1 SIBERIA

SIBERIA is a computer model for simulating the evolution of landscapes under the action of runoff and erosion over long time scales (up to 1000 years). The hydrology and erosion models are based on ones that are simple and widely accepted in the hydrology and agricultural communities since the 1960s. The sophistication of SIBERIA lies in (1) its use of digital terrain maps for the determination of drainage areas and geomorphology and (2) its ability to efficiently adjust the landform with time in response to the erosion that occurs on it (Wilgoose 2000).

The SIBERIA landscape evolution model has been used as a tool for testing rehabilitation proposals for the Australian government after the completion of approximately 30 years of mining (Willgoose and Riley 1998). While SIBERIA is used to predict the development of landscapes, few field studies have been performed to prove that the landforms predicted by SIBERIA for the waste rock dump are correct (Hancock 2004).

5.2.2.3 Gully Erosion

The concentration of runoff under many circumstances encourages the formation of rills, which, if unchecked, grow into gullies (Figure 5.2-2). This is arguably the most severe type of erosion of cover systems soils at landfill and waste remediation sites.

Figure 5.2-2. 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 LANL covers shall 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.

5.2.2.3.1 Tractive Force Method for Vegetated Surface Layers

The tractive force method (Temple et al. 1987, DOE 1989) can be used to calculate the allowable shear stress, τ_a (kPa), of a vegetated surface layer as:

$$\tau_a = \tau_{ab} C_e^2 \geq 0.9 \text{ kPa} \qquad \textbf{Equation 5.2}$$

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 graphical determinations for graphs for both τ_{ab} and C_e values.

The allowable shear stress (Equation 5.3) must be equal to or greater than the effective shear stress applied to the surface layer by the flowing water, τ_e (kPa):

$$\tau_a \geq \tau_e = \gamma_w DS(1-C_F) (n_s/n)^2 \qquad \textbf{Equation 5.3}$$

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 5.4) (DOE, 1989):

$$D = (qn/S^{0.5})^{0.6}$$ **Equation 5.4**

where:

q = peak rate of runoff (ft^3/sec) 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).

5.2.2.4 **Wind Erosion Equation** (Woodruff and Siddaway, 1965)

Wind erosion physically removes the lighter, less dense soil constituents such as organic matter, clays, and silts (Figure 5.2-3). Thus it removes the most fertile part of the soil and lowers soil productivity (Lyles 1975). During the 1930s, a prolonged dry spell culminated in dust storms and soil destruction of disastrous proportions. The WEQ for predicting soil loss due to wind erosion is:

Figure 5.2-3. Wind erosion in arid climate

E=f (I K C L V). **Equation 5.5**

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.

5.2.3 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 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 semiarid climates, gully erosion can be orders of magnitude greater than sheet flow erosion. Consequently, all cover systems designed and constructed at LANL shall have a rock/soil admixture applied to the surface. Rock/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 5-2.4 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 saturated hydraulic conductivity requirement imposed on the site. Severe winds eroded the newly installed cover soils, leaving behind some desiccated clay and minimal fines stabilized by sparse vegetation (Figure 5.2-4). Of the two feet of soil originally installed as the cover, less than a foot remained after a year. An ET cover was utilized with native soils, and a rock/soil admixture similar to that seen in Figure 5.2-6 was installed. The cover is working very well today after the fix.

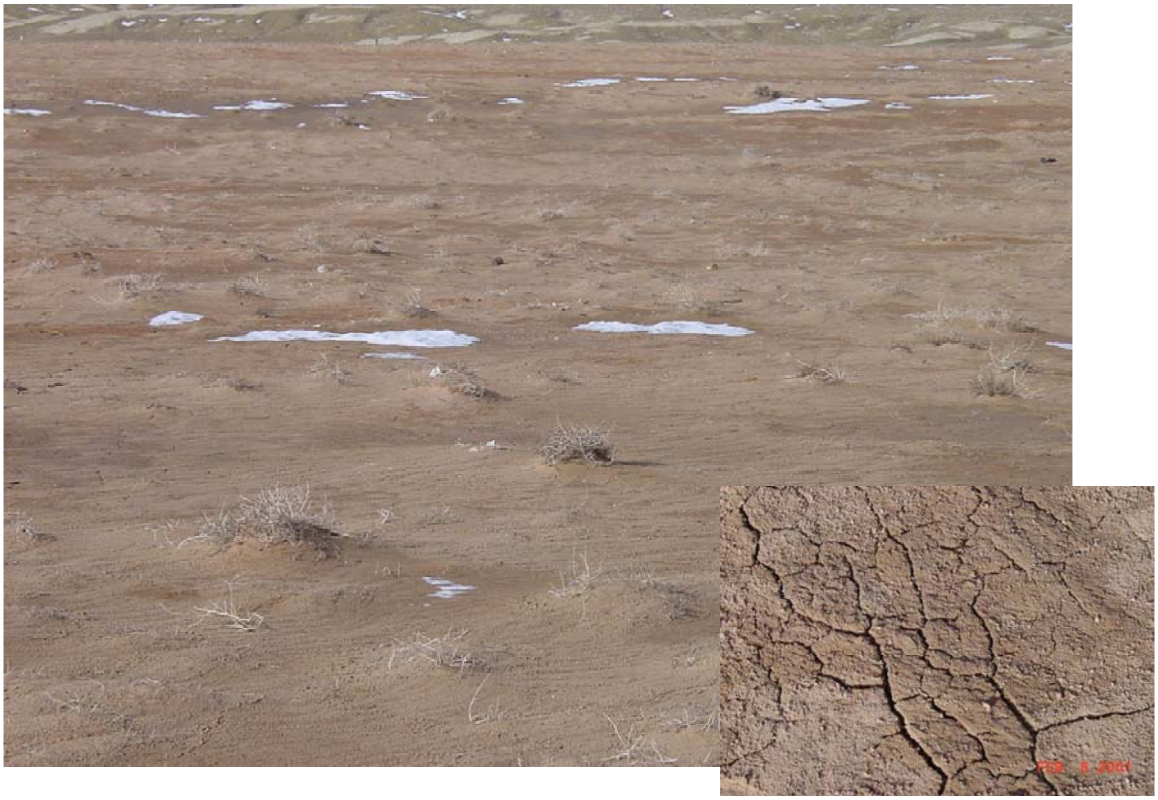


Figure 5.2-4. Landfill cover located on the Navajo Reservation that experienced significant wind erosion and desiccation cracking

The design of a gravel admixture layer shall be based primarily on the need to protect the soil cover from water and wind erosion. A gravel admixture generally protects 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 runoff 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-hour, 100-year storm produces more than 10 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 (Figure 5.2-1). When runoff is channeled into the developing gullies, the velocity increases and thus erosion increases (Figure 5.2-5). For a cover surface, gully formation is particularly problematic because it can compromise the function of the cover system to isolate the underlying waste. Thus gully formation in response to extreme rainfall events is of particular concern for landfill cover systems at LANL, particularly due to the long design lives.

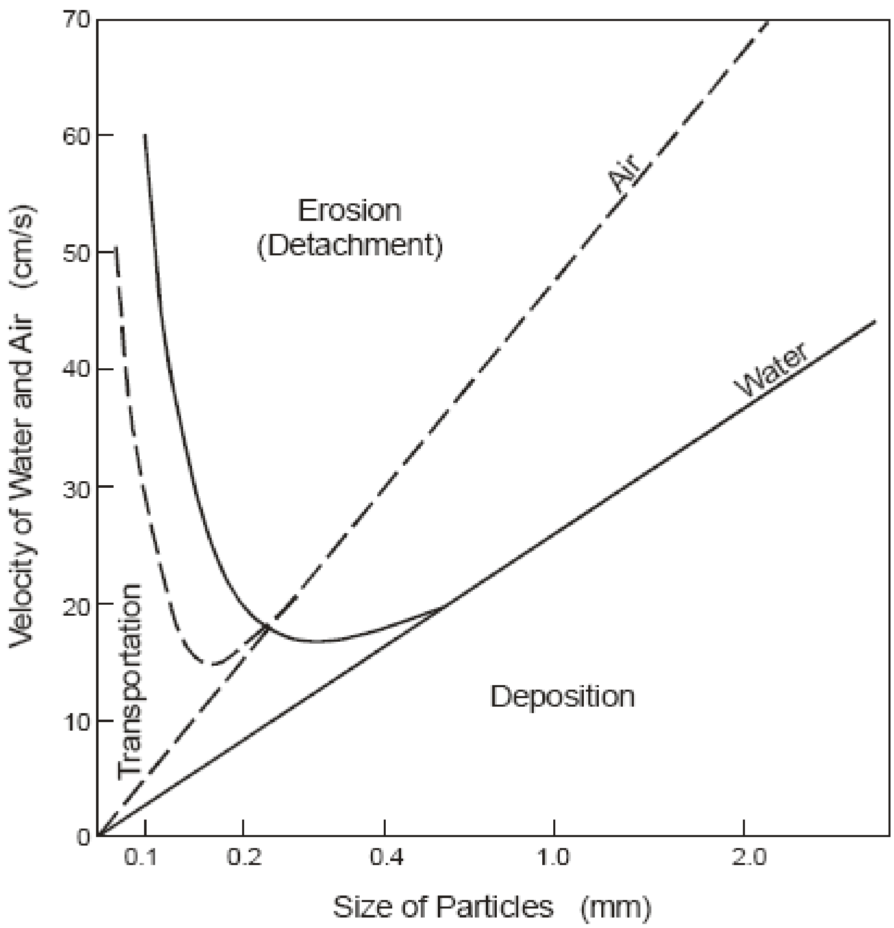


Figure 5.2-5. Relationship between erosion mechanism (air or water), particle size, and fluid velocity (Garrels 1951 as referenced by Mitchell 1993)

Erodibility of soils increases as particle size gets smaller (Figure 5.2-5). 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 2003). 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 runoff and wind erosion.

5.2.3.1 Soil/Rock Admixture Design Methodology

There is no universally accepted method to design a soil/rock admixture to serve as a surface “armor” or “desert pavement” (Figure 5.2-6). Consequently, an approach was developed that combines analytical and empirical relationships in a step-by-step process (Dwyer et al. 1999).

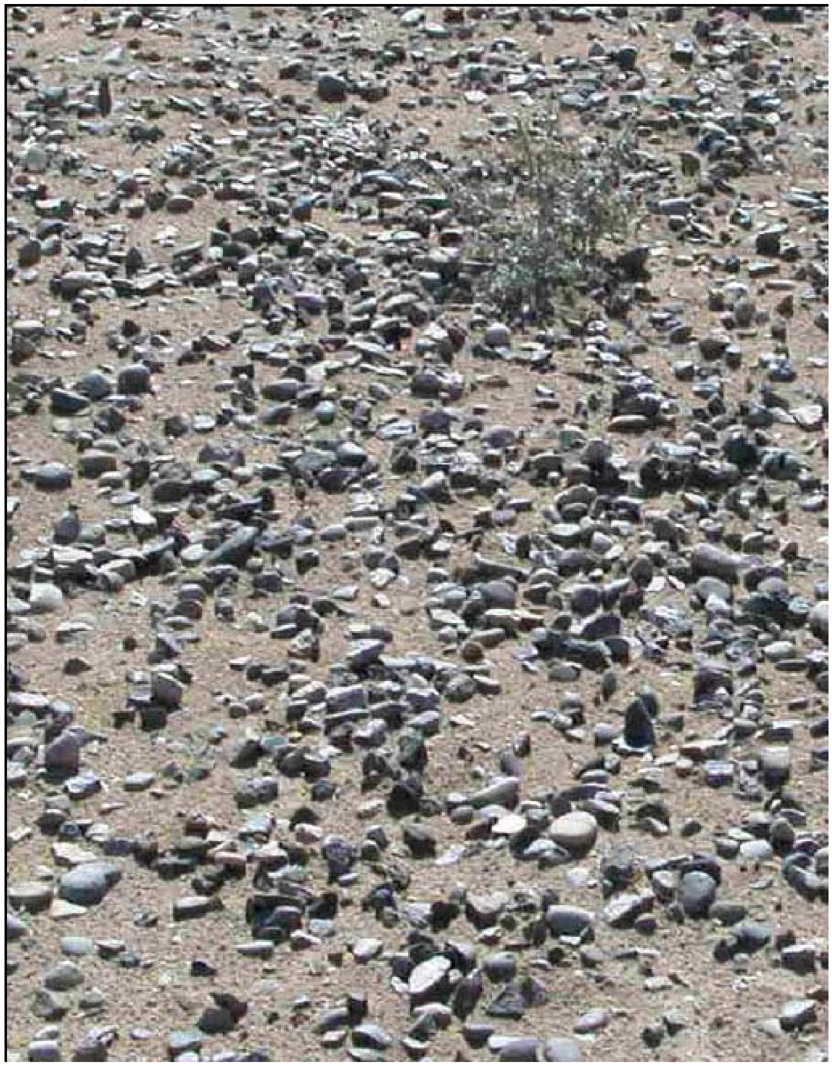


Figure 5.2-6. Gravel recently installed on Superfund closure in Farmington, NM

The following steps are involved in the design methodology:

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

5.2.3.1.1 Design Rainfall Event

Use the 100-year-return period as the design event for RCRA-equivalent sites (refer to "LANL Engineering Standards Manual," OST220-03-01-ESM, Section G20). The methodology described in DOE (1989) that utilizes the Probable Maximum Precipitation (PMP)/Probable Maximum Flood (PMF) shall be used for sites governed by DOE 435.1.

5.2.3.1.2 Runoff Prediction

The "rational method" is one of the simplest and best-known analysis methods routinely applied in urban hydrology. It is commonly used in civil engineering applications and is a method approved by DOE (1989) for design of cover systems for sites regulated by the Uranium Mill Tailings Radiation Control Act of 1978 (i.e., UMTRA sites). Refer to "LANL Engineering Standards Manual," Section G20 (http://engstandards.lanl.gov/engrman/3civ/pdfs/Ch3_G20-R1.pdf). The rational method is based on the assumption that rainfall occurs uniformly over the watershed at a constant intensity for a duration equal to the time of concentration. This method is typically used for areas about 100 acres (40 ha) in size. Other more complex methodologies may be used, but the Rational Formula will be described here because it is fairly straightforward and easily explained.

Using the rational method, the peak rate of runoff, (Q), in cubic feet per second (cfs) (runoff is actually in acre-inches/hour but is rounded to equate to cfs) is given by the following expression:

$$Q = C\ I\ A$$ **Equation 5.6**

where:

C = Runoff coefficient (dimensionless)

I = Rainfall intensity (in/hr)

A = Surface area that contributes to runoff (acres)

The appropriate value for "I" in this case where erosional processes are being evaluated in the peak intensity is dependent on the design life of the cover system. The duration of the peak rainfall intensity is often derived from the "time of concentration," which represents the time for runoff 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." Typical values for C are listed in Table 5.2-1 as well as in the "LANL Engineering Standards Manual." However, for storms with return periods longer than 100 years, DOE recommends the use of C = 1.0 (DOE 1989).

Table 5.2-1
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 contributory area is found from the following Figure 5.2-7.

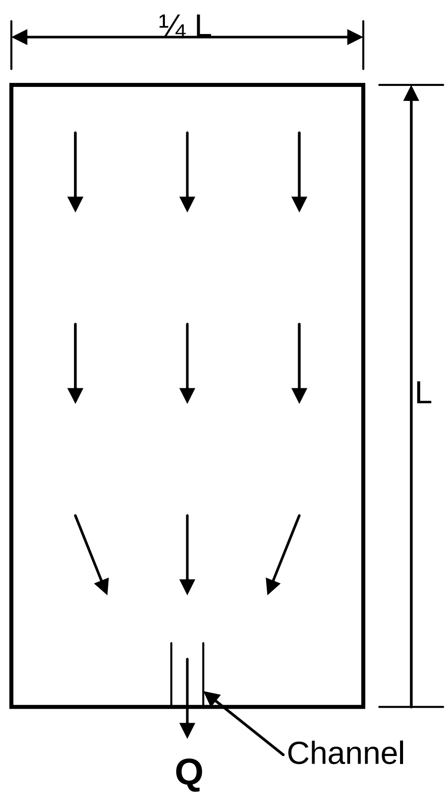


Figure 5.2-7. Contributory area for gully formation

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 be about one-quarter that of the slope length based on professional experience and consultation with experts. Consequently, the cross-sectional area is equal to $1/4L^2$.

5.2.3.1.3 Channel Geometry

The channel geometry shown in Figure 4.2-8 is that assumed for the gully formation.

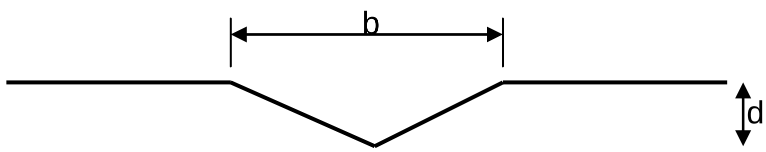


Figure 5.2-8. Channel geometry

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

$$b = 37 \left(Q_m^{0.38} / M^{0.39} \right)$$ **Equation 5.7**

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% and 20% of the peak rate of runoff (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:

$$b = 0.5 F^{0.6} F_r^{-0.4} Q^{0.4}$$ **Equation 5.8**

where:

F = width to depth ratio = b/dh;

F_r = 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.

5.2.3.1.4 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 5.9**

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:

$$\tau = \gamma\, d_h\, S$$ **Equation 5.10**

where:

S = slope (ft/ft).

5.2.3.1.5 Depth of Scour and Armoring 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 5.2-9) to establish an armor layer is given by (Pemberton and Lara 1984):

$$Y_s = Y_a\,[(1/P_{c)}-1]$$ **Equation 5.11**

where:

Y_s = scour depth;

Y_a = armor layer thickness;

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

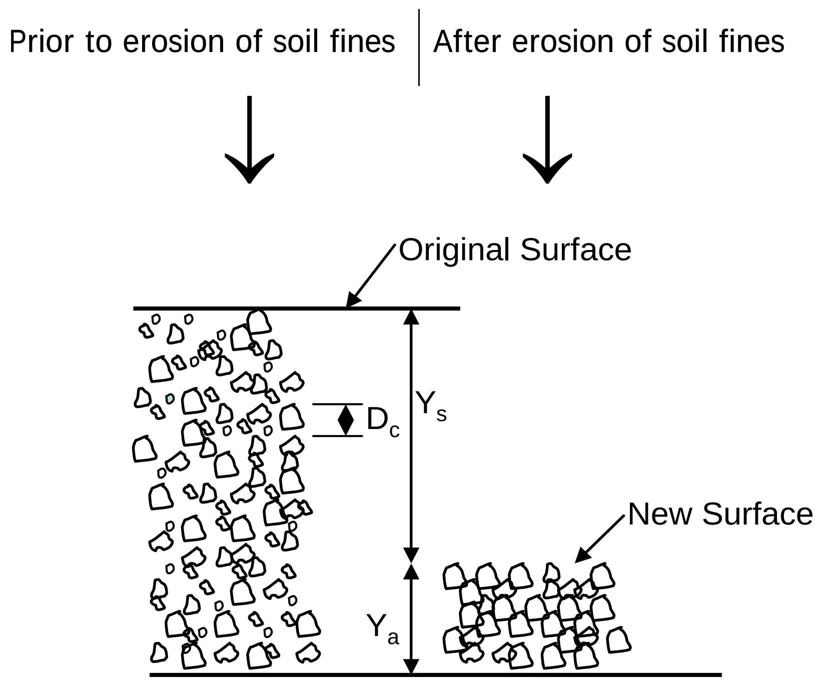


Figure 5.2-9. "Desert Pavement" development

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

- Rock mixed into the soil/rock admixture on the top slope and side slope shall satisfy NRC criteria for durability as determined by the NRC (NUREG 1999).
- The hydraulic properties of interstitial soil would match the underlying water storage soil layer.
- The interstitial soil would be live topsoil with favorable fertility, microbiology, propagules, and nominal phytotoxicity.

5.2.4 Riprap Design

Riprap is often used to protect soils against erosion from surface runoff. Riprap can be placed on landfill side slopes or just at the base or toe of the side slopes where gully erosion is calculated to be a potential. It can also be used to line drainage channels. Methods and recommended equations to size riprap as described in DOE (1989) may be used to design the size and depth of riprap. The design of riprap for stormwater controls is also included in the "LANL Engineering Standards Manual." The design steps are as follows:

1. Adequate material must be identified either in an accessible borrow site or purchased locally.
2. The characteristic velocities of the flood flow on and adjacent to the pile can be determined. Flood flow can occur either from a storm occurring in the watershed above the waste site and producing

a flood flow adjacent to the waste site, or from a storm occurring on the pile and producing sheet flow across the top and down the slopes of the waste site.

3. The mean rock size needed to resist erosion can be determined from the calculated velocities and depths of flow. For sizing riprap or side slopes greater than 10%, Stephenson's Method is most applicable. When determining the rock size gradation, the grain size distribution shall meet the criteria used by the Corps of Engineers (COE 1970).

4. Rock borrow source data shall be reviewed to determined rock durability. If rock durability meets the criteria described in section 5.2.6, *no* adjustment in the rock size will be needed; if rock does not meet the criteria, the rock sizes shall be increased proportionally to the percent that the rock failed the tests below 80%.

5. The filter requirements for the rock against the cover soil shall be calculated to determine if there is a need for a filter between the two layers.

These methods combined with applicable engineering parameters described in the "LANL Engineering Standards Manual, Chapter 3, Civil" may be used to design any desired riprap-covered side slopes, or protect the toe of a side slope. It is important to note that for RCRA-equivalent cover systems, either a geotextile or smaller filtered rock, shall be used underneath the riprap to protect the subgrade soils from being eroded away.

5.2.5 Filter Criteria

The filter criteria described in Cedergren (1989) can be used. To prevent piping from the overlying cover soil into the filter layer, and from the filter into the drainage layer, these criteria require, respectively:

D15 (filter)/D85 (cover soil) < 4 to 5.

To maintain adequate permeability of the filter layer and drainage layer, these criteria require, respectively:

D15 (filter)/D15 (cover soil) > 4 to 5;

where: D85 = particle size at which 85% by dry weight of the soil particles are smaller (mm); and
D15 = particle size at which 15% by dry weight of the soil particles are smaller (mm).

The criteria shall be satisfied for all layers or media in the drainage system, including cover soil, filter material, and drainage material.

If a graded filter layer is required between riprap and a fine-soil layer, the filter design criteria summarized in Table 4.2-3 (DOE 1989) as well as the following requirements can also be used:

- The filter material shall pass the three-inch sieve for minimizing particle segregation and bridging during placement. Smaller maximum particle sizes may be specified if practical. Also, filters must not have more than 5% passing the No. 200 mesh sieve to prevent excessive movement of fines in the filter.
- Filter material shall be reasonably well graded throughout the in-place layer thickness.
- Filters for gap-graded base soils may require a more finely graded filter than the filter determined using the criteria above.

- The minimum thickness of the layer shall be six inches in order to facilitate ease of construction during placement.

5.2.6 Rock Durability

The design of long-term (i.e., 1000-year design life) covers that include rock shall require this rock to meet specified durability requirements. Most resistant rock types have long been used as construction materials, in monuments, or for decorative purposes, with varying degrees of success (Abt et al. 1994). The NRC has prepared guidance for determining the durability of rock used in long-term covers (NUREG 1999). In assessing the long-term durability of erosion protection, the NRC staff has relied on the results of durability tests performed at several U mill tailings sites and on information and analyses, which provided methods for assessing rock oversizing requirements to meet long-term stability criteria. These procedures have also considered actual field data from several sites and have been modified to provide flexibility to meet construction requirements. These procedures are based on methods that have been demonstrated to be successful in construction practice. Note: Rock durability requirements are only applicable for exposed rock or rock that is expected to become exposed during the design life of the cover system. Rock or concrete used within the cover such as in a bio-barrier are not required to meet this criteria. This rock need only be “sound” rock based on engineering judgment.

5.2.6.1 Design Procedures

The first step in the design process when using rock in a cover system is to determine the quality of the rock, based on its physical properties. The second step is to determine the amount of oversizing needed, if the rock is not of good quality. Rock size is determined in design procedures of riprap for erosion protection (see Riprap Design, section 5.2.4) and gravel admixture for surface treatment (see Rock/Soil Admixture, section 5.2.3). Various combinations of good-quality rock and oversized marginal-quality rock may also be considered in the design, if necessary.

The suitability of rock to be used as part of a long-term protective cover shall be assessed by laboratory tests to determine the physical characteristics of the rocks. Several durability tests shall be performed to classify the rock as being of poor, fair (intermediate), or good quality. For each rock source under consideration, the quality ratings shall be based on the results of three to five different durability test methods for initial screening and five test methods for final sizing of the rock(s) selected for inclusion in the design. Procedures for determining the rock quality and determining a rock quality "score" are developed in Table 5.2-2.

Table 5.2-2
Scoring Criteria for Determining Rock Quality (NUREG 1999)

	Weighting Factor			Score										
	Limestone	Sandstone	Igneous	10	9	8	7	6	5	4	3	2	1	0
Specific Gravity (SSD)	12	6	9	2.75	2.70	2.65	2.60	2.55	2.50	2.45	2.40	2.35	2.40	2.25
Absorption (%)	13	5	2	0.1	0.3	0.5	0.67	0.83	1.0	1.5	2.0	2.5	3.0	3.5
Sodium Sulfate (%)	4	3	11	1	3	5	6.7	8.3	10	12.5	15	20	25	30
Abrasion (%)[1]	1	8	1	1	3	5	6.7	8.3	10	12.5	15	20	25	30
Schmidt Hammer	11	13	1	70	65	60	54	47	40	32	24	16	8	0
Tensile Strength (psi)	5	4	10	1400	1200	1000	833	666	500	400	300	200	100	<100

[1] 100 revolutions. Use only ASTM C131 for scoring purposes for consistency with basis for scoring system (DePuy 1965).

Notes:

1. Scores derived from Tables 6.2 and 6.7 of NUREG/CR-2642.
2. Any rock to be used must be qualitatively rated at least “fair” in a petrographic examination conducted by a geologist experienced in petrographic analysis.
3. Weighting Factors are derived from Table 7 of DePuy (1965), based on inverse of ranking of test methods for each rock type.
4. Test methods shall be standardized (e.g., ASTM) and shall be those described in DePuy (1965).

5.2.6.2 Oversizing Criteria

Oversizing criteria vary, depending on the location where the rock will be placed. Oversizing does not apply to rock used as bedding or filter material; it only applies to rock used to resist erosion. Areas that are frequently saturated are generally more vulnerable to weathering than occasionally saturated areas where freeze/thaw and wet/dry cycles occur less frequently. The amount of oversizing to be applied will also depend on where the rock will be placed and its importance to the overall performance of the reclamation design. For the purposes of rock oversizing, the following criteria have been developed:

1. Critical Areas. These areas include, as a minimum, frequently saturated areas, all channels, poorly drained toes and aprons, control structures, and energy dissipation areas.

Rating	
80–100	No oversizing needed.
65–80	Oversize using factor of (80-Rating), expressed as the percent increase in rock diameter. For example, a rock with a rating of 70 will require oversizing of 10%.
Less than 65	Reject.

2. Non-Critical Areas. These areas include occasionally saturated areas, top slopes, side slopes, and well-drained toes and aprons.

Rating	
80–100	No oversizing needed.
50–80	Oversize using factor of (80-Rating), expressed as the percent increase in rock diameter.
Less than 50	Reject.

5.2.6.3 Design Recommendations

1. Using the scoring criteria given in Table 5.2-2, the results of a durability test determines the score; this score is then multiplied by the weighting factor for the particular rock type. The final rating shall be calculated as the percentage of the maximum possible score for all durability tests that were performed.

2. For final selection and oversizing, the rating may be based on the durability tests indicated in the scoring criteria. Not all of these tests must be performed to assess the rock quality. The petrographic examination is important to determine mineral composition in order to eliminate rock with detrimental composition. Petrographic examinations should be x-ray diffraction. An experienced geologist should be used to evaluate the acceptability of riprap materials. Other tests may also be substituted or added, as appropriate, depending on rock type and site-specific factors. The durability tests given in Table 5.2-2 are not intended to be all-inclusive. They represent some of the more commonly used tests or tests where data may be published or readily available. Designers may wish to use other tests than those presented. Scoring criteria may be developed for other tests, using procedures and references recommended in Table 5.2-2. Further, if a rock type barely fails to meet minimum criteria for placement in a particular area, with proper justification and documentation, it may be feasible to throw out the results of a test that may not be particularly applicable and substitute one or more tests with higher weighting factors, depending on the rock type or site location. In such cases, consideration shall be given to performing several additional tests. The additional tests shall be those that are among the most

applicable tests for a specific rock type, as indicated by the highest weighting factors given in the scoring criteria for that rock type.

3. The percentage increase of oversizing shall be applied to the diameter of the rock.

4. The oversizing calculations represent minimum increases. Rock sizes as large as practicable shall be provided. (It is assumed, for example, that a 12-inch layer of 4-inch rock costs the same as a 12-inch layer of 6-inch rock.) The thickness of the rock layer shall be based on the constructability of the layer, but shall be at least 1.5 × D_{50}. Thicknesses of less than 4 inches may be difficult to construct, unless the rock size is relatively small.

5. Sandstone may be used in areas that require large rock sizes but, in general, shall not be used on the top slopes of a cover system where drainage may be poor.

The thickness of the rock layer shall not be less than the spherical diameter of the upper limit of D_{100} rock or less than 1.5 times the spherical diameter of the upper limit of D_{50} rock, whichever is greater.

Sand and gravel filter layers can also be designed in accordance with the methodology and design recommendations outlined in the National Engineering Handbook (1994), Chapter 26.

5.2.7 Other Design Considerations

The previous discussion centered on design and analysis techniques to minimize erosion in a closure system. There are a number of areas that require additional attention not covered by the previous discussion. Some of these areas include aprons for channel flow, convergence of channels, changes of slope within a slope length, and the beginning and end of any erosion or surface water management control. These potential problem areas require special attention during design and construction. Many of these topics are discussed in DOE (1989). The methodologies described in DOE (1989) shall be used on sites governed by DOE 435.1 where applicable and if the subject is not addressed in this guidance document.

5.3 Surface Water Management

Surface water management analyses and design shall be performed for all LANL MDA sites. It is important to control runoff as well as prevent and control run-on. Each LANL site will dictate the design storm events used with the respective design. That is, surface hydrology design for LANL sites shall utilize the engineering parameters recommended in the “LANL Engineering Standards Manual, Chapter 3, Civil.” These standards are available on the internet (http://engstandards.lanl.gov/engrman/3civ/htmls/civilnew2.htm). Specifically, the Rational Method (described in section 3 of this document) shall be utilized for drainage areas less than five acres. The applicable C-factors to be used are described in the “LANL Engineering Standards Manual,” Chapter 3, Table G20GEN-1 to compute peak flows. The methodology outlined in the “National Engineering Handbook,” Part 630, Hydrology should be used for larger drainage areas. However, for storms with return periods longer than 100 years (i.e., sites governed by DOE 435.1), DOE recommends the use of C=10 (DOE 1989).

In accordance with DOE Standard 1020 (http://www.eh.doe.gov/techstds/standard/std1020/STD-10202002.pdf), the potential for flooding shall be considered for all LANL sites. Both 100-year and 500-year flood plain levels have been calculated and plotted for drainage basins in LANL (RRES-Water Quality & Hydrology Group maintains this documentation). Utilize this information for the evaluation of local flooding potential and surface drainage analysis. (LANL contact: Steve McLin, WQH, 505-665-1721). For design of RCRA-equivalent facilities subject to flood plain hydrology, use DOE-STD-1020

guidance of a 25-year, 6-hour (conservatively, 1 inch/hour) rainfall event for design of surface drainage or water collection systems.

Use the Rainfall Intensity-Duration-Relationship Curve developed in the "LANL Engineering Standards Manual," Figure G20GEN-1, in conjunction with previously described methodologies for RCRA-equivalent covers. Use the PMP/PMF method described in DOE (1989) for sites governed by DOE 435.1.

5.3.1 Design Sequence

As described in DOE (1989), a determination of the hydrologic impacts to any LANL site requires an assessment of several design situations. These design situations involve impacts to the site as a result of the following:

1. Runoff across the top and side slopes of the site from intense, local precipitation events.
2. Runoff from small upland watersheds.
3. Flooding from nearby large streams or rivers.
4. Human-related discharges.

The following steps are essential for an adequate evaluation of hydrologic impacts:

- Collection and review of available data.
    - ➢ Topographic and soil survey maps.
    - ➢ Aerial photographs.
    - ➢ Records from nearby stream gauges and weather stations.
    - ➢ Any existing flood studies for the same or nearby drainage areas.
    - ➢ Present land use and future land use plans.
    - ➢ Vegetation and soil infiltration characteristics.
    - ➢ Location of existing water control structures, including design and operating characteristics.
- Field investigation.
    - ➢ Discussion with applicable LANL personnel and local authorities of present and future land use plans if necessary.
    - ➢ Identification of size and location of existing water control structures, including design and maintenance information.
    - ➢ Estimation of cross-sections of stream or drainage routes at selected locations in drainage basin.
    - ➢ Observation of vegetation, soil, erosion, and deposition characteristics of drainage area, especially nearby streams.
- Hydrologic description of the site.
    - ➢ Identification of the relationships of the site to surface water features in the site area.

   - ➢ Identification of mechanisms such as floods and dam failures that may require the implementation of special design features.

- Flooding determinations.

   - ➢ Selection of a design flood event that will meet regulations outlined in "LANL Engineering Standards Manual, Chapter 3, Civil."

   - ➢ Assessment of the precipitation potential, precipitation losses, and runoff response characteristics of the watershed.

   - ➢ Determination of the critical water levels and velocity conditions at the site due to the design flood event runoff occurring off the pile, from small upland watersheds, or from large nearby streams.

- Geomorphic considerations (section 4.6).

   - ➢ Identification of types of geomorphic instability.

   - ➢ Assessment of potential changes and impacts to predicted flood levels and velocities due to geomorphic changes.

   - ➢ Evaluation of mitigative actions for erosion protection design that will reduce or control any geomorphic instability.

- Erosion protection design (section 5.2).

   - ➢ Summary of the flooding and water erosion conditions for each design situation to determine critical condition(s) for cover design.

   - ➢ Assessment of erosion protection requirements.

   - ➢ Evaluation of the capability of achieving long-term stabilization with erosion protection designs that is economically feasible.

   - ➢ Assessment of potential reductions in design criteria while still meeting EPA standards, should the cost of erosion protection be clearly excessive.

5.3.2 Probable Maximum Precipitation (PMP) Determination
(DOE 1989)

The PMP is commensurate with the site's design life. Prior to determining the runoff from the design drainage basin, the analysis requires determination of the PMP amounts and hydrographs for the various regions in the drainage basin. Techniques for determining the PMP and the resulting hydrograph have been developed for the entire United States, primarily by the National Oceanographic and Atmospheric Administration in the form of hydrometeorological reports for specific regions. These techniques are commonly accepted and provide straightforward procedures with minimal variability.

5.4 Cover Slopes

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 shall 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 5.4-1).

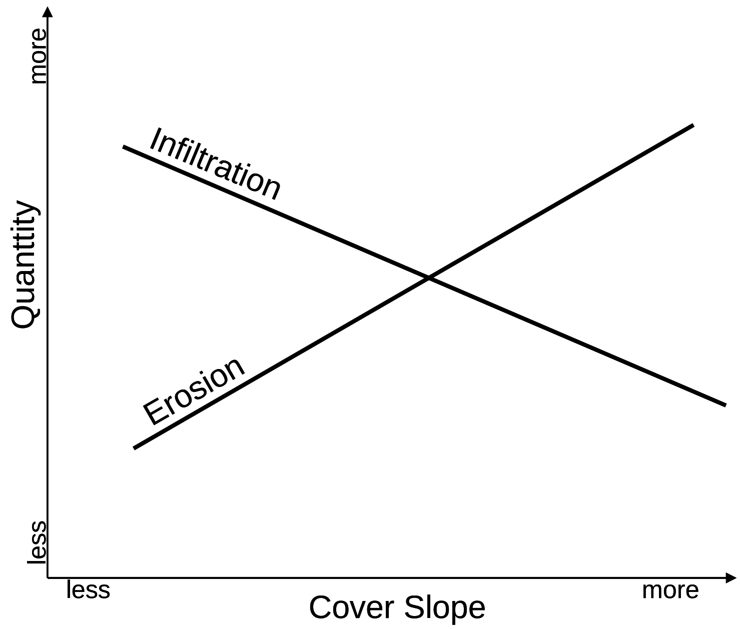


Figure 5.4-1. Infiltration/erosion vs. cover slope

The evaluation of greatest risk is to be considered when determining the final cover slope and shape. Most MDAs' greatest risk is due to contaminant transport due to biointrusion and/or erosion. Infiltration poses a risk of groundwater contamination at some MDAs. Prior to final design activities, a F&T model will be completed for each MDA. Part of the F&T modeling exercise will determine the cover flux that poses a risk of groundwater contamination. The flux determined during the F&T exercise will establish a maximum allowable flux rate. This information will allow the design engineer(s) to evaluate whether infiltration is a significant risk at each MDA. Furthermore, regulatory concerns and recommendations are to be considered in the determination of the final cover slope. The EPA (1991) recommends the final cover top slopes be between 3 and 5%. The draft EPA Landfill Cover Guidance (Dwyer et al. 2004) has decreased the minimum slope recommended from 3% to 2%. However, at LANL, because the biodegradation of waste is generally not a concern, this slope can be further reduced if the site allows for it. That is, if minimal differential settlement is expected at the site, the top slope can be reduced to a minimal slope that still allows for shedding of surface water. A positive slope is to be maintained at all times to shed surface water. Ponding on the cover surface is to be avoided. Ponding leads to increased infiltration and thus increased leachate production and contaminant transfer. The increased infiltration leads to increased vegetation in the isolated area and significantly increased rooting depths. The increased root depths can pose a larger problem than the increased infiltration due to intrusions of the roots into the underlying waste and potential uptake of contaminants.

