Appendix B

Cover Material Information

(Compact Disc)

Appendix B-1

Cover System Design Guidance and Requirements Document

LA-UR-06-4715
April 2007
EP2006-0667

Title:

Cover System Design Guidance and Requirements Document

Authors:

Stephen F. Dwyer, PhD, PE
Ronald E. Rager, PE
John Hopkins, PhD

Los Alamos
NATIONAL LABORATORY
EST. 1943

Prepared by the
Environmental Programs-Environmental Restoration Support Services

Los Alamos National Laboratory (LANL), operated by Los Alamos National Security (LANS), LLC, for the U.S. Department of Energy under Contract No. DE-AC52-06NA25396, has prepared this document to support the investigation and cleanup, including corrective action, of contamination at LANL, as required by the Compliance Order on Consent, signed March 1, 2005. The public may copy and use this document without charge, provided that this notice and any statement of authorship are reproduced on all copies.

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. Composite Barrier Layer. 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. Drainage Layer. 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. Topsoil Vegetation Layer. 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. Optional Layers. Optional layers include gas vent, Rn barrier (compacted clay layer can serve as the Rn barrier), and biointrusion layers.

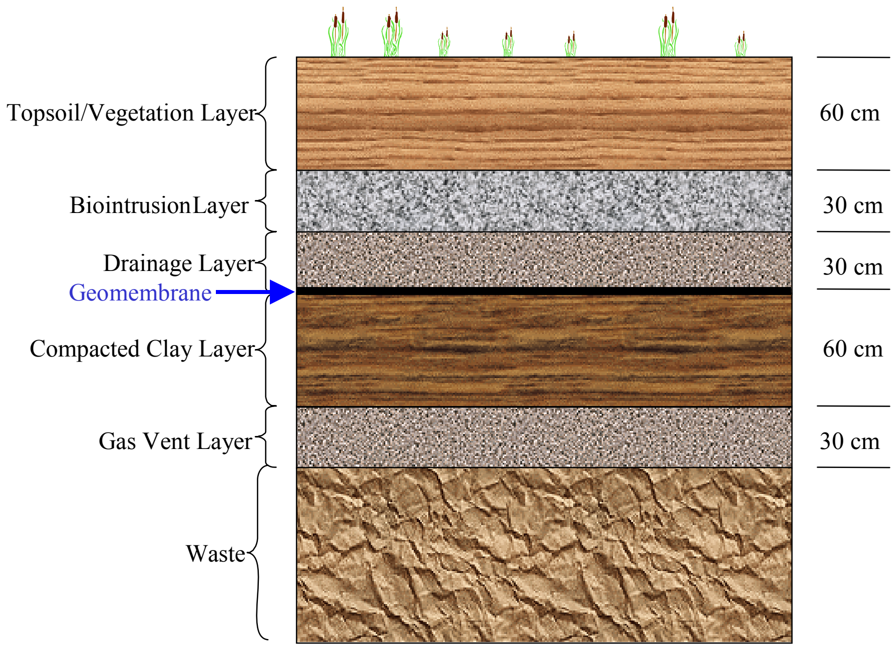


Figure 2.1-1. RCRA Subtitle C compacted clay cover (EPA 1991)

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 (http://hq.environmental.usace.army.mil/epasuperfund/geotech/index.html).

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.

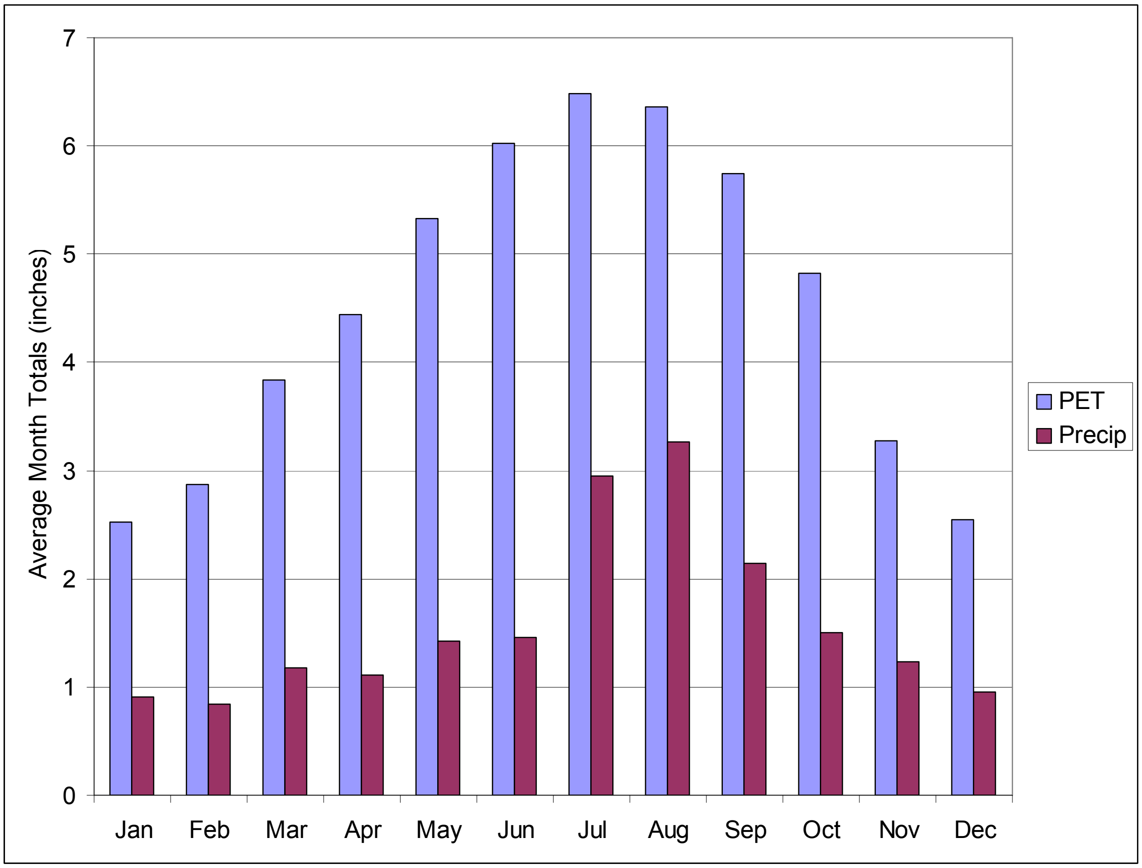


Figure 2.2-1. Climate's demand for water (PET) vs. supply of water (precipitation) for Los Alamos, NM

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).