LANL sites have minimal organic wastes and thus should realize minimal settlement due to biodegradation of organics. However, several LANL waste sites have construction and miscellaneous debris, as well as containerized waste, that may degrade with time and collapse, thereby producing isolated differential settlement events. Sites that pose a risk for differential settlement shall be evaluated

first for the potential to eliminate or minimize this risk prior to the construction of the final cover system. Techniques described later in this section, such as compaction or subsurface grouting, may be employed. These sites shall also include in the post-closure monitoring evaluation of any differential settlement. Inspectors shall identify any isolated depressions or surface tension cracks that have formed.

RCRA-equivalent site closure can mitigate detrimental effects due to differential settlement in their post-closure monitoring plan. For sites governed by DOE Order 435.1, the initial 100-year post-construction period can outline plans in the post-closure maintenance plan to repair such events. However, after this initial 100-year period, any site that may pose a significant subgrade collapse or differential settlement event must incorporate this potential in the design of that closure.

The 5% maximum EPA (1991) recommended top slope is to mitigate soil loss due to erosion of the topsoil. However, the surface treatment required for each cover system (rock/soil admixture) as described earlier in this section can prevent excessive erosion to greater slopes, generally as high as 10%.

Side slopes are generally governed by the existing topography of each site and its relation to adjacent facilities and landscape features such as mesa edges. Side slopes shall be limited to 3:1 slopes where practical. Slopes steeper than this must be approved by the project's LANL technical representative.

5.5 Slope Stability

Slope stability is a critical issue in the design of cover systems, especially when considering uncertainties associated with underlying waste and foundation materials. Steeper slopes (greater than 3:1) are to be avoided if practical. The long-term design lives of LANL closure sites increase the potential difficulties with both stability and erosion on steep slopes.

Natural slopes evolve as a result of natural processes such as erosion and movement over a long period of time. Stable slopes result from the soil having sufficient shear strength to resist gravitational forces and the slope acquiring a suitable geometry. Man-made slopes such as side slopes of landfills are imposed on nature, and for stability they have to be designed with a suitable combination of geometry and strength. Slope instability results when in situ shear stresses exceed the available shear resistance of the soil. There are three predominant types of slope instability or failure:

1. translational slide,
2. rotational failure or composite (circular slip surfaces), and
3. noncircular slip surfaces developed due to the influence of the ground stratigraphy.

Causes of slope instability when geosynthetic materials are included in the slope are obvious in that the induced shear forces exceed the resisting interface shear between the soil and geosynthetic. Common causes in soil slope instability without geosynthetics include the following (Sarsby 2000):

1. Unsuitable geometry. The slope is too steep or too high for the available soil shear strengths, or the geometry is adversely changed due to erosion or undercutting.
2. Change in groundwater regime. This can result from extreme precipitation events or changes in surface water controls that allow for subsurface moisture conditions to change dramatically.
3. Presence of unforeseen or unrecognized weak planes, bands, or layers. Often the stability analyses in these types of cases overestimated the slope material strength parameters.
4. Increase in the effective slope height, commonly caused by excavation near the toe.

5. Additional surcharge loading near the crest of the slope.

6. Progressive deformation. This can come into play when factors of safety are too low and localized failures are allowed to continue.

It is recommended that conventional slope stability analyses techniques be employed at LANL sites. These techniques are commonly used and explained well in multiple publications including DOE (1989), and Dwyer et al. (2004). Consequently, only brief descriptions are included.

5.5.1 Static Slope Stability

Methods of static slope analyses used include circular and noncircular limiting equilibrium analyses, wedge analyses, and infinite slope analyses. The method of analysis used depends on the actual site and soil conditions. For failures of infinite slope, the FS for slope stability is simply expressed as:

$$FS = \tan \Phi / \tan \beta$$ **Equation 5.12**

where:

Φ = the angle of internal friction of the slope's soil

B = the slope angle relative to the horizontal

As described above, there are multiple failure mechanisms for slopes and thus stability analyses must be addressed accordingly. Various, validated computer programs are available.

5.5.1.1 Translational Slide

Translational slide slope failures occur after construction of the slope (Figure 5.5-1). Initially the pore pressures in the slope soils near the surface are relatively small because of compaction efforts on fill slopes or removal of stresses on cut slopes. However, with time these pore pressures can increase due to infiltration or lateral migration of moisture into the slopes. The increase in pore pressure in these soils reduces their effective stress (shear strength), allowing for shear failure. The soil can begin to slide down the hill. Analysis should ensure that the slopes are designed with an adequate FS. The FS for this type of failure is determined from the ratio of resisting forces to disturbance forces.

$$FS = T / (W \sin \beta)$$ **Equation 5.13**

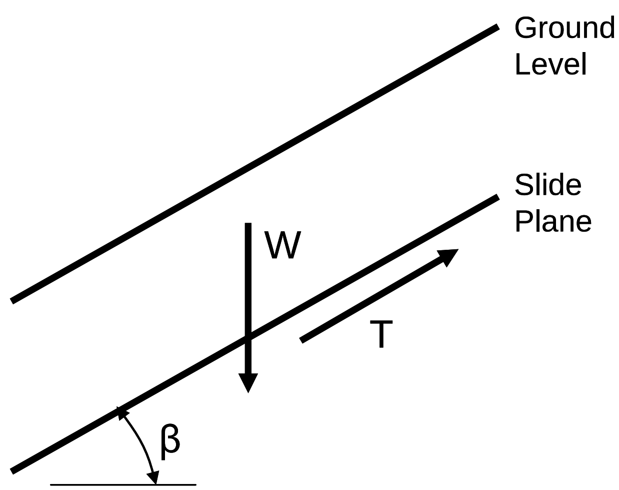


Figure 5.5-1. Translational slope stability

5.5.1.2 Rotational Failure

Rotational failure surfaces are curved and penetrate to greater depths than translational failures. These failure surfaces are generally represented as circular. The FS can be defined as the ratio of total available resisting movement to the total disturbing moment. The Method of Slices is often used for this analysis.

5.5.1.3 Noncircular Failure

A noncircular failure surface may develop where layered strata exist. The analysis can be similar to that for rotational failure with added complications.

5.5.2 Seismic Slope Stability

Seismic conditions are commonly analyzed by the pseudo-static approach. For the pseudo-static analysis, a horizontal seismic coefficient (k) based on the peak value of the derived site surface acceleration of the design earthquake is selected. Evaluation of the seismic stability of a cover system involves four steps, each of which can be performed using either conservative, simplified approaches or more complex, detailed analyses. These four steps are as follows:

1. Conduct a seismic hazard evaluation to estimate peak horizontal bedrock accelerations for a site and representative causative earthquake events to associate with that acceleration. This evaluation must be consistent with LANL Engineering Standards available on the Internet at http://engstandards.lanl.gov/.

2. Perform a seismic response analysis to evaluate peak horizontal accelerations at the ground surface or in the waste mass cover system due to the causative earthquake events.

3. Select shear strength properties for cover system materials and interfaces to use in seismic slope stability and/or deformation analyses. Because of the nature of the soil in the LANL area, it is recommended that typical literature values not be used except as noted in section 5.5.7, but rather testing of actual soils be measured and verified.

4. Perform seismic slope stability analyses. There are a number of validated computer software packages commercially available that can be utilized to perform this analysis. Simplified approaches such as the pseudo-static FS method can also be used.

5.5.2.1 Pseudo-Static FS Method

Due to its simplicity, the pseudo-static FS method remains the most common method of analysis used in practice for seismic design of cover systems. This method of analysis involves the computation of the minimum FS against sliding by inclusion in the analysis of static horizontal and vertical forces of some magnitude. These horizontal and vertical forces are usually expressed as a product of horizontal or vertical seismic coefficients and the weight of the potential sliding mass. The horizontal pseudo-static force decreases the FS by reducing the resisting force and increasing the driving force. The vertical pseudo-static force typically has less influence on the FS since it affects positively (or negatively) both the driving and resisting forces, and for this reason this is ignored by many engineers. The FS obtained for the calculation is compared to a minimum acceptable FS to determine the adequacy of the design. The FS of a slope depends on the value of seismic coefficient used. The seismic coefficient equals the fraction of the weight of the potential failure mass that is applied as a horizontal force to the centroid of the mass in a pseudo-static limit equilibrium stability analysis.

The main drawback of the pseudo-static FS approach lies in the difficulty in relating the value of the seismic coefficient to the characteristics of the design earthquake. Use of the peak acceleration at the top of the waste mass as the seismic coefficient, coupled with a pseudo-static FS of 1.0, results in a very conservative design basis. However, this is likely warranted due to the uncertainties associated with buried waste. A seismic coefficient smaller than that corresponding to the peak ground acceleration is sometimes used, but the magnitude of cover system displacement in this case is unknown.

5.5.3 Seismic Analysis Engineering Parameters

Engineering parameters used in the analysis of slope stability at LANL must be consistent with the “LANL Engineering Standards Manual.” These standards state that DOE-STD-1020, “Natural Phenomena Hazards Design and Evaluation Criteria for DOE Facilities,” and DOE-STD-1021, “Natural Phenomena Hazards Performance Categorization Criteria for Structures, Systems and Components,” are to be followed. DOE-STD-1021 determines the hazard category based on the expected return period. For any LANL site closure, RCRA-equivalent sites will be classified as hazard category PC-1 because the return period is less than 500 years, while sites governed by DOE 435.1 will be classified as PC-2 sites consistent with a return period of 1000 years. For both PC-1 and PC-2 facilities, the applicable seismic parameters can be determined from the latest version of the International Building Code (IBC) per DOE-STD-1020.

An importance factor of 1.0 shall be used for PC-1 facilities while an importance factor of 1.25 will be used for PC-2 facilities. The peak ground acceleration of seismic factor can be determined for the LANL site from the IBC or a very conservative peak ground acceleration as described in UCRL 15910 (1990), specifically for LANL as 0.18g.

For seismic analysis of slopes under construction and at the end of construction, analysis can be performed using a seismic factor or peak ground acceleration equal to one-half of the site peak surface acceleration. For long-term stability, the minimum value of seismic factor used at any site is 0.10 (DOE 1989). If two-thirds of the site peak surface acceleration is greater than 0.10, the greater value is adopted as the seismic factor. This value is reduced to two-thirds of the peak in order to provide a mean value for input into the long-term stability analysis.

5.5.4 Factors of Safety Against Slope Failure for LANL Sites

The recommended minimum factors of safety for the slope stability analyses are (DOE 1989)

- long-term static stability greater than 1.5 and
- long-term seismic stability greater than 1.0.

5.5.5 Shear Strength Parameters Required for Analyses

It is recommended that laboratory testing using project-specific materials, coupled with testing procedures and conditions representative of the anticipated field application, be performed to establish design shear strength parameters on a project by project basis. Sabatini et al. (2001) have shown that for a given FS, designs based on project-specific laboratory testing programs are more reliable and less prone to slope instability than designs that utilize shear strength parameters obtained from more general sources, such as databases or the published technical literature.

The various methods used for laboratory shear strength testing of soils are well known and are fully described in a number of geotechnical textbooks and laboratory guides (Lambe 1951, Holtz and Kovacs 1981, Bardet 1997). The most commonly used methods for laboratory shear strength testing of soils are the triaxial compression test and direct shear test.

Project-specific shear strength testing programs are designed to simulate the anticipated field conditions by selecting appropriate testing procedures and conditions. These include the soil compaction conditions (i.e., water content and density), soil consolidation stress and time, wetting conditions for the materials and interfaces, range of applied normal stresses, direction of shear for geosynthetic interfaces, and shear displacement rate and magnitude.

It is anticipated testing for the interface properties (friction angle and cohesion) between the soil and geosynthetics will not be performed for projects at LANL where geosynthetics are to be included. Values for these interface properties will come from applicable literature available.

5.5.6 Construction Considerations of Landfill Side Slopes

The following construction considerations are provided with respect to placement of soil materials in the side slopes’ cover systems:

- By placing cover soils from the bottom of the slope upward, a passive, stabilizing soil wedge is established at the toe of the slope prior to placement of soil higher on the slope. The operation of construction equipment over this lower wedge tends to compact and strengthen the wedge.
- Relatively small, wide-track dozers (i.e., low-ground pressure dozers) are recommended for placing the soil cover material. This type of equipment limits both the dynamic force imparted to the slope during acceleration and braking and the tractive force applied through the dozer tracks.
- Downslope dynamic forces can be limited further by limiting the dozer speed on the slope and by instructing the dozer operator to avoid hard braking, particularly when backing downslope.

5.5.7 Other Slope Stability Considerations

Site-specific soil strength properties are not required for

- slopes less than 20%,

- slopes less than 15 feet (4.6 m) in height, and
- site-specific parameters not required for bedrock.

5.6 Settlement

Settlement and especially differential settlement is to be minimized at sites where its potential exists. Differential settlement can lead to surface ponding and thus increased infiltration as well as creating other issues such as discontinuities in multiple-layer systems. Increased infiltration can also lead to increased biointrusion via roots. Differential settlement generally occurs at landfills and waste sites due to inconsistencies and voids created during placement of wastes and materials. Further differential settlement can occur due to degradation of waste containers such as metal drums and wood boxes. If substantial subsidence in a landfill is expected, there are various treatments that can be incorporated into the final closure to decrease the amount of settlement that will occur. Among these is the acceleration of consolidation in underlying waste by any of a number of methods, including compaction with standard equipment if the landfill is thin enough or the use of dynamic compaction if the landfill is thicker. There are techniques to reduce potential settlement that are not applicable to sites that can reduce release contaminates of concern if applied. It is the design team's responsibility to understand the limitations of the specific site.

5.6.1 Methods to Reduce Settlement

Grouting and/or chemical stabilization are other methods that can be used to stabilize and/or reduce settlement. These methods can be very expensive. Jet grouting can be used to force materials such as cement into the landfill to fill voids and strengthen the foundation for application of a final cover. Soil cement, the process of mixing cement and soil to increase the strength of that soil mass, can also be used. Soil stabilization with materials such as lime, cement, fly ash, or any combination of these can also be used.

5.6.1.1 Compaction

One method that can be utilized at LANL to mitigate the effects of differential settlement is compaction. Soil compaction is defined as the method of mechanically increasing the density of soil. In addition to minimizing differential settlement, compaction can

- increase load-bearing capacity
- prevent soil settlement and frost damage
- provide stability
- reduce water seepage, swelling and contraction

For general purposes, there are four types of compaction effort on soil:

- vibration
- impact
- kneading
- pressure

These different types of effort are found in the two principal types of compaction force: static and vibratory.

Static force is simply the deadweight of the machine, applying downward force on the soil surface, compressing the soil particles. The only way to change the effective compaction force is by adding or subtracting the weight of the machine. Static compaction is confined to upper soil layers and is limited to any appreciable depth. Kneading and pressure are two examples of static compaction.

Vibratory force uses a mechanism, usually engine-driven, to create a downward force in addition to the machine's static weight. The vibrating mechanism is usually a rotating eccentric weight or piston/spring combination (in rammers). The compactors deliver a rapid sequence of blows (impacts) to the surface, thereby affecting the top layers as well as deeper layers. Vibration moves through the material, setting particles in motion and moving them closer together for the highest density possible. Based on the materials being compacted, a certain amount of force must be used to overcome the cohesive nature of particular particles.

Every soil type behaves differently with respect to maximum density and optimum moisture. Therefore, each soil type has its own unique requirements and controls, both in the field and for testing purposes.

NOTE: It is important to assess the affect of compaction on any monitoring instrumentation deployed during closure activities, such as lysimeters and soil moisture monitoring equipment. Impact, kneading, and possibly vibratory force methods can potentially harm installed instrumentation.

Several methods that can be employed to minimize the potential for settlement by altering or structurally improving the waste soils are described below.

5.6.1.2 Dynamic Compaction

Dynamic compaction is simply the dropping of heavy weights on the ground surface to densify soils at depth. Dynamic compaction can accelerate expected differential settlement in waste sites at LANL. Generally, dynamic compaction drop weights are about 10–30 tons. The drop height is 50–100 feet. The impact grid is 7 ft × 7 ft to 20 ft × 20 ft. Obviously, the site must be evaluated for sensitivities due to the large expected vibrations from dynamic compaction, but as a minimum, no structure should exist with a distance of 100–150 ft from the impact areas.

5.6.1.3 Grouting

The site can be grouted to solidify the substrate, thus mitigating any potential for differential settlement. Examples include jet grouting and compaction grouting. Jet grouting is a versatile ground modification system used to create in situ cemented geometries of soil crete. Compaction grouting uses displacement to improve ground conditions. A very viscous (low-mobility), aggregate grout is pumped in stages, forming grout bulbs, which displace and densify the surrounding soils. Significant improvement can be achieved by sequencing the grouting work from primary to secondary to tertiary locations.

5.6.1.4 Soil Mixing

Soil Mixing, also known as the Deep Mixing Method, is the mechanical blending of the in situ soil with cementitious materials (reagent binder) using a hollow stem auger and paddle arrangement. The intent of the soil mixing program is to achieve improved character, generally a design compressive strength or shear strength and/or permeability. Soil mixing can also be used to immobilize and/or fixate contaminants as well as a treatment system for chemical reduction to a more “friendly” substrate.

5.6.2 Settlement Analyses

The level of effort expended on settlement analyses is dependent upon the perceived risk for a particular site. Settlement is time dependent. It occurs in three stages: (1) instantaneous settlement occurs during construction activities, (2) short-term settlement or primary consolidation which occurs shortly after construction, and (3) long-term settlement or secondary consolidation which is generally less than primary settlement.

Not all types of settlement require detailed analyses. The method of analysis depends on the material type, the data collected for that material, and the condition of the material in place. Calculations based on elastic analyses are used for nonplastic soils; consolidation theory, as described by Lambe and Whitman (1969), is used for clays and clayey materials. Other methods of analysis such as those based on finite strain may be used if appropriate. Some theories that may be used to calculate settlements include

- elastic theories as presented in Lambe and Whitman (1969) and NAVFAC DM-7.1 (1982),
- conventional consolidation theory as presented in Lambe and Whitman (1969) and Duncan and Buchignani (1976),
- multilayered analyses using conventional consolidation theory as presented by Gray (1946),
- finite strain settlement techniques as developed by Schiffman et al. (1984),
- cone penetration techniques as presented by Robertson and Campanella (1983) and Schmertmann (1978), and
- analysis of secondary consolidation as presented by Holtz and Kovacs (1981).

Where appropriate, total combined settlement (excluding instantaneous settlement) is plotted as a surface contour map in order to evaluate differential settlement, cover cracking, and flow concentrations. Cover cracking is evaluated using the approach described by Lee and Shen (1969) or using computer model deformation methods (e.g., PLAXIS).

6.0 MODELING

Hydrologic modeling is a design tool used by engineers to evaluate the water balance of a cover system. It is important to note that models do not predict reality; they merely serve to assist engineers in the design process. Dwyer (2003) and Roesler and Benson (2002) have shown that although no model is completely accurate, they still provide a useful tool to assist with final cover profile designs.

The two types of programs discussed in this section are the Hydrologic Evaluation of Landfill Performance (HELP) program (Schroeder et al. 1994) and Richards' Equation-based models such as UNSAT-H (Fayer and Jones 1990) and HYDRUS (Simunek et al. 1998). HELP is a software package that was developed with EPA funding and has been a popular software package used by practitioners for many aspects of landfill design. NMED suggests that equivalence between a prescriptive and alternative cover system is dependent on flux (NMED 1998). They suggest that the HELP Model (Schroeder et al. 1994) be used to perform the comparison. However, the document does state that it is for guidance only and that other means to prove equivalence may be submitted. It is routinely used for prescriptive cover designs. Equivalence for LANL MDA sites shall be determined as described in section 7. However, HELP is not well suited for alternative earthen covers (ITRC 2003, EPA 2004) due to its technical deficiencies. Rather, models based on the Richards' Equation are recommended for alternative earthen covers such as ET covers (ITRC 2003, EPA 2004). UNSAT-H (Figure 6.2-1) and HYDRUS are popular programs used for the analyses and design of alternative earthen landfill covers.

6.1 HELP Overview

HELP is a quasi-two-dimensional program developed by the U.S. Army Corps of Engineers for the EPA. This program estimates percolation, surface runoff, soil-water storage, lateral drainage, and ET for landfill covers, as well as calculates flow through the underlying waste, leachate collection system, and the bottom liner. Schroeder et al. (1994) provides a detailed description of the algorithm HELP uses to route water into different components of the water balance. A schematic illustration of how HELP handles the water balance in a landfill cover profile is shown in Figure 6.1-1.

HELP requires that each layer of the landfill cover be specified as a vertical percolation layer, barrier soil liner, lateral drainage layer, or GM liner depending on the function and hydraulic properties of the layer. A vertical percolation layer generally has moderate to high saturated hydraulic conductivity and unsaturated flow of water occurs in the vertical downward direction. A barrier soil layer has a low saturated hydraulic conductivity and is assumed to be fully saturated. A lateral drainage layer has a relatively high hydraulic conductivity and is underlain by a barrier layer. A lateral drainage layer allows for the vertical downward movement of water similar to a vertical percolation layer, as well as lateral saturated flow.

HELP divides precipitation into surface runoff and infiltration based on a modified version of the Soil Conservation Service (SCS) runoff curve number method. The SCS runoff curve number used by HELP is based on the hydraulic conductivity of the surface layer, condition of vegetation (i.e., LAI), and the slope and slope-length of the cover. If the air temperature is less than or equal to 0°C, precipitation is stored as a snowpack. The snowpack is allowed to melt only when the air temperature rises above 0°C. The infiltrated water either remains in storage or is subjected to ET, lateral drainage, and/or percolation.

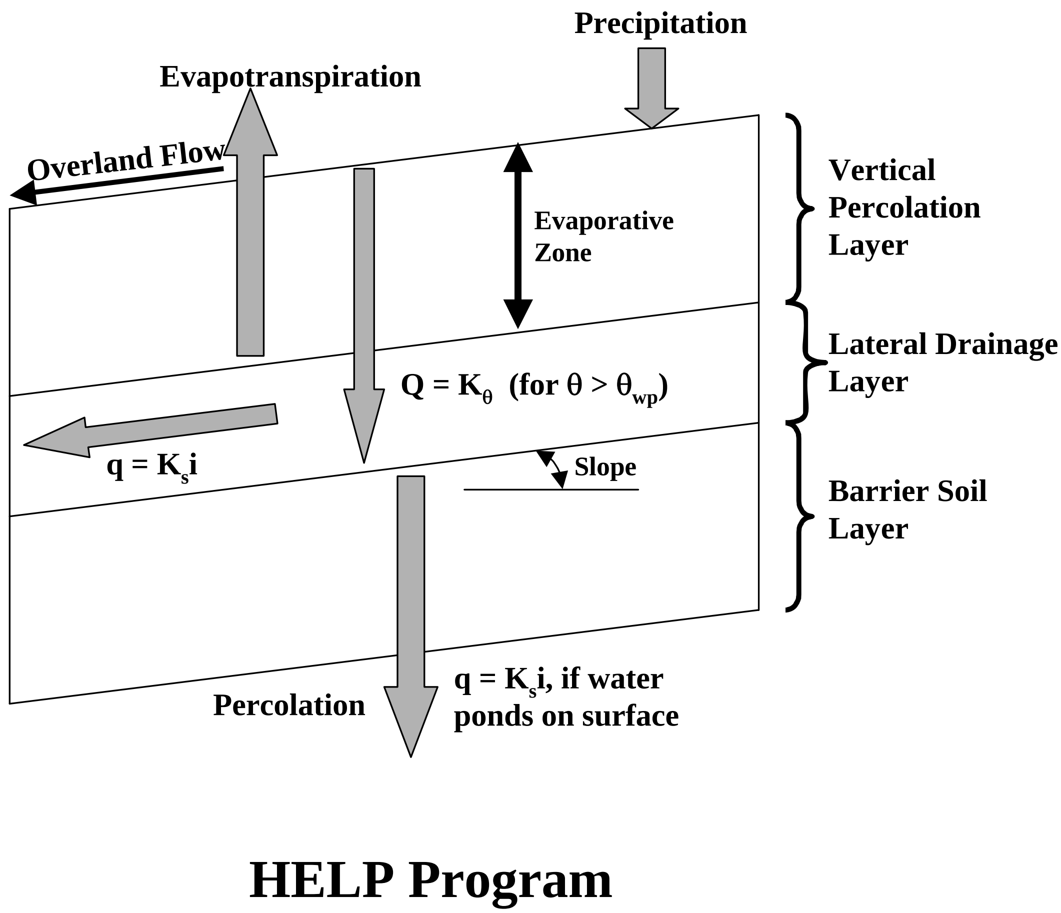


Figure 6.1-1. Schematic representation of water balance computations by HELP (Dwyer 2003)

Water removal via ET occurs from the evaporative depth of the cover only. A vertical percolation layer is the only layer type that allows for water removal via ET. Consequently, the evaporative depth of the cover cannot be greater than the top vertical percolation layer. HELP provides default values for evaporative depth based on the location of the site and the condition of the vegetation. The quantity of water removed by ET is computed using an approach recommended by Ritchie (1972) and was a function of PET and the availability of water stored in the soil profile. PET is calculated using a modified form of the Penman (1963) equation.

If the layer is a vertical percolation layer, the water stored in the soil layer is routed under a unit hydraulic gradient in the vertically downward direction (Figure 6.1-1) using the unsaturated hydraulic conductivity (K_θ) computed by Campbell's (1974) equation. ET removes water from the vertical percolation layer if the water content is above the permanent wilting point (θ_{WP}). The permanent wilting point is defined as the lowest amount of water that remains in the soil because a plant is unable to extract it. Field capacity is the amount of water in a wetted soil after it has drained. The size of the reservoir of water in a soil that can be used by plants to maintain life is the moisture range between the permanent wilting point and field capacity.

If the layer is a barrier soil layer, the saturated hydraulic conductivity and the depth of ponded water on the surface of the barrier soil layer are used with Darcy's Law to compute percolation (Figure 6.1-1). The soil's saturated hydraulic conductivity is used because the barrier layer is assumed to be fully saturated.

6.1.1 HELP Input Parameters

HELP is a user-friendly computer program that contains default values for most input parameters included within the software. Input parameters required for the HELP program include the site location (nearest city); weather data (daily precipitation, temperature, and solar radiation); ET data (LAI, evaporative zone depth, and growing season); soil data (total porosity, field capacity, wilting point saturated hydraulic conductivity, and initial moisture conditions); runoff data (SCS runoff curve information, slope, and slope length); installation information about geosynthetics used, if any (i.e., installation quality and number of defects in GM); and, finally, a cover profile description (depth of layer and type of layer, such as barrier or vertical percolation layer). The input parameters used for modeling simulations shall be determined from laboratory and field testing as well as expert opinion.

6.1.1.1 Weather Data

A LANL weather station shall be used as the design site. An example of available weather data is found at http://www.weather.lanl.gov/. It is good practice to use several average years in front of the selected model years to establish appropriate antecedent conditions. An additional year (also average weather) beyond the simulation period can also be included to allow for transient data to dissipate.

6.1.1.2 Vegetation Data

The onset and termination of the plant growing season (allowable transpiration period) for the site shall be determined. An applicable LAI also serves as an input parameter. A maximum evaporative zone depth shall be established within the cover profile (only vertical percolation layers allow for evaporation).

6.1.1.3 Runoff Data

The SCS runoff curve number is computed by the HELP program based on the slope length, slope, possible runoff area of the landfill area, the respective soil texture for each cover, and a quality of surface vegetation.

6.1.1.4 Soil Properties and Model Geometries

Many design engineers use one of the various default set of values for given soils within the HELP model. It is preferred that measured soil values be used. The model geometry is dependent on the cover profile desired.

6.2 UNSAT-H Overview

UNSAT-H is a one-dimensional, finite-difference computer program developed at Pacific Northwest Laboratory by Fayer and Jones (1990). UNSAT-H can simulate the water balance of landfill covers as well as soil heat flow (Fayer 2000). UNSAT-H simulates water flow through soils by solving Richards' Equation and simulates heat flow by solving Fourier's heat conduction equation. This approach for analyzing water flow in earthen covers is distinctly different from the approach used by HELP.

A schematic illustration on how UNSAT-H computes the water balance is shown in Figure 6.2-1. UNSAT-H separates precipitation falling on a landfill cover into infiltration and overland flow. The quantity of water that infiltrates depends on the infiltration capacity of the soil profile immediately prior to rainfall (e.g., total

available porosity). Thus the fraction of precipitation shed as overland flow depends on the saturated and unsaturated hydraulic conductivities of the soils characteristic of the final cover. If the rate of precipitation exceeds the infiltration capacity, the extra water is shed as surface runoff. UNSAT-H does not consider absorption and interception of water by the plant canopy, or the effect of slope and slope-length when computing surface runoff.

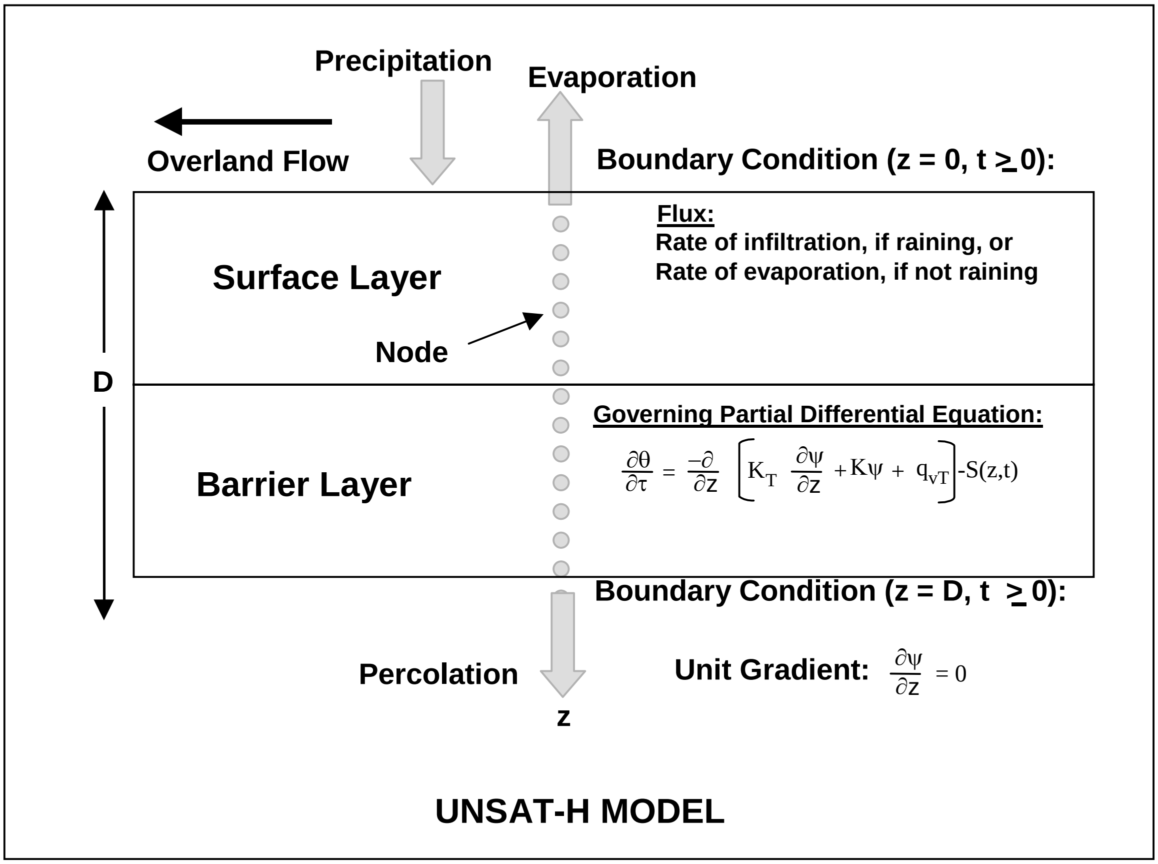


Figure 6.2-1. Schematic representation of water balance computation by UNSAT-H (modified from Khire 1995)

Water that has infiltrated a soil profile during an UNSAT-H simulation moves upward or downward as a consequence of gravity and matric potential (Figure 6.2-1). Evaporation is computed using Fick's law. Water removal by transpiration of plants is treated as a sink term in Richards' Equation (Figure 6.2-1). PET is computed from the daily wind speed, relative humidity, net solar radiation, and daily minimum and maximum air temperatures using a modified form of Penman's equation given by Doorenbos and Pruitt (1977). Soil-water storage is computed by integrating the water content profile. Flux from the lower boundary is via percolation (Figure 6.2-1). UNSAT-H, being a one-dimensional program, does not compute lateral drainage.

Infiltration. The UNSAT-H model simulates infiltration in a two-step process. First, infiltration is set equal to the precipitation rate during each time step. Second, if the surface soil saturates, the solution of that time step is repeated using a Dirichlet boundary condition (with the surface node saturated). The resulting flux from the surface into the profile is the infiltration rate.

Runoff. The UNSAT-H model does not simulate runoff explicitly. Instead, it equates runoff to the precipitation rate that is in excess of the infiltration rate. There is no provision for run-on or surface detention.

Soil-water and heat flow. The UNSAT-H model simulates liquid water flow using the Richards' Equation, water vapor diffusion using Fick's law, and sensible heat flow using the Fourier equation. Convective airflow is not considered. Options for describing soil-water retention include linked polynomials, the Haverkamp function, the Brooks and Corey function, the van Genuchten function, and several special functions that account for water retention of very dry soils. In addition, the van Genuchten function can also be treated hysteretically. Options for describing hydraulic conductivity include linked polynomials, the Haverkamp model, the Mualem model, and the Burdine model.

Drainage and lower boundary heat flow. The UNSAT-H model has several options for the boundary conditions. For water flow, the user can specify Dirichlet or Neumann conditions, or a unit hydraulic gradient condition. For heat flow, the user can specify Dirichlet or Neumann conditions, or a temperature gradient.

Evaporation. The UNSAT-H model simulates evaporation in two ways. In the isothermal mode, UNSAT-H uses the PET concept. The user supplies either daily values of PET or daily weather data, with which the code calculates daily PET values using the Penman equation. During each time step, the code attempts to apply the potential evaporation rate. If the soil surface dries to or above a user-defined matric potential limit, the time step is re-solved using a Dirichlet condition at the surface. In this situation, the surface potential is held constant at the matric potential limit and evaporation is set equal to the flux from below. In the thermal mode, UNSAT-H calculates evaporation as a function of the vapor density difference between the soil and the reference height (the height at which air temperature and wind speed are measured) and the resistance to vapor transport. The resistance to vapor transport is a function of several factors, including air temperature, wind speed, and atmospheric stability.

Transpiration. The UNSAT-H model simulates the effects of plant transpiration using the PET concept. There is no provision to simulate both water and heat flow in a plant canopy. Plant information is supplied to the code to partition the PET into potential evaporation and potential transpiration. The potential transpiration is applied to the root zone using the root distribution to apportion it among the computational nodes that have roots. The withdrawal of water from a particular node is dependent on the suction head of the node. The user provides suction head values that define how the potential transpiration rate applied to a particular node is reduced. Below the minimum value, sometimes known as the wilting point, transpiration is unable to remove any water. When all nodes with roots reach this level of suction head, transpiration is reduced to zero.

6.2.1 UNSAT-H Input Parameters

These parameters shall be developed based on field and laboratory measurements, values from the literature, as well as expert opinion.

6.2.1.1 Model Geometry

Model geometry shall be based on the respective depth of the cover system desired.

6.2.1.2 Boundary Conditions

The flow of water across the surface and lower boundary of the cover profile of interest is determined by boundary condition specifications. For infiltration events, the upper boundary used is set to a maximum hourly flux (commonly 1 cm/hr). The surface boundary condition during evaporation can be modeled as a

flux that required daily weather data. Applicable weather data shall be used based on the desired design life of the cover system. The UNSAT-H program partitions PET into potential evaporation (E_p) and potential transpiration (T_p). Potential evaporation is estimated or derived from daily weather parameters (Fayer 2000). Potential transpiration is calculated using a function (Equation 6.1) that is based on the value of the assigned LAI and an equation developed by Ritchie and Burnett (1971) for cotton and grain sorghum:

$T_p = PET\ [a + b\ (LAI)^c]$ where $d \leq LAI \leq e$ **Equation 6.1**

where:

a, b, c, d, and e are fitting parameters;

a = 0.0, b = 0.52, and c = 0.5, d = 0.1, and e = 2.7 (Fayer 2000)

6.2.1.3 Vegetation Data

This set of parameters includes the LAI, rooting depth and density, root growth rate, as well as the suction head value that corresponds to the soil's field capacity, wilting point, and water content above which plants do not transpire because of anaerobic conditions. A percent bare area must also be determined based on desired or worst case scenarios. The maximum rooting depth shall be assumed to be representative of desired or expected plants on the cover and the final cover profile (Foxx et al. 1984, Weaver 1920). The root length density (RLD) was assumed to follow an exponential function:

$RLD = a \exp(-b\ z) + c$ **Equation 6.2**

where:

a, b, and c are fitting parameters;

Z = depth below surface.

Fayer (2000) suggests the parameters used for the RLD functions are: a = 0.315, b = 0.0073, and c = 0.076 for cheat grass. The root depth must also be established as a function of time.

A suction head value of 15,000 cm is often the head value used corresponding to the wilting point, while 330 cm is the head value used corresponding to field capacity. A value of 30 cm can be used as the head value corresponding to the water content above which plants do not transpire because of anaerobic conditions (Dwyer et al. 1999). Not all of the water stored in the soil can be removed via transpiration. 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.

6.2.1.4 Soil Properties

The soil hydraulic properties for the borrow source in TA-61 and the Nambe soils have been determined (Shaw 2006). Saturated hydraulic conductivity values and moisture characteristic curves shall be determined at soil densities described in the section 3 design steps. The saturated hydraulic conductivity of the soils can be obtained using a falling head permeameter (ASTM D 5856). Unsaturated soil properties can be obtained from data using pressure plates and water columns, depending on the suction values, to develop moisture characteristic curves for each soil layer. These moisture characteristic curve

data can then be used as input into the RETC code (van Genuchten et al. 1991) to compute van Genuchten parameters. The Mualem conductivity function is assumed to describe the unsaturated hydraulic conductivity of the soils. The van Genuchten “m” parameter for this function was assumed to be “1-1/n.” The initial soil conditions are suction head values that corresponded to the average moisture content between each soil layer’s field capacity and permanent wilting point determined from each respective soil layer’s moisture characteristic curve at as-built conditions.

6.3 HYDRUS

Like UNSAT-H, the HYDRUS 1-D program is a numerical model for simulating the one-dimensional movement of water, heat, and multiple solutes in variably saturated media. However, HYDRUS also has a 2-D model as well as a recently released 3-D model. Both UNSAT-H and HYDRUS numerically solve the Richards' equation for saturated and unsaturated water flow and Fickian-based advection dispersion equations for heat and solute transport. The flow equation incorporates a sink term to account for water uptake by plant roots.

The HYDRUS program is a finite element model for simulating the two- and three-dimensional movement of water, heat, and multiple solutes in variably saturated media. The HYDRUS program numerically solves the Richards’ Equation for saturated-unsaturated water flow and convection-dispersion type equations for heat and solute transport. The flow equation incorporates a sink term to account for water uptake by plant roots. The heat transport equation considers movement by conduction as well as convection with flowing water. The governing convection-dispersion solute transport equations are written in a very general form by including provisions for nonlinear nonequilibrium reactions between the solid and liquid phases, and linear equilibrium reaction between the liquid and gaseous phases. Hence, both adsorbed and volatile solutes such as pesticides can be considered. The solute transport equations also incorporate the effects of zero-order production, first-order degradation independent of other solutes, and first-order decay/production reactions that provide the required coupling between the solutes involved in the sequential first-order chain. The transport models also account for convection and dispersion in the liquid phase, as well as for diffusion in the gas phase, thus permitting one to simulate solute transport simultaneously in both the liquid and gaseous phases. HYDRUS at present considers up to fifteen solutes which can be either coupled in a unidirectional chain or may move independently of each other. Physical nonequilibrium solute transport can be accounted for by assuming a two-region, dual-porosity type formulation which partitions the liquid phase into mobile and immobile regions. Attachment/detachment theory, including the filtration theory, is included to simulate transport of viruses, colloids, and/or bacteria.

The program may be used to analyze water and solute movement in unsaturated, partially saturated, or fully saturated porous media. HYDRUS can handle flow domains delineated by irregular boundaries. The flow region itself may be composed of nonuniform soils having an arbitrary degree of local anisotropy. Flow and transport can occur in the vertical plane, the horizontal plane, a three-dimensional region exhibiting radial symmetry about a vertical axis, or in a three-dimensional region.

The water flow part of the model can deal with (constant or time-varying) prescribed head and flux boundaries, as well as boundaries controlled by atmospheric conditions. Soil surface boundary conditions may change during the simulation from prescribed flux to prescribed head type conditions (and vice versa). The code can also handle a seepage face boundary through which water leaves the saturated part of the flow domain, and free drainage boundary conditions. Nodal drains are represented by a simple relationship derived from analog experiments.

For solute transport the code supports both (constant and varying) prescribed concentration (Dirichlet or first-type) and concentration flux (Cauchy or third-type) boundaries. The dispersion tensor includes a term reflecting the effects of molecular diffusion and tortuosity.

The unsaturated soil hydraulic properties are described using van Genuchten (1980), Brooks and Corey (1964), Durner (1994), Kosugi (1999), and modified van Genuchten-type analytical functions. Modifications were made to improve the description of hydraulic properties near saturation. The HYDRUS code incorporates hysteresis by using the empirical model introduced by Scott et al. (1983) and Kool and Parker (1987). This model assumes that drying scanning curves are scaled from the main drying curve, and wetting scanning curves from the main wetting curve. As an alternative, we also incorporated in HYDRUS the hysteresis model of Lenhard et al. (1991) and Lenhard and Parker (1992) that eliminates pumping by keeping track of historical reversal points. HYDRUS also implements a scaling procedure to approximate hydraulic variability in a given soil profile by means of a set of linear scaling transformations which relate the individual soil hydraulic characteristics to those of a reference soil.

The governing equations are solved numerically using a Galerkin-type linear finite element method applied to a network of triangular elements. Integration in time is achieved using an implicit (backwards) finite difference scheme for both saturated and unsaturated conditions. The resulting equations are solved in an iterative fashion, by linearization and subsequent Gaussian elimination for banded matrices, a conjugate gradient method for symmetric matrices, or the ORTHOMIN method for asymmetric matrices. Additional measures are taken to improve solution efficiency in transient problems, including automatic time step adjustment and checking if the Courant and Peclet numbers do not exceed preset levels. The water content term is evaluated using the mass-conservative method proposed by Celia et al. (1990). To minimize numerical oscillations upstream, weighing is included as an option for solving the transport equation.

In addition, HYDRUS implements a Marquardt-Levenberg-type parameter estimation technique for inverse estimation of selected soil hydraulic and/or solute transport and reaction parameters from measured transient or steady-state flow and/or transport data (only in 2D). The procedure permits several unknown parameters to be estimated from observed water contents, pressure heads, concentrations, and/or instantaneous or cumulative boundary fluxes (e.g., infiltration or outflow data). Additional retention or hydraulic conductivity data, as well as a penalty function for constraining the optimized parameters to remain in some feasible region (Bayesian estimation), can be optionally included in the parameter estimation procedure.

7.0 RCRA-EQUIVALENCE DETERMINATION

7.1 Introduction

The objective of a surface cover is to isolate the underlying waste or source materials from the environment until that waste no longer poses a significant risk to potential receptors. NMED (1998) requires that the use of an alternative earthen cover system be accompanied by a justification that it meets RCRA equivalence. A primary goal of a cover system is to minimize flux (40 CFR 264.310) through the cover, given the assumption that water infiltrating the waste or source material will serve as a transport mechanism for contaminants away from the site and increase the risk to potential receptors. RCRA-equivalence based on a cover system's flux can be justified based on modeling (NMED 1998) or the use of applicable field data, as discussed below. NMED (1998) was developed for solid waste rather than hazardous waste landfills; however, it has applicability to other types of closures where the objective of the cover design is to minimize flux (e.g., 40 CFR 264.310).

7.2 RCRA-Equivalence Determination Via Modeling

When modeling is required to justify equivalence or acceptable performance, an appropriate unsaturated flow model shall be used based on the Richards' Equation (e.g., HYDRUS or UNSAT-H). EPA (2004) and ITRC (2003) suggest these Richards' Equation-based models are much better suited for unsaturated flow than HELP. Refer to section 6 for further discussion on modeling. The modeling effort will verify that the flux though the cover system has been minimized per the Dwyer Point of Diminishing Returns (Dwyer et al. 1999) discussed in section 3 (Figure 7.2-1). This method simply determines the soil depth flux through the cover has been minimized. That is, additional soil depth will no longer significantly reduce flux through the cover system. This satisfies the 40 CFR 264.310 closure and post-closure care requirement whereby flux has been minimized through the cover system.

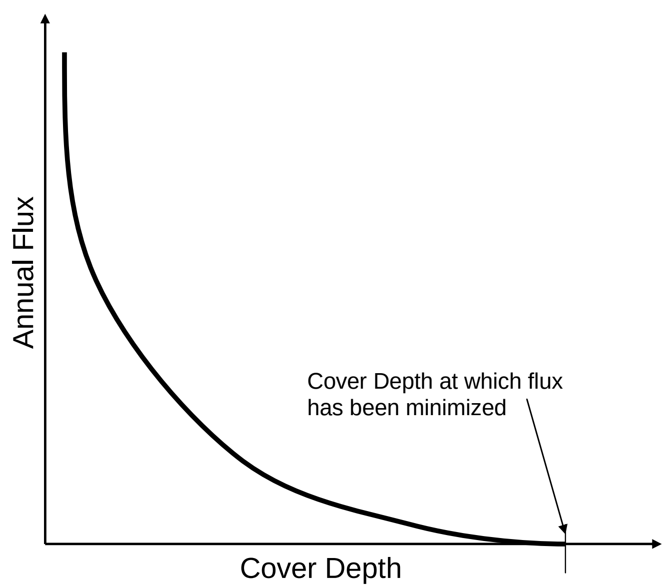


Figure 7.2-1. Annual flux vs. cover soil depth

NMED suggests that equivalence between a prescriptive and alternative cover system is dependent on flux (NMED 1998). NMED suggests that the HELP Model (Schroeder et al. 1994) be used to perform the

comparison. The document does state that it is for guidance only and that other means to prove equivalence may be submitted.

NMED (1998) further suggests that the as-built saturated hydraulic conductivity be utilized for modeling. This severely biases the equivalence determination toward prescriptive covers. Pedogeneses in the soil barrier layer significantly increase the saturated hydraulic conductivity by several orders of magnitude (Waugh and Smith 1997, Dwyer 2003, Benson et al. in press). Dwyer (2003) field measurements indicated that desiccation cracking in prescriptive soil barrier layers is extensive in dry environments that lead to substantial increase in preferential flow through theses covers. Benson et al. (in press) suggest that pedogenic effects on soil barrier layers can increase the saturated hydraulic conductivity by as much as four orders of magnitude. Waugh and Smith (1997) also concluded that the saturated hydraulic conductivity of a soil barrier layer can increase by up to three orders of magnitude. Saturated hydraulic conductivity is the most sensitive parameter in HELP (Dwyer 2003). Consequently, NMED's suggestion to use the "as-built" value for soil barrier layers will severely bias the calculated flux predictions in favor of a prescriptive cover versus an alternative earthen cover system. However, even with the extreme bias built-in, modeling with an unsaturated flow model using the Dwyer Point of Diminishing Returns Method will likely produce a zero flux, thus satisfying any equivalence basis based on percolation through the cover system.

Further biases using HELP to model prescriptive covers involves the assumed characteristics of the GM utilized in the cover profile. Modeling of cover systems containing a GM with the HELP model requires estimations of flaws in those GMs. Schroeder et al. (1994) and Koerner (1998) state that only a few flaws in GMs are expected that are generally either pinholes or holes less than 1 cm^2. This has been suggested to be significantly underestimated (Rollin et al. 2002, Rollin et al. 2004, Collucci and Lavagnolo 1995, Nosko and Touze-Foltz 2000). Field measurements made suggest that GMs installed in cover systems can receive substantial damage. Rollin et al. (2002) and Rollin et al. (2004) state that it is common for GMs installed to have leaks associated with holes, tears, cuts, and seam problems. It can be seen in Collucci et al. (1995) (Table 7.2-1) and Nosko et al. (2000) (Table 7.2-2) that assumed defect sizes of 1 cm^2 or smaller as described in Schroeder et al. (1994) and Koerner (1998) are grossly underestimated. The author of this guidance document has witnessed flaws described in Rollin et al. (2002), Rollin et al. (2004), Collucci et al. (1995), and Nosko et al. (2000). These flaws are often results of earthwork activities, installing earthen soil layers on top of the GM after the GM subcontractor has installed their product and completed required quality control (QC) activities.

Table 7.2-1
Leak Size As a Function of Leak Type (Collucci et al. 1995)

Leak Size (mm2)	Holes	Tears	Cuts	Seams	Total	%Total
0-20	44	31	12	11	98	23
20-100	37	49	21	4	111	26
100-500	60	49	2	8	119	28
500-1000	22	11	0	4	37	9
1000-10,000	10	22	0	1	33	8
≥10,000	15	9	0	0	24	6
Subtotal	188	171	35	28	422	100

Similar findings are found in Nosko et al. (2000).

Table 7.2-2
Leak Size As a Function of Leak Type (Phaneuf and Peggs 2001)

Defect Size (mm)	Punctures	Gouges	Cuts	Tears	Burns	Scrapes	Bonds	Seams	%Total
< 1	10	1	2			1	1	1	12
2–10	28	11		1	8	7	4	1	46
11-50	7	1	7	2		3	2	1	18
51-100			3	1		1		1	6
101-500	1		1			1		1	3
501-1000							1	2	2
> 1000						2	1	2	3
Unknown	4	3		1		2	1	2	10
%Total	38	12	10	4	6	13	8	9	100

The HELP model does not accurately account for the physics of a soil cover system (refer to section 6). Furthermore, the ITRC (2003) suggests that HELP is not useful for alternative earthen cover systems. The EPA has recognized this and no longer encourages the use of the HELP model for soil cover systems (EPA 2004). Dwyer (2003) showed that the HELP model does not accurately reflect water balance performance of a cover system in dry environments.

7.3 RCRA-Equivalence Determination Via Field Testing

Another means to determine equivalence between a prescriptive cover and an alternative cover is a side-by-side direct comparison field test. It is not anticipated that additional field testing will be performed at LANL to verify this. There are many applicable studies that can be used to help facilitate any RCRA-equivalence determination of a propsed cover system design (Nyhan et al. 1990a, 1990b, 1997; Hakonson et al. 1994; Dwyer 1997, 2001, 2003; Fayer and Szecsady 2004; Albright et al. 2006). This has been successfully completed for semiarid climates at nearby Sandia National Laboratories (Dwyer 2003). This field test was performed to directly assess various cover profiles under identical climatic conditions. The Alternative Landfill Cover Demonstration project (Dwyer 1997, Dwyer 2001, Dwyer 2003) was constructed at Sandia National Laboratories in Albuquerque, New Mexico. The project was endorsed by the Western Governors Association. This endorsement brought funding from DOE to state and federal regulatory agencies to allow active participation by regulators in the development, design, construction, and monitoring of the demonstration project. This was done to ensure that a quality project was well designed so results would be readily accepted. At least one regulator from the majority of state environment departments across the country, all EPA region offices, and many tribal environment departments participated. NMED had two people assigned to the advisory team. Many other stakeholders were also actively involved, such as environmental groups (e.g., Sierra Club) as well as private companies such as Waste Management. This team met weekly. The active participation by these stakeholders with the principal investigator of the project led to acceptance of alternative cover concepts and a rewrite of the EPA RCRA/CERCLA Landfill Closure Design Guidance (Dwyer et al. 2004). Many

alternative landfill covers were permitted based on the findings of this project. One of the first such covers was deployed at Warren Air Force Base in Cheyenne, Wyoming, on a hazardous waste landfill, where it was estimated that the construction savings due to the deployment of an ET cover was about $16 million versus that estimated for deployment of a prescriptive Subtitle C Cover.

The cover profiles tested included two prescriptive covers to be used as baselines and four alternative covers (Figure 7.3-1). The first baseline cover was a RCRA Subtitle D Soil Cover, used to close municipal landfills and constructed to meet minimum requirements set forth in 40 CFR 258. The second baseline cover was a RCRA Subtitle C compacted clay cover, used to close hazardous waste landfills, built to meet minimum guidelines set by the EPA RCRA/CERCLA Landfill Closure Guidance Document (EPA 1991). The alternative covers were a Geosynthetic Clay Liner (GCL) Cover, two capillary barrier designs [(a) multiple-layered system and (b) Anisotropic Barrier], and a monolithic soil profile referred to as an ET cover.

The two baseline covers and the first alternative cover (GCL Cover), termed resistive barriers, were cover profiles designed to have a very low saturated hydraulic conductivity and thus block or “resist” the movement of water through them. The remaining three were “alternative earthen covers” referred to as “store and release” covers that rely on water storage capacity to prevent water from passing through them. These covers were designed to store water within their soil layers until it could be removed via ET and are generally considered to be appropriate for dry climates.

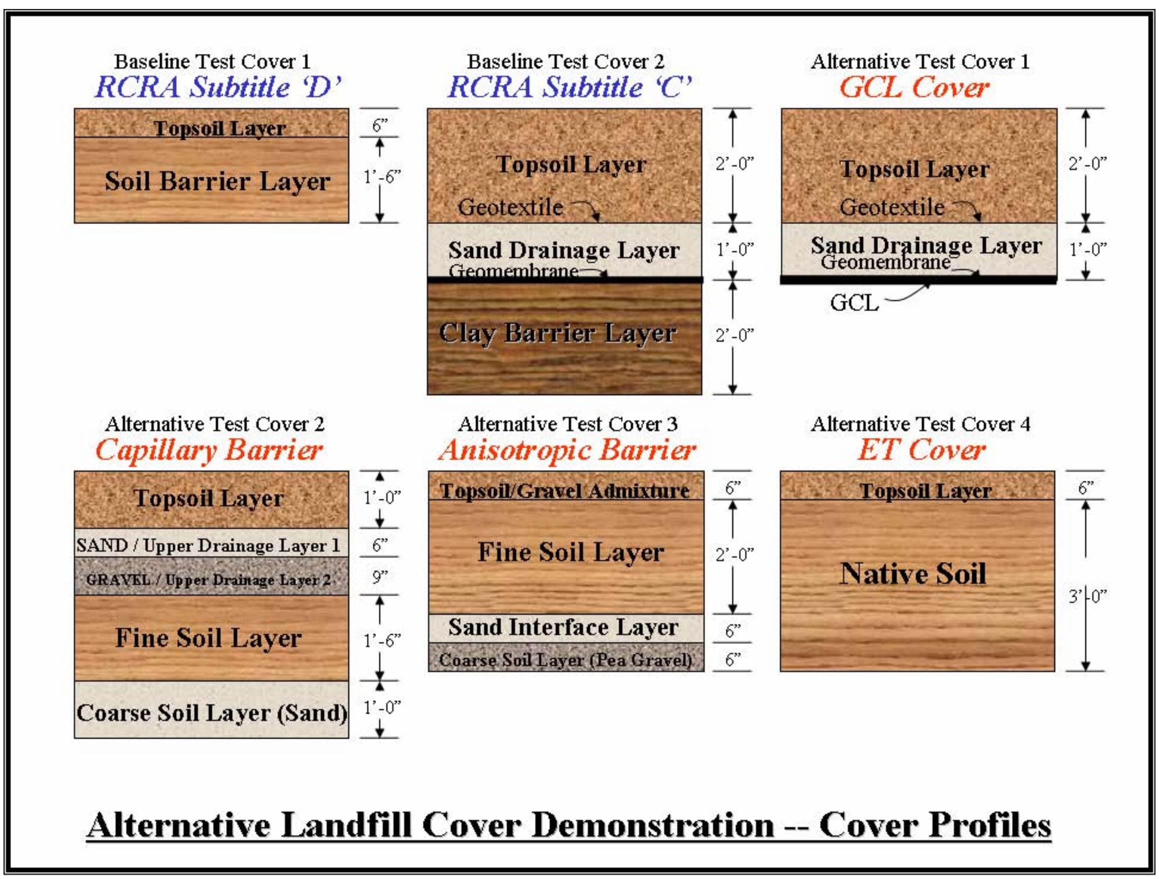
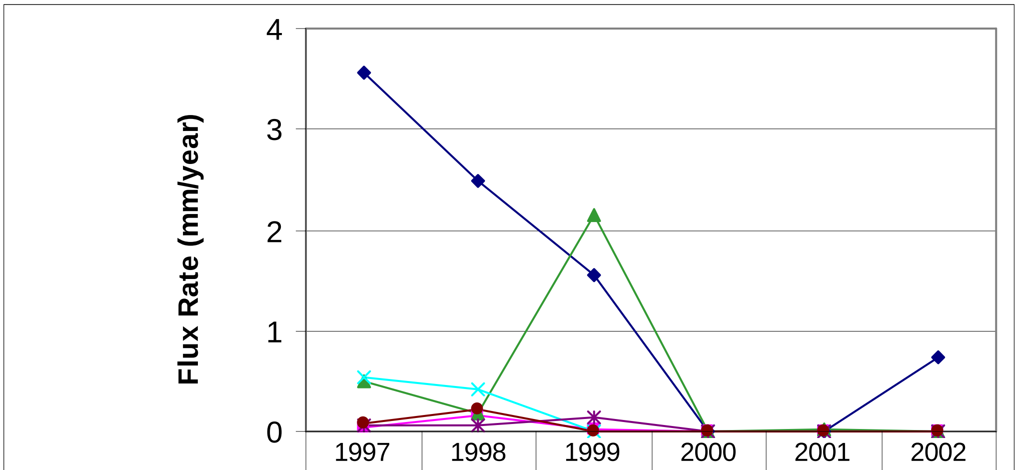


Figure 7.3-1. Profile of test covers (Dwyer 2003)

The covers were monitored from 1997 through 2002. The best performing covers were the ET cover, Anisotropic Barrier, and Subtitle C Cover with a GM (40 mil): each yielded less than an average annual flux of 0.05 mm (Figure 7.3-2, Table 7.3-1). The ET cover was preferable to both the Subtitle C and Anisotropic Barrier for dry climates because its performance was comparable, but its construction was less expensive (Dwyer 1998) and easier (Dwyer 2000). The Subtitle D cover without a GM was the worst performing profile. Poor performance of Subtitle D type covers may be a significant contributing factor to why virtually all parts of the country have experienced groundwater contamination due to a leaking landfill (EPA 1988).



	1997	1998	1999	2000	2001	2002
Subtitle D	3.56447	2.47911	1.56115	0.00000	0.00000	0.73966
Subtitle C	0.04131	0.15161	0.01756	0.00000	0.00000	0.00000
GCL Cover	0.50628	0.18831	2.15408	0.00018	0.02091	0.00000
Capillary Barrier	0.54412	0.40907	0.00000	0.00008	0.00002	0.00005
Anisotropic Barrier	0.05135	0.06888	0.13937	0.00035	0.00047	0.00021
ET Cover	0.07546	0.21837	0.00538	0.00002	0.00000	0.00000

Figure 7.3-2. Annual flux (Dwyer 2003)

Table 7.3-1
Average Annual Flux (Dwyer 2003)

Cover	Average Annual Flux (mm/yr)
Subtitle D Cover	1.39
GCL Cover	0.48
Subtitle C Cover	0.04
Multiple Layered (Capillary) Barrier	0.16
Anisotropic Barrier	0.04
ET Cover	0.05

Resistive barriers are susceptible to failure because the fine-grained barrier layers are easily damaged by weathering and distortion. Cracking due to frost can dramatically increase the layers' saturated hydraulic conductivity, in some cases by as much as four orders of magnitude (Benson et al. 1995). The barrier layer in the Subtitle D Cover was within the frost zone for the site (UBC 1997). Desiccation (Figure 7.3-3) can lead to the development of cracks and thus create preferential flow paths for percolating water (Montgomery and Parsons 1990, Suter et al. 1993, Benson et al. 1994b, Dwyer 2003). Shallow excavation of the Subtitle D Cover during the fall of 2002 revealed extensive cracking in the barrier layer. Furthermore, root intrusion into the barrier layer can increase saturated hydraulic conductivity by as many as three orders of magnitude (Waugh et al. 1999).

Figure 7.3-3. Desiccation cracking in clay barrier layer

The GCL Cover had the highest measured flux in 1999. The GCL experienced degradation. Measurements taken in 2003 of the GCL membrane removed from the test site revealed that the saturated hydraulic conductivity had increased several orders of magnitude. It was the only cover profile that experienced an increased flux rate between 1997 and 1999. Degradation of a GCL may be the result of desiccation cracking and/or ion exchange issues (James et al. 1997; Melchior 1997a, 1997b; Lin and Benson 2000). Dwyer (2003) has shown GCL products significantly degrade with time, measuring hydraulic conductivity increases by as many as four orders of magnitude.

8.0 PERFORMANCE GOALS AND MONITORING

LANL final cover systems will each have performance goals associated with them dependent on applicable regulations and site-specific risks. The cover systems will be monitored to ensure they meet these goals and continue to perform as intended.

8.1 Performance Goals

Each cover system shall be designed to mitigate any contaminant release vectors deemed significant. Specifically, each cover shall have performance goals related to flux minimization based on site-specific risk, erosion minimization not to exceed 2 tons/acre/year (4.5 tonnes/ha/year) (EPA 1991), and limit radioactive exposure.

8.1.1 Cover System Flux

The design of the cover systems will incorporate the Dwyer Point of Diminishing Returns Method (Dwyer et al. 1999) as a basis to determine the minimum water storage capacity required by the cover and thus the minimum cover soil depth. This method involves modeling the cover profile to determine the soil depth at which flux is minimized and is described in section 3. Additions to this depth will be driven by other design considerations such as optional layers or predicted soil losses due to erosion. The water balance variables in the cover system and flux during design will be based on modeling of the cover system supported by applicable field data and natural analogs. Additional thickness may also be warranted to satisfy desired factors of safety.

The monitoring of the cover systems will be included to ensure that the cover profile is providing adequate protection to human health and the environment. Each site containing radioactive waste will have a site-specific F&T modeling effort performed. A key input boundary condition to the F&T modeling is the flux through the cover system. Therefore, sensitivity analyses of the F&T modeling effort will produce a maximum allowable flux criterion for the cover system for the specific site. This maximum allowable flux will serve as the basis for water balance monitoring of the installed cover system.

8.1.2 Cover System Erosion

The cover system shall be designed to minimize erosion. Design features shall be included to minimize erosion. Monitoring of the cover systems will be included to ensure that total erosional soil losses does not exceed that intended in the design.

8.1.3 Radioactive Dose Limits

Each cover system shall be designed based on the site specifics to ensure that maximum dose limits are not exceeded as described in section 1.2.

8.2 Performance Monitoring

Monitoring of landfill covers generally centers on the monitoring of flux through the cover. Because surface erosion due to both water and wind is of major concern, monitoring of the final landfill covers shall also be included. Erosion can be monitored by the use of erosion pins or monuments, visual observation, surveyed elevations, or a number of other choices.

8.2.1 Water Balance Monitoring for LANL Sites

Flux through a cover system is often the primary concern of regulators. Moisture monitoring can provide immediate feedback on the integrity of a cover system. Significant changes in the water balance of a

cover system can also provide feedback for degradation due to erosion, biointrusion, or other means. Because LANL has such a deep vadose zone, installed final cover systems will likely require an accurate monitoring system installed to detect early problems—long before they are detected in groundwater. It is expected that groundwater monitoring will continue to be performed at LANL. The monitoring performed on cover systems should be correlated with groundwater monitoring and any local and applicable vadose zone monitoring performed to verify that the remediation efforts, whether they are solely a final cover system or a cover system in combination with other remediation technologies, are working as their designs intended.

It is important to note that there is no perfect vadose zone monitoring equipment available. Consequently, it is common to use multiple monitoring systems together to allow strengths in one system to assist or offset weaknesses in another. For LANL final cover systems, the monitoring scheme to be deployed is to include multiple pan lysimeters in combination with time domain reflectometry (TDR). Lysimeters can be installed to directly measure percolation through a cover, while TDR can be used to indirectly measure it.

Each cover system installed at LANL will have multiple pan lysimeters installed. That is, several locations within the cover system will be monitored separate from each other. It is recommended that the size and shape of the site dictate the number and location of lysimeters to be used. For example, for a larger cover with significant slopes should include a lysimeter on a north- and south-facing slope. Each of these slopes will likely produce different flux values. The lysimeters shall be placed in a manner to produce a good indication of overall cover performance. That is, lysimeters should not just be placed in areas considered to produce worse-case flux, and conversely, they should not just be placed in areas that will likely produce the least amount of flux.

Complementary to each lysimeter installed, TDR probes at varying depths will also be installed. At a location at the same slope relationship in a cover system, a set of TDR probes will be installed approximately 5–10 feet (1.5–3 m) from the nearest outside edge of the lysimeter. The probes will be placed vertically in a given hole starting at the base of the cover system (lowest fine-textured soil layer or within the interim cover system). The vertical spacing will be no greater than 1 foot from the bottom-most probe to the top probe (placed at 6 inches [15 cm] beneath the cover surface).

8.2.1.1 Lysimeters

Soil lysimeters are used for collecting deep drainage or percolation data and estimating recharge. The most commonly used lysimeter in covered systems is a simple variation of the soil lysimeter called a pan lysimeter. The pan lysimeter is an impervious pan installed beneath or within the soil in the plot of interest. Water collected in the pan drains to a collection system where it is subsequently quantified. There are numerous designs of lysimeters; however, they are typically less than 6.5 ft (2 m) in depth (Stephens 1996) and their plan dimensions are proportioned according to the desired accuracy and shape of the plot being monitored. Generally, the larger the lysimeter, the greater the accuracy. The rate of soil-water collected per unit area monitored is extrapolated and used to estimate the percolation rate of the entire cover system. It is important to note that only an estimate can be gained with this method. A certain amount of uncertainty always exists with lysimeter measurements. Lysimeters are best installed prior to the placement of a cover system.

8.2.1.1.1 Advantages and Disadvantages of Lysimeters

The principal advantage of soil lysimeters is that they provide direct measures of soil-water flux. Percolation rates can be measured with relative precision using lysimeters (Gee and Hillel 1988, Benson et al. 1994a, Ward and Gee 1997). Pan lysimeters are the most common means used to measure flux

through a cover system today. Precise changes in soil-water storage can also be measured when weighing lysimeters are employed.

The most significant disadvantage of lysimeters is the artificial no-flow boundary induced by the barrier at the base of the lysimeter. This boundary, which does not exist in the actual field setting, prevents upward and downward flow of vapor and liquid across the base of the lysimeter. In effect, the lysimeter acts as a rectifier. All water that migrates downward to the base of the profile is collected and routed out of the system. Consequently, the collected water can never move upward as a result of natural upward gradients induced by ET and temperature gradients, as might occur under natural conditions. Coons et al. (2000) indicate that percolation rates measured using lysimeters can be as much as 3 mm/yr too large due to the artificial trapping of water vapor by the lower boundary.

Most lysimeters also include an earthen or geosynthetic drainage layer directly on top of the lower boundary for directing percolation to a measuring point. The larger pores associated with drainage layers induce a capillary break at the base of the cover profile that might not exist under natural conditions (Khire et al. 1999). As a result, an artificial increase in the storage capacity of the cover profile may be incurred relative to natural conditions, as well as an artificial reduction in percolation rate. This issue is only problematic if the drainage layer has very different pores than the material over which the ET cover is being installed or the cover being monitored is very thin (< 1 m). For typical solid wastes, the air and water entry suctions are very low (~10 mm) (Benson and Wang 1998), and most ET covers have a thickness greater than or equal to 1 m. Thus the capillary break effect generally does not significantly affect percolation estimates (Benson et al., in press).

Lateral diversion can be a significant problem with lysimeters if the areal extent of the lysimeter is insufficient and the lysimeter does not have vertical sidewalls (Figure 8.2-1) (Bews et al. 1999). Diversion occurs under unsaturated conditions due to the tendency for water to be retained within finer-textured cover soils rather than coarser-textured drainage layers (i.e., due to a capillary break). Lysimeters that are too small or narrow collect too little water and underestimate the percolation rate. Chiu and Shackelford (1994, 2000) suggest that the breadth of a lysimeter should be at least five times the depth of the profile being monitored to prevent diversion from affecting the percolation rate.

The precision of percolation rates measured with lysimeters is also affected by leakage, which is minimized or eliminated through careful construction and post-construction testing. Artificial root water uptake (i.e., uptake of water stored in the drainage collection system that would drain below the root zone if the lysimeter was not present) can also affect measurements of percolation rate.

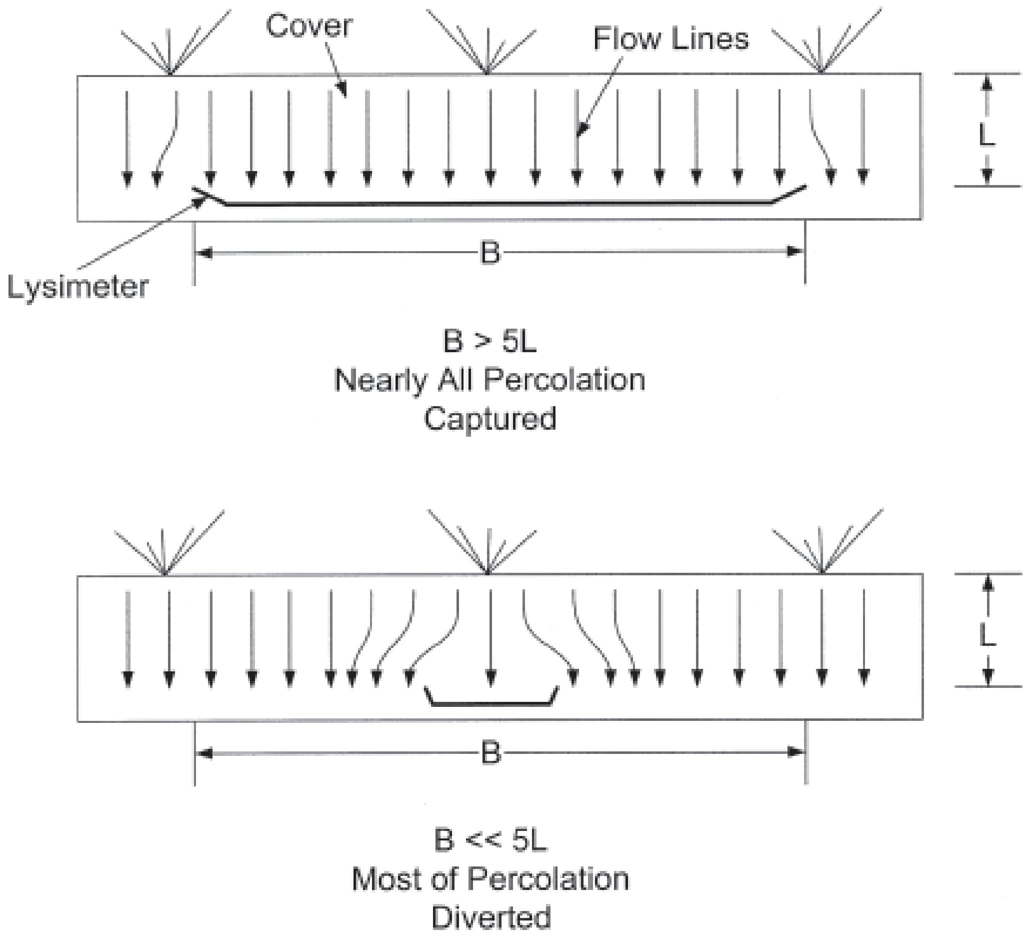


Figure 8.2-1. Effect of lysimeter width on diversion of percolation (modified from Benson et al. in press)

8.2.1.2 Time Domain Reflectometry

The process of sending pulses through a cable and observing the reflected waveform is called TDR. TDR can be used to measure soil-water content, bulk EC, and rock mass deformation. TDR measurements are nondestructive and offer excellent accuracy and precision. The type of material surrounding the conductors influences a waveform traveling down a coaxial cable or waveguide. If the dielectric constant of the material or medium surrounding the conductors is high, the electronic signal propagates slower. Because the dielectric constant of water is much higher than most materials, a signal within a wet or moist medium propagates slower than in the same medium when dry. Ionic conductivity affects the amplitude of the signal but not the propagation time. Thus moisture content can be determined by measuring the propagation over a fixed length probe embedded in the soil medium being measured.