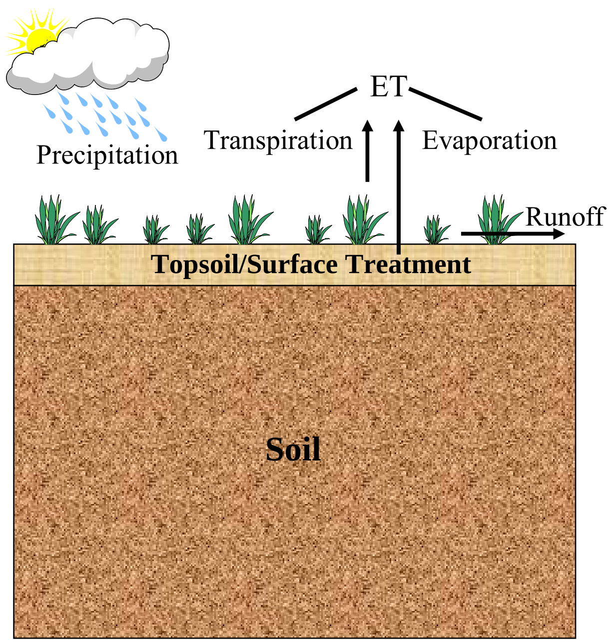


Figure 2.2-2. Typical ET cover profile

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.

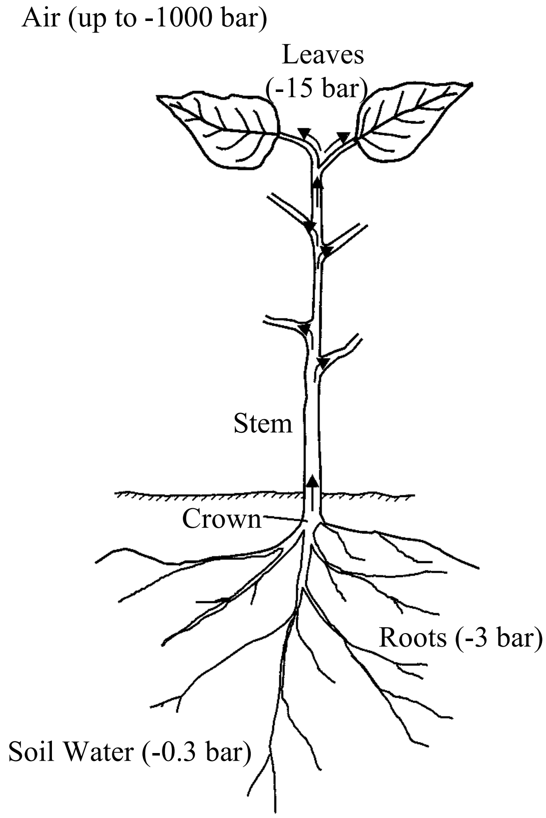


Figure 2.2-3. Typical soil-plant-atmosphere water potential variation (Hillel 1998)

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).

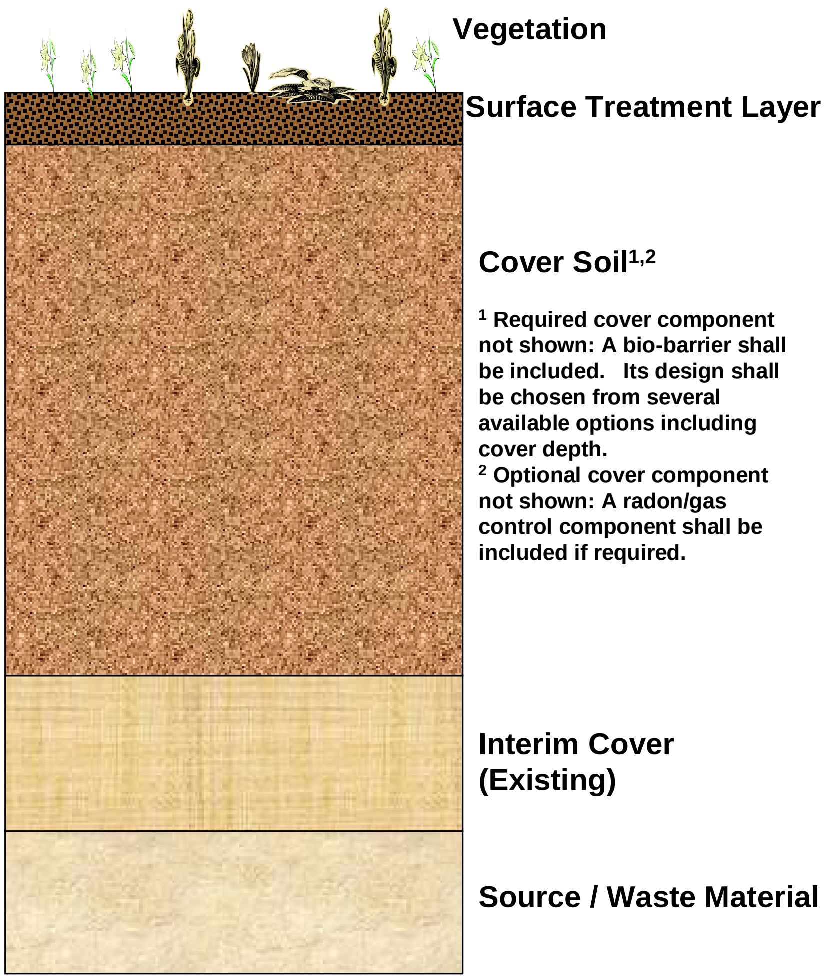


Figure 3.0-1. Typical LANL ET cover profile

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.