Traditional TDR equipment generally consists of a cable tester (e.g., Tektronix model 1502b) or a specially designed commercial TDR unit, multiplexer units (assuming multiple probes are used), probes, and associated coaxial cable. It is recommended that cable tester not be employed, but rather a system similar to that described below by Campbell Scientific, Inc. (CSI). A generic calibration equation developed by Topp et al. (1980) can be used. However, the probes should be calibrated for their specific application (e.g., soil texture and density and cable length) to yield accurate soil moisture measurements

(Lopez et al. 1997). Calibration is critical to ensure accuracy. Lopez et al. (1997) describe a developed TDR calibration procedure.

A major advantage to the use of TDR for soil moisture content measurement is the ability to fully automate the system. Additionally, once installed, the system can have a long lifespan. Accuracy in many soil types is very good. A TDR system's accuracy in general is about the same as that for neutron probes (Schofield et al. 1994). TDR, however, can be expensive to use. Besides the greater expense, a major disadvantage of TDR is the fact that accuracy decreases with increased cable length. Soils with high water content lengthen the propagation time of the electrical pulse, and this phenomenon is reflected as an apparent increase in the travel distance. Soils with high water content and a high EC rapidly attenuate the electrical pulse. If the attenuation is great enough, there will be no return signal and the probe cannot be used. However, probes can be coated to help reduce the errors created by this problem.

A typical TDR system can be purchased from vendors such as CSI, among a number of similar vendors providing products of equal quality and precision. The principal components of CSI TDR system are the CSI data logger, TDR100 Reflectometer, SDMX50-series coaxial multiplexers, interconnecting cabling, and TDR probes. The TDR100 is controlled using PCTDR Windows software or using a TDR100 instruction with a CR10X or CR23X data logger. Typically, the system is powered with a user-supplied, deep-cycle battery that is recharged by a 20-watt solar panel. Installations that have access to AC power may be able to use the PS100 sealed rechargeable battery in a CR10X installation, or the CR23X's rechargeable battery. The system components are:

- TDR100 Time Domain Reflectometer: The TDR100 is the core of the CSI TDR system. The TDR100 (1) generates a very short rise time electro-magnetic pulse that is applied to a coaxial system which includes a TDR probe for soil-water measurements and (2) samples and digitizes the resulting reflection waveform for analysis or storage. The elapsed travel time and pulse reflection amplitude contain information used by the on-board processor to quickly and accurately determine soil volumetric water content, soil bulk EC, rock mass deformation, or user-specific, time-domain measurement.

- SDMX50-series Multiplexers: The SDMX50-series multiplexers are eight-channel coaxial switching devices. Three levels of switching allows up to 512 soil-water content or rock mass deformation cables to be connected to one TDR100. The multiplexers are controlled by a CR10X or CR23X data logger during automated measurements. The multiplexers can be controlled by the TDR100 when using PCTDR or connected to a PC. Three multiplexer models are available: the SDMX50, SDMX50LP, and SDMX50SP. All provide reliable and programmable channel selection, but are packaged differently to allow flexibility for a range of installation methods.

- TDR Enclosure: The reflectometer, data logger, multiplexer and power supply should be housed in an environmental enclosure to protect the equipment from weather, condensing humidity, and dust. Campbell Scientific offers the ENCTDR100 for this purpose. It can house the data logger, data logger's power supply, TDR100, and SDMX50SP (the SDMX50 includes its own enclosure and the SDMX50LP is intended to be mounted in a separate user-supplied enclosure). The ENCTDR100 includes interconnecting SDM and coaxial cabling, grounding wires, desiccant, humidity indicator, and hardware for mounting the enclosure on a pole, tripod mast, or tower leg.

- TDR Probes: The TDR probes act as a wave guide. Impedance along the rods varies with the dielectric constant of the surrounding soil. Because the dielectric constant of soil primarily depends on the amount of water present, soil volumetric water content can be inferred from the reflected measurements. Soil bulk EC is determined from the attenuation of the applied pulse. CSI has two soil probe models available. Both models consist of three pointed, large-diameter

rods and a large epoxy head allowing use in rugged environments. The models only differ in their connector cables, and are selected based on the desired cable length.

8.2.1.2.1 Flux Calculation Using TDR Data

The method includes the use of Darcy's Law (Equation 8.1). Darcy's Law is a phenomologically derived constitutive equation that describes the flow of a fluid through a porous medium (typically water through an aquifer). Darcy's Law (an expression of conservation of momentum) is a relationship determined experimentally by Henry Darcy, which has since been proved theoretically from simplifications made to the Navier-Stokes equations. It is analogous to Fourier's law in the field of heat conduction, Ohm's law in the field of electrical networks, or Fick's law in diffusion theory. This simple relationship relates the instantaneous discharge rate through a porous medium to the local hydraulic gradient (change in hydraulic head over a distance) and the hydraulic conductivity at that point.

Darcy's Law: $Q = K_{sat}\ i\ A$ **Equation 8.1**

where:

Q = flow rate;

K_{sat} = saturated hydraulic conductivity;

A = x-sectional are

$$i = \frac{\Delta H}{L} = \frac{hydraulic\ \ head\ \ difference}{sample\ \ length}.$$

Darcy's Law deals with saturated water flow. Darcy's Law was later modified by Buckingham for unsaturated flow to produce the Darcy-Buckingham flux law (Equation 8.2):

$$J_w = \frac{Q}{A} = K_{unsat} \frac{\Delta H}{L} = flux$$ **Equation 8.2**

where:

K_{unsat} = unsaturated hydraulic conductivity;

Reconfigured to describe vertical unsaturated flow between any two points (Equation 8.3). Refer to Figure 8.2-2.

$$J_w = K_{unsat}\left(\frac{H_2 - H_1}{Z_2 - Z_1}\right)$$ **Equation 8.3**

where:

H_2 = matric potential at TDR 2

H_1 = matric potential at TDR 1

Z_2 = elevation at TDR 2

Z_1 = elevation at TDR 1

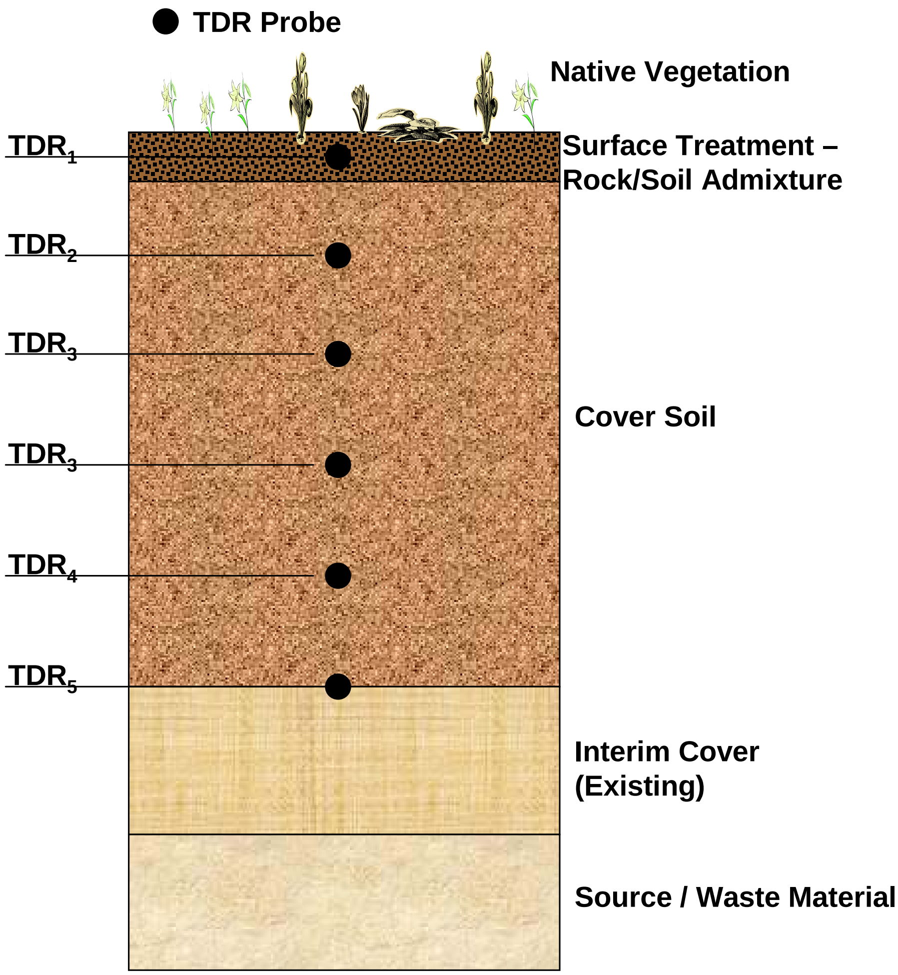


Figure 8.2-2. Example locations of TDR probes

Steps to obtain matric potential head often referred to as soil suction (H), elevation potential head (Z), and unsaturated hydraulic conductivity include the following:

1. Matric Potential Head:

    - Using TDR instrumentation as described above, calculate an average daily moisture content value for a given point from daily TDR measurements. This daily moisture content value can then be correlated with the matric potential at that moisture using the laboratory-measured moisture characteristic curve for the given soil (Figure 8.2-3).

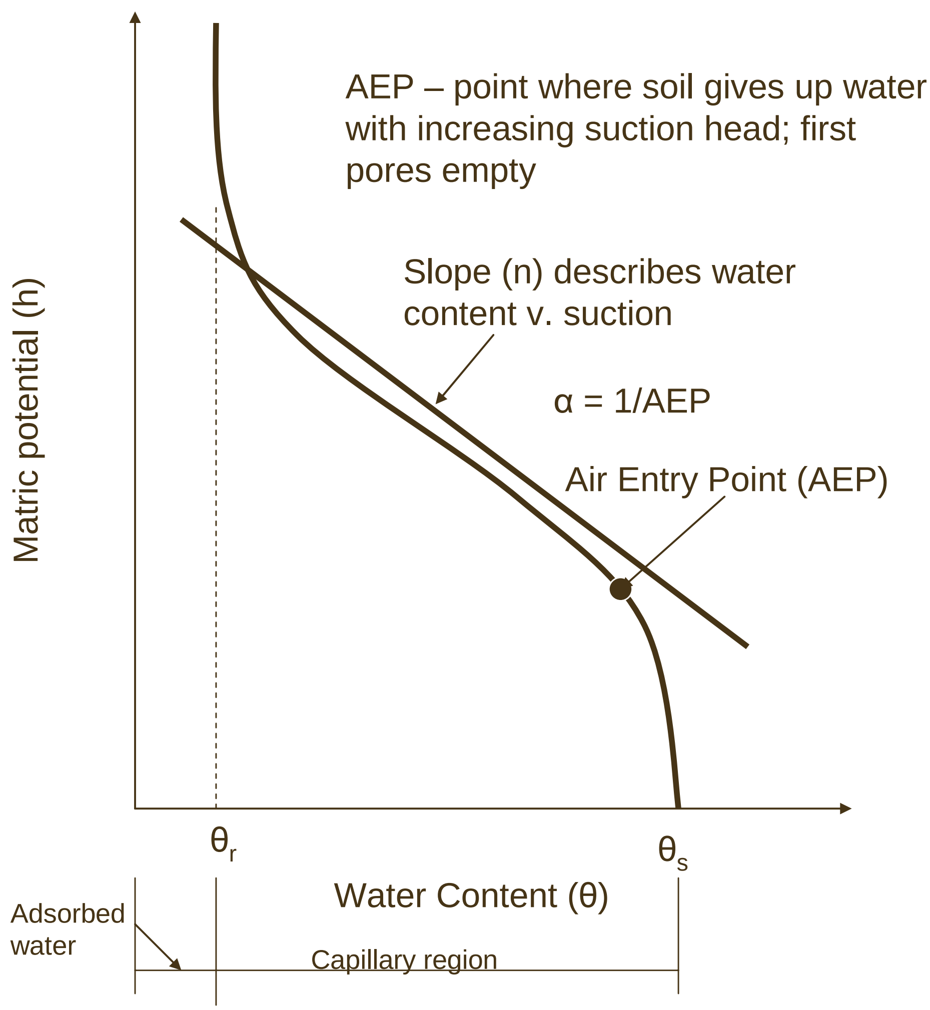


Figure 8.2-3. Moisture characteristic curve

2. Elevation Potential Head:

    - The elevation for each TDR probe deployed shall be measured and recorded.

3. Unsaturated Hydraulic Conductivity:

    The unsaturated hydraulic conductivity shall be the average value (Equation 8.4) between the two points of interest (TDR_1 and TDR_2).

$$\frac{K_{unsat1} + K_{unsat2}}{2} = K_{unsat,average}$$ **Equation 8.4**

Unsaturated hydraulic conductivity as a function of matric potential (Equation 8.5). Figure 8.2-4 illustrates three soil types with their hydraulic conductivity plotted as a function of matric potential.

$$K(H) = \left(\frac{K_{sat} \left\{ (1 - \alpha H)^{mn} \left[1 + (\alpha H)^n \right]^{-m} \right\}^2}{\left[1 + (\alpha H)^n \right]^{m/2}} \right)$$ **Equation 8.5**

where:

α, n = van Genuchten parameters

m = 1 – 1/n

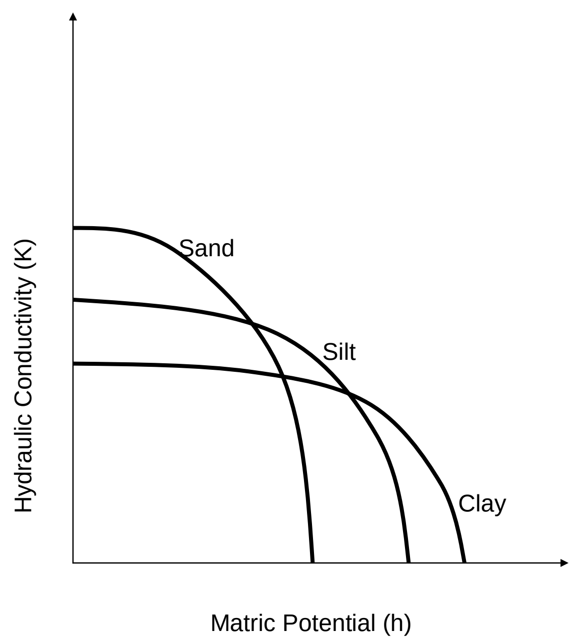


Figure 8.2-4. Hydraulic conductivity as a function of matric potential

Unsaturated hydraulic conductivity as a function of water content (Equations 8.6 and 8.7).

$$K(\theta) = K_{sat} \theta^{1/2} \left[1 - \left(1 - \theta^{1/m} \right)^m \right]^2$$ **Equation 8.6**

$$(\theta) = \left[1 + (\alpha h)^n \right]^{-m}$$ **Equation 8.7**

where:

θ = normalized water content

Figure 8.2-5 illustrates three soil types with the hydraulic conductivity plotted as a function of water content.

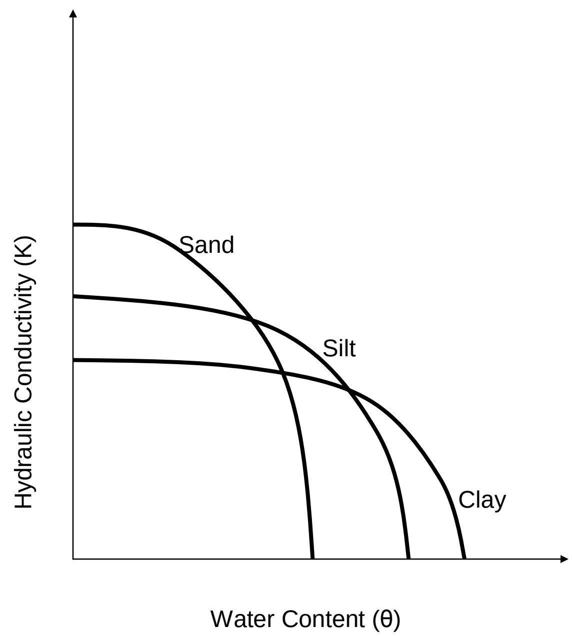


Figure 8.2-5. Hydraulic conductivity as a function of water content

8.2.2 Erosion Monitoring

Erosion inspections should determine the location and amount of erosion that has occurred at the surface of the cover. Erosion measurements can be used to determine the corrective action necessary. Two different types of monitoring for erosion may be used: erosion control monuments or erosion control pins—both are used to estimate the amount of soil loss due to erosion.

Erosion control monuments can be installed during construction to indicate the amount of subsequent surface erosion. Each erosion control monument is placed at an elevation that is representative of the surrounding ground elevation. The elevation and state plane coordinates of erosion control monuments should be surveyed in conjunction with the topographic survey performed at the completion of the project. To determine erosion, measure the cover surface at each erosion control monument and at four elevations evenly spaced and approximately 10 feet from the control monument using a global positioning system (GPS) with a horizontal and vertical accuracy of ±0.10 feet. The measurements can be taken in the four cardinal directions (north, south, east, and west) as determined by GPS. The average of the four measurements can be compared to the baseline established during the initial site survey to assess the extent of and/or potential for erosion. Surveying the elevations outward from the erosion control

monument and comparing those elevations to the baseline elevations determines the extent of the deficient area.

Place erosion pins similar to that shown in Figure 8.2-6 in a grid spaced at 100 feet (30 m). The erosion pins shall extend a minimum of 3 ft (1 m) into the cover profile. Measurements shall be made on a periodic basis consistent with the cover system post-construction monitoring. As a minimum, erosion measurements shall be made after each major precipitation event for the first two post-construction years and annually thereafter. Because the allowable annual soil loss on a cover system is very small (about 0.28 mm/year), the erosion pin markings and depth gauge must allow for accuracy to this extent.

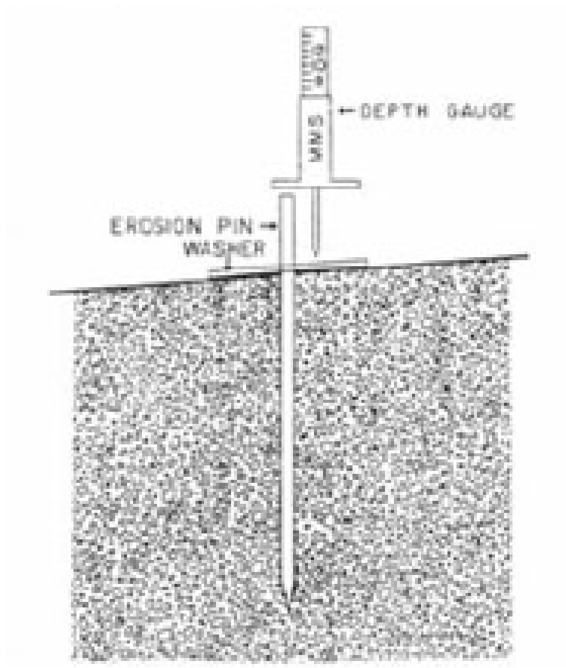


Figure 8.2-6. Typical erosion pin measurement system

9.0 QUALITY ASSURANCE

QA is a planned system of activities that provides confidence quality is achieved. QA is the responsibility of everyone involved in an activity. Documentation that QA was achieved is generally the responsibility of the owner and often designated to the design engineer(s) or other designated party. QC is a planned system of inspections used to directly monitor and control the quality of the construction process and materials used. Performance and documentation of QC activities and testing is generally the responsibility of the contractor building the facility. The QA requirements depend on organizational and contractual relations developed for each project and this section deals primarily with the QC requirements for cover construction. This section discusses requirements for a quality approach consistent with processes and contracting arrangements planned for procurement of the design and construction of covers at LANL.

9.1 QA Plan

The purpose of a QAP is to accurately identify the quality requirements applicable to activities performed by LANL's ERSS and its subcontractors and to provide a process to implement the requirements in those activities. ERSS quality requirements are the regulatory quality requirements identified from DOE documents, specified industry standards, the March 1, 2005 Consent Order, and LANL requirements documents.

The QAP for ERSS (LA-UR-06-4108) describes the QA requirements in a flow-down process to be implemented by subtier contractors performing work activities at LANL. This flow-down process describes the requirements that specifically address quality management; define the planned work activities and subsequent safe work conduct; and finally how LANL management has designated for all LANL policy procedures to be followed to meet these requirements.

The subcontractor QAP for any given LANL ERSS project shall be consistent with IP 330.3, Los Alamos National Laboratory Quality Assurance Program. DOE Order 414.1C, Quality Assurance, has been imposed on all contractors, including the prime Contractor, LANS. It requires the integration of multiple QA requirements including those in 10 CFR 830.122. It also requires that contractors apply a voluntary national or international consensus standard for nuclear work and any additional standards as necessary to address any unique or specific work activities. Among the consensus standards to be applied to ERSS include: the American Society of Mechanical Engineers (ASME); Quality Assurance Requirements for Nuclear Facilities Applications, Part 1, requirements for Quality Assurance Programs for Nuclear Facilities (ASME NQA-1, 2000) for its nuclear activities; American National Institute Standards Institute (ANSI), American Society of Quality (ASQ); ANSI/ISO/ASQ Q9001-2000, Quality Management System Requirements for non-nuclear activities; and Quality Systems for Environmental Data and Technology Programs, Part 6, Collection and Evaluation of Environmental Data (ANSI/ASQ E4-2004, Part 6). Additionally, although not a national standard, LANL management has chosen to include the quality plan contained in the Consent Order.

DOE further requires (10 CFR 830.7) that contractors apply a graded approach to implement the requirements of this part. ERSS applies a grading process commensurate with the safety risk as defined and accepted by DOE in documented safety analyses. ERSS considers several factors in the grading process to ensure that the workers, the public, and the environment are protected:

1. The relative importance to safety, safeguards, and security;
2. The magnitude of any hazard involved;

3. The life cycle stage of a facility;
4. The programmatic mission of a facility;
5. The relative importance of radiological and non-radiological hazards; and
6. Any other relevant factor.

The ERSS grading process is identified in procedure, EP-ERSS-5019, Application of Grading. This grading process can also be used in the development of a distinctive QA Project Plan for work activities that are programmatic in nature.

LANL requires subcontractors performing design and construction activities to prepare a QA/QC Plan that tailors the ERSS requirements to activities and organizations specific to the implementation of the cover design. The plan should describe the organizational roles and responsibilities of individuals responsible for day-to-day QA activities as well as QC requirements needed for control of materials and processes as delineated in the design. Methods of controlling records and documentation of construction oversight should be described to provide control over implementing processes affecting quality of the final product. The QA portion of the QA/QC plan shall be consistent with the requirements set forth in the ERSS QAP.

9.2 Specific QC Requirements for Materials to be Used in a Cover System

Design specifications shall address the type and quality of materials to be used in each cover system. The QA/QC plan shall describe how to ensure these materials will meet specifications while ensuring the placement of the materials satisfies the intent of the design. There are several required layers in the ET cover system recommended for use at LANL. The general QC requirements to be contained in the QC portion of the QA/QC Plan are described below for each of these components, followed by specific tests and frequencies to be administered.

9.2.1 Surface Treatment – Rock/Soil Admixture

Each cover will contain a surface treatment composed of a mixture of rock and soil (refer to Figure 2.1-1). The objective of this surface treatment is to provide a medium that allows for plant establishment and growth while minimizing soil loss due to erosion. The topsoil used shall possess adequate levels of plant-essential nutrients to encourage the establishment and productivity of non-woody indigenous plants. Additionally, this rock/soil admixture shall be placed without compaction. The ratio of rock to soil as well as the size of rock shall be determined in the design stage and specified. QC shall ensure these requirements are met. The rock shall adhere to the durability requirements described in section 5.2.6.

QC on materials and processes used to construct this soil layer shall assure the quality by accomplishing the following objectives:

1. Ensure the layer materials are suitable,
2. Ensure the rock and soil are uniformly mixed to the correct ratio, and
3. Ensure layer materials are properly placed.

9.2.2 Cover Soil

Each cover will be an ET cover with an adequate depth of suitable cover soil. The objective of the cover soil is to install a uniform layer that provides for water storage capacity while providing for an adequate rooting medium to allow successful plant establishment.

QC of the cover soil shall accomplish these objectives:

1. Ensure layer material quality meets the range of specifications developed in the design, and
2. Ensure layer materials are properly placed.

Soils used in the surface treatment and as cover soil must have an adequate quantity of fines, have a specified range of rock, have no object larger that the maximum size specified, have an adequate water storage capacity, possess a specified range of clay, have an adequate hydraulic conductivity, and possess an adequate supply of plant nutrients while limiting the amount of salts. With adequate evaluation of the borrow area during design, pre-approval of specific materials may limit the amount of QC testing to that necessary to provide assure the quality of the placed materials.

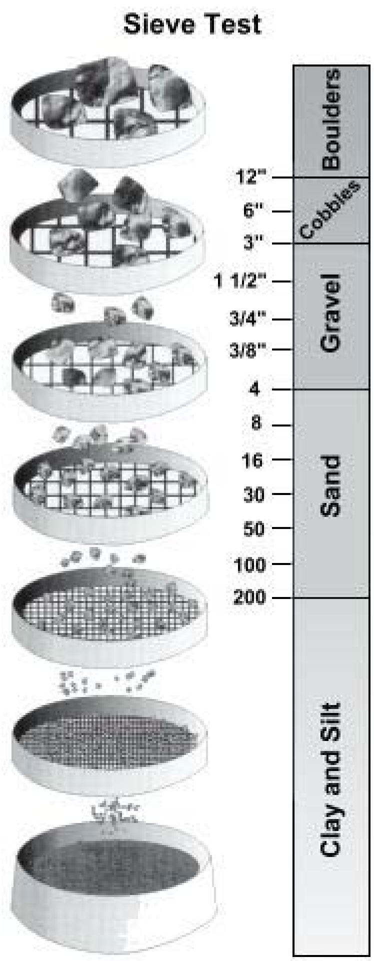


Figure 9.2-1. Soil particle size distribution

The amount of fines (particles passing the 200 sieve) is proportional to the water storage capacity of that soil. Fines are made up of both silt and clay (Figure 9.2-1). The minimum amount of fine soil required in the cover will be developed during the design phase. This process will evaluate the available borrow sources and determine which soils are adequate and which are not. Generally, unsaturated flow modeling

using software such as UNSAT-H or HYDRUS will be utilized to verify that the soils will effectively minimize flux. This modeling combined with borrow soil tested of both its hydraulic properties will determine whether the soil has an acceptable storage capacity and hydraulic conductivity.

The surface treatment layer will have a specified rock to soil ratio with an acceptable tolerance for this mixture. It will also specify the allowable range of rock size with an associated tolerance. This rock as well as any cobble/riprap used to control surface water or stabilize a slope must adhere to the rock durability requirements described in section 5.2.6.

The maximum size allowed for objects (i.e., clods and rocks) within any cover soil shall be specified. Coarse fragments pose a greater potential for problems in dry, hard soils than in wet soils. Rocks and other large foreign matter must be removed, and clods shall be broken down and/or remolded. If sufficiently large quantities of these large objects remain in the soil material to alter the in-place gradation, higher hydraulic conductivity and thus preferential flow paths may occur in portions of the cover.

The cover soil used will have a minimum and maximum quantity of gravel specified based on calculations performed as described in section 5.2.3. This specification will further stress that any gravel present must be uniformly mixed within the profile to ensure no pockets of gravel. Pockets of gravel will allow for increased preferential flow.

Consistent with minimizing desiccation cracking that leads to increased preferential flow, clay shall be limited. Clay, especially expansive clay, tends to crack as it dries (Suter et al. 1993, Dwyer 2003). Clay also has less storage capacity than a loam material.

Soil nutrients shall be determined to be acceptable or be amended to meet these requirements (Table 5.1-1). Salts within cover soil shall be limited to an acceptable range (Table 5.2-2).

Lift thickness shall be maximized for placement and compaction of the cover soil. During cover placement, it is crucial that each lift be bonded to the previous lift. This cuts down on the creation of inter-lift passageways (cracks) for the water to travel along as it passes from an overlying lift to a lower one (Figure 9.2-2). To minimize the creation of inter-lift passageways, if a smooth-rolled compactor is used, each lift shall be scarified to a depth of 2–4 inches (5 – 10 cm) prior to the placement of the next lift, thus establishing continuity between the lifts. Test pads prior to cover material placement may prove beneficial in determining appropriate lift thickness/placement and compaction equipment combinations.

Compaction of soil shall be carried out at “dry of optimum” moisture content, yet still within the acceptable moisture range to achieve the required minimum dry density. This ACZ is described in section 3.

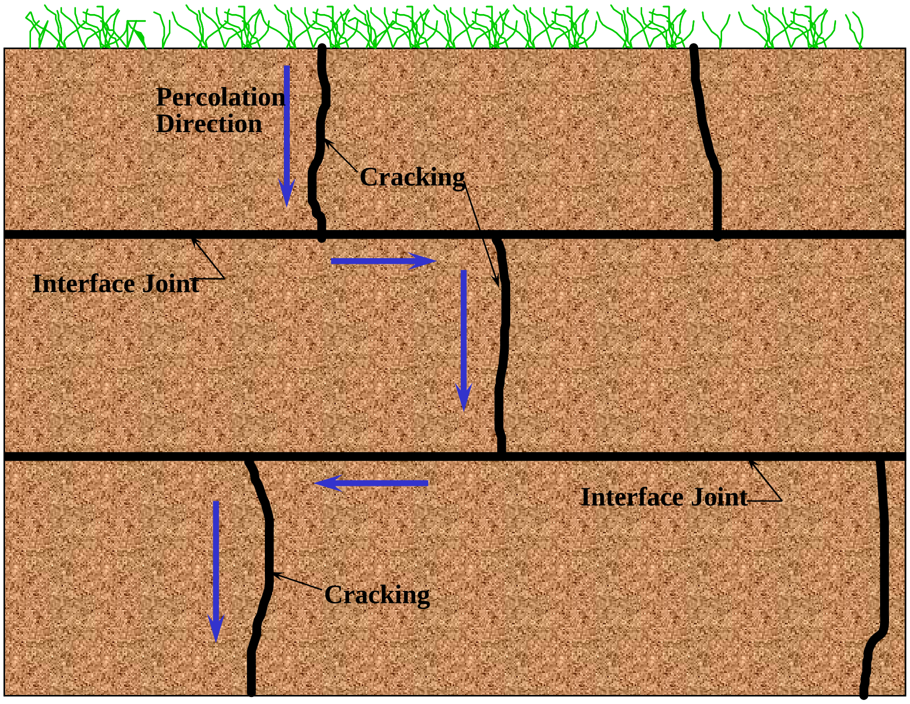


Figure 9.2-2. Preferential flow due to desiccation crack/interface joint

9.2.3 Seeding

Vegetation is critical to the success of an ET cover system. It provides for long-term stability of the cover surface, minimizes erosion, and reduces flux. Ensuring an adequate stand of vegetation begins with ensuring the quality of seed used. The seeding contractor shall be required to develop and submit a seeding plan detailing all seeding equipment to be used, fertilizer types, and mulch sources for inspection prior to initiation of work. Seed and fertilizer formulation certifications from the suppliers shall be submitted prior to material use.

Qualified seeding contractors and operators shall be employed. Qualifications of the seeding contractor shall be submitted for approval by LANL. Seeding native seed mixes requires experience and familiarity with the various seed types to ensure proper planting. The proper equipment for seeding the specified native mix must be used. Not all seed drills are capable of proper planting of native grass/forbs mixes.

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

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

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

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

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

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

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

The vendor shall package seed such that the acre coverage of each container is equal for convenience of inventory. Prior to planting any seed, the seed labels and certification documentation shall be inspected by QC personnel to ensure the seed provided meets the requirements specified. The process shall include tracking methods precluding the unauthorized use of rejected materials.

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

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

9.2.4 Cover System and other Design Component QA/QC Requirements

Specific QC tests and their frequency for common elements involved in cover system installation are described below in Table 9.2-1.

Table 9.2-1

QC Tests To Be Performed

Component	Description	Property, Test	Acceptance	Min. Frequency	Response to Nonconformance
COVER MATERIALS					
Subgrade Preparation / Interim Cover Material (upper 1-foot [31 cm])	Existing Soil	Std. Proctor, ASTM D698	n/a	1 per 10 field density tests	n/a
		Min. Density, ASTM D2922	95% of max. dry density	1/400 sy; 2/day min.	Rework
		Min. Density, ASTM D1556	95% of max. dry density (verify nuclear gauge accuracy)	1 per 10 ASTM D2922 tests	Rework
		Max. Water Content, ASTM D3017	Dry of Optimum Moisture Content per ASTM D698	1/400 sy; 2/day min.	Rework or remove and replace
		Max. Water Content, ASTM D4643 or ASTM D2216	Dry of Optimum Moisture Content per ASTM D698 (verify nuclear gauge accuracy)	1 per 10 ASTM D3017 tests	Rework or remove and replace
		Complete coverage, observation	n/a	Continual	n/a
Borrow Material for Cover Soil	Soil	Particle Size Distribution, ASTM C136	20% min. or as determined by design	1/100 cy	Reject
		Particle Size Analyses, ASTM D422, ASTM D1140	20% min. or as determined by design	1/100 cy	Reject
Surface Treatment; Rock/Soil Admixture	Soil	Percent Fines (200 sieve), ASTM D1140	20% min. or as determined by design	1/1000 cy	Reject or reprocess, re-evaluate
		Max. Water Content, ASTM D4643 or ASTM D2216	Dry of Optimum Moisture Content per ASTM D698	1/1000 cy	Rework or remove and replace
		Max. density, visual	No compaction, loose	Continual	Rework
		Max. object size	4 inch (10 cm)	Continual	Remove and discard large objects

Component	Description	Property, Test	Acceptance	Min. Frequency	Response to Nonconformance
	Soil Nutrients	CEC	Greater than 15	1/borrow site & then as needed based on visual observation	Reject, re-evaluate borrow source
		Percent organic matter	Greater than 2% (g/g)	1/borrow site & then as needed based on visual observation	Reject, re-evaluate borrow source
		Nitrogen	Greater than 6 ppm	1/borrow site & then as needed based on visual observation	Reject, re-evaluate borrow source
		Phosphorous	4 to 7 ppm	1/borrow site & then as needed based on visual observation	Reject, re-evaluate borrow source
		Potassium	61 to 120 ppm	1/borrow site & then as needed based on visual observation	Reject, re-evaluate borrow source
	Max. Salt Content	Elec. Conductivity	less than 8 µS/cm	1/borrow site & then as needed based on visual observation	Reject, re-evaluate borrow source
		Sodium Adsorption Ratio	less than 6	1/borrow site & then as needed based on visual observation	Reject, re-evaluate borrow source
		ESP	less than 15% (g/g)	1/borrow site & then as needed based on visual observation	Reject, re-evaluate borrow source
		$CaCO_3$ content, ASTM D 4373	less than 10% (g/g)	1/borrow site & then as needed based on visual observation	Reject, re-evaluate borrow source
	Rock	Percent and size of gravel, ASTM D 422	Size and ratio as determined in design		
		Max Object Size	4 inch (10 cm)		

Component	Description	Property, Test	Acceptance	Min. Frequency	Response to Nonconformance
		Petrographic Exam, ASTM C295 Durability • Specific Gravity • Absorption • Sodium Sulfate Abrasion, LA Rattler	See section 5.2.6 for durability and oversizing requirements.		
Rooting Medium, Layer for Cover Soil	Soil	Percent Fines (200 sieve)	20% min. or as determined by design	1/borrow site & then as needed based on visual observation	Reject, reevaluate borrow operation
		Percent Gravel (greater than 4 sieve)	10% max., uniformly mixed into soil	1/borrow site & then as needed based on visual observation	Reject, reevaluate borrow operation
		Max. Stone/Clod, Observation	4-inch max	continual	Remove and discard large objects
		ACZ for acceptable density and water content	See section 3	1/100 cy	Rework or remove and replace
	Seed	Blend, Approved standard	See section 4, Table 4.1-1, or that determined in design	Approve source, vendor certificate	Reject
		Purity, Approved standard			
		Germination, max.			
		Weed seed.			
		Application, Drill-seed or approved standard			
	Fertilizer	Nitrogen	Approved standard	Approve source, vendor certificate	Replace
		Phosphoric acid	Approved standard		
		Soluble potash	Approved standard		
	Vegetative mulch	Composition	Approved standard	Approve source, vendor certificate	Replace, rework
Bio-Barrier	Gravel & cobbles	Gradation	Approved Standard, section 5	Approve source; vendor cert./10,000 cy	Reject
		Durability–rock/concrete is to be 'sound'	Engineering Judgment	Approve source; vendor cert./10,000 cy	Reject

Component	Description	Property, Test	Acceptance	Min. Frequency	Response to Nonconformance
Filter Layer	Sand/Gravel	Particle Size Analyses, ASTM D422	Approved Standard, section 5	Approve source; vendor cert./10,000 cy	Reject
		Durability – rock/concrete is to be ‘sound’	Engineering Judgment	Approve source; vendor cert./10,000 cy	Reject
Side Slope Cover Materials	Gravel/Cobble	Gradation	Approved size	Approve source; vendor cert./10,000 cy	Reject
		Durability • Specific Gravity • Absorption • Sodium Sulfate Abrasion, LA Rattler	See section 5.2.6 for durability and oversizing requirements.	Approve source; vendor cert./10,000 cy	Reject
	Soil	Acceptable density and water content per the ACZ	See section 3	1 per borrow source/area	Replace or rework
General Fill (cover soil)	Borrow Source Dependent	Particle Size Distribution, ASTM C136	20% min. or as determined by design	1/100 cy	Reject
		Particle Size Analyses, ASTM D422, ASTM D1140	20% min. or as determined by design	1/100 cy	Reject
Radon Barrier	Soil	Percent Fines (200 sieve), ASTM D1140	20% min. or as determined by design	1/100 cy	Reject, reevaluate borrow operation
		Percent Gravel (greater than 4 sieve)	10% max. or as determined by design, uniformly mixed into soil	1/100 cy	Reject, reevaluate borrow operation
		ACZ for acceptable density and water content	See section 3	1/100 cy	Rework or remove and replace
EROSION PROTECTION					
Erosion Protection (side slope)	Gravel / Cobbles	Gradation	Approved Standard	Approve source; vendor cert	Reject or reprocess, re-evaluate
		Petrographic Exam, ASTM C295 Durability • Specific Gravity • Absorption • Sodium sulfate Abrasion, LA Rattler	See section 5.2.6 for durability and oversizing requirements.	Approve source; 1 vendor cert	Reject, re-evaluate borrow source
Gravel Surface	Gravel	Placement	Approved	Observation	Continual

Component	Description	Property, Test	Acceptance	Min. Frequency	Response to Nonconformance
Veneer		Thickness	Standards.		
		Gradation	Particle Size Analyses, ASTM D422	Approve source; vendor cert.	Reject material
		Durability • Soundness Specific Gravity • Absorption • Sodium Sulfate Abrasion, LA Rattler	See section 5.2.6 for durability and oversizing requirements.	Approve source; vendor certificate	Reject material
Riprap	Cobbles	Placement Thickness	Approved Standard	Observation	Continual
		Gradation	Particle Size Analyses, ASTM D422	Approve source; vendor cert.	Reject material
		Durability • Soundness Specific Gravity • Absorption • Sodium Sulfate Abrasion, LA Rattler	See section 5.2.6 for durability and oversizing requirements.	Approve source; vendor certificate	Reject material
SURFACE WATER MANAGEMENT					
Drain & Filter Layer	Gravel or sand	Particle Size Analyses, ASTM D422	Approved Standard, section 5	Approve source; vendor cert./10,000 cy	Reject
		Durability – rock/concrete is to be 'sound'	Engineering Judgment	Approve source; vendor cert./10,000 cy	Reject
Coarse Gravel Drain	Gravel	Particle Size Analyses, ASTM D422 Durability – rock/concrete is to be 'sound'	Approved Standard, section 5 Engineering Judgment	Approve source; vendor cert./10,000 cy Approve source; vendor cert./10,000 cy	Reject Reject
Metal Culvert Pipe	Metal Pipe	Material Requirements, AASHTO M36		Approve source; vendor certificate d	Remove & replace
	Subgrade & Backfill	Layout/orientation, Survey		Check of Survey	Redo
		Std. Proctor, ASTM D698	n/a	1 per 10 field density tests	n/a

Component	Description	Property, Test	Acceptance	Min. Frequency	Response to Nonconformance
		Min. Density, ASTM D2922	95% of max. dry density	1/400 sy; 2/day min.	Rework
		Min. Density, ASTM D1556	95% of max. dry density (verify nuclear gauge accuracy)	1 per 10 ASTM D2922 tests	Rework
		Max. Water Content, ASTM D3017	Dry of Optimum Moisture Content per ASTM D698	1/400 sy; 2/day min.	Rework or remove and replace
		Max. Water Content, ASTM D4643 or ASTM D2216	Dry of Optimum Moisture Content per ASTM D698 (verify nuclear gauge accuracy)	1 per 10 ASTM D3017 tests	Rework or remove and replace
		Complete coverage, observation	n/a	Continual	n/a
Retention Ponds/Sedimentation Basins	Embankments Earth Liners	Std. Proctor, ASTM D698	n/a	1 per 10 field density tests	n/a
		Min. Density, ASTM D2922	95% of max. dry density	1/400 sy; 2/day min.	Rework
		Min. Density, ASTM D1556	95% of max. dry density (verify nuclear gauge accuracy)	1 per 10 ASTM D2922 tests	Rework
		Max. Water Content, ASTM D3017	Dry of Optimum Moisture Content per ASTM D698	1/400 sy; 2/day min.	Rework or remove and replace
		Max. Water Content, ASTM D4643 or ASTM D2216	Dry of Optimum Moisture Content per ASTM D698 (verify nuclear gauge accuracy)	1 per 10 ASTM D3017 tests	Rework or remove and replace
		Complete coverage, observation	n/a	Continual	n/a
Drainage Ditches	Excavation	Layout/orientation, Survey		Check surveying	Redo
	Subgrade & Backfill	Std. Proctor, ASTM D698	n/a	1 per 10 field density tests	n/a
		Min. Density, ASTM D2922	95% of max. dry density	1/400 sy; 2/day min.	Rework
		Min. Density, ASTM D1556	95% of max. dry density (verify nuclear gauge accuracy)	1 per 10 ASTM D2922 tests	Rework

Component	Description	Property, Test	Acceptance	Min. Frequency	Response to Nonconformance
		Max. Water Content, ASTM D3017	Dry of Optimum Moisture Content per ASTM D698	1/400 sy; 2/day min.	Rework or remove and replace
		Max. Water Content, ASTM D4643 or ASTM D2216	Dry of Optimum Moisture Content per ASTM D698 (verify nuclear gauge accuracy)	1 per 10 ASTM D3017 tests	Rework or remove and replace
		Complete coverage, observation	n/a	Continual	n/a
Drainage Channels /Ditches	Gravel or cobble	Placement Thickness	Approved Standard.	Observation	Continual
		Gradation	Particle Size Analyses, ASTM D422	Approve source; vendor cert.	Reject material
		Durability • Soundness Specific Gravity • Absorption • Sodium Sulfate Abrasion, LA Rattler	See section 5.2.6 for durability and oversizing requirements.	Approve source; vendor certificate	Reject material

9.2.5 Miscellaneous QC Considerations

There are a number of miscellaneous QC considerations during construction activities which shall be included in the QA/QC Plan. For example, hold points can be important in that they allow for a mandatory inspection point prior to continuing to ensure all interested parties are in agreement. A hold point can further be used for installation of monitoring equipment that is required within the constructed facilities. Table 9.2-2 lists a few miscellaneous considerations that may be pertinent for installation of MDA cover systems and associated equipment and facilities at LANL.

Table 9.2-2
QA Plan Considerations (MK-Environmental Services 1993)

Item	Description	Discussion
Hold Point	A mandatory inspection point identified by the LANL designated representative in the subcontract documents, beyond which work specific to a certain activity shall not proceed until such time that the project manager has conducted an inspection and documented that the inspection results are acceptable. Hold point inspection may involve the project manager's QA/QC, Health Physics, or Engineering personnel. (See also Witness Point.)	The designer engineer or project manager, when listing specific hold points, shall indicate the estimated time period for the project manager to conduct necessary inspections and tests. The designer shall also indicate how much notification is required (e.g., 24 hours) from the subcontractor.
Nonconformance	Establish procedures to define, identify, and document nonconformances or deviations from the plans, specifications, or procedures; to control, approve, and implement the necessary corrective action; for follow-up to ensure that proposed corrective actions have been implemented.	Guidelines will be provided by the designer engineer to be used by the project manager in developing procedures to deal with nonconformances.
Observations of appropriate methods and equipment (quantitative observations)	In some cases the specifications may require specific methods of construction or type of equipment (such as using a smooth-rolled compactor rather than kneading compactor to prevent harm to buried soil instrumentation).	Designers will need to carefully identify and describe all methods and equipment that will be relevant to quality and provide instructions to be used by the inspector in making the appropriate observations. The designer shall also develop or collaborate with the inspector to develop record-keeping forms to document conformance to the specified methods and equipment.
Precision	The designer shall determine the appropriate number of significant digits to use for each specified test method, in accordance with ASTM E29.	Report relative compaction and water content both be reported to the nearest 0.1%.
Rounding	As described in ASTM E29, either an absolute or rounding method may be used for evaluating conformance with specifications.	Rounding method shall be used. This method used shall be used consistently throughout the project to avoid potential confusion and argument.

Table 9.2-2 (continued)

Item	Description	Discussion
Statistical Methods:	Acceptance criteria shall be used where a certain number of consecutive tests must meet a certain criteria (e.g., 90% relative compaction). In addition, all tests must satisfy minimum acceptable criteria (e.g., 88% relative compaction). This method is prescribed for concrete in ASTM C94, Section 17. For certain properties it may be appropriate to use a running average method. To facilitate recognition and understanding of ongoing patterns of compliance or noncompliance, additional statistical methods are described in Kotzia et al. (1993).	For example, rather than requiring a relative compaction of 90%, the specification could require a running average of 92% with an allowable variance to ensure that the soil was uniformly placed to mitigate preferential flow and differential settlement.
Stop Work Orders	Describe situations when a "Stop Work Order" may become necessary. Establish procedures and levels of authority for issuing a "Stop Work Order" and a mechanism for resolving the corresponding nonconformance(s).	Guidelines shall be developed to deal with a stop work order.
Test Locations	Two general methods are commonly used for selecting test locations. First, locations may be selected by a random method, such as the Caltrans use of a special deck of cards designed for this purpose. A hundred cards are used, each with numbers 00 through 99 randomly distributed across a grid on the card. The contractor (subcontractor) is allowed to select a card at random from the sorted deck. The last two digits of the serial number of the upcoming test are found on the card, and the grid location of this number indicates the location to take a test. Other methods may also be used to randomly select test locations. Second, test locations may be selected by the inspector. Rationale may range from trying to be relatively random, to trying to test material that appears to be representative, to intentionally testing material that appears to be the poorest quality with the assumption that if this test passes there can be good confidence all the material would pass.	The designer shall specify which of these methods and strategies shall be used for each activity or suggest how to mix the methods in order to achieve the optimal QC. Permanent features for remediation, features which cannot readily be required or maintained, and other critical features must be sampled in a manner which yields a high degree of confidence that all work is acceptable. Simple random sampling may not provide this confidence.

Table 9.2-2 (continued)

Item	Description	Discussion
Visual examination of quality of operations (qualitative observations)	Much of the work will require ongoing field observations. In some cases these observations will be the primary evaluation method. In other cases, observations will supplement test criteria (such as observing good coverage with a compactor to supplement field density testing).	Designers will need to carefully identify and describe activities that will be relevant to quality and provide instructions to be used by the inspector in making the appropriate observations. The designer shall also develop or collaborate with the inspector to develop record-keeping forms to document conformance to the specified methods and equipment.
Witness Point	An inspection point, identified by the project manager in the subcontract documents, where it is mandatory that the subcontractor formally notify the project manager when he has reached (or is about to reach) a certain stage of the work activity. At that time the project manager may elect to conduct and document an inspection. Witness points will generally be employed when interested stakeholders, regulators, or LANL personnel have determined they be present at or during a specific activity or element of construction. (See also Hold Point.)	The designer or project manager, when listing specific witness points, shall indicate how much notification is required (e.g., 24 hours) from the subcontractor. Also, language shall be added by the project manager to the subcontract documents to indicate that witness points for inspection are not to be confused with land survey witness points.

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Appendix A

Problems with Prescriptive Cover Systems

A-1.0 STUDIES REVEALING PHYSICAL PROBLEMS WITH PRESCRIPTIVE COVERS

Prescriptive covers (resistive covers) presently in use for RCRA Subtitle “C” and “D” regulated facilities as recommended by the EPA are used throughout the country with little regard for regional conditions. Experience in the western United States has shown these designs to be vulnerable to such things as desiccation cracking when installed in arid environments. 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.” The clay barrier layer in the traditional Subtitle “C” Cover must be constructed to yield a maximum hydraulic conductivity of 1×10^{-7} cm/sec. To achieve this, the soil often requires an amendment (e.g., mixed with bentonite) and should be compacted ”wet of optimum.” Compacting this layer “wet of optimum” in dry environments leads to drying and cracking of this layer. Desiccation, which can occur by several mechanisms, is an important failure mechanism for compacted soil hydraulic barriers, especially in arid environments (Suter et al. 1993, Dwyer 2003). The barrier layer in Subtitle “D” covers is also subject to desiccation cracking as well as deterioration due to freeze/thaw cycles.

Traditional covers, such as the Subtitle “C” covers, are not only inherently problematic but are very expensive (Dwyer 1998) and difficult to construct (Dwyer 1998). A study (EPA 1988) of existing landfills revealed that RCRA landfill cover technologies may not be working as well as intended. Randomly selected landfills revealed that the vast majority are leaking. Many have serious problems, including groundwater contamination and serious ecological impacts such as flora and fauna mortality. Virtually all parts of the nation have experienced water contamination due to leachate leaking from landfills to some degree (EPA 1988). Not all of these problems are the result of inadequate covers. Many older landfills were crudely installed (e.g., poor siting, inadequate or lack of liner) and thus destined for failure, but these problems can be mitigated by capping the entire landfill with a properly designed cover. A study (Mulder and Haven 1995) titled the California Solid Waste Assessment Test Report found that 72–86% of existing landfills with compacted clay barrier layers are failing (Figure A-1.0-1). It also concluded that these clay barriers leak regardless of climate or site-specific geology.

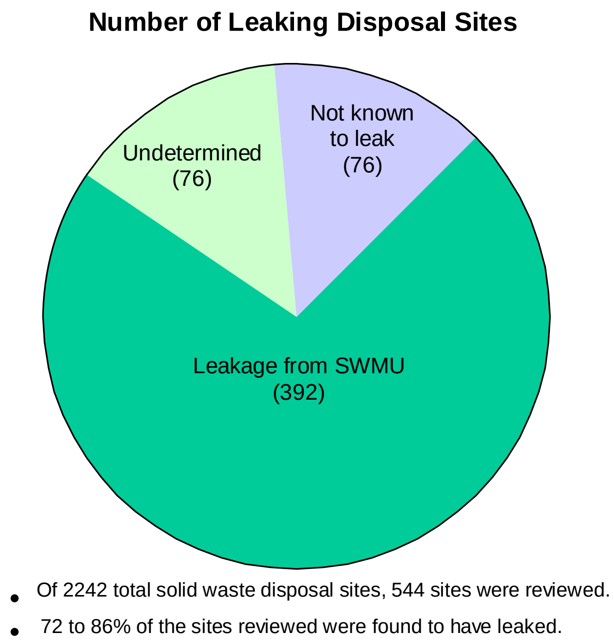

Figure A-1.0-1. California Solid Waste Assessment Test Report findings (Mulder and Haven 1995)

A-2.0 PHYSICAL PROBLEMS

An investigation of a clay barrier in a Uranium Mill Tailings Disposal Site (Waugh and Smith 1997) concluded that these clay barrier layers' hydraulic conductivity will increase several orders of magnitude with time. Dwyer (2003) and Benson et al. (in press) had similar findings. The study noted that root intrusion, insect and earthworm intrusion, density changes, and desiccation effects will all contribute to increase the saturated hydraulic conductivity of the clay barrier layer (Figure A-2.0-1). This revealed the incorrect assumption that the design of prescriptive covers is based on: that saturated hydraulic conductivity at construction will hold for the life of the cover system. In the past, the changed hydraulic conductivity properties would have been deemed a failure of the cover—but in reality, considering all environmental factors, the cover may still have prevented moisture from reaching the underlying waste. It has been shown that even with higher hydraulic conductivity values, flux rates can still decrease because of an increase in transpiration due to the root intrusion.

Figure A-2.0-1. Root and earthworm intrusion into clay barrier layer

Prescriptive covers that are only designed to meet the regulations are prone to a variety of physical problems. Federal regulations call for barrier layers to be designed to meet a minimum thickness and saturated hydraulic conductivity value. Hence, soils generally high in clay content are placed and compacted to relatively high densities and water contents in order to achieve these low saturated hydraulic conductivity values. For example, the constructed volumetric water content of a preferred soil is approximately 20%. After installation, the soil dries to a state similar to that in the soils adjoining the landfill or in their undisturbed state. Soil-water contents in the dry climates can be as low as 5%. Consequently, over time the soils will have about 15% volumetric reduction. Soil high in clay will have a high cohesion resulting in detrimental desiccation cracking, as shown in Figure A-2.0-2. Cracking provides preferential pathways for water migration downward into the underlying waste and defeats the purpose of trying to install a relatively impermeable (low saturated hydraulic conductivity) barrier layer.

Figure A-2.0-2. Desiccation cracking in clay barrier layer

In addition to the required high soil densities required by regulations for the barrier layers, relatively high cohesions also lead to serious problems from cracking due to differential settlement (Figure A-2.0-3). The underlying waste settles with time due to consolidation and biodegradation. Because the waste materials are often inconsistent and randomly placed, the settlement occurs differentially. Potential cracks in the cover allow for surface runoff to enter the waste, thus increasing leachate generation and increasing the risk for leakage from the landfill into the underlying and surrounding soils, harming the surrounding community.

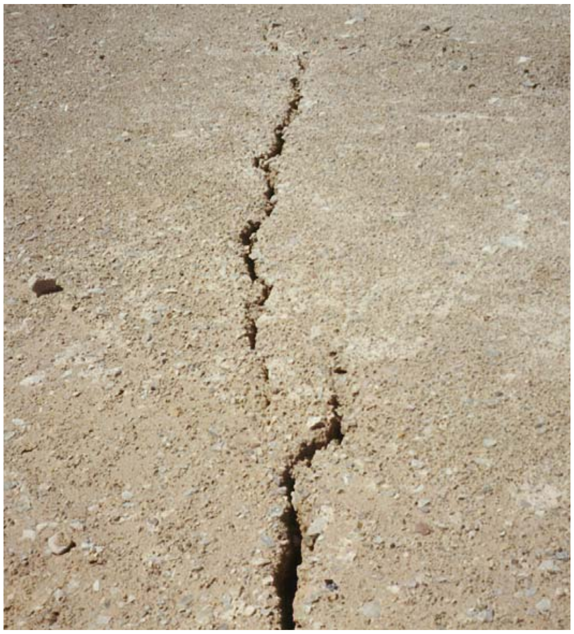

Figure A-2.0-3. Longitudinal cracking due to differential settlement

Vegetation or erosion layers are also often designed to meet only the minimum federal requirements. Vegetation is critical to stabilize the soil, protecting it from erosion and, perhaps most importantly, removing the moisture the soil layers have stored from past precipitation events. These thin layers as dictated by regulations or design guidance documents are often not adequate to sustain a healthy and diverse plant community. Often they do not have adequate water storage capacity or adequate soil nutrients. Figure A-2.04 shows two different cover systems installed side-by-side (Dwyer 2003). The two cover surfaces looked identical after their first year because it was a relatively wet year. However, after a severe drought the vegetation on the cover to the left was unable to survive because that cover did not have an adequate water-holding capacity in its upper fine soil layer. The cover on the left is a multiple-layered cover with a very thin (30-cm) surface soil layer, while the cover on the right is an ET cover with a thicker (107-cm) soil layer capable of enough water-holding capacity to better enable a stand of native vegetation to survive a drought. Without a stable plant community the landfill cover soil is much more susceptible to surface erosion, will see less moisture removal due to transpiration, and will see barrier layer intrusion from deep-rooting shrubs searching for water at greater depths during dry periods.

Figure A-2.0-4. Surface vegetation of undisturbed rangeland versus landfill (Dwyer 2003)

A-3.0 THEORETICAL PROBLEMS WITH PRESCRIPTIVE COVER REGULATIONS

A problem with current landfill cover regulations centers on the fact that they are essentially "resistive" barriers designed to block the vertical infiltration of water from moving into the underlying waste. The soil characteristic chosen to determine the effectiveness of the "resistive" barrier layer is saturated hydraulic conductivity. For Subtitle "D" facilities, this value is to be no higher than 1×10^{-5} cm/sec, while the Subtitle "C" barrier layer is to be constructed to a value less than or equal to 1×10^{-7} cm/sec. A flawed assumption with the use of prescriptive landfill covers is that flow occurs under saturated conditions. On the contrary, flow generally occurs under unsaturated conditions.

Darcy's Law can be used to represent the fundamental equation of flow for both scenarios:

Saturated systems: $Q = K_{sat}\, i\, A$

where:

Q =	flow rate
K_{sat} =	saturated hydraulic conductivity
i =	hydraulic gradient = *f*(gravity and positive pressure)
A =	area

Unsaturated systems: $Q = K_{unsat}\, i\, A$

where:

Q =	flow rate
K_{unsat} =	unsaturated hydraulic conductivity
i =	hydraulic gradient = *f*(gravity and matric potential)
A =	area

Moisture is driven by total potential difference toward equilibrium. Water moves toward regions of higher water potential and is consequently governed by gravity and matric potential for unsaturated flow. Under saturated conditions, the soil's matric potential is zero.

$$\psi_{Total} = \psi_{grav} + \psi_{matric} + \psi_s + \psi_a$$

where:
- ψ_{Total} = total soil-water potential
- ψ_{grav} = gravitational potential
- ψ_{matric} = matric potential or soil suction
- ψ_s = solute potential
- ψ_a = air pressure potential

But ψ_s and ψ_a are generally considered to be zero for landfill cover applications; therefore, the relationship can be simplified to:

$$\psi_{Total} = \psi_{grav} + \psi_{matric}$$

However, in the field, water movement patterns are complicated by a number of things such as climatic conditions, plants, structural voids, secondary pathways, non-homogenous soils, and hysteresis. Both saturated and unsaturated soil conditions must be taken into account when designing landfill covers.

Appendix B

Field Data

B-1.0 INTRODUCTION

EPA maintains a website with a partial list of sites that have deployed alternative earthen covers (http://www.clu-in.org/products/altcovers/). The EPA also funded a study that monitored alternative earthen cover deployments at sites across the country referred to as the Alternative Cover Assessment Program (ACAP). The goal of the ACAP was the development of field-scale performance data for landfill final cover systems. Both prescriptive RCRA and alternative cover designs were tested in the project. ACAP is part of the EPA National Risk Management Research Laboratory's Superfund Innovative Technology Evaluation Program established to promote the development of new and innovative technologies used to address hazardous waste problems. Test sections have been installed at landfills in Sacramento County, California; Lake County, Montana; Lewis & Clark County, Montana; Monticello, Utah; Cedar Rapids, Iowa; Omaha, Nebraska; Boardman, Oregon; Altamont, California; Monterey, California; and the Marine Corps Logistics Base in Albany, Georgia. In addition, retrofit monitoring (to study existing alternative covers constructed prior to ACAP) has been established in Cincinnati and Logan, Ohio (http://www.acap.dri.edu/). Although ACAP was relatively short term, it revealed that ET cover types worked well in dry climates.

Perhaps the best applicable data for LANL cover systems is that from a longer-term research project (Dwyer 1997, 2001, 2003) located at Sandia National Laboratories located in Albuquerque, New Mexico, referred to as the Alternative Landfill Cover Demonstration (ALCD). For equivalence determination to meet NMED requirements for deployment of an alternative earthen cover, this ALCD data should be considered. This project showed that a well-designed ET cover or capillary barrier cover system can perform as well or better than a prescriptive cover system, even with a geomembrane within it.

B-2.0 ALTERNATIVE COVER DEPLOYMENTS AND FIELD DEMONSTRATIONS

B-2.1 ACAP Program

There are a number of sites monitored under the ACAP to track the effectiveness of landfill closures across the country. Those most applicable to the LANL site include demonstrations at Polson, MT; Helena, MT; Boardman, OR; Sacramento, CA; and Altamont, CA. Figure B-2.1-1 shows these sites' approximate geographical locations.

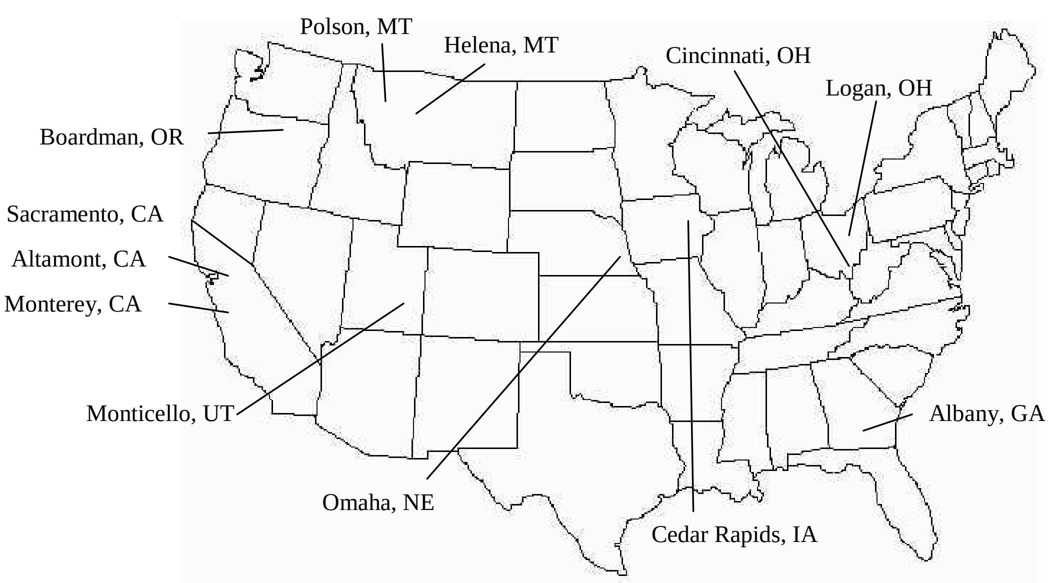

Figure B-2.1-1. ACAP sites

B-2.1.1 Finley Buttes Regional Landfill Oregon (Arid Site)

The Finley Buttes Regional Landfill located in Boardman, Oregon, is an active regional solid waste management facility, which serves the Pacific Northwest. It has a capacity of 500,000 tons/year. Access to the site is by highway, Columbia River barge system, and rail. The landfill is located 10 miles south of Boardman, Oregon, in the vicinity of Finley Buttes, on a 1,802-acre parcel of land.

Regulatory Agency/Contact:
Sacramento County Public Works Agency
Chris Richgels
9850 Goethe Road
Sacramento, CA 95827-3561
916.875.7011
richgelse@saccounty.net

Type of Facility: RCRA D (MSW, industrial, commercial, C&D debris).

Annual Precipitation: 8.7 inches.

Test Covers:

1. Composite/GCL: 1 m of soil over a geomembrane over a GCL.
2. Thin ET cover: 1.2 m of soil.
3. Thick ET cover: 1.8 m of soil.

Figure B-2.1-2. Finley Buttes Regional Landfill test covers installation

Vegetation: A mixture of crested wheat grasses, alfalfa, and clover that are adapted to the semiarid climate.

Soil Properties: Sagehill fine sandy/silt loam used to store incidental precipitation and provide nutrients to the vegetation has an available water storage capacity of between 12.5 and 16.7 percent. The soil material at Finley Buttes consists of a windblown assemblage of sand and silt with a small percentage of clay-size constituents that is classified as ML in the Unified system and silt in the USDA system.

Table B-2.1-1. General Characteristics of Sagehill Fine Sandy/Silt Loam

MODERATE RELATIVE DENSITY	MODERATE TO HIGH COMPRESSIBILITY
Slightly plastic	High frost susceptibility
Non-expansive	Low permeability
Mod. low friction angle	High capillary potential
Slight cohesion	Low to moderate corrosion potential

Table B-2.1-2. Summary of Laboratory Test Results for Sagehill Fine Sandy/Silt Loam

SOIL CHARACTERISTIC	AVERAGE OR TYPICAL VALUE
Field Moisture	15% on weight basis 0.21 volumetric basis (m^3/m^3)
Saturation	40%
Dry Density	97 pcf
Moist Density	111.6 pcf
Saturated Density	123.8 pcf
Saturated Moisture	27.2% on weight basis 0.42 volumetric basis (m^3/m^3)
Buoyant Density	61 pcf
Maximum Density	112 pcf
Optimum Moisture	14.5%
Volume of Solids	0.57
Volume of Voids	0.43
Field Capacity	0.33 volumetric basis (m^3/m^3)
Wilting Point	0.09 volumetric basis (m^3/m^3)

Table B-2.1-2. (continued)

SOIL CHARACTERISTIC	AVERAGE OR TYPICAL VALUE
Void Ratio	0.75
Specific Gravity	2.71
Air Entry Potential	-4 kpa
Coefficient of Permeability	5×10^{-6} cm/sec

Table B-2.1-3. Sagehill Fine Sandy/Silt Loam Gradation Requirements

UNIFIED CLASSIFICATION	PERCENT PASSING
Sand – No. 4	100%
No. 10	95–100%
No. 100	85–100%
Silt – No. 200	70–90%
0.05 mm	50–70%
0.01 mm	5–20%
Clay – 0.005 mm	0–15%
0.001 mm	0–5%

Table B-2.1-4. Recommended Amendments to Sagehill Fine Sandy/Silt Loam

TOTAL FERTILITY NEEDS	APPLICATION RATE
Nitrogen	60 lbs. per acre – N
Phosphorus	70 lbs. per acre – P205
Sulfur	15 lbs. per acre – Actual S
Zinc	5 lbs. per acre – Actual Zn

Fertility needs and nutrient requirements are dependent upon the actual soils that are utilized for the construction of the AEC.

Data collection at the Boardman site began December 9, 2000. Water balance summaries for the test sections at the Boardman site are shown in Table B-2.1-5. Total recorded precipitation during the 31-month data collection period was 336 mm. Mean annual precipitation for the site is about 220 mm. Trace amounts of percolation (< 1 mm) were recorded for all three test sections.

Table B-2.1-5. Boardman, Oregon, Test Cover Results

Cover Design	Start Date	Current Data	Avg. Annual Precip (mm)	Cum. Precip (mm)	Cum. Percola-tion (mm)	Cum. Surfac e Runoff (mm)	Cum. Lateral Flow (mm)	Cum. ET (mm)
			219					
Composite / GCL	12/09/00	07/2/03		336	Trace	0	0	368
ET-thin	12/09/00	07/2/03		336	Trace	0	—	351
ET-thick	12/09/00	07/2/03		336	Trace	0	—	399

B-2.1.2 Lake County Landfill
Polson, Montana (Semiarid Site)

The Lake County Landfill occupies a 51-acre site approximately three miles southwest of Polson, Montana. The landfill is owned and operated by the Lake County Solid Waste Management District, 106 4th Avenue East, Polson, MT 59860. The landfill serves all of Lake County plus two small adjoining communities for a total population of about 28,000. The landfill began accepting waste in 1976. The site is licensed by the Montana Department of Environmental Quality as a Class 2 Municipal Waste Landfill. Under that definition, the landfill can accept municipal solid waste, commercial waste, nonhazardous industrial waste, and construction debris. The post-closure intended use of the site is as non-irrigated open space. In the fall of 1997, the Lake County Solid Waste Management District began the design work for an expansion onto 95 acres of adjoining properties. The expansion area license application was submitted to the Montana Department of Environmental Quality in January of 1999. During the review process, it was recommended by the state agency that the District consider use of an ET cover system. The suggestion was made primarily due to the high seismic rating for Lake County, as the alternative cover would prove more stable. A secondary benefit of the alternative cover would be the on-site use of soils that would have to be removed as excess to the operation with the prescriptive cover design.

Lake County Solid Waste Management District
Mark Nelson
12 Fifth Ave East
Polson, MT 59860
406.883.7325
trashman@compuplus.net
Annual Precipitation: 13.6 inches.

Test Covers:

1. Prescriptive: Composite Clay Cover: 15 cm topsoil over 45 cm silty sand over 60 mil geomembrane over 45 cm compacted silt over 45 cm sandy gravel.
2. ET cover/capillary barrier: 15 cm topsoil over 45 cm silt over 45 cm silty sand over 45 cm sandy gravel.

Vegetation: Thickspike, Bluebunch, Slender and Crested Wheat grasses, Mountain Brome, Idaho Fescue, Prairie Junegrass, Needle-and-Thread, Meadow Brome, Canada and Kentucky Bluegrasses, Yarrow, Fringed Sagewort, Alfalfa, Rubber Rabbit brush, Prickly Rose, Arrowleaf Balsamroot, Dolted Gayfeather, Lewis Flax, Silky Lupine, and Cicer Milkvetch.

Soil Properties:

Table B-2.1-6. Physical Properties of Polson, MT, Lake County Landfill Borrow Soils

Soil Sample	Source 1	Source 2	Source 3
Saturated hydraulic conductivity (cm/sec)	1.3×10^{-4}	8.9×10^{-4}	2.8×10^{-6}
Saturated water content	0.3937	0.4153	0.4134
Residual water content	0.0431	0.0181	0.0200
Calculated unsaturated hydraulic parameters:			
a (cm^{-1})	0.0053	0.0211	0.0015
n	2.0090	1.5650	1.4900
Particle size characteristics: 2µm clay	4	2	4
% fines	46	28	69
d_{10} (mm)	0.014	0.037	0.0043
d_{30} (mm)	0.057	0.08	0.015
d_{50} (mm)	0.083	0.12	0.049
d_{60} (mm)	0.11	0.14	0.061
Cu	7.9	3.8	14
Cc	2.1	1.2	0.86
Summary of Atterberg limits: LL	NA	NA	34.0
PL	NA	NA	26.9
PI	NA	NA	7.1
Classification: USCS	SM	SM	ML
USDA	Loamy sand	Sand	Sandy loam

Table B-2.1-7. Monitoring Results for Polson, MT, Lake County Landfill Test Covers

Cover Design	Start Date	Current Data	Avg. Annual Precip (mm)	Cum. Precip (mm)	Cum. Percolation (mm)	Cum. Surface Runoff (mm)	Cum. Lateral Flow (mm)	Cum. ET (mm)	Cover Design
			382						
Composite / comp. clay	11/19/99	07/2/03		1116	1.5	18	41	1036	Composite / comp. clay
ET / cap. barrier	11/19/99	07/2/03		1116	0.2	18	--	1135	ET / cap. barrier

B-2.1.3 Lewis and Clark County Landfill Helena, MT (Semiarid Site)

The Lewis and Clark County Landfill occupies a 320-acre site in southeastern Lewis and Clark County, approximately 10 miles northeast of Helena. The landfill is owned by Lewis and Clark County and operated by the Lewis and Clark County Public Works Dept. (3402 Cooney Dr., Helena, MT 59602). It serves urban and rural areas near Helena. Currently (1994) permitted operations (Phase I) include an active fill footprint confined to an 80-acre portion of the site. The landfill began accepting waste in 1994. The operational site life for Phase I has been projected to about the year 2045. The Lewis and Clark Landfill is a Class II disposal site and receives municipal solid wastes, commercial wastes, nonhazardous industrial wastes, and construction debris. Post-closure intended use of the site is as non-irrigated open space, consistent with the surrounding land use and zoning. Approximate elevations of the natural grade range from 3800 ft to 3910 ft msl. As of May 1999, an estimated 353,700 cubic yards of disposal volume had been consumed. In accordance with Montana and federal regulations, current plans for final cover at the Lewis and Clark Landfill specify installation of a prescriptive cover. Lewis and Clark County has begun investigation of the use of an alternative final cover design of equivalent performance, largely for long-term stability and economic reasons. The site contains ample sources of fine-textured borrow material appropriate for use in an infiltration-limiting application. The site owner has developed an alternative design that will be evaluated by participation in ACAP. The proposed design is a monofill-type cover utilizing sufficient on-site soils to support a vegetation community based on native grassland-type vegetation to limit deep percolation through the cover.

Regulatory Agency/Contact:
Lewis and Clark County Public Works Dept.
Will Selser
3402 Cooney Dr.
Helena, MT 59602
406.447.1635
selser@co.lewis-clark.mt.us

Type of Facility: RCRA D (MSW, industrial, commercial, C&D debris).

Annual Precipitation: 12 inches.

Test Covers:

ET cover: 15 m topsoil over 120 cm sandy clay over 30 cm sandy gravel.

Vegetation: Bluebunch, Slender, West Wheat grasses, Sandburg Bluegrass, Sheep Fescue, Blue Gamma, Green Needlegrass, and Needle-and-Thread.

Soil Properties: Sandy Clay Loam (Table B-2.1-8).