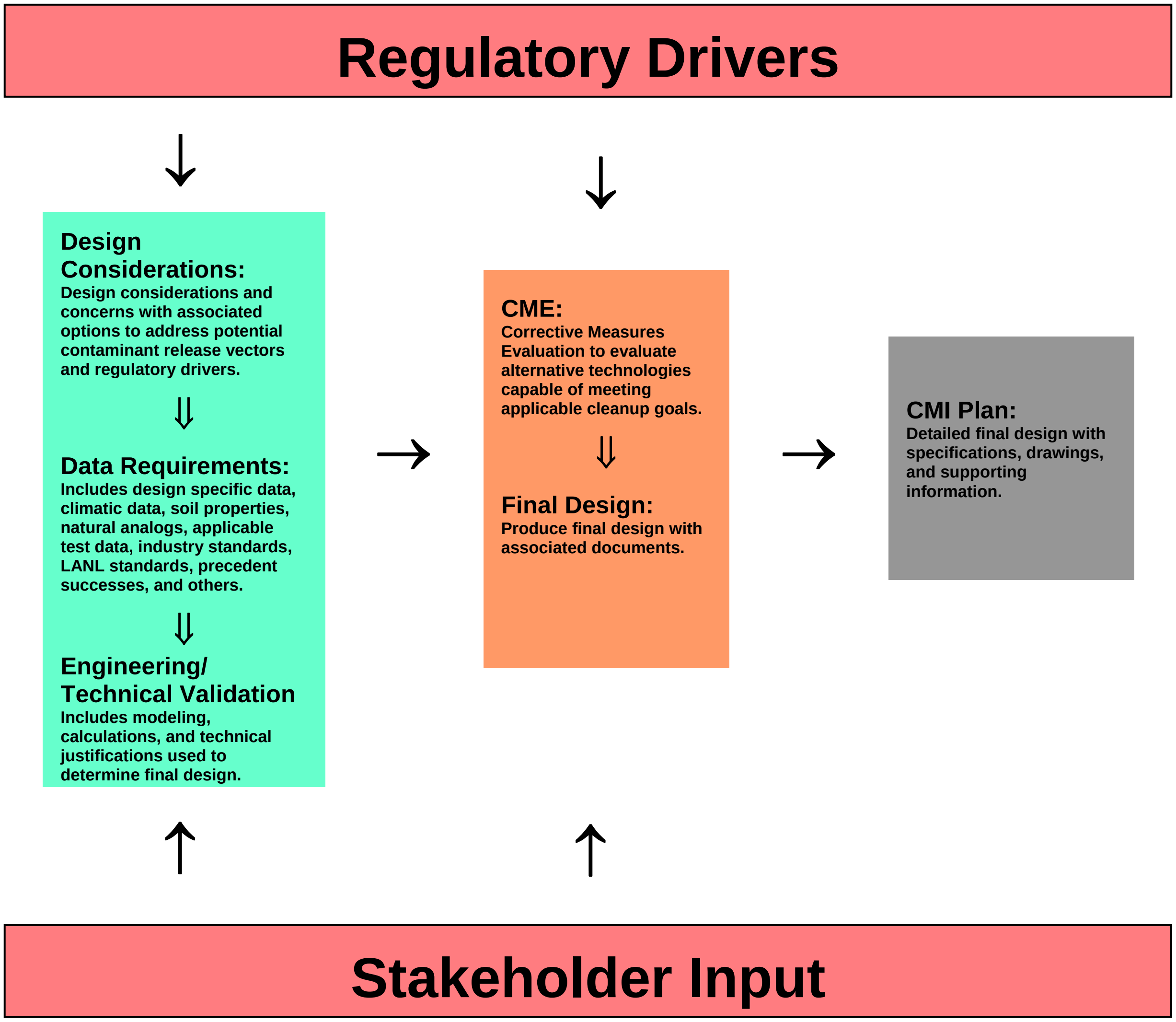


Figure 3.0-2. Design process

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.

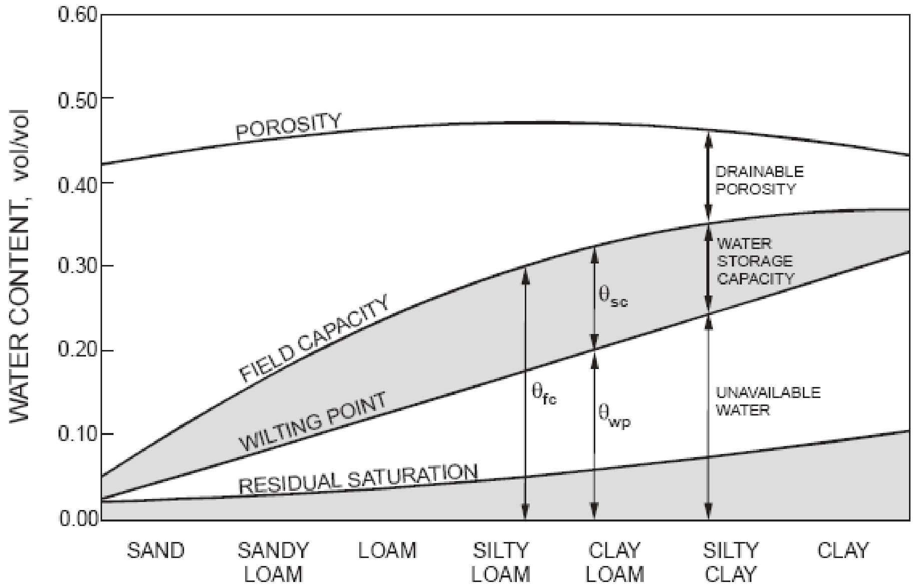


Figure 3.1-1. Relation between moisture retention parameter and soil texture class (modified from Schroeder et al. 1994)

- 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).

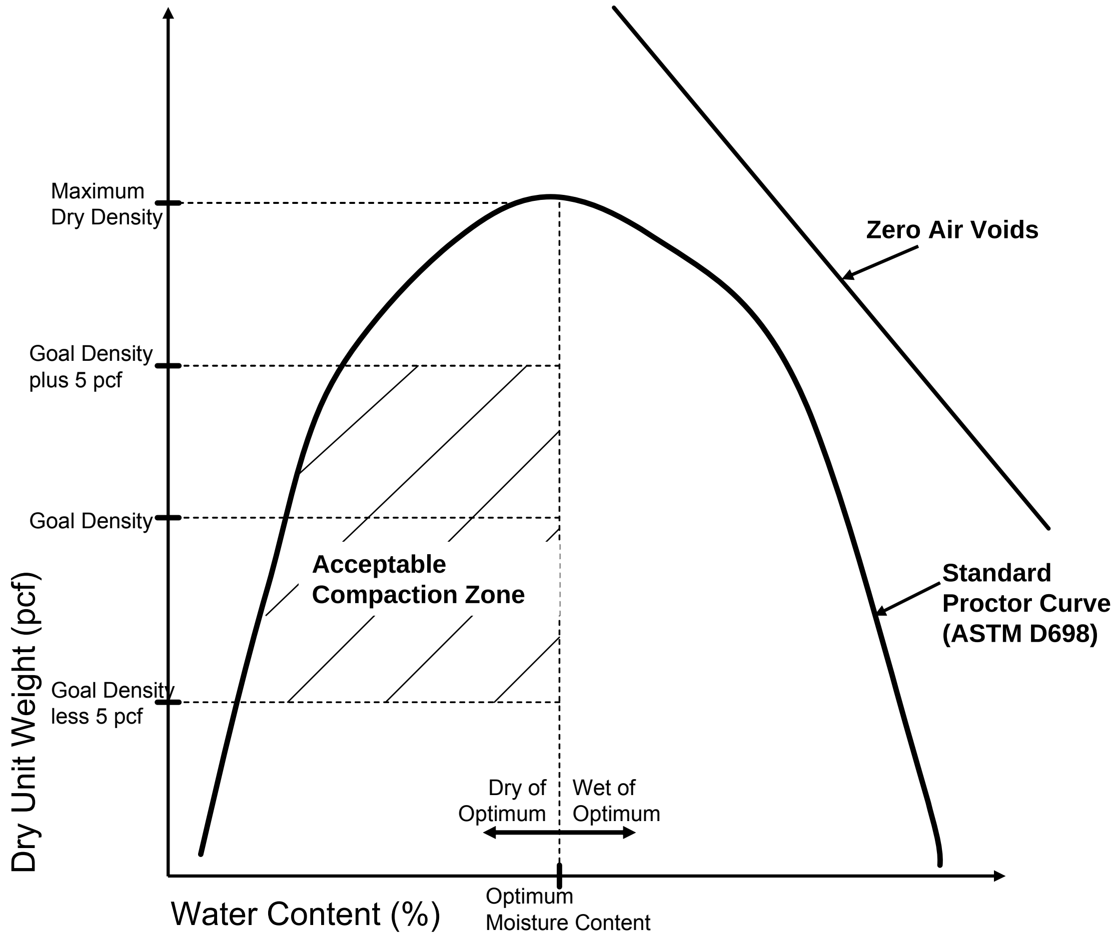


Figure 3.1-2. ACZ for soil placement

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.