Table B-2.1-8. Physical Properties of Lewis and Clark County Landfill Borrow Source

Soil Sample		**1**	**2**	**3**	**4**
Saturated hydraulic conductivity (cm/sec)		7.9×10^{-6}	1.6×10^{-6}	8.6×10^{-8}	1.6×10^{-8}
Saturated water content		0.4576	0.4494	0.4874	0.4791
Residual water content		0.00	0.0237	0.00	0.00
Calculated unsaturated hydraulic parameters					
	a (cm^{-1})	0.0031	0.0024	0.0015	0.0017
	n	1.2586	1.3034	1.2175	1.2002
Particle size characteristics:	2µ clay	22	20	32	32
	% fines	32.42	30.69	54.96	48.9
	d_{10} (mm) d_{30} (mm)	NA 0.052	NA 0.066	NA NA	NA NA
	d_{50} (mm)	0.39	0.43	0.050	0.092
	d_{60} (mm)	0.58	0.62	0.13	0.22
	Cu Cc	NA NA	NA NA	NA NA	NA NA
Summary of Atterberg limits	LL	64.3	74.7	105.3	88.4
	PL	19.6	17.0	18.7	18.6
	PI	44.6	57.6	86.6	69.8
Classification:	USCS	CH	CH	CH	CH
	USDA	Sandy clay loam	Sandy clay loam	Sandy clay loam	Sandy clay loam

Table B-2.1-9. Monitoring Results of Lewis and Clark County Landfill Test Cover

Cover Design	Start Date	Current Data	Avg. Annual Precip (mm)	Cum. Precip (mm)	Cum. Percolation (mm)	Cum. Surface Runoff (mm)	Cum. Lateral Flow (mm)	Cum. ET (mm)
ET / cap. barrier	10/19/99	07/2/03	305	760	0	50	—	680

B-2.1.4 Kiefer Landfill
Sacramento, CA (Semiarid Site)

The Kiefer Landfill occupies a 1,084-acre site in eastern Sacramento County, approximately 15 miles southeast of the Sacramento, California metropolitan area. The landfill is owned and operated by the Sacramento County Public Works Agency, Waste Management and Recycling Division (9850 Goethe Rd, Sacramento, CA, 95827-3561) and primarily serves rural portions of the county. Currently (1998) permitted operations include 660 acres, with the active fill footprint confined to a 232-acre portion of the site (the 165-acre Module M-1 and Module M-1L [67 acres]). The landfill began accepting waste in 1967. The operational site life has been projected to about the year 2035. Kiefer Landfill is a Class III disposal site and receives municipal solid wastes, commercial wastes, nonhazardous industrial wastes, and construction debris. Post-closure intended use of the site is as non-irrigated open space, consistent with the surrounding land use and zoning.

Regulatory Agency/Contact:
Sacramento County Public Works Agency
Chris Richgels
9850 Goethe Road
Sacramento, CA 95827-3561
916.875.7011
richgelse@saccounty.net

Type of Facility: RCRA D (MSW, industrial, commercial, C&D debris).

Annual Precipitation: 17.2 inches.

Test covers:

1. Thin ET cover: 1.22-m clay loam soil with native grass vegetation.
2. Thick ET cover: 2.44-m clay loam soil with Poplar/Eucalyptus tree vegetation surface.

Vegetation:

1. Thin ET cover: California Brome, Purple Needlegrass, Zorro Fescue, Arroyo Lupin, and Oleander bushes.
2. Thick ET cover: hybrid poplar or eucalyptus trees.

Soil Properties: (Table B-2.1-10).

Table B-2.1-10. Physical Properties of Kiefer Landfill Borrow Soil

Soil Property	Value
Saturated hydraulic conductivity (cm/sec)	1.23×10^{-6}
Calculated unsaturated hydraulic parameters: a (cm^{-1})	0.00133
n	1.16864
Particle size characteristics: 2µm clay	9.4%*
% fines	40.4%*
d_{10} (mm)	0.0026*
d_{30} (mm)	0.052*
d_{50} (mm) d_{60}(mm)	0.17*
0.45*Cu 2.31*Cc172.4*	
Summary of Atterberg limits: LL	52*
PL	29*
PI	23*
Classification: USCS	SM*
USDA	Sandy loam*

Table B-2.1-11. Monitoring Results of Kiefer Landfill Test Covers

Cover Design	Start Date	Current Data	Avg. Annual Precip (mm)	Cum. Precip (mm)	Cum. Percolation (mm)	Cum. Surface Runoff (mm)	Cum. Lateral Flow (mm)	Cum. ET (mm)
thin ET-type	07/29/99	07/2/03	440	1380	102	106	—	1340
thick ET-type	07/29/99	07/2/03	440	1380	10	67	—	1088

B-2.1.5 Altamont Landfill and Resource Recovery Facility Livermore, California (Semiarid Site)

Regulatory Agency/Contact:
Waste Management, Inc.
Ken Lewis
10840 Altamont Pass Road
Livermore, CA 94550-9745
925.455.7350
klewis@wm.com

Type of Facility: RCRA D (MSW, industrial, commercial, C&D debris).

Annual Precipitation: 13.5 inches.

Test covers:

1. Prescriptive Cover: 30-cm topsoil over a geomembrane over 30 cm of compacted soil.
2. ET cover: 30-cm minimum of intermediate cover foundation layer, 60-cmof compacted support layer, 45-cmof vegetative soil layer.

Vegetation: Soft chess, slender oats, foxtail chess, Italian ryegrass, red-stemmed filaree, black mustard, yellow star-thistle, prickly lettuce, bull thistle, prickly sow-thistle, blue dicks, California poppy, purple owl's-clover, and miniature lupine.

Soil Properties: Soil for both the intermediate cover and compacted low-permeability/support layers will be obtained on-site and will generally consist of soils ranging in USCS classification from SC or SM with greater than 30% fines to CH or MH. The vegetative soil layer will be on-site soils, lightly compacted and hydroseeded with native plant species.

Table B-2.1-12. Monitoring Results of Altamont Landfill Test Covers

Cover Design	Start Date	Current Data	Avg. Annual Precip (mm)	Cum. Precip (mm)	Cum. Percolation (mm)	Cum. Surface Runoff (mm)	Cum. Lateral Flow (mm)	Cum. ET (mm)
Composite / comp. clay	11/10/00	07/2/03	368	903	4	59	4	825
ET-type	11/10/00	07/2/03	368	903	4	84	—	818

B-2.2 Solid Waste Facilities with Approved Alternative Landfill Covers

B-2.2.1 Kirtland Air Force Base Albuquerque, NM (Arid Site)

Kirtland Air Force Base has had three alternative final covers approved using an ET cover to close three separate solid waste facilities. Kirtland Air Force Base is located in the southwest portion of Albuquerque, NM near the Manzano Mountains. The landfills average about 40 acres each in size. The first cover was constructed and completed in 2003 (Figure B-2.2-1).

Figure B-2.2-1. ET cover installation on Kirtland Air Force Base

Regulatory Agency/Contact:
New Mexico Environment Department

Type of Facility: Solid Waste Facility, RCRA Subtitle D.

Annual Precipitation: 8.5 inches.

Test covers:

Used the ALCD, Sandia National Laboratory test covers data – see under Test Covers section.

Vegetation: Native grasses.

Table B-2.2-1. Soil Properties at KAFB

Layer	Thickness (cm)	Dry Density (g/cm^3) @ Specific Gravity	Saturated Hydraulic Cond. (cm/hour)	Porosity	Van Genuchten Parameters			
					θ_s (vol/vol)	θ_r (vol/vol)	α (1/cm)	n
Com-pacted Soil	120	1.6 @ 2.7	1.43856	0.41	0.3951	0.06	0.0508	1.36

B-2.2.2 New ET Cap Technology Covers Landfills at Fort Carson

Fort Carson, Colorado, completed in October 2000: The first of three ET covers relying on the use of native soils and plants as cap material rather than the more typical plastic sheeting and imported clay.

While not compromising performance, savings could reach approximately $100,000 per acre compared to conventional RCRA Title C landfill caps, according to the Fort Carson Directorate of Environmental Compliance and Management.

Figure B-2.2-2. Discing soil prior to seeding

Fifteen of the 20 acres of the World War II-era landfill were covered by an ET cover. The remaining five acres will be capped conventionally, paved over, and then used for the location of an Army Reserve motor pool.

Fort Carson demonstrated to the regulators that the ET cap technology was safer for the environment and less expensive than prescriptive landfill covers.

In addition, Fort Carson is using about 500 tons of biosolids (sewage sludge) from its wastewater treatment plant as a soil amendment on top of the cap. The installation will monitor the cap to make certain it performs as predicted.

B-2.2.3 Other Solid Waste Facilities with Alternative Landfill Covers in Semiarid to Arid Climates from U.S. EPA's Website

Yucaipa Landfill, Yucaipa, CA

Monolithic ET cover approved and monitored consisting of 48 inches of silty sand. LEACHM water balance model used for approval. Initial data for moisture content shows consistency with model.

Twenty Nine Palms MCAGCC, Twenty Nine Palms, CA

Monolithic ET cover approved and monitored consisting of 73 inches of poorly graded sand with silt. Water balance model used for application was HELP (probably accounted for the overly thick cover). No measurable infiltration detected to date.

Coyote Canyon Landfill, Somis, CA

Monolithic ET cover approved with monitoring. Results showed that water migrated downward to 36 inches but had no impact on dry soils at 51 inches that remained dry. Flux showed strong upward suction, which draws stored water up to the surface, where it was evaporated.

Lopez Canyon Landfill, CA

Monolithic ET cover approved with monitoring in Los Angeles area. Design was silt sand/clayey sand layer overlying 2-foot foundation layer. UNSAT-H model predicted no percolation in first year and less than the conventional cover in the next 10 years. First three years of data show a less than 5% change in relative volumetric moisture at bottom compared to 90% near surface. Approval obtained for final cover construction.

Pantex Plant, Amarillo, TX

Monolithic ET cover installed over C&D site consisting of 12–18 inches of topsoil and 18 inches of fill soil. Native grasses and winter wheat used for plants.

Denver Arapahoe Disposal Site, Arapahoe County, CO

Monolithic ET cover approved consisting of 6 inches of topsoil and 30 inches of lightly compacted soil (minimum of 28% fines). Compacted to 80–90% of maximum dry density. Monitored with six leachate sumps for quantity over time. UNSAT-H used for water balance.

Gaffey Street Sanitary Landfill, Wilmington, CA

Capillary barrier ET cover approved and installed. UNSAT-H used for model showing less than 3 cm/year infiltration or 0.2% of total precipitation plus irrigation.

Coyote Canyon Landfill, Somis, CA

Monolithic ET cover approved and operational since 1994. Design was 78 inches local soils with 30 inches of fine-grained soil for barrier layer. Total thickness was due to support of habitat of threatened California gnatcatcher. Monitoring with soil moisture probes showed strong upward flux and uneven infiltration due to microclimates on each side of landfill.

Kirtland AFB, Albuquerque, NM

Monolithic ET cover approved and operational since 2003.

Mr. “M” Landfill, Lewiston, MT

Monolithic ET cover installed and approved consisting of 6 inches of topsoil, 30 inches of soil. Water Balance model was Chemflo.

Norton Air Force Base, CA

Monolithic ET cover approved and installed.

California Valley Landfill, CA

Monolithic ET cover installed.

Del Rio Landfill, Phoenix, AZ

Monolithic ET cover approved.

El Toro Marine Corps, Station, CA

Monolithic ET cover approved for full scale.

Sunshine Canyon Landfill, CA

Monolithic ET cover approved for full scale.

Azusa Landfill, CA

Monolithic ET cover approved for full scale.

Bishops Canyon Landfill, Los Angeles, CA

Monolithic ET cover approved for full scale.

Bradley Landfill, Sun Valley, CA

Monolithic ET cover approved for full scale.

B-2.3 Superfund Sites with Approved Alternative Landfill Covers

B-2.3.1 Rocky Mountain Arsenal Denver, CO (Semiarid Site)

Multiple landfills and sites to be closed covering hundreds of acres: Former Basin F, Complex & Shell Trenches Basin A, South Plants Central Processing.

RMA is currently closing multiple sites with ET covers and capillary barriers. The RMA was once considered the most contaminated site in the United Sates. It is the site of the military's biological chemical weapons fabrication. Some areas in the site are deemed too hazardous to remove and thus must be closed in place by means of an ET cover.

Type of Facilities: CERCLA (Hazardous).

Annual Precipitation: 19 inches.

Vegetation: Native grasses.

Soil: Silty sand.

B-2.3.2 Operating Industries, Inc. (OII) Superfund Landfill Monterey Park, CA (Semiarid Site)

OII Superfund landfill in southern California closure constitutes the first ET cover approved by the EPA for construction at a Superfund site.

Type of Facility: CERCLA.

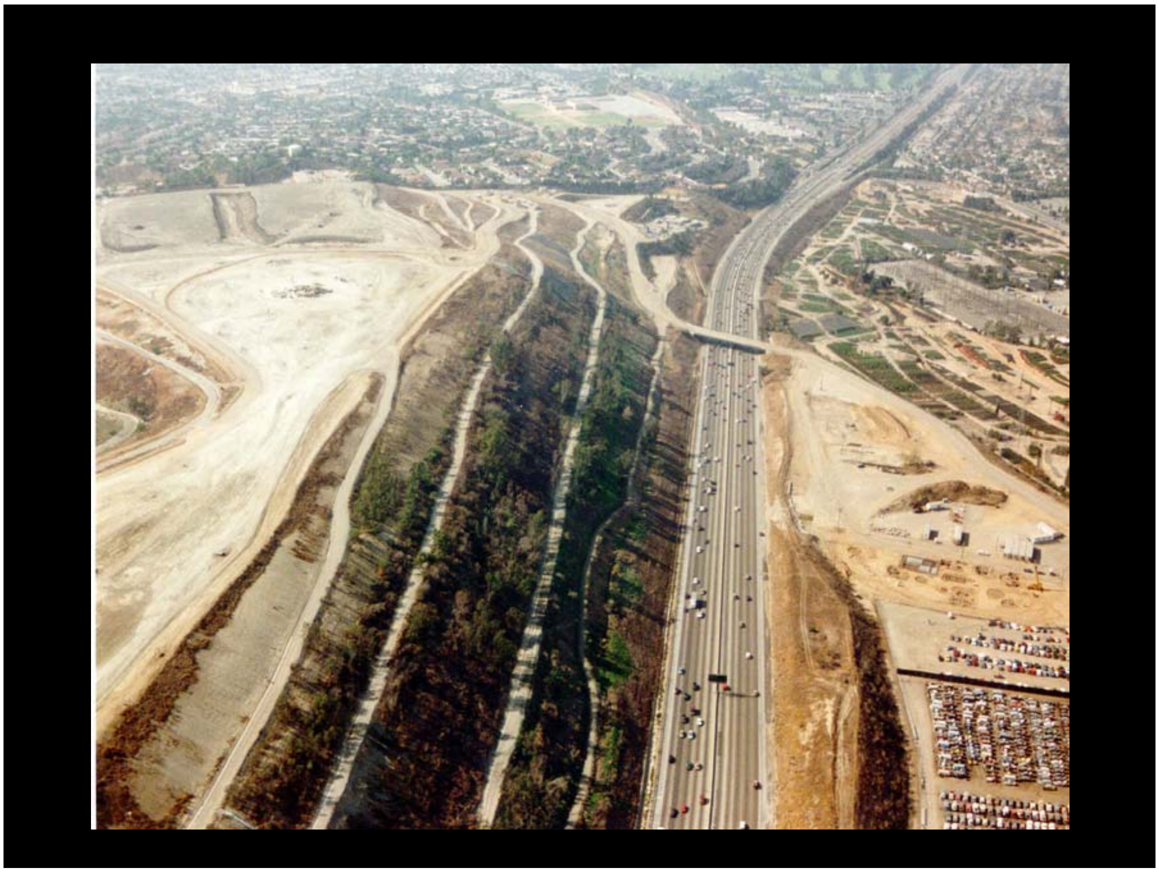

Figure B-2.3-1. OII Landfill

Average Precipitation: 14.9 inches per year.

The selected baseline cover was a 1500-mm-thick single soil layer with a saturated hydraulic conductivity of 1027 m/s and moisture retention characteristics typical of silty soils. The average fines content reported for these soils is 54% and the plasticity index is 5% ~USCS designation ranges over CL to ML. Campbell's fitting parameters used for the baseline cover are listed in Table B-2.3-1. Weather data needed for the analyses includes daily precipitation and daily minimum and maximum air temperatures. Weather conditions generated for 30 years using data for southern California led to an average precipitation of 379 mm/year and an average evapotranspiration of 1015 mm/year.

Table B-2.3-1. Properties Used in Baseline Cover Analysis[1]

Property Value	
Soil Campbell parameter *a*	24.89
Campbell parameter *b*	4.215
Weather yearly average precipitation	379 mm
Vegetation rooting depth	300 mm
Data wilting point	1500 kPa
Minimum root potential	3000 kPa
Maximum potential/actual transpiration ratio	1.1
Root resistance ratio	1.05
Crop cover fraction	0.75
Modeling initial volumetric moisture	23%

[1] "Journal of Geotechnical and Geoenvironmental Engineering" © ASCE / May 2003 / 429

B-2.3.3 Lee Acres Superfund Site Farmington, NM (Arid Site)

Point of Contact:
Steve Dwyer of Dwyer Engineering, LLC
DwyerEngineering@yahoo.com

Monitoring over a multiple-year period indicated zero flux. Farmington, NM is located in the northeast corner of New Mexico near the four corners region of New Mexico, Arizona, Utah, and Colorado. The site was originally permitted as a municipal landfill in 1962. However, in 1980 it was expanded to include the disposal of liquid waste. Containment berms were built where liquid waste was dumped. Plumes formed that found their way to the groundwater that was used by a local community. This groundwater was contaminated. The landfill was closed to liquid waste disposal in 1985 and solid waste disposal in 1986. Lee Acres is listed on the EPA's National Superfund Database, identification number NMD980750020. The Record of Decision stated that the site will be covered with a capillary barrier. A test cover was placed and monitored at the site in 1997.

Figure B-2.3-2.   Lee Acres Landfill, Farmington, NM

Regulatory Agency/Contact:
Sai Appaji
Remedial Project Manager
USEPA Region 6, Superfund Division
Dallas, TX 75202
214.665.3126

Type of Facility: CERCLA (hazardous waste).

Annual Precipitation: 7 inches.

Test Cover:

Capillary barrier 15 cm soil gravel admixture surface treatment over 76 cm soil layer over 15 cm of pea gravel.

Actual Cover: Same as test cover.

Vegetation: Native grasses.

Soil Properties:

The soil to be used comes from a nearby borrow source composed of silty sand (Denoted SM).

Table B-2.3-2. Lee Acres Landfill Soil Properties

Dry Density (g/cm^3)	Sat. Hydraulic Conductivity (cm/sec)	Porosity	Van Genuchten Parameters			
			θs	θr	α (1/cm)	n
1.70	8.37e-4	0.371	0.333	0.036	0.0444	1.56

B-2.3.4 Idaho National Engineering and Environmental Laboratory (INEEL) Idaho Falls, Idaho (Arid Site)

A number of landfills have been established on the INEEL that contain municipal, hazardous, or radiological waste. Several of these landfills have been closed (or are approved to be closed), with surface covers emplaced over the buried waste. Covers range from simple evapotranspiration designs to protect human health and the environment for existing historical disposal sites at Central Facilities Area (CFA) and Naval Reactor Facility (NRF) to a complex multi-layered surface cover at the ICDF that was developed for an engineered, long-term treatment, storage, and disposal facility. Two sets of research covers have been studied at the INEEL. The alternative covers installed at the site are summarized in Table B-2.3-3. The Protective Cap/Biobarrier Experiment (PCBE) landfill covers mainly focused on the ecological relationship to cover designs, and the Engineered Barrier Test Facility (EBTF) covers examined surface barrier hydrologic performance with high surface infiltration rates.

Precipitation: 8.7 inches per year.

Table B-2.3-3. Summary of INEEL Landfills and Their Covers

LANDFILL					COVER							
Name	Type	Installed (yr)	Waste Disposal Method	Contents	Type	Total Thick-ness m (ft)	Vegetative Cover Thickness m (ft)	Bio-Barrier Thickness m (ft)	Geomem-brane	Surface Slope (%)	Gas Venting	Monitoring System
CFA Landfill I	Municipal	Early 1950s	Trenches	Construction debris, paper, cafeteria garbage, wood, paper, flammable materials	Native soil ET		Yes	N/A	None		None	Cap –TDR, neutron probe Vadose – soil gas Aquifer – monitoring wells
CFA Landfill II	Municipal	1972	Direct disposal	Trash sweepings, cafeteria garbage, wood and scrap lumber, masonry/ concrete, metals, liquid waste	Native soil ET		Yes, with riprap over NE face	N/A	None		None	Cap – TDR, neutron probe Vadose – soil gas Aquifer – monitoring wells
CFA Landfill III	Municipal	1982	Trenches	Trash sweepings, cafeteria garbage, wood and scrap lumber, masonry/ concrete, waste asphalt, paint	Native soil ET		Yes	N/A	None		None	Cap –TDR, neutron probe Vadose – soil gas Aquifer – monitoring wells
NRF landfills	Radio-logical	2004	Leach fields	Soil	ET with bio-barrier	1.75 (5.7)	Grasses and forbs	0.45 (1.5)	None		None	Surface – rad sampling Cap – neutron probe Aquifer – monitoring wells

Table B-2.3-3. (continued)

LANDFILL					COVER							
Name	Type	Installed (yr)	Waste Disposal Method	Contents	Type	Total Thick-ness m (ft)	Vegetative Cover Thickness m (ft)	Bio-Barrier Thickness m (ft)	Geomem-brane	Surface Slope (%)	Gas Venting	Monitoring System
PCBE	8 m × 8 m test plots	1997	N/A	N/A	ET with shallow biobarrier	2.5 (8.2)	1) wheatgrass, 2) 12 native plants	0.5 (1.6)	None	0	None	Cap – soil moisture, changes vegetation, plant rooting depths
PCBE	8 m × 8 m test plots	1997	N/A	N/A	ET with deep biobarrier	2.5 (8.2)	1) wheatgrass, 2) 12 native plants	0.5 (1.6)	None	0	None	Cap – soil moisture, changes vegetation, plant rooting depths
EBTF	4 (??)– 3 m × 3 m cells	1996	N/A	N/A	ET	??	None	0	None	0	None	Cap – tensiometers, TDR's, heat dissipation sensors, thermocouples, neutron probe
EBTF	4 – 3m × 3 m cells	1996	N/A	N/A	Capillary barrier	2.51 (8.2)	None	0.76 (2.5)	Yes	0	None	Cap – tensiometers, TDR's, heat dissipation sensors, thermocouples, neutron probe

B-2.3.5 Hastings Groundwater Contamination Superfund Site Hastings, NE

Monolithic ET cover approved to minimize infiltration and reduce contaminant migration in groundwater. Design is 27 inches native soil. Water balance model is UNSAT-H. Accepted in place of GCL cover. ARARs require an alternative cover design provides “equivalent reduction” in infiltration and “equivalent protection” from wind and water erosion when compared to conventional designs. Cover design agreed to by EPA, state, and PRPs was based on data from ET cover performance from ACAP projects and other sources. Conceptual design approved in September 2002.

B-2.4 Landfill Cover Demonstrations

B-2.4.1 DOE-Hanford Superfund Site Richland, WA

A barrier development program was started in the mid-1980s at the Hanford Site as recommended by the “Final Environmental Impact Statement for the Disposal of Hanford Defense High-Level, Transuranic, and Tank Wastes.” The goals of the barrier program were to develop reliable technology for permanent, long-term containment of near-surface radioactive waste or waste/residuals that were too deep, hazardous, and/or expensive to excavate. It was determined that test lysimeters should be constructed and designed for outside experiments to simulate actual climatic conditions at Hanford. A lysimeter can measure quantities of water used by plants, evaporated from soil, and lost by deep percolation. In 1987, the Field Lysimeter Test Facility (FLTF) was constructed and data collected up to 1994 under the Protective Barrier Program. Between the end of 1994 and 2004, the Integrated Disposal Facility project sponsored the tests. The original tests helped to design the Hanford Barrier, which is a full-scale cover system completed in 1994 and monitored to date. Lysimeter tests conducted between 1994 and present also incorporated effects of erosion and dune sand migration. Figure B-2.4-1 shows the original FLTF in 1988.

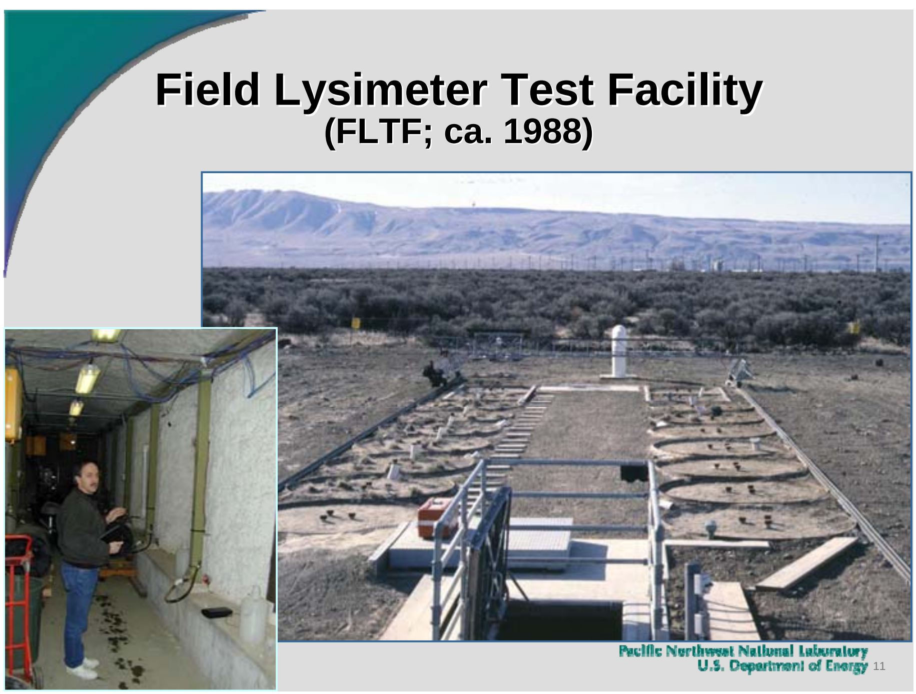

Figure B-2.4-1. Field Lysimeter Test Facility, ca. 1988 (Fayer 2005)

The FLTF contains a total of 24 lysimeters of three types: 14 drainage, 4 weighing, and 8 small-tube lysimeters.

The climate of Hanford typically is hot, dry summers and cool, wet winters. Annual precipitation is 160 mm. November through January typically receive about 45% of average annual precipitation; in July through September, 13% of annual precipitation occurs. Snowfall accounts for about 38% of the precipitation moisture content, accumulating an average of 335 mm.

Small-Tube Lysimeters (five with similar dimensions)

Small-tube lysimeters are 169 cm long and 30.4 cm in diameter. Each tube was fitted with a drain port and could be weighed to determine water storage to within an accuracy of 1.4 mm. Five different cover designs were tested as capillary barrier ET covers:

1. 15 cm of 1–3-cm diameter gravel to control erosion, 135 cm of silt loam over a three-layer sand and gravel filter, tested with and without vegetation as Cheatgrass.
2. 150 cm of silt loam over a 20-cm sand and gravel mixture with and without vegetation as Cheatgrass.
3. 150 cm of silt loam over a 20-cm graded sand filter with and without Cheatgrass.
4. 20 cm of silt loam mixed with 30% gravel (by weight) to control erosion, 130 cm of silt loam over a three-layer sand and gravel filter with and without Cheatgrass.
5. 150 cm of silt loam over a three-layer sand and gravel filter with and without vegetation as Cheatgrass.

The results for all five cover designs that used silt loam as the moisture-holding layer showed no infiltration for the 3–3.5 years of monitoring, even with those with supplemental irrigation representing twice the average monthly precipitation. This was the case regardless if there was a vegetation layer. It was also shown that erosion control can be enhanced with a significant quantity of gravel as an admixture without negatively altering the drainage or water storage characteristics of the cover design. Monitoring with three times precipitation after the original 3.5-year test showed drainage through the barrier, but only for those lysimeters without vegetation. These tests showed that silt loam is the key design element for the full-scale Hanford Barrier.

Small Tube Clear Lysimeter (two with similar dimensions)

The two small tube clear lysimeters are 3 m in depth and 0.3 m in diameter. A drainage port at the bottom allows drainage to be collected and weighed. The cover designs for the two lysimeters are as follows:

1. 1.5 m of screened sand over 1.5 m of gravelly sand with and without Cheatgrass vegetation.
2. 0.15 m of coarse gravel, 1.35 m of screened sand, and 1.5 m of gravelly sand with and without vegetation.

For the first three years, supplemental irrigation was applied at twice the annual average for the first three years and for the next three years, irrigation was increased to three times the annual average. During the six-year study, infiltration was observed, but the cover design with vegetation drained the least for both design cases. The first designs represented the Pitrun Sand taken from the on-site borrow pit to evaluate hydraulic characteristics of this component of the Hanford Barrier. This design had an average of 21.8 mm/year of infiltration under ambient precipitation and 63.5 mm/year under enhanced precipitation. The second design represented the gravel mulch component of the Hanford Barrier full-scale operation and had 89.1 mm/year of infiltration under ambient precipitation and 332 mm/year under enhanced precipitation.

Drainage Lysimeters

There are two different cover designs represented in these test lysimeters. The drainage lysimeter is a steel cylinder 2 m in diameter and 3 m in length. Each lysimeter has drain fittings and access ports allowing installation of thermocouples, psychrometers, tensiometers, and neutron probes for monitoring soil moisture. The two different cover designs tested are described as follows:

1. 1.5 m silt loam and 0.3 m of sand and gravel mixture over 0.1-m diameter rock in a steel with and without Cheatgrass vegetation.
2. 1.0 m silt loam and 0.3 m of a sand and gravel mixture over 0.1-m diameter rock with and without Cheatgrass vegetation.

The first lysimeter represented the design thickness of the top layer of silt loam of the Hanford Barrier, and the second lysimeter mimicked an eroded Hanford Barrier by reducing the thickness of silt loam from 1.5 m to 1.0 m. The test results for infiltration show that the first lysimeter with plants performs well below the design specification of 0.5 mm/year to date. Without plants, it functions even at two times normal precipitation. Only at less than three times precipitation did the lysimeter with no plants allow drainage to occur. The second lysimeter with shrub-steppe vegetation only continues to show no drainage, even for the enhanced precipitation regimes.

The following show a summary of the original and additional FLTF and infiltration results, as follows:

Results of Original FLTF Tests

Description	Precip. Trtmt.*	Plant Trtmt.	Reps	Obs. Periods (yr)	Avg. Drainage (mm/yr)
Hanford Barrier (1.5 m silt loam)	Ambient	Shrub-steppe	4	4.3 to 14.8	all **0.0**
	Ambient	No plants	3	8.2 to 11.6	**0.0** to **0.2**
	Enhanced	Shrub-steppe	4	4.0 to 12.8	all **0.0**
	Enhanced	No plants	3	7.9 to 12.0	**6.1** to **16.2**
Hanford Barrier w/Gravel Admix (1.5 m silt loam)	Ambient	Shrub-steppe	2	4.3 to 7.3	both **0.0**
Eroded Hanford Barrier (1.0 m silt loam)	Ambient	Shrub-steppe	2	8.2 to 12.6	both **0.0**

Battelle *Enhanced Precipitation = 32 cm/yr for 3 years, then 48 cm/yr

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Figure B-2.4-2. Results of original FLTF tests (Fayer 2005)

Results of Additional FLTF Tests

Description	Plant Trtmt.	Reps	Avg. Drainage (mm/yr) Ambient Precipitation	Avg. Drainage (mm/yr) Enhanced Precipitation*
Gravel Mulch	No plants	1	**89.1**	**332.0**
Pitrun Sand	Shrub-steppe	1	**21.3**	**69.0**
Basalt Side Slope	No plants	1	**53.9**	**269.0**
Sandy Gravel Side Slope	No plants	1	**109.0**	**365.0**
Hanford Barrier: Eroded, then Dune Sand Deposition	Shrub-steppe	2	**0.0, 0.0**	**58.5, 123**
Modified RCRA Subtitle C Barrier	Shrub-steppe	1	**0.0**	**0.0**

*Enhanced Precipitation = 32 cm/yr for 3 years, then 48 cm/yr

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Figure B-2.4-3. Results of additional FLTF tests (Fayer 2005)

Other lysimeter tests were conducted for construction materials for the side slopes as seen in Figure B-2.4-3. It is interesting to note that the gravel mulch had significantly more drainage than the basalt side slope, even though the basalt had larger rock size and void space. The Hanford Barrier silt loam also performed well simulating erosion. No infiltration occurred under normal precipitation. At three times precipitation, no significant drainage occurred.

The modified RCRA Subtitle C Barrier uses a 1-m silt loam soil. The first upper half is amended with pea gravel (15% by weight) and the lower half is compacted, to create a low conductivity layer. The sand filter and gravel drainage layer were placed below. This vegetated test lysimeter shows no drainage, even with three times precipitation treatment.

Hanford Barrier Prototype Full-Scale Test Results

After 10 years of research, including the lysimeter testing program, a multi-layered earthen barrier was developed and a prototype barrier constructed in 1994 over an existing waste site. The cover system was highly instrumented to provide a complete water balance, including accurately measured drainage from cover and side slope. Monitoring of the cover system has been ongoing since 1994. Details of the design of the Hanford Barrier are shown in Figure B-2.4-4 for the rip-rap side slope section and the Pitrun gravel side slope section.

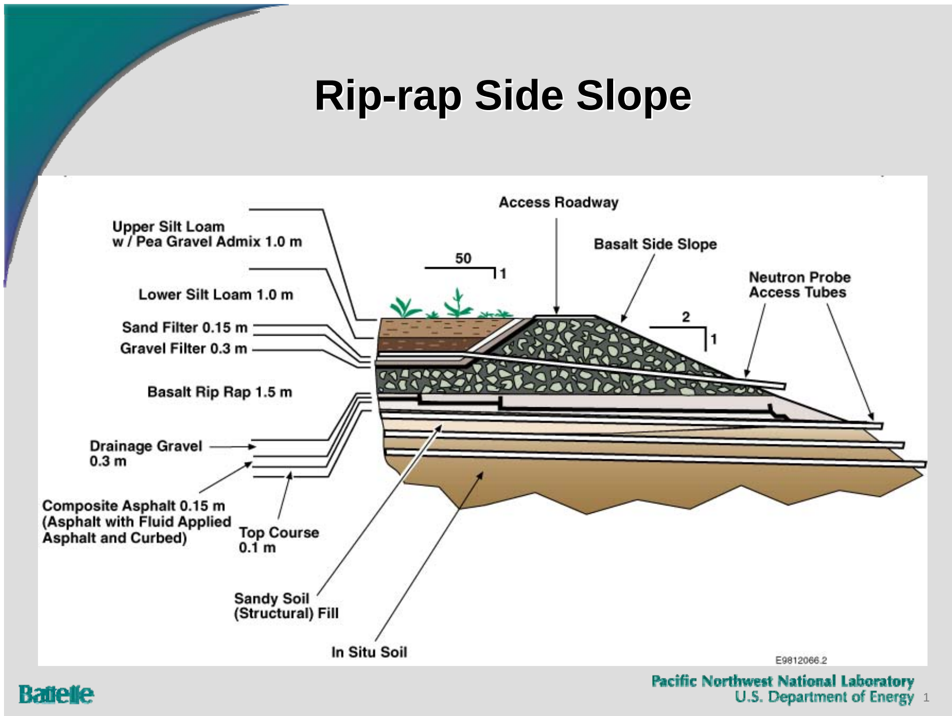

Figure B-2.4-4. Rip-rap side slope (Fayer 2005)

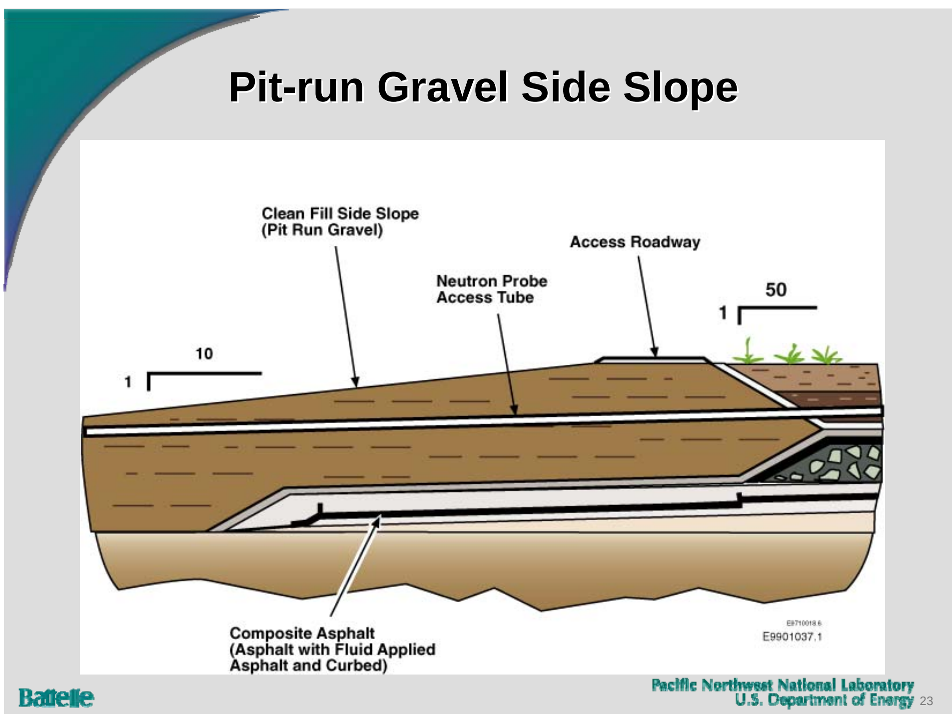

Figure B-2.4-5. Pit-Run gravel side slope (Fayer 2005)

The cover system is instrumented with a 6.5-meter square basin lysimeter beneath the asphalt pad of one of the collection basins to monitor infiltration through the asphalt layer. Fourteen water balance monitoring stations are located throughout the cover and allow use of a neutron probe, capacitance probe,

segmented time domain reflectometry, and heat dissipation units for monitoring soil moisture. Drainage from the collection zones is monitored with use of tipping bucket gauges and dosing siphons. Plant community and burrowing animal activities are monitored. Rock creep gauges and differential settlement gauges are surveyed using electronic distance measuring equipment to determine movement with the cover. The area of the cover is 6.9 acres with Cheatgrass vegetation.