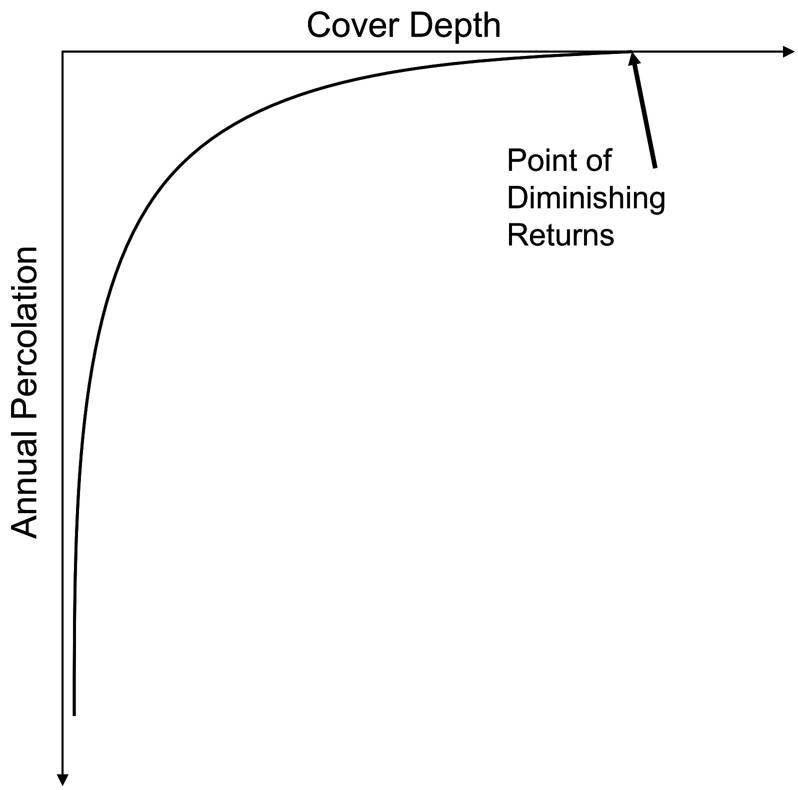


Figure 3.1-3. Cover depth vs. annual percolation

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.

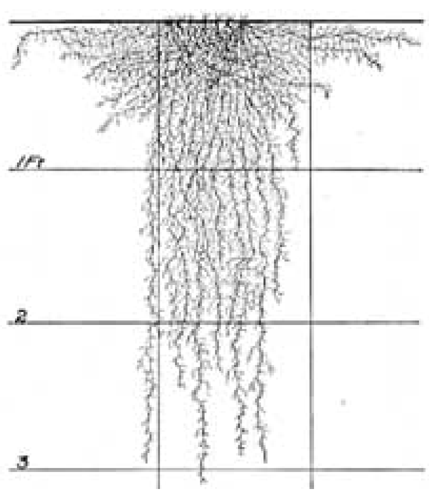


Figure 4.1-1. Blue grama grass root system

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.

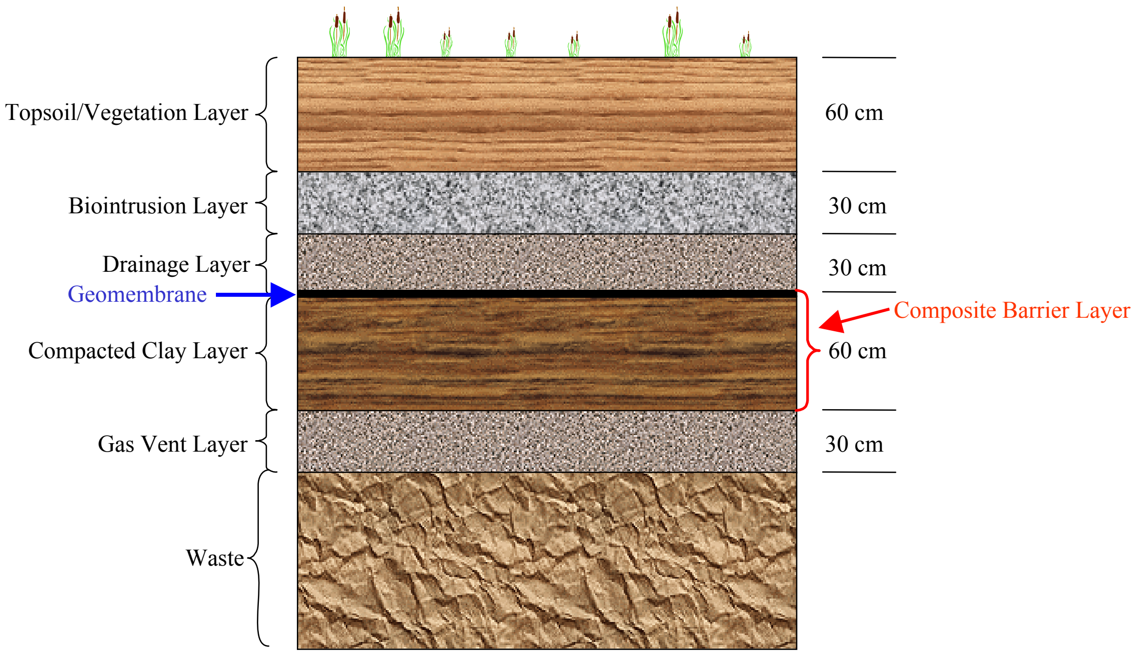


Figure 4.2-1. Typical prescriptive RCRA Subtitle C cover profile (modified from EPA 1991)

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.

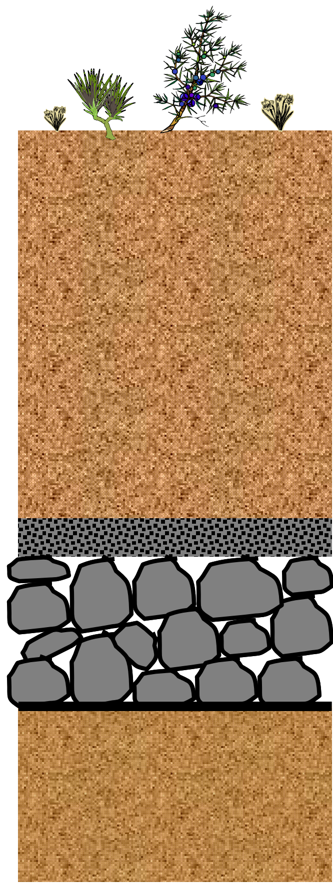


Figure 4.2-2. ET cover profile with a bio-barrier

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).

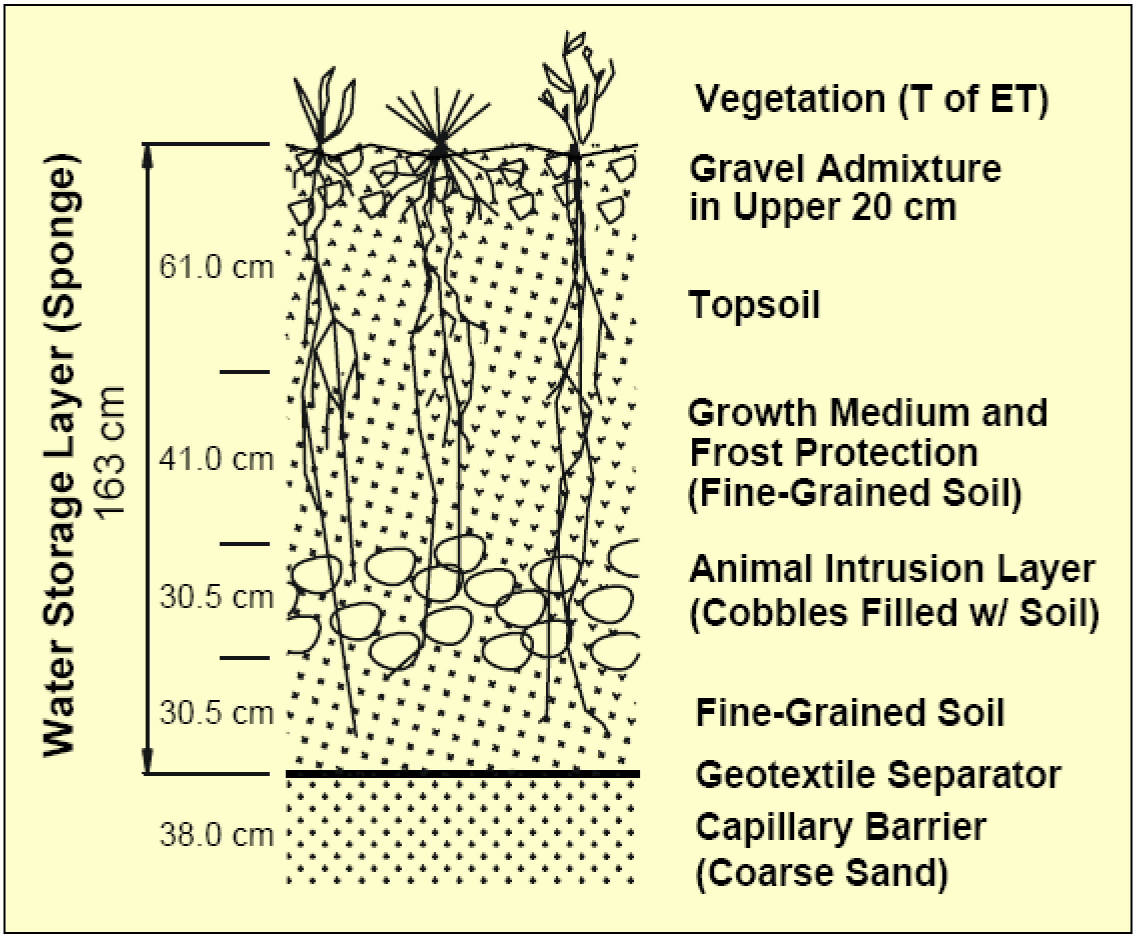


Figure 4.2-5. Monticello, Utah landfill cover profile

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).

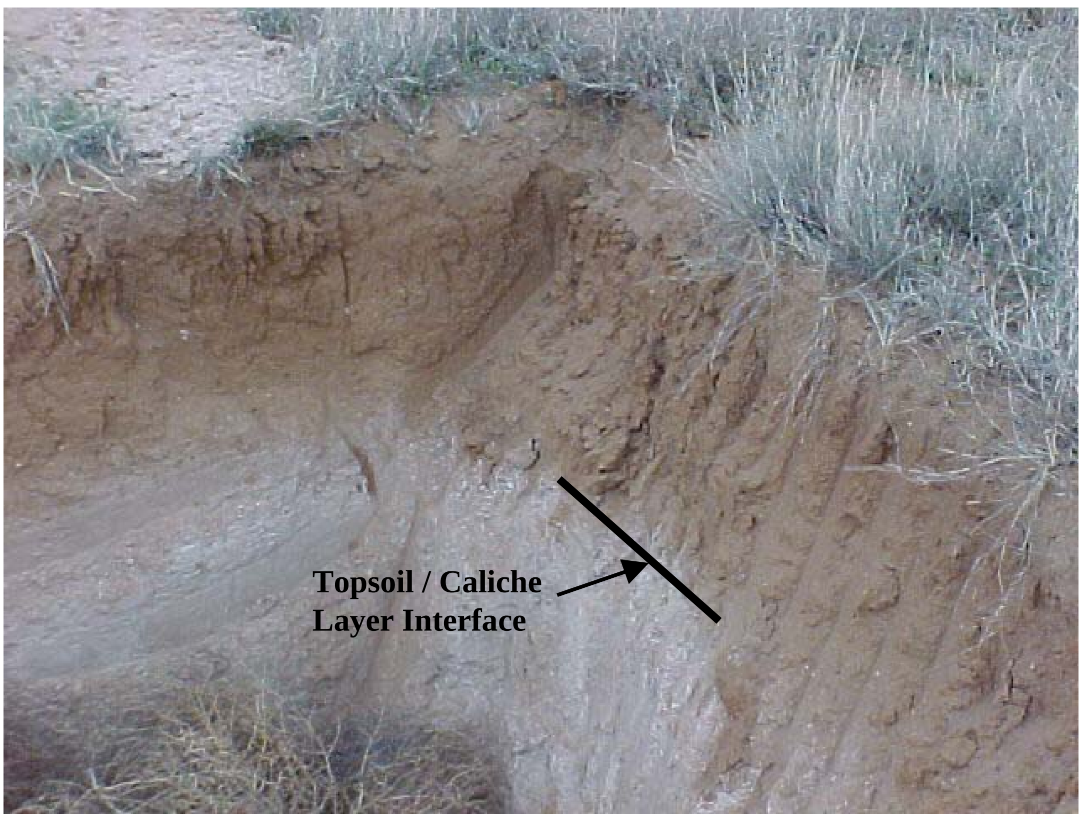


Figure 4.4-1. $CaCO_3$/soil interface at shallow depth

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.