Results to date: Of over nine years of monitoring, percolation occurred in only one test plot (less than 2 mm) following the third simulated 1,000-year storm event. Total percolation was less than 5% of the prescribed limit of 5 mm/year. Percolation from the remaining plots has been very small, attributed to condensation in drainage pipes. However, the side slopes, as noted in the above table, have generated significant amounts of drainage. About 23% of the total precipitation was infiltrated on the irrigated gravel slope and 21% for the non-irrigated gravel slope. In contrast, the non-irrigated rip-rap basalt rock slope drained only 15% of precipitation, whereas the irrigated rip-rap basalt rock slope drained about 23%. This discrepancy has been attributed to water loss from wind action on the rock surfaces, which acts to reduce drainage from the rock slopes.

B-2.4.2 ALCD
Sandia National Laboratories
Albuquerque, NM (Arid Site)

PI: Stephen F Dwyer, PhD, PE
505.844.0595

Six large-scale landfill test covers were constructed and monitored for water balance from May 1997 through June 2002 (Figure B-2.4-6). Two of the covers were used as EPA standard baseline prototypes for comparison: one that met minimum requirements set forth for municipal landfills (RCRA Subtitle D Cover) and the other meeting minimum requirements set forth for hazardous waste landfills (RCRA Subtitle C Cover). Four alternative covers were then constructed side-by-side with the baseline covers to enable direct comparison under the same ambient conditions. The first alternative cover featured a GCL designed for low saturated hydraulic conductivity. The remaining three covers were designed specifically for optimal performance in dry environments; specifically, they were designed to take advantage of the storage capacity of the cover and maximize removal of water via evapotranspiration. Two of the dry environment alternative landfill covers featured capillary barriers within their profiles while the last cover consisted of a simple monolithic soil cover, referred to as an ET cover. Details of the project are described in Dwyer (2003).

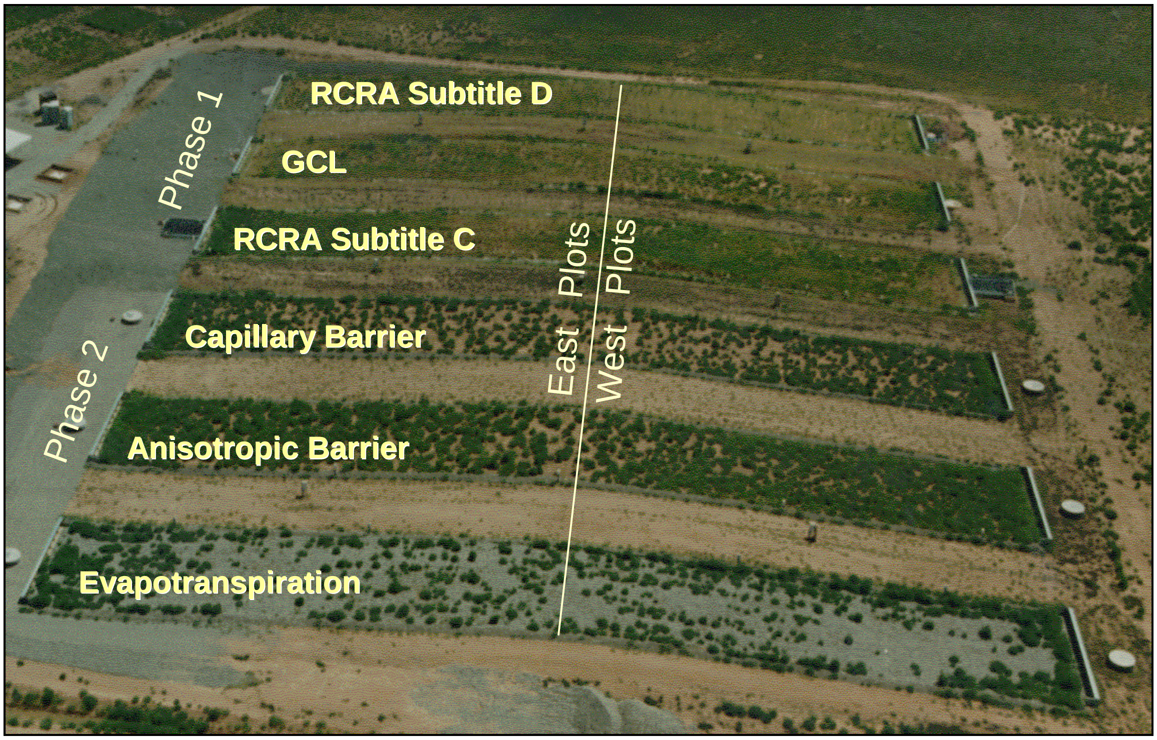

Figure B-2.4-6. ALCD @ Sandia National Laboratories

Table B-2.4.1 Seed Mix for ALCD Vegetation:

Desired Establishment	Quantity in Mixture(1) (% of total vegetation) (kg/hectare	Seed(2)
Warm Season Grasses:		
Bouteloua gracilis (Blue Grama)	20	1.1
Hilaria jamesii (Galleta)	10	3.4
Sporabolis cyptandrus (Sand Dropseed)	50	0.6
<u>Cool Season Grasses</u>:		
Oryzopsis hymenoides (Indian Ricegrass)	10	3.4
Stipa comata (Needle & Thread)	10	4.5

(1) Approximate percentage of total species present in number of plants per given area.
(2) Note that differences in weight among the various species can result in large differences in the mass ratio (kg/ha) of seed required in the seed mixture.

Table B-2.4-2. Subtitle D Cover in ALCD
Soil Properties:

Layer	Thick-ness (cm)	Dry Density (g/cm^3) @ Specific Gravity	Saturated Hydraulic Cond. (cm/hour)	Porosity	Van Genuchten Parameters				Initial Suction Value (cm)
					θ_s (vol/vol)	θ_r (vol/vol)	α (1/cm)	n	
Topsoil	15	1.5 @ 2.7	3.6374	0.45	0.4328	0.06	0.1057	1.36	700
Barrier Soil	45	1.7 @ 2.7	0.004426	0.37	0.3587	0.06	0.033	1.36	1000
Pea Gravel (1)	23	1.65 @ 2.64	15,912	0.374	0.374	0.017	2.5075	2.47	11

Table B-2.4-3. Capillary Barrier in ALCD

Layer	Thick-ness (cm)	Dry Density (g/cm^3) @ Specific Gravity	Saturated Hydraulic Cond. (cm/hour)	Porosity	Van Genuchten Parameters				Initial Suction Value (cm)
					θ_s (vol/vol)	θ_r (vol/vol)	α (1/cm)	n	
Topsoil	30	1.5 @ 2.7	3.6374	0.45	0.4328	0.06	0.1057	1.36	1000
Sand	15	1.66 @ 2.64	65.52	0.37	0.34	0.026	0.0597	2.81	16
Pea Gravel	23	1.65 @ 2.64	15,912.	0.374	0.374	0.017	2.5075	2.47	11
Compacted Soil	45	1.6 @ 2.7	1.43856	0.41	0.3951	0.06	0.0508	1.36	10,000
Sand	30	1.66 @ 2.64	65.52	0.37	0.34	0.026	0.0597	2.81	16

Table B-2.4-4. Anisotropic Barrier in ALCD

Layer	Thick-ness (cm)	Dry Density (g/cm^3) @ Specific Gravity	Saturated Hydraulic Cond. (cm/hour)	Porosity	Van Genuchten Parameters				Initial Suction Value (cm)
					θ_s (vol/vol)	θ_r (vol/vol)	α (1/cm)	n	
Topsoil	30	1.5 @ 2.7	3.6374	0.45	0.4328	0.06	0.1057	1.36	1000
Compacted Soil	45	1.6 @ 2.7	1.43856	0.41	0.3951	0.06	0.0508	1.36	1000
Sand	30	1.66 @ 2.64	65.52	0.37	0.34	0.026	0.0597	2.81	16
Pea Gravel	23	1.65 @ 2.64	15,912.	0.374	0.374	0.017	2.5075	2.47	11

Table B-2.4-5. ET Cover in ALCD

Layer	Thick-ness (cm)	Dry Density (g/cm^3) @ Specific Gravity	Saturated Hydraulic Cond. (cm/hour)	Porosity	Van Genuchten Parameters				Initial Suction Value (cm)
					θ_s (vol/vol)	θ_r (vol/vol)	α (1/cm)	n	
Topsoil	30	1.5 @ 2.7	3.6374	0.45	0.4328	0.06	0.1057	1.36	2643
Compacted Soil	45	1.7 @ 2.7	0.1563	0.41	0.3587	0.06	0.033	1.36	2643
Pea Gravel (1)	23	1.65 @ 2.64	15,912	0.374	0.374	0.017	2.5075	2.47	11

(1) Modeled to simulate the bottom lysimeter.

Table B-2.4-6. Average Annual Flux Measured Results

Landfill Cover	Average Annual Flux (mm/year)
Subtitle D	1.39
GCL Cover	0.48
Subtitle C	0.04
Capillary Barrier	0.16
Anisotropic Barrier	0.04
ET Cover	0.05

B-2.4.3 Other Demonstration Sites

Uranium Mill Tailings Repository, Monticello, UT

Demonstration project consisting of horizontal lysimeter with instrumentation within soil. Design is 8 inches soil/gravel admixture, 36 inches of fine-grained soil, 12 inches of soil/rock admixture (biointrusion layer), 12 inches of fine-grained soil, geotextile filter, and 14 inches of sand. Results showed less than 0.1 mm/yr percolation relative to precipitation of 350 mm/yr.

Nevada Test Site, NV

Monolithic ET cover approved for full scale operational. Monitored by TDR at 8 depths from 1 to 8 feet. Design is 1 foot topsoil and 10 feet of compacted native alluvium soil. After two years of monitoring, water infiltrated less than 2 feet into cover before being removed via ET.

Milliken Landfill, San Bernardino County, CA

Monolithic ET cover of 60 inches of silty sands and native grasses and shallow rooting shrubs. Lysimeters and soil moisture probes constructed, including prescriptive cover as comparison. Monitoring shows less than 0.04% infiltration compared to rainfall.

Apple Valley Landfill, Apple Valley, CA

Monolithic ET cover over large vertical cylinder of MSW with leachate collection to evaluate cover effects of thickness of landfill. Infiltration will be evaluated based on leachate quantity results over time.

Phelan Landfill, Phelan, CA

Monolithic ET cover demonstration installed in 1998 consisting of four horizontal lysimeters and eight moisture capacitance probes. Design was 1.5 m of gravelly sands with silt and native annual grasses and shrubs. Infiltration varied with aspect and soil depth, with north slopes having more infiltration than east slopes.

Other demonstration projects are summarized below in tabular format.

Table B-2.4-7. Field Data from Landfill Cover Test Plots

Location	Reference	Design	Size	Flux [(1)]	Comments
Los Alamos National Laboratory, Los Alamos, NM	Nyhan et al., 1990	1. Subtitle D 'type' Cover (20 cm sandy loam, 108 cm crushed tuff)	3 m × 10.7 m	10.6 cm	Precipitation = 173.7 cm
		2. Capillary Barrier (71 cm sandy loam over sand and gravel)		2.6 cm	
Los Alamos National Laboratory, Los Alamos, NM	Nyhan et al., 1997	1. Subtitle C 'type' Cover (61 cm loam, 30 cm sand, 30 cm bentonite amended tuff – no geomembrane)	1 m × 10 m	0 to 0	5% to 25% slope; no vegetation on covers; 1991 to 1995 monitoring period
		2. Capillary Barrier #1 (15 cm topsoil, 76 cm crushed tuff, 30 cm gravel)		17.40 cm to 3.09 cm	
		3. Capillary Barrier #2 (30 cm loam, 76 cm fine sand, 30 cm gravel)		9.64 cm to 0	
		4. Capillary Barrier #3 (30 cm loam and bentonite, 76 cm fine sand, 30 cm gravel)		5.59 cm to 0	
Wenatchee, WA	Khire et al., 1997; Benson et al., 1994	1. Subtitle D Cover (15 cm topsoil, 60 cm silty clay)	18.3 m × 12.2 m	0.5 cm	1992 to 1995 monitoring period
		2. Capillary Barrier (15 cm topsoil, 75 cm sand)		3.2 cm	

Location	Reference	Design	Size	Flux (1)	Comments
Hill Air Force Base, Utah	Hakonson et al., 1994	1. Subtitle C 'type' Cover (120 cm topsoil, 30 cm sand, 60 cm bentonite amended loam – no geomembrane)	5 m × 10 m	0.01 cm	1990 to 1994 monitoring period; covers vegetated with native grasses –capillary barrier #2 also included shrubs; 4% slope; precipitation = 173 cm
		2. Soil Cover (90 cm sandy loam)		41 cm	
		3. Capillary Barrier #1 (150 cm topsoil, 30 cm gravel)		24 cm	
		4. Capillary Barrier #2 (150 cm topsoil, 30 cm gravel)		30 cm	
Omega Hills Landfill, Milwaukee, Wisconsin	Montgomery and Parsons, 1990	1. Subtitle D 'type' Cover (15 cm topsoil, 120 cm clay)	6 m × 12 m	6.11 cm	1986 to 1989 monitoring period; 33% slope
		2. Subtitle D 'type' Cover (45 cm topsoil, 120 cm clay)		9.67 cm	
		3. Capillary Barrier (15 cm topsoil 30 cm glacial till, 30 cm sand, 60 cm clay)		10.30 cm	
Grede Foundries, Reedsburg, Wisconsin	Verbicher Associates, 1996	1. Subtitle D Cover (15 cm topsoil, 60 cm clay)	None given	108 mm/yr	1992 to 1996 monitoring period; test located on mine tailings pile
		2. Subtitle D 'type' Cover (15 cm topsoil, 90 cm native soil, 60 cm clay)		45 mm/yr	
		3. Capillary #1 (15 cm topsoil, 90 cm sand, 60 cm clay)		1.1 mm/yr	
		4. Capillary Barrier #2 (15 cm topsoil, 90 cm sand, 90 cm bentonite amended sand)		1.3 mm/yr	
		5. Capillary Barrier #2 (15 cm topsoil, 90 cm sand, 150 cm bentonite amended sand)		2 mm/yr	
Nuclear Regulatory Commission, Beltsville, MD	O'Donnell et al., 1994; Schultz et al., 1995	1. Vegetated Soil Cover (400 cm native soil)	13 m × 19 m	127 cm	1990 to 1994 monitoring period
		2. Resistive Barrier with Riprap (riprap, 30 cm gravel, 45–60 cm clay)		0	
		3. Resistive Barrier with Vegetation (20 cm topsoil, 30 cm gravel, 45–60 cm clay		0	

Location	Reference	Design	Size	Flux [(1)]	Comments
		4. Capillary Barrier with Vegetation (20 cm topsoil, 30 cm gravel, 45–60 cm clay, 20 cm native soil, 20 cm gravel)		0.13 cm	
Geogrswerder, Germany	Melchior, 1997	1. Subtitle C ‘type’ Cover (75 cm topsoil, 25 cm sand, 60 cm compacted soil – no geomembrane) @ 4% slope	10 m × 50 m	138 mm	1987 to 1993 monitoring period
		2. Subtitle C ‘type’ Cover (75 cm topsoil, 25 cm sand, geomembrane, 60 cm compacted soil) @ 4% slope		3 mm	
		3. Capillary Barrier (75 cm topsoil, 25 cm sand, 30 cm gravel, 30 cm sand, 40 cm compacted soil) @ 4% slope		10 mm	
		4. Subtitle C ‘type’ Cover (75 cm topsoil, 25 cm sand, 60 cm compacted soil – no geomembrane) @ 20% slope		75 mm	
		5. Subtitle C ‘type’ Cover (75 cm topsoil, 25 cm sand, geomembrane, 60 cm compacted soil) @ 20% slope		4 mm	
Little Packington Landfill, Birmingham, England	Rust, 1996	1. 50 cm topsoil, 100 cm compacted (engineered) clay @ 10% slope	2 m × 5 m	7.8 mm	1992 to 1994 monitoring period
		2. 50 cm topsoil, 100 cm compacted (non-engineered) clay @ 10% slope		7.4 mm	
		3. 50 cm topsoil, 100 cm compacted (engineered) clay @ 20% slope		2.4 mm	
		4. 50 cm topsoil, 100 cm compacted (non-engineered) clay @ 20% slope		8.3 mm	

(1) Flux is cumulative over monitoring period unless noted as an annual flux.

Appendix C

Biointrusion Data

C-1.0 BURROWING ANIMAL AND INSECT INTRUSION

Excessive burrowing animals and insects can have a detrimental effect on a landfill cover system. Burrowing animals can produce preferential flow (Hakonson 1986, Bowerman and Redente 1998, Cadwell et al. 1989, Pratt 2000). Dwyer (2003) revealed that preferential flow can provide flux through a cover system under unsaturated conditions, but this flow generally does not occur until the soil moisture approaches saturation where the matric potential is reduced to about 1000 cm. Burrowing organisms have the potential to redistribute contaminants within the soil profile, to transport them to the ground surface, and to become contaminated in the process. The importance of animal burrowing at a given LANL site will depend on the vertical location of waste in the landfill, cover system design (soil type, soil depth, type, and longevity of intrusion barrier), nature of the waste in the near surface environment, plant cover (species composition, quantity, and changes with time), fauna and/or insects that occupy the site (species composition, changes with time), and the stability of the cover over the long term (disturbances from fire, drought, etc.). Figure C-1.0-1 shows typical small mammal burrow holes.

Figure C-1.0-1. Small burrow holes found on mixed waste landfill at Sandia National Laboratories

Some species of kangaroo rats are known to burrow to depths of 25–175+ cm below the ground surface (Coulombe 1971). The activities of pocket gophers can account for the transport of large quantities of buried waste to the ground surface and have been shown to have a wide range of both positive and negative effects on the integrity of ET covers (Cox 1990, Ellison 1946, Ellison and Aldous 1952). Studies of pocket gophers on low-level radioactive waste sites at LANL brought 11,255 kg of material to the ground surface over a 14-month period. This resulted in large areas of void space in the landfill (Gonzales et al. 1995, Hakonson et al. 1982b). Macropores (e.g., void spaces left over by decaying roots and animal passages) also provide direct conduits for water movement into the soil profile (Hakonson et al. 1994).

Insects also have the ability to tunnel deep into a landfill cover (Figure C-1.0-2). Biointrusion into a landfill cover profile by ants (Johnson and Blom 1997, Gaglio et al. 1998), earthworms (Edwards et al. 1988, Lee 1985, MacKay and Kladivko 1985, Waugh et al. 1999), or roots (Waugh et al. 1999, Reynolds 1990) is a contributing factor to preferential flow. Harvester ants (Figure C-1.0-2) can develop tunnel systems to depths of 6 m and have been responsible for significant increases in contaminant levels found on the surfaces of landfills (Cole 1968).

Studies in Idaho showed that infiltration of water into areas disturbed by ants is higher than in non-disturbed areas (Blom et al. 1994) but that ant mound soil moisture dries out quicker than non-mound soil.

Figure C-1.0-2. Anthill on landfill cover

Some field studies (O'Farrell and Gilbert 1975, Winsor and Whicker 1980, Arthur and Markham 1983, Hakonson et al. 1982b) showed that burrowing animals may alter the vertical distribution of soil radionuclides present near the ground surface and in the process the animals themselves can become contaminated, thus further spreading the radionuclides. Other studies show that animal burrowing can influence water balance, erosion, and vegetation species composition and biomass on landfill caps by changing the physical and hydrologic characteristic of cap soil (Sejkora 1989), Gonzales et al. 1995, Hakonson 1998). Burrowing activity loosens the soil, creates surface roughness, increases infiltration, and increases soil moisture at least temporarily (Hakonson 1998). Controlled studies of this potential problem show that increased soil moisture does not necessarily lead to increased percolation of moisture into the waste when a vegetation cover is present on the cap (Sejkora 1989, Hakonson 1998, Gonzales et al. 1993). The increased soil moisture resulting from burrowing effects on infiltration can actually

stimulate increased plant growth, leading to an increase in plant transpiration (Hakonson 2000, Gonzales et al. 1993) with a resulting net decrease in flux.

C-2.0 BURROW DEPTHS

Fossorial animals spend much of their life underground in tunnel systems created for resting, breeding, feeding, and excreting of waste products. Assumptions for ecological risk assessments usually use tunnel depths of about 60 cm. However, there is ample evidence in the literature that fossorial mammals can excavate burrows to greater depths. For example, pocket gophers develop very extensive tunnel systems in the soil although most of the tunnel system is concentrated in the upper rhizosphere. Gopher tunnel systems can extend to depths of 2 m (Miller 1957). Prairie dogs excavate tunnels to over 4 m while ground squirrels, depending on species, can burrow to depths of 30-120 cm (Reynolds and Wakkinen 1987, Linsdale 1946). Larger species such as the badger (Figure C-2.0-1) may create burrows to at least 150 cm deep and 15–20 cm in diameter. Estimates of burrowing depths for various species are given in Table C-2.0-1.

Figure C-2.0-1. Badger hole found adjacent to a radioactive waste landfill in Hanford, WA

Table C-2.0-1

Burrowing Depths of Some Representative Burrowing Animals (from Cline et al. 1982)

Species Recorded	Tunneling Depth (cm)
Marmota monax (marmot)	40–50
Cynomys ludovicianus (black tailed prairie dog)	91–427
Spermophilus townsendi (ground squirrel)	50–80
Thomomys talpoides (pocket gopher)	10–30
Perognathus longimembris (pocket mouse)	52–62
Dipodomys spectabilis (kangaroo rat)	40–50
Dipodomys merriami (Merriam's kangaroo rat)	26–175+
Spermophilus townsendi (ground squirrel)	50–80
Thomomys talpoides (pocket gopher)	10–30
Perognathus longimembris (pocket mouse)	52–62
Dipodomys spectabilis (kangaroo rat)	40–50
Dipodomys merriami (Merriam's kangaroo rat)	26–175+
Spermophilus townsendi (ground squirrel)	50–80

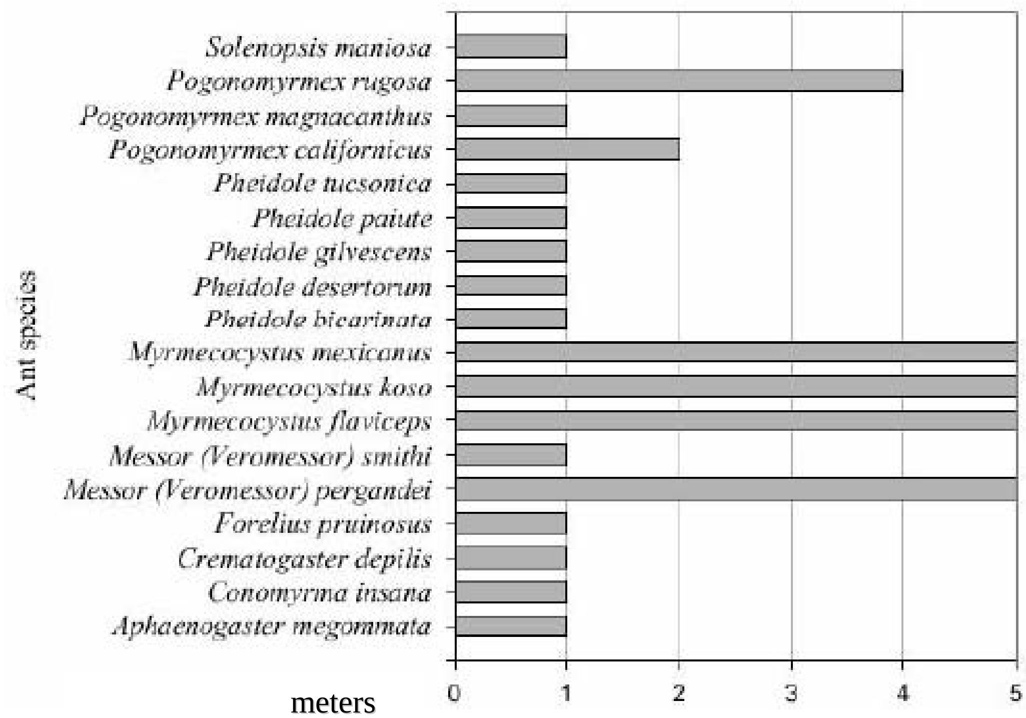

Figure C-2.0-2. Burrowing depths of some representative ant species (Jensen 2000)

C-3.0 RATES OF SOIL TURNOVER

Pocket gophers, and other burrowing mammals, have the potential to displace large amounts of soil as a consequence of burrowing. Maximum pocket gopher densities have been reported to range from 54 to 120 animals per ha (Hansen 1965). Actual amounts of soil moved to the surface by pocket gophers have ranged from 16 to 103 ton/ha/yr (Mielke 1977, Spencer et al. 1985). Estimates of 12–20 ton/acre/yr have been reported for pocket gopher densities on the order of 10 per acre (Grinnell 1923, Ellison 1946). However, much of the displaced soil is not pushed to the surface, but is re-deposited within the burrow system. For example, Andersen (1987) found that 41–87% of excavated soil was deposited as backfill within the tunnel systems below ground.

Hakonson et al. (1982b) conducted a study of soil excavation rates by pocket gopher on a LLW site at LANL. They found that over a 401-day study period on a study area (total area was 0.95 ha), pocket gophers produced about 5 mounds per day per ha. The total mass of the soil in these mounds over the 401-day study period was 11 ton per ha per year, for an average excavation rate of about 30 kg per ha per day. Mound-building activity was greatest in the late summer and fall, when a total of about 60 kg per ha of soil was brought to the surface of the landfill each day.

Hakonson et al. (1982b) also found that the digging activity of pocket gophers on the LLW site at LANL turned over less than 1/10% of the cap soil during the 401-day observation period. However, the 11,255 kg of material brought to the soil surface over the 14-month period represented a volume of about 8.3 m^3 —so, presumably, about 8.3 m^3 of void space was created within the cover profile. Based on an average tunnel cross-sectional area of 30 cm^2, based on filed measurements, 8.3 m^3 of void space within the cover profile represents about 2800 m of pocket gopher tunnel system per ha.

C-4.0 LANL STUDY ON GOPHERS

Gophers are the primary burrowing mammal of concern for cover systems at LANL. A study at Los Alamos (Hakonson 1998) on ET cover plots showed that pocket gopher burrowing in the presence of vegetation resulted in large decreases in runoff, erosion, and contaminant loss (tracer cesium [Cs]-133) via erosion but increased migration of the surface applied tracer into the subsurface soil due to increased infiltration. Vegetation slightly decreased runoff but greatly decreased erosion and contaminant loss by erosion. As with gophers, vegetation enhanced movement of contaminant into the soil. Gophers alone had an effect similar to vegetation alone in that they decreased runoff and erosion and only slightly decreased contaminant losses due to erosion. The study concluded that the effects of pocket gopher burrowing in degrading ET cover plots were minimal when vegetation was a component of the cover. Burrowing decreased erosion of the cover but did so at the expense of increasing water and surface contaminant migration into the soil. Those effects, however, were mitigated by soil moisture removal by the vegetation.

C-5.0 ADDITIONAL GOPHER EFFECTS ON EROSION/INFILTRATION

Gophers can have a positive impact on soil covers if their burrowing activity is not excessive. Their burrowing can enhance infiltration (Marshall and Holmes 1979), Lysikov 1982, Aubertin 1971, and Grant et al. 1980) that leads to a more robust stand of vegetation. The burrowing activity can mix soil nutrients vertically within the soil profile (Culver and Beattie 1983, Czerwinski et al. 1971, Levan and Stone 1983, Lockaby and Adams 1985). The combination of increased infiltration and soil nutrient mixing can lead to a healthier diversity of vegetation cover (Mielke 1977, Tilman 1983, Grant et al. 1980, Ellison and Aldous 1952, Laycock and Richardson 1975).

A study by Sejkora (1989) is relevant to LANL covers because it was designed specifically to evaluate the effects of pocket gopher burrowing and vegetation cover on water balance, erosion, and contaminant transport on an ET cover. Sejkora used a 50-foot diameter rotating boom rainfall simulator to apply several storm events over a two-year period, applied at 60 mm/hr over one hour, to measure erosion from 8 - 3 × 11-m plots with a 5% surface slope. The plots were either vegetated or devoid of vegetation and designed with or without pocket gopher burrowing. Compared to plots without pocket gopher burrowing, Sejkora found that burrowing activities of pocket gophers reduced surface runoff by an average of 21%, decreased soil erosion by 42%, and reduced erosional transport of tracer Cs applied to the surface of the plots by 33%. Sediment yields from the plots containing gophers were reduced due to an average decrease of 30% in flow velocity and a decrease of 10–75% in calculated erosion. Conversely, Sejkora found that total water infiltration increased by an average of 95% on plots disturbed by gophers and, due to reduced runoff velocity brought about by the increased surface roughness, a 27% enrichment in the silt and clay fraction in eroded soil leaving the plots. Although enriched in fines, the total mass of material eroded from the plots with gophers and vegetation averaged just 28% of that eroded from vegetated plots without gophers. Of the dependent variables investigated in Sejkora's study, total soil loss was most affected by surface treatment. Soil loss for the non-vegetated, no gopher treatment remained relatively uniform over the two-year duration of the study, while soil loss associated with the other three treatments (i.e., non-vegetated with gophers, vegetated, and vegetated with gophers) showed a general decline through time. For example, at the end of the two-year study, sediment yields from these three treatments averaged from 5–25% of that measured on these same plots at the beginning of the study. Averaged over the two-year period, vegetated plots had 72% less soil loss than plots without plant cover, while plots that were both vegetated and contained pocket gophers had about 4% of the soil loss measured on the bare plot treatments without gophers.

This burrowing by gophers and other mammals and insects can have significant negative impacts, however. The burrowing can create a pathway for release of hazardous waste. Cover designs that rely on

vegetation for water extraction and erosion control also create habitat for animals that may contribute to the degradation of the cover. Burrowing animals can mobilize contaminants by vertical displacement or by altering erosion, water balance, and gas release processes (Hakonson and Lane 1992, Suter et al. 1993, Bowerman and Redente 1998). Vertical displacement results as animals excavate burrows, and can be followed by ingestion or external contamination on skin and fur (Hakonson et al. 1982b), McKenzie et al. 1982). Once in the surface environment, contaminants may then be transferred through higher trophic levels and carried offsite (e.g., O'Farrell and Gilbert 1975, Arthur and Markham 1983). Loose soil cast to the surface by burrowing animals is vulnerable to wind and water erosion (Winsor and Whicker 1980, Cadwell et al. 1989). Burrowing influences soil-water balance and gas releases by decreasing runoff, increasing rates of water infiltration and gas diffusion, but also increasing evaporation due to natural drafts (Cadwell et al. 1989, Sejkora 1989, Landeen 1994). The cover thickness can be the primary biointrusion deterrent. Water retention in the soil creates habitat for relatively shallow-rooted plants, and the thickness of a cover soil profile can exceed the depth of most burrowing vertebrates in the area. Periodic inspection is the most efficient means for monitoring encroachment and intrusion of covers by animals. Inspectors shall look for and document evidence of animal traffic on the cover such as tracks, trails, and droppings. If evidence of animals that could damage the cover is observed, such as fecal material from large ungulates that could overgraze or trample vegetation, then institutional controls such as fencing shall be considered to prevent animal access. Inspectors should also look for animal burrows and holes large enough to cause channeling of water or displacement of loose soil to the surface where it is vulnerable to erosion.

C-6.0 TRANSPORT OF RADIOACTIVE WASTE VIA FAUNA

As with vegetation, the resuspension of soil particles can be a major source of contaminants to animals living in arid ecosystems. Soil particles can be transported to animals in association with exterior surfaces of food and by direct transfer of soil to the animal via inhalation, ingestion, and contamination of the pelt (Hakonson and Lane 1992).

Plutonium is the best example of a radionuclide whose transport to animals in arid ecosystems is dominated by physical processes. Data from many field sites and source conditions show that gut availability of plutonium and other contaminants bound to soil in a variety of animals including rodents, deer, and cattle is very low (gut to blood transfer $<10^{-5}$), leading to very low concentrations of contaminant in internal tissues and organs (Smith 1977, Moore et al. 1977, Hakonson and Nyhan 1980, Arthur et al. 1987). Highest concentrations of most soil contaminants in dry, dusty environments are usually found in tissues exposed to the external environment. Those tissues include the pelt, gastrointestinal tract, and lungs. At Los Alamos, about 96% of the plutonium body burden in rodents from the canyon liquid waste disposal areas was in the pelt and gastrointestinal tract (Hakonson and Nyhan 1980).

Because soil passes through the gastrointestinal tract of free-ranging animals on a daily basis, there is a potential to redistribute soil radionuclides across the landscape. Studies at the Nevada Test Site with cattle (Moore et al. 1977), at Rocky Flats Plant with mule deer and small mammals (Little et al. 1980, Arthur and Alldredge 1979), and at Idaho National Engineering Laboratory with small mammals and coyotes (Arthur and Markham 1983,) demonstrate that horizontal (and vertical in the case of burrowing animals) redistribution of soil plutonium does occur as animals move within and outside contaminated areas. However, the magnitude of this transport was shown to be very small over the short term (Arthur 1979, Arthur and Markham 1983, Arthur et al. 1987).

There are circumstances where animal transport of soil contaminants can assume more importance. For example, fission product sludge containing strontium (Sr)-90 and Cs-137 in a salt form was released to unlined cribs at Hanford and the cribs were backfilled with clean soil. A large animal, probably a coyote or badger, then burrowed down to the sludge and created direct access for other animals seeking the salts,

including jackrabbits (O'Farrell and Gilbert 1975). Jackrabbits ingested the radioactive salts, became contaminated, and then excreted Sr-90 on the ground surface. Levels of Sr-90 in excreta were found over a 15 km^2 surface area (O'Farrell and Gilbert 1975). This incident with Sr-90 and jackrabbits was a special case that involved liquid waste sludge disposal trenches that were not adequately covered.

Potentially more soluble Sr and Cs transport to animals in arid ecosystems involves a combination of physical and physiological processes. The more tightly bound these radionuclides are to soil (related to clay content of soil and local climate), the more their transport will be governed by soil particle transport. Data on Sr-90 and Cs-137 in small mammals from Nevada Test Site (Romney et al. 1987) and at a burial ground at Idaho National Engineering Laboratory (Arthur et al. 1987) show relatively high concentrations of these radionuclides in lung, pelt, and gastrointestinal tract similar to plutonium. This suggests that physical transport of these more "soluble" radionuclides is also important as with plutonium. The bioavailability of radionuclides such as Cs and Sr will depend on chemical form, local environmental conditions, and the structure and function of the relevant food webs.

Tritium would be one of the few exceptions to the general observation that physical transport mechanisms dominate in the transport of soil surface contaminants to biota. Uptake by roots or sorption through the leaf surface would dominate in tritium transport to vegetation. Levels of tritium in animals would reflect levels in the source (i.e., concentration ratios are 1 or less) since tritium is not concentrated as it moves through abiotic and biotic pathways. Furthermore, tritium in vegetation is available to nectivorous organisms such as honeybees as well as herbivores. While tritium is readily transported through ecosystems, it is rapidly turned over in biological systems at rates corresponding to water turnover in these systems. In humans, body water turnover is about three days (Radiological Health Handbook 1970).