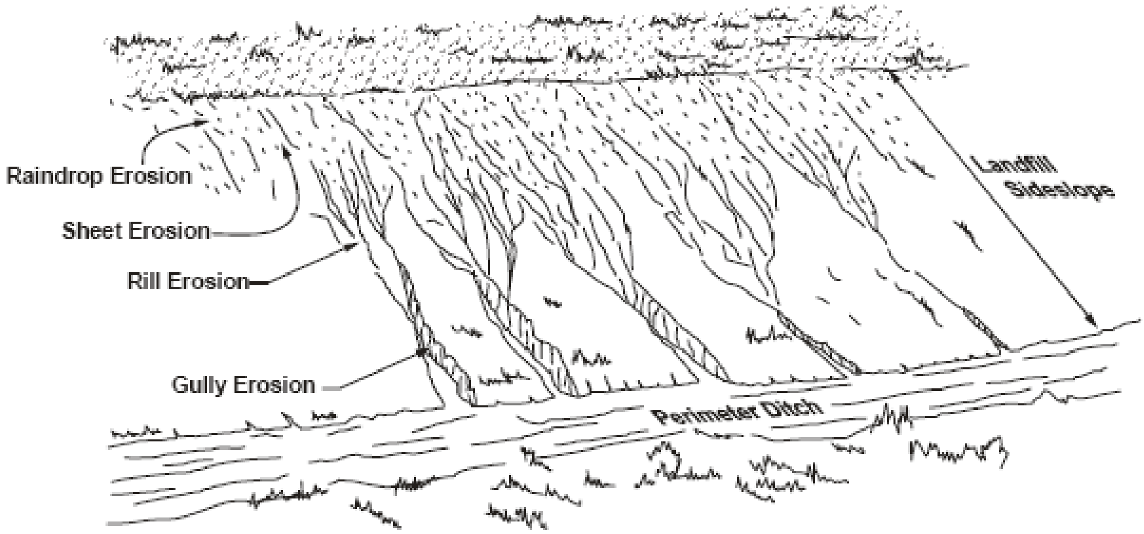


Figure 5.2-1. Types of water erosion that may occur on a cover system

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):

$$A_s = R_e\, K\, (LS)\, C\, P_c \qquad \textbf{Equation 5.1}$$

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:

$$\tau_a = \tau_{ab} C_e^2 \geq 0.9 \text{ kPa}$$ **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):

$$\tau_a \geq \tau_e = \gamma_w DS(1-C_F)(n_s/n)^2$$ **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.

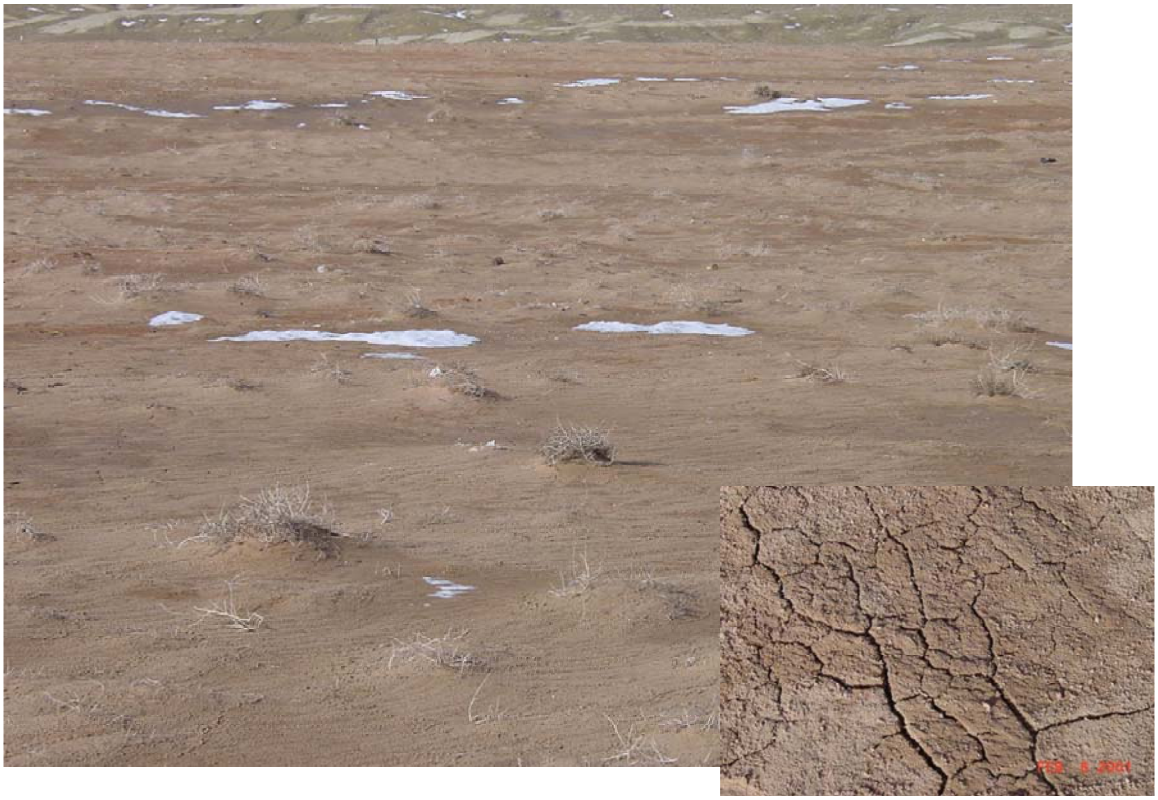


Figure 5.2-4. Landfill cover located on the Navajo Reservation that experienced significant wind erosion and desiccation cracking

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.

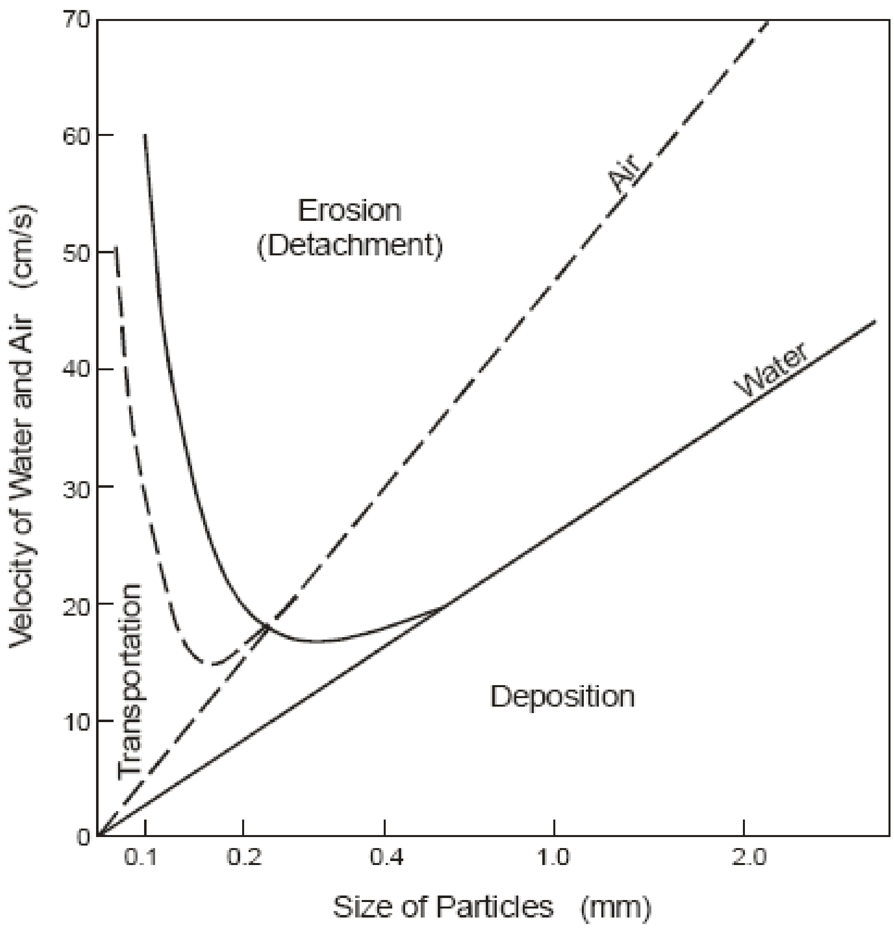


Figure 5.2-5. Relationship between erosion mechanism (air or water), particle size, and fluid velocity (Garrels 1951 as referenced by Mitchell 1993)

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).

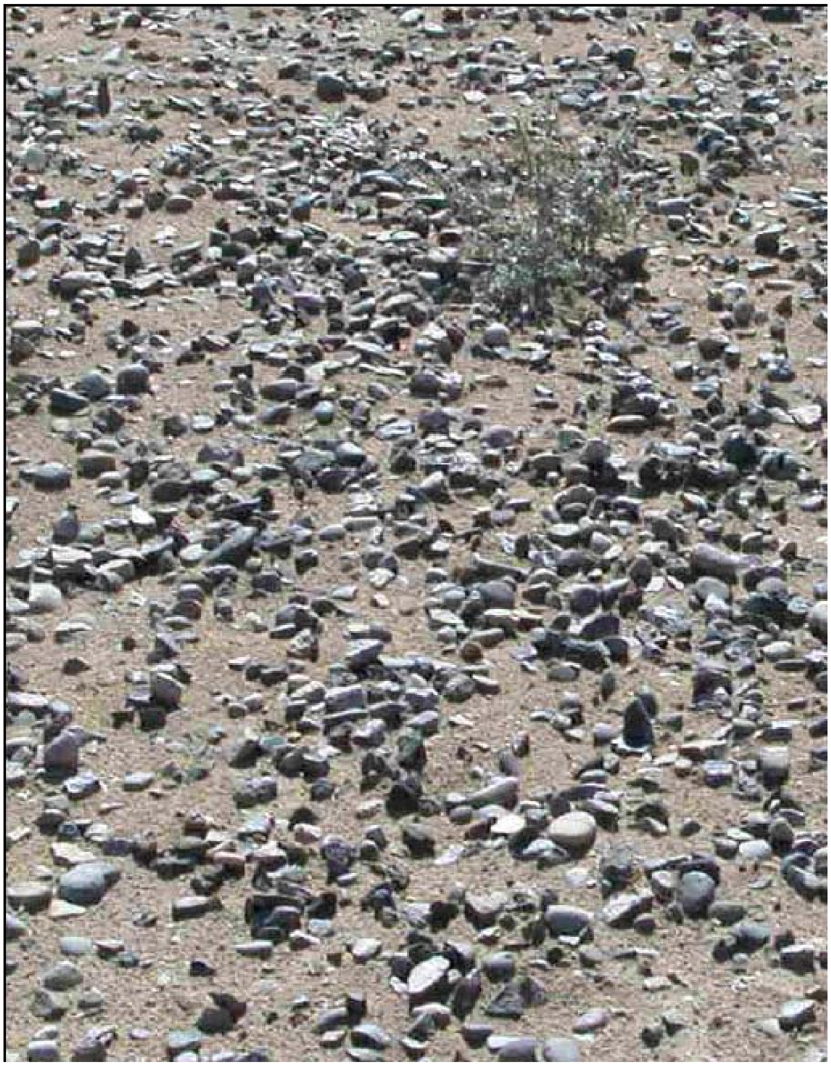


Figure 5.2-6. Gravel recently installed on Superfund closure in Farmington, NM

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:

$$Q = C\ I\ A \qquad \textbf{Equation 5.6}$$

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.

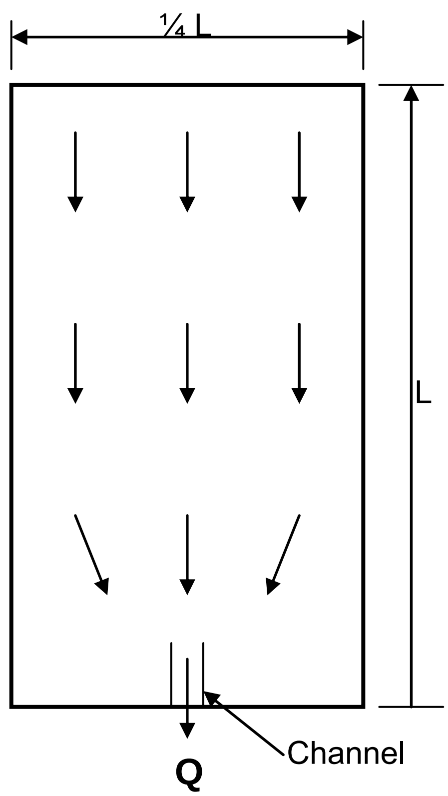


Figure 5.2-7. Contributory area for gully formation

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.

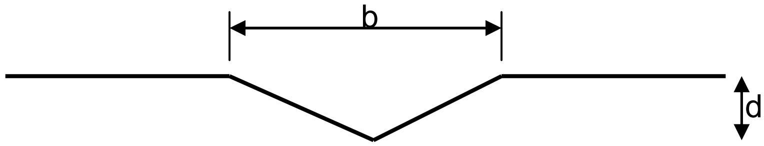


Figure 5.2-8. Channel geometry

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:

$$b = 37\ (Q_m^{0.38} / M^{0.39})$$ **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.