C-7.0 FLORA INTRUSION

Many lessons have been learned from the UMTRA program. The UMTRA program began by designing each layer of the final cover system individually to address a specific issue rather than designing the cover to act as a system within a dynamic ecosystem. An example involves the use of rock riprap as a surface cover to prevent biointrusion (Figure C-7.0-1). The effects of this layer actually changed the cover system by introducing a nonconductive surface layer, thus significantly reducing evaporation and creating a saturated soil layer beneath that, in turn, attracted deep woody rooted plant species that were not intended.

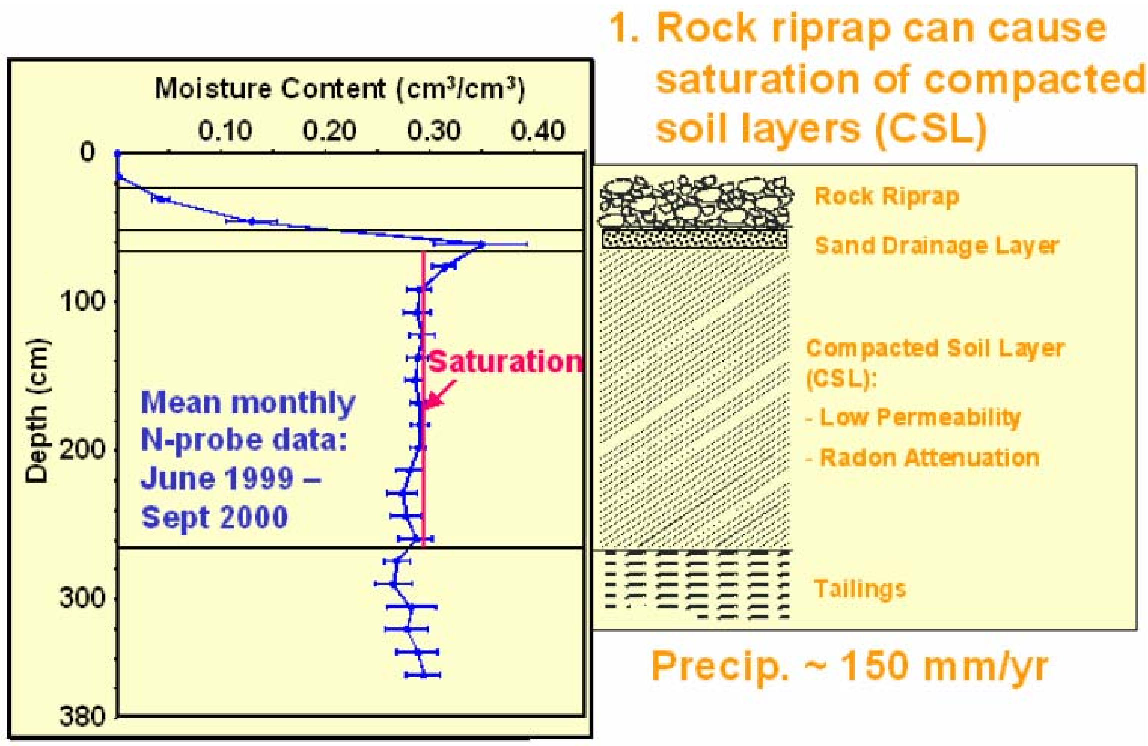

Figure C-7.0-1. Cover profile from UMTRA cover (Waugh 2004)

The larger woody roots from trees and shrubs can provide significant preferential pathways for moisture to move through the cover. However, they can also pull moisture out from much deeper in the profile. The variance in matric potential is much stronger from soil to plant to atmosphere than directly from soil to atmosphere. Often the deep penetration of roots into the waste is a problem to be avoided, however. It has been noted these roots have provided preferential pathways, but have also extracted waste to the surface in the plants themselves (Adriano et al. 1980, Arthur 1982, Foxx et al. 1984, Tierney and Foxx 1987). There are many examples of waste brought to the surface unintentionally through the plant. An example from the Hanford site is the infamous radioactive tumbleweeds (Dabrowski 1973) where roots penetrated subsurface radioactive waste. The weeds ingested some of the radioactive material. After the weeds died, the waste was transported by winds blowing the weeds across the site. There are ongoing research efforts and studies that have looked at using plants to remediate sites by allowing the selected vegetation to extract the unwanted subsurface wastes. Nitrates have been remediated in this manner. However, this is generally termed phytoremediation, whereas landfills by definition generally warrant the isolation of the underlying waste.

The plant community on a cover system is often reflective of the cover profile and the soils in that profile. A research effort demonstrating various alternative landfill cover system performed in Albuquerque, New Mexico (Dwyer 2003) produced an altered plant covering. The soils used were obtained from the same borrow source. The covers were installed side-by-side; therefore, the climatic conditions were identical for all (Figure C-7.0-2). Cover 1 shown is a simple prescriptive municipal waste type landfill that is 60 cm thick and heavily compacted to meet minimum saturated hydraulic conductivity requirements. It produced a relatively average yield of grasses and shrubs representative of the surrounding environment. Cover 2 also had a 60-cm-thick surface soil layer, but this layer was not compacted. This soil was found to have greater than 10% by weight $CaCO_3$ content that negatively influenced the vegetation establishment. Cover 3 was similar to cover 2 except the $CaCO_3$ was less than 10%, thus producing a better stand of

vegetation. Cover 4 only had a 30-cm-thick surface soil layer that was too thin to maintain a vegetation layer. The thin (30 cm) topsoil layer did not have adequate water storage capacity to maintain native vegetation, especially during dry periods. Cover 5 had an adequate soil thickness that also had gravel mixed into the surface soil (25% by weight) to minimize erosion. This gravel admixture served as mulch and produced the best stand of native grasses of the six covers. Cover 6 was similar to cover 5, except that the surface treatment used was a gravel veneer (2–4 cm thick) on the surface. This was also deployed to reduce surface erosion. The gravel veneer reduced the evaporation from the underlying soil (not as much as a thick riprap layer) that in turn allowed for moisture retention just below this gravel layer that allowed for a higher percentage of surface vegetation. This thin gravel layer on the surface also served to hold seed in place until germination. The added vegetation covering increased the available transpiration capacity. A higher percentage of shrubs and weeds were present on this cover than the others, thus resulting in a higher LAI.

1. 2-ft thick compacted topsoil layer

2. 2-ft thick uncompacted, high calcium carbonate

3. 2-ft thick uncompacted. low calcium carbonate

4. 1-ft thick uncompacted, low calcium carbonate

5. Gravel/Soil admixture surface treatment

6. Gravel veneer surface treatment

Figure C-7.0-2. Surface treatment effects on vegetation establishment (Dwyer 2003)

C-8.0 TRANSPORT OF RADIOACTIVE WASTE VIA FLORA

Although vegetation is very important in controlling erosion and percolation in landfill covers (Nyhan et al. 1984), deeply penetrating plant roots have the potential to access buried waste and bring plant available constituents, including landfill contaminants, to the surface of the site (Klepper et al. 1979, Foxx et al. 1984, Tierney and Foxx 1987). Contaminants such as tritium can be incorporated within plant tissue and enter the food web of herbivorous or nectivorous organisms. For example, at LANL tritium transport away from a controlled LLW site occurred via the soil moisture/plant nectar/honeybee/honey pathway (Hakonson and Bostick 1976). As another example, deep-rooted Russian thistle (Salsola kali) growing over the waste burial cribs at Hanford penetrated into the waste, mobilized Sr-90, and then transferred it to the ground surface. The contaminated surface foliage was transferred away from the cribs when the matured thistle (tumbleweeds) blew away from the site (Klepper et al. 1979). Two mechanisms for soil contaminant transport to terrestrial plants are absorption by roots and deposition of contaminated soil particles on foliage surfaces. Field studies suggest that deposition of soil particles on foliage surfaces is a major transport mechanism for soil-associated contaminants under many arid site and contaminant source conditions (Romney and Wallace 1976, Romney et al. 1987, White et al. 1981, Arthur and Alldredge 1982).

C-9.0 SOIL PROPERTY CHANGES

Figure C-9.0-1 reveals the intrusion of roots that led to an increase in the saturated hydraulic conductivity of the cover soil. Thinner roots like these can be beneficial by increasing transpiration even though they can increase the saturated hydraulic conductivity of the soils from their as-built status.

Figure C-9.0-1. Root intrusion into landfill cover soil

Preferential flow through soil profiles is a phenomenon that exists (Beven and Germann 1982), yet is generally unaccounted for in cover designs or the design tools (computer programs) used in the designs (Dwyer 2003). Flury et al. (1994) believe the occurrence of preferential flow is the rule rather than the exception. Hornberger et al. (1990) determined that the most significant amount of flow through a soil profile in Orono, Maine was through preferential flow channels. Watson and Luxmore (1986) determined that approximately 96% of water was transmitted through only 0.32% of the soil volume. They concluded that the larger the water flux, the larger the macropore contribution to total water flux. Many other studies (Rawls et al. 1993, Edwards et al. 1988) have concluded that preferential flow is the largest contributor to water flux through soil profiles. Aubertin (1971) in a study of macropores in forest soils attributed

increases in hydraulic conductivity to void spaces left by decomposing roots and animal passages. These macropores provided direct conduits for water movement into the soil profile. Lysikov (1982) reported hydraulic conductivities of 6.7 mm/min on non-mound soil in an area disturbed by moles (Talpa europaea) compared to 96.4 mm/min on mounds less than one year old. Grant et al. (1980) reported a twofold increase in hydraulic conductivity on pocket gopher (Thomomys talpoides) mounds compared to that of adjacent, undisturbed prairie soil.

Dwyer (2003) showed that as barrier soil layers reached a volumetric moisture content of about 20%, preferential flow occurred. This 20% moisture content corresponded to a matric potential for the given soil conditions of about 1000 cm. Preferential flow can easily take place at a suction of 1000 cm (Stormont 1999).

Dwyer (2003) used a simple set of calculations to illustrate that preferential flow occurred through a soil cover. The hydraulic conductivity for the cover was calculated using the van Genuchten (1980) formula at the peak barrier soil moisture content of 20% that produced the largest measured percolation event (Equations C-1 and C-2).

$$\theta = [1+(\alpha h)^n]^{-m} \qquad \textbf{Equation C-1}$$

where: θ = normalized water content,

h = suction head,

α, n = fitting parameters,

$m = 1 – 1/n$,

$$K(\theta) = K_s * \theta^{0.5} [1 - (1- \theta^{1/m})^m]^2 \qquad \textbf{Equation C-2}$$

where: K_s = saturated hydraulic conductivity.

Given: K_s = 1.23E-6 cm/sec, α = 0.033, n = 1.36, m = 0.26;

θ = 0.50,

Thus $K(\theta)$ = <u>3.26E-10 cm/sec</u>

Using the Darcy Buckingham (Jury et al. 1991) formula (Equation C-3) to calculate the hydraulic conductivity from the measured flux rate (J_w), assuming a unit gradient flow (constant matric potential):

$$J_w = K(h)\, \partial H/\partial z, \qquad \textbf{Equation C-3}$$

where: $\partial H/\partial z = 1$ (unit gradient),

H = total potential,

z = depth,

and h = 100 cm (for measured moisture content = 20%).

$J_w = K(h)$ = 2.5 mm/month = <u>9.3E-8 cm/sec</u>

Thus the expected hydraulic conductivity of the soil is two orders of magnitude lower than that estimated from the measured flux. The assumption governing here is that this difference is due to flow occurring preferentially through regions with a substantially greater hydraulic conductivity than that expected for the bulk of the soil, that is, preferential flow. Preferential flow increased with time even though the overall flux decreased with time (Dwyer 2003). This relative increase in preferential flow corresponded with ongoing ecological changes observed on the cover profiles (i.e., desiccation cracking, root intrusion, earthworm

activity, and animal intrusion) as well as soil pedogenic processes that led to changed soil properties, as measured with a field tension infiltrometer (Dwyer 2003). The decease in flux was attributed to the maturation of the surface vegetation.

Figure C-9.0-2 shows a cross-section of the barrier layer in a landfill cover with an earthworm hole.

Figure C-9.0-2. Earthworm hole in barrier soil layer

Given a wormhole the size of that shown above (about 1 mm in diameter), the following calculations illustrate just how much preferential flow a single wormhole can produce. Using Poiseulle's Law (Equation C-4) (Jury et al. 1991):

$Q = \pi R^4 \rho_w g(L+d)/(8L\nu)$, **Equation C-4**

where:

Q = water volume flow rate;

R = radius of wormhole = 0.5mm;

ρ_w = water density = 1 g/cm^3;

L = depth of cover profile = 60 cm;

d = diameter of soil column (assume 1 wormhole per diameter of 10 cm);

ν= water viscosity = 0.01 g/cm*sec

Q = 0.3 cm^3/sec.

Assuming one wormhole per square meter of surface area for a given landfill cover:

$Q = \{(0.3\ cm^3/sec)/(1\ m^2)\}/(100\ cm)^2 = 3 \times 10^{-5}$ cm/sec

It is understood that wormholes do not run vertically from top to bottom of a soil profile, but meander through it. Nonetheless, it is clear that structural voids such as those created by fauna intrusion can have a dominant effect on water movement through a cover.

Ants have been found to loosen the dry bulk density of soil in the immediate area of the anthills. Salem and Hole (1968) reported 20% of the volume of ant (*Formica exsectoides*) mounds being occupied by voids 2–23 mm in diameter. By applying Darcy's Law describing movement of fluid through a porous medium, the intrinsic permeability of the soil is proportional to the squared radius of the soil pores (Marshall and Holmes 1979). The range of void dimensions in the above case would result in a 100-fold difference in hydraulic conductivity. Lockaby and Adams (1985) found a significant reduction in bulk density on non-mound and mound soils, respectively, in the vicinity of fire ant (*Solenopsis invicta*) activity in a forest soil. Similar findings were reported by Baxter and Hole (1967) on ant (*F. cinerea*) mounds in a prairie soil. Decreases in bulk density imply a higher fraction of pore space in the soil.

Lower bulk densities on mound vs. non-mound soils have also been reported for pocket gopher mounds (Laycock and Richardson 1975, Ross et al. 1968). This increase in pore space has an influence on hydraulic conductivity of the soil. Mielke (1977) found that soil moisture content increased from 2.6–7.7% on non-mound vs. mound soils in an area disturbed by pocket gophers. Although not statistically significant, the findings of Grant et al. (1980) indicated a tendency for higher moisture content on gopher mounds. Conversely, Skoczen et al. (1976) documented the drying effect brought about by mole tunnels. This drying effect was attributed to airflow through the open tunnels.

Ross et al. (1968) found that other animals more frequently disturb the soil present on and near mima-type mounds. Ground squirrels (Citellus spp.), badgers (Taxidae taxus), and toads (Bufo hemiophzts) were among the species found at these sites. The increase in animal activity in the vicinity of these mounds is thought to perpetuate the effects of the mound in modifying bulk density, soil chemistry, and vegetation distribution. Movement of soil material by animal activity can influence the distribution of primary particles (sand, silt, and clay) in the soil. Baxter and Hole (1967), Salem and Hole (1968), Alvarado et al. (1981), and Levan and Stone (1983) reported that soil material in ant mounds has a higher proportion of clay than adjacent non-mound soil. The findings of Laycock and Richardson (1975) also indicate a tendency for enrichment of soil fines in mounds resulting from pocket gopher burrowing.

In addition to affecting the compaction, porosity, and particle size distribution of the soil, animal activity has been shown to influence the amount and distribution of chemicals in the soil. Many of the studies on the influence of ant activity have indicated significant increases in levels of K, P, Ca, Mg, and iron in mound vs. non-mound soils (Baxter and Hole 1967, Culver and Beattie 1983, Czerwinski et al. 1971, Levan and Stone 1983, Lockaby and Adams 1985, Salem and Hole 1968).

Increases in plant nutrients have also been shown to occur in mounds created by burrowing mammals (Abaturov 1968, Mielke 1977). Laycock and Richardson (1975) also showed a slight increase in nitrogen on gopher mounds. However, Spencer et al. (1985) reported lower levels of some nutrients in mound soils.

These discrepancies may be due to specific site characteristics and time since disturbance (Turner et al. 1973). Since clay content of soil has a direct influence on the CEC, the differences in clay content of mound vs. non-mound soils noted earlier may contribute to the observed differences in soil chemistry. Clay also is important to soil structure and the stability of aggregates, factors which affect the detachment of soil by rainfall and runoff (Alberts et al. 1980).

Appendix D

Capillary Barrier

D-1.0 CAPILLARY BARRIER

Capillary barriers, consisting of fine-over-coarse soil layers (Figure D-1.0-1), are another alternative cover system used in final landfill closures, especially in dry climates. Capillary barriers may be designed to take advantage of the hydraulic enhancements they offer, but at LANL they will only be used as a consequence of the inclusion of optional layers (i.e., biointrusion or gas vent layers) that result in a fine–over-coarse soil arrangement. Differences in pore size distribution between two soil layers cause infiltrated water to be retained in the upper soil layer under unsaturated flow conditions, as long as the contrast in unsaturated properties (e.g., soil-moisture characteristics and unsaturated hydraulic conductivities) of the soils in the two soil layers is sufficiently large (Dwyer 1997).

Figure D.1-1. Profile of capillary barrier

In general, the upper soil layer must consist of a soil exhibiting a significantly greater retention (matric potential) than the lower soil layer at the same water content (Figure D-1.0-2). Thus a capillary barrier effect results when a “relatively fine-grained soil” overlies a “relatively coarse-grained soil.” The capillary pressure head in the fine-grained upper soil layer typically must approach a value near zero (i.e., saturated conditions) before any appreciable flow occurs into the lower coarse-grained layer (Dwyer 1997).

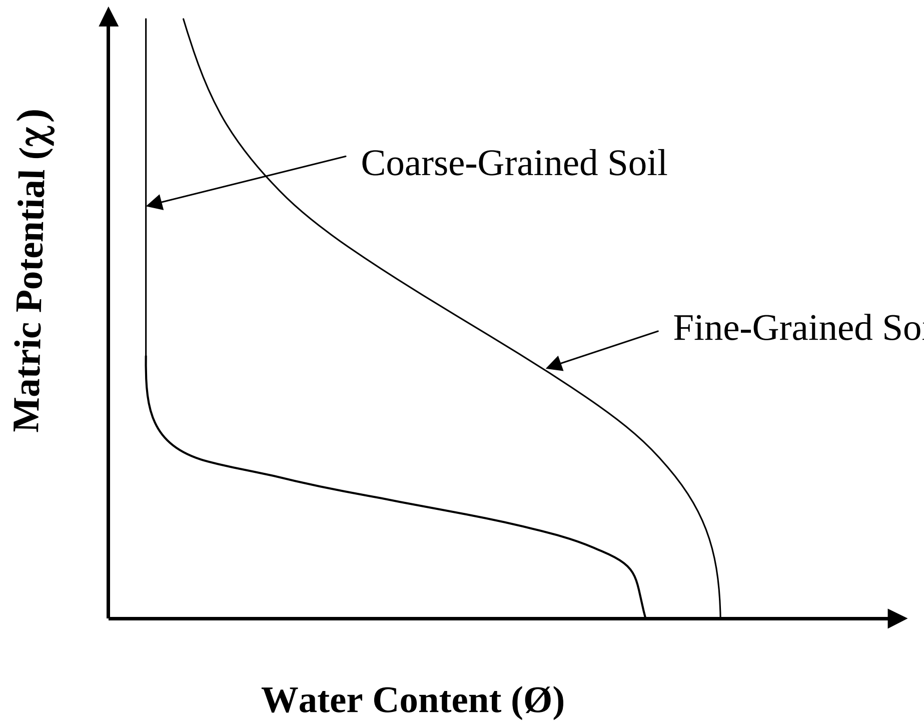

Figure D-1.0-2. Typical soil moisture characteristic curves for fine- and coarse-grained soils

The performance of a capillary barrier can be explained by considering Figure D-1.0-3. Beginning at relatively dry conditions, that is, at high suctions, the fine soil has a finite hydraulic conductivity, whereas the hydraulic conductivity of the coarse layer will be immeasurably small. With increasing water content and decreasing suction head, the hydraulic conductivity of the fine layer will increase gradually. The hydraulic conductivity of the coarse layer will remain immeasurably small until its water entry head is overcome. Under these conditions, water will not move from the fine layer into the coarse layer, but increase the water content of the fine layer. Breakthrough into the coarse layer occurs when the suction head at the contact equals the water entry head of the coarse layer. When the suction head decreases below this value, the hydraulic conductivity of the coarse layer will increase rapidly and eventually exceed that of the fine layer.

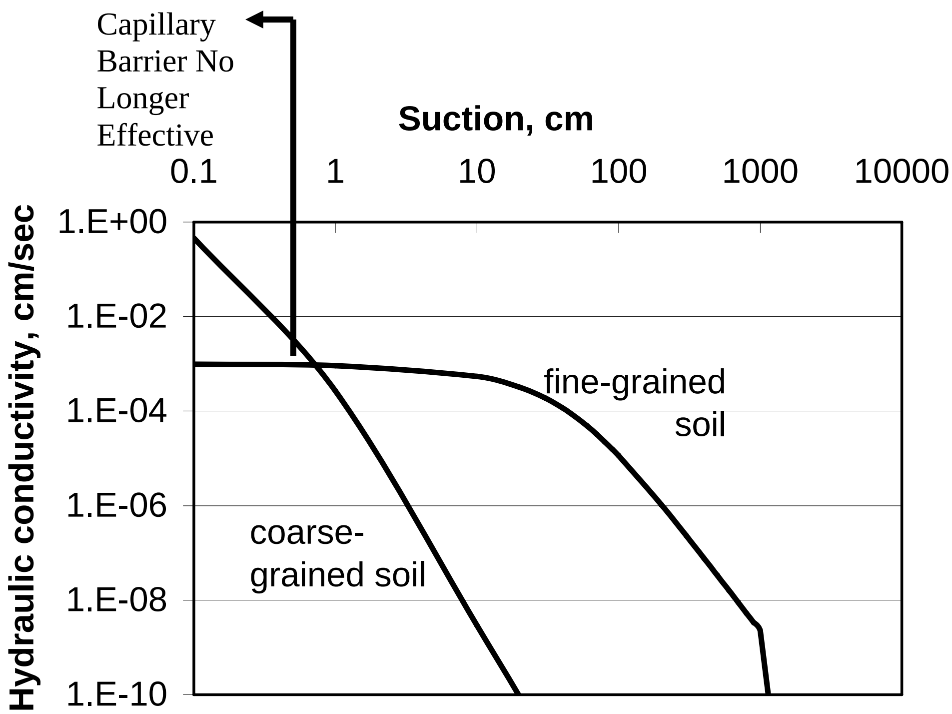

Figure D-1.0-3. Suction vs. hydraulic conductivity for fine- and coarse-grained soil

Soil-water is removed from a non-sloped capillary barrier system only by ET, or by percolation (breakthrough) into the underlying coarse layer. If the water storage capacity of the fine-textured soil layer is sufficient to store the expected infiltration at a particular site, then non-sloping capillary barriers can prevent vertical water movement (breakthrough) into the underlying waste.

The lateral movement of water in a sloped capillary barrier system shall be considered. Lateral diversion is essentially gravity-driven unsaturated drainage within the fine layer. Because the water content in the fine layer is usually greatest near its interface with the underlying coarse-textured soil layer, and the hydraulic conductivity of an unsaturated soil increases with water content, lateral diversion is concentrated near this interface. Laterally diverted water will result in increasing water content in the downdip direction. The diversion length is the distance which water is diverted along the fine/coarse interface before there is appreciable breakthrough into the coarse layer (Figure D-1.0-4).

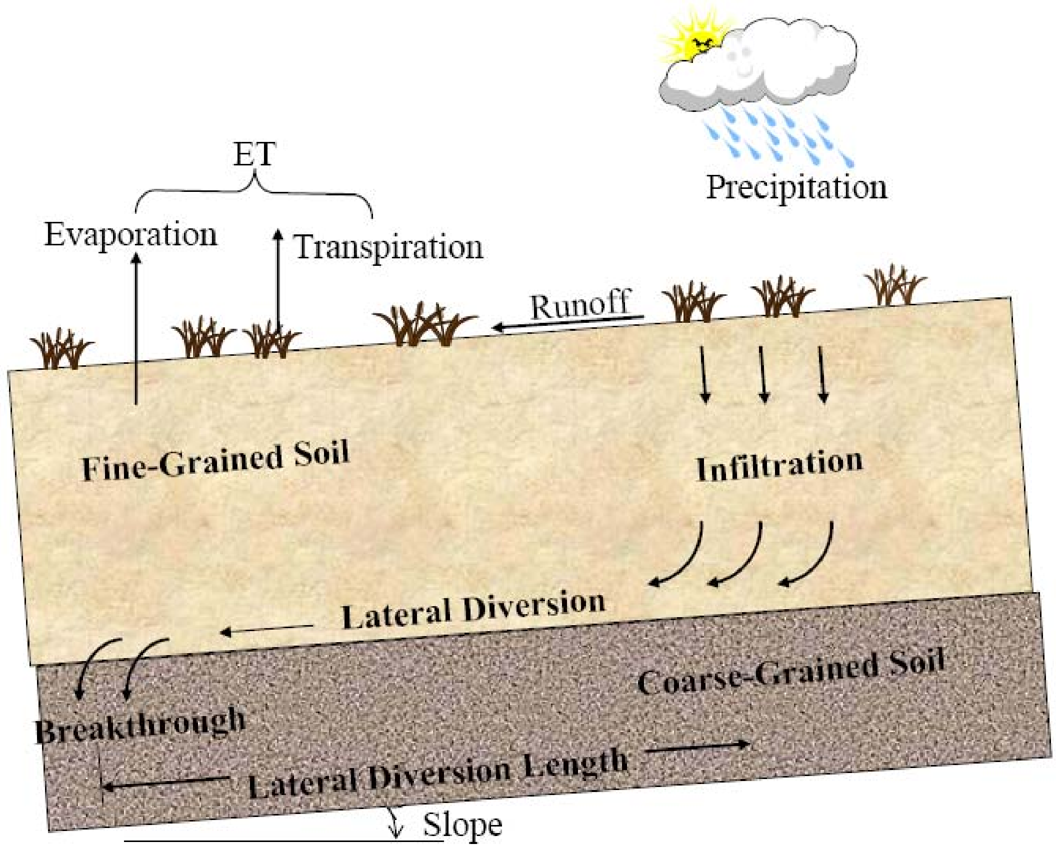

Figure D-1.0-4. Sloped capillary barrier

Advantages of incorporating a capillary barrier in a cover system include:

1. The fine-textured soil layer of a capillary barrier system will store more water than a comparable layer without the capillary break (i.e., a free-draining layer). Compared to a simple soil cover, the additional storage capacity will either serve to reduce overall percolation, or reduce the total thickness requirements of the overlying cover soil to yield the same degree of percolation inhibition.

2. The additional water stored within a capillary barrier system will tend to encourage the establishment and development of the surface vegetation. The increased vegetation cover, in turn, will remove more soil-water due to greater ET. Furthermore, plants serve an important function in reducing surface erosion.

3. In addition to providing the capillary break, the coarse layer of the capillary barrier system can serve as a biointrusion barrier and/or gas collection layer.

Disadvantages of incorporating a capillary barrier system into a landfill cover system include:

1. Significant desiccation cracking in the fine-textured soil layer can be detrimental to a capillary barrier system. Every reasonable effort shall be made to avoid desiccation cracking (e.g., compacting the soil “dry of optimum” rather than ”wet of optimum”; use soils that are less susceptible to desiccation cracking, such as sandy silts or silty sands rather than clay).

2. A capillary barrier system may not be effective in wetter climates or where appropriate soil materials are not readily available.

3. Slope can be an advantage in laterally diverting water but, in turn, can be a huge disadvantage if the diversion length of the cover system is inadequate, thereby resulting in significant breakthrough. If a capillary barrier system is sloped, the two-dimensional (lateral and vertical) effects of soil-water movement must be taken into account.

4. Differential settlement can introduce significant discontinuities in the fine-over-coarse soil layer interface, thus rendering the capillary barrier system less effective. This is especially true for sloped capillary barrier systems.

5. Costs are generally higher for a capillary barrier than an ET cover (Dwyer 1998).

6. Construction can be more difficult to build a capillary barrier than an ET cover (Dwyer 2000).

Figures D-1.0-5 and D-1.0-6 show pictures of capillary barrier cover systems. Figure D-1.0-5 is a capillary barrier over a hazardous waste site that is a Superfund closure in Farmington, New Mexico. Figure D-1.0-6 is a capillary barrier cover system at RMA in Denver, Colorado.

Figure D-1.0-5. Capillary barrier under construction on Superfund site, Farmington, NM

Figure D-1.0-6. Capillary barrier over contaminated site at RMA, Denver, Colorado

D-2.0 DESIGN CONSIDERATIONS FOR A CAPILLARY BARRIER

Design considerations for the fine-textured soil layer of the capillary barrier system include all of those listed for the ET cover system. In general, the capillary barrier enhances the water storage capacity of the fine-textured soil layer. Consequently, this layer will not need to be as thick as that in an ET cover system. In fact, the fine-textured soil layer must be thick enough to store infiltrating water, yet thin enough so that all of the stored water can later be removed via ET. Thus the design considerations for a capillary barrier involve determining the proper fine-textured soil layer thickness and slope gradient to minimize the percolation of water through this layer. In general, layer thickness and slope gradient requirements depend on climatological information for the specific site (e.g., precipitation, temperature, and humidity) and the characteristics of the soils used in the cover (e.g., water storage capacity, hydraulic conductivity, and texture). Other factors that shall be taken into consideration include such things as slope stability, vegetation characteristics, and desiccation (Dwyer 1997).

D-2.1 Selection of Soils

D-2.1.1 Fine Soil Layer

The soil used for the fine layer or cover layer will often be the near-surface soil (topsoil) stockpiled during clearing and preparation of the site, or material taken from a nearby borrow pit. Important considerations in the design and performance of the cover layer are its ability to serve as a rooting medium, the soil-water storage capacity, as well as the cover's lateral diversion capacity (when designing a sloped capillary barrier system).

Rooting medium – Plants generally play an essential role in the stability and performance of a cover system. Beyond the logistical and economic constraints of importing a non-local soil, the use of soils similar to those of the surroundings has merit from the consideration of its function as a rooting medium for native plants. Each site has a characteristic climax plant community (that is, the species and density of plants that are best suited for the particular climate, soil, and topography). It is probable that regardless of the initial condition of a plot of ground (from bare to vegetated), the climax community will eventually be established. Thus using local soil should result in more predictable vegetation, consistent with vegetation that has evolved naturally for that location. While it is possible to amend a soil to improve its characteristics as a rooting medium, any additional processing or amendments will increase costs.

Water storage capacity – The water storage capacity of the cover layer soils depends upon the physical characteristics of the soil and the presence of the underlying capillary break. The water storage capacity of a capillary barrier can be estimated from the soil moisture characteristic curve of its fine soil layer to indicate the additional storage capacity as a result of the underlying capillary break (Stormont and Morris 1998). The texture of this overlying fine soil is important in determining the additional water storage capacity. The water storage capacity of a capillary barrier was measured in a field-scale (14 m^2 surface area) water balance experiment (Stormont 1996). In this test, a 900-mm-thick silty sand was placed over a uniform gravel to form a capillary barrier. The water content in the fine layer was measured as water was added at a constant rate of about 10 mm/day. Breakthrough into the coarse layer was detected by collecting water that drained from the coarse layer. The water content in the fine layer at breakthrough was about 40% by volume near the interface. The total amount of water stored in the capillary barrier at breakthrough was estimated by integrating the measured water content over the thickness of the fine layer. Expressed as a normalized quantity with respect to area (volume of water divided by surface area), the capillary barrier stored 285 mm of water at breakthrough. The storage capacity of the capillary barrier can be compared to that estimated for a simple monolithic soil cover. Without the capillary break, water will drain approximately to a characteristic water content of a soil termed its field capacity or drained upper limit. The field capacity for the same soil (silty sand) is estimated at 20%. By integrating this water content over the same 900-mm thickness, the silty sand in a simple soil cover configuration would be expected to store about 180 mm of water before it drained. Thus an additional 105 mm of water storage was gained by the capillary break for the same cover soil thickness. Alternatively, a simple soil cover would need to be about 1425 mm thick to store the same amount of water as 900 mm of the same soil in a capillary barrier configuration.

The type of soil used for the fine or cover soil layer affects the water storage capacity of a capillary barrier. A finer-grained soil is expected to store more water than a more coarse-grained soil in a comparable configuration. The difficulty with soil selection is that one is normally governed by available local soils. Desiccation cracking in the fine layer of a Capillary barrier system would be detrimental and shall be avoided. Silty sands or sandy silts, although their water-holding capacity may be less than a clay and consequently require a thicker overlying fine soil layer, will be less vulnerable to desiccation cracking. Compacting the fine layer “dry of optimum” rather than “wet of optimum,” as recommended with resistive clay barriers, should also help minimize the chance for desiccation cracking as well as having a lower initial moisture content, thus increasing its initial excess water storage capacity.

Lateral diversion – The lateral diversion capacity of the fine layer is dependent in large part on the hydraulic conductivity of the fine layer. In general, the hydraulic conductivity of clays, silts, and loams is too low to permit appreciable lateral diversion. Field tests of capillary barriers with homogeneous fine layers indicate the effective diversion lengths are less than 10 m (Nyhan et al. 1990b), Hakonson et al. 1994, Stormont 1995, Stormont 1996). These short diversion lengths are a consequence of the relatively low hydraulic conductivity of the fine-grained soils compared to the infiltration rate during stressful periods when the soil is relatively wet (e.g., spring snowmelt). Thus soils that are often preferred as a rooting medium and

for their water storage capacity (e.g., loams and silts) may not be conductive enough to substantially divert soil-water laterally.

Utilizing "transport layers" or "unsaturated drainage layers" within the fine layer (Stormont 1995) can increase the diversion capacity of capillary barriers. Transport layers are one or more relatively conductive layer(s) that drain water laterally within the cover's fine soil layer while remaining unsaturated. Because soil-water tends to accumulate near the fine/coarse interface and unsaturated hydraulic conductivity increases with water content, a transport layer near the interface is most effective in laterally diverting water. Lateral diversion can be designed into a capillary barrier by means of a relatively thin (e.g., <300-mm) transport layer placed at the fine/coarse interface. The transport layer shall be relatively fine-grained, uniform sand that possesses as great a hydraulic conductivity as possible under low to moderate values of suction head. The lateral diversion afforded by a transport layer will complement the water storage function of the overlying soil, expanding the conditions and climate for which a capillary barrier could be effective.

D-2.1.2 Coarse Soil Layer

The coarse layer soil could range from coarse sand to cobbles. The primary function of the coarse layer is to form a capillary break, but it may also serve as a biointrusion barrier or a gas collection layer.

Capillary break – The movement of water from the overlying layer into the underlying layer is controlled by the water entry suction of the underlying layer. The water entry suction is the suction associated with the movement of water into the smallest pores that form a continuous network. Water will not move from an initially dry medium at suctions larger than the water entry suction of the underlying layer. Minimizing the water entry suction gradient delays the movement of water from the overlying fine layer into the coarse layer, permitting more water to be stored in the fine layer near the interface. The water entry head can be roughly approximated by the height of capillary rise within a soil (Hillel and Baker 1988). Thus the water entry head is expected to be small for a uniform coarse-grained soil and increase as the amount of fines in the soil increases.

D-2.2 Stability of the Fine-Over-Coarse Soil Layers

In general, the effectiveness of a capillary break is increased with an increased contrast in texture or particle-size distribution of the fine and coarse materials (Stormont 1997). There is concern, however, that fine soil particles will move into the pores of the coarse soil, degrading the interface and reducing the effectiveness of the capillary break. The conventional approach for evaluating the stability of the fine-over-coarse system is to ensure the soils satisfy soil retention or filtering criteria. Although a large number of criteria have been developed, most are similar in that they are based on some measure of the particle-size distributions of the fine and coarse soils. The following criterion is widely used:

$$\frac{D_{15}}{d_{85}} \leq 5$$ **Equation D-1**

where:

D_{15} = particle size of the coarse soil for which 15% of the particles are finer,

d_{85} = particle size of the fine soil for which 85% of the particles are finer.

From conventional criteria, interface stability is favored by soils having similar particle-size distributions, apparently in conflict with maximizing the effectiveness of a capillary break. Conventional criteria,

however, have been developed using high hydraulic gradients for applications such as dams. In contrast, capillary barriers would only rarely, if ever, experience positive pore pressures, and the associated hydraulic gradients would be small. Furthermore, capillary barriers will be subjected to cycles of wetting and drying in response to climatic conditions. Thus interface stability shall be considered under dry conditions, as well as under relatively small positive water pressures.