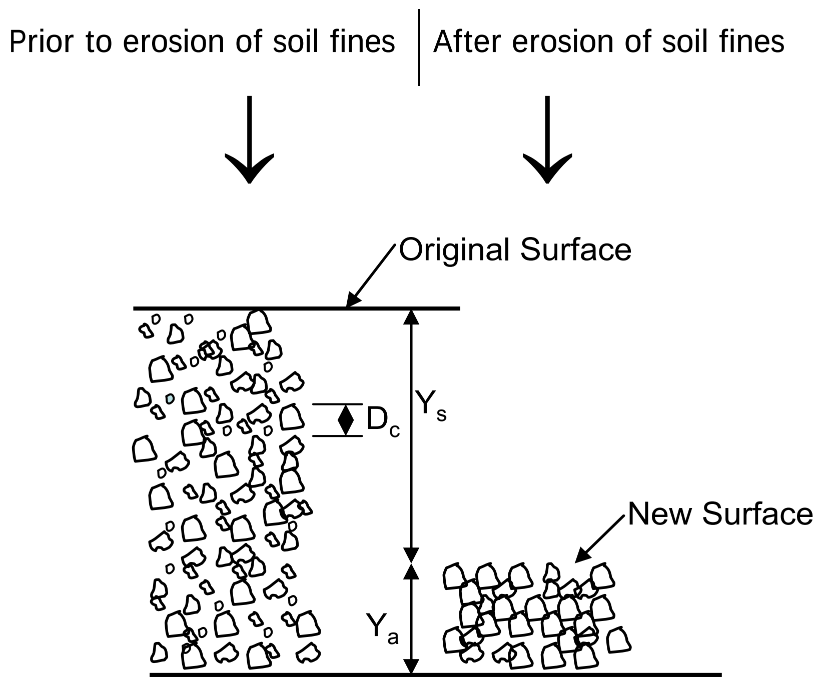


Figure 5.2-9. "Desert Pavement" development

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.

   <u>Rating</u>

   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.

   <u>Rating</u>

   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).

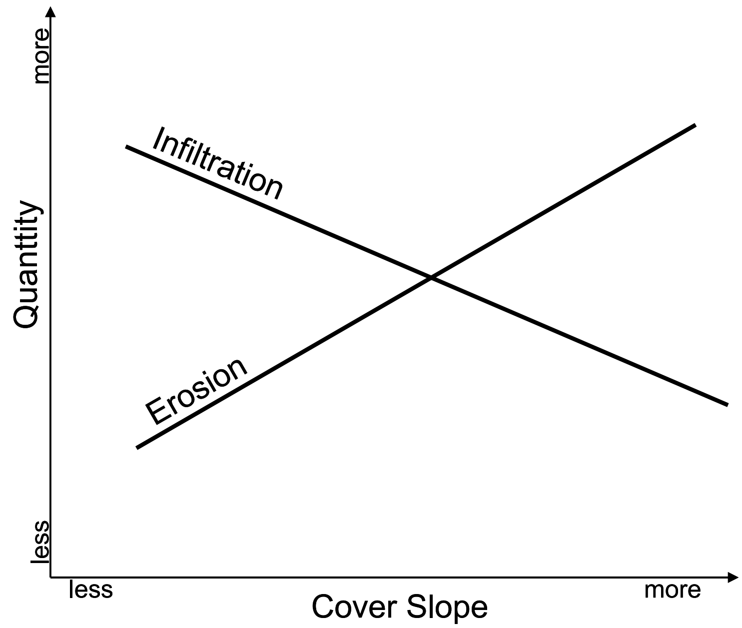


Figure 5.4-1. Infiltration/erosion vs. cover slope

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**

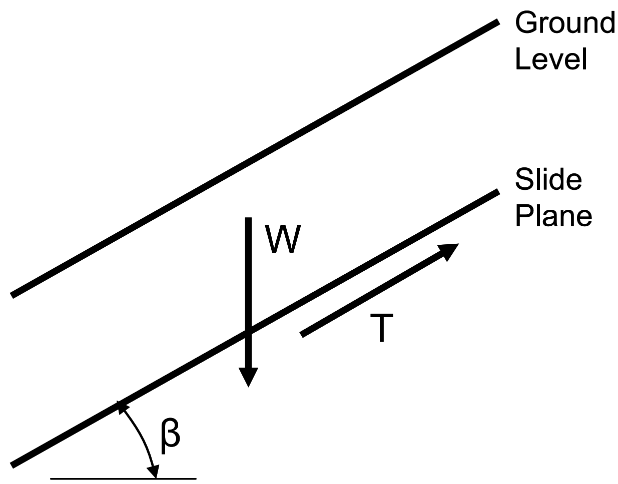


Figure 5.5-1. Translational slope stability

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.

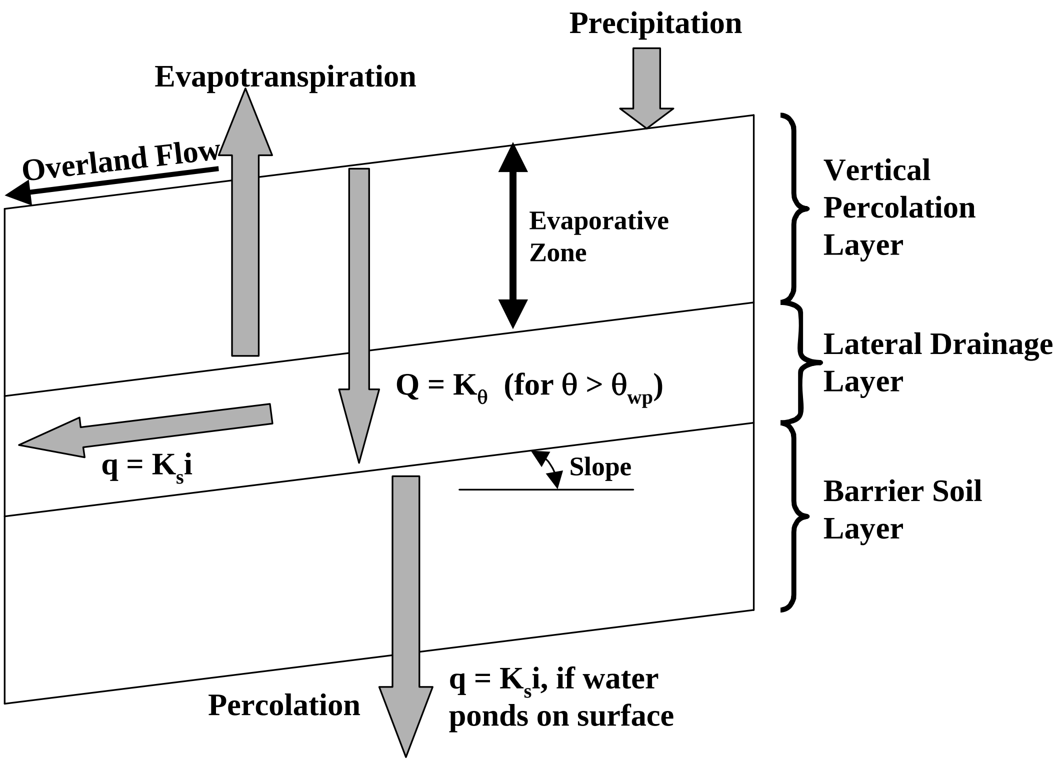
The two types of programs discussed in this section are the Hydrologic Evaluation of Landfill Performance (HELP) program (Schroeder et al. 1994) and Richards' Equation-based models such as UNSAT-H (Fayer and Jones 1990) and HYDRUS (Simunek et al. 1998). HELP is a software package that was developed with 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.



HELP Program

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.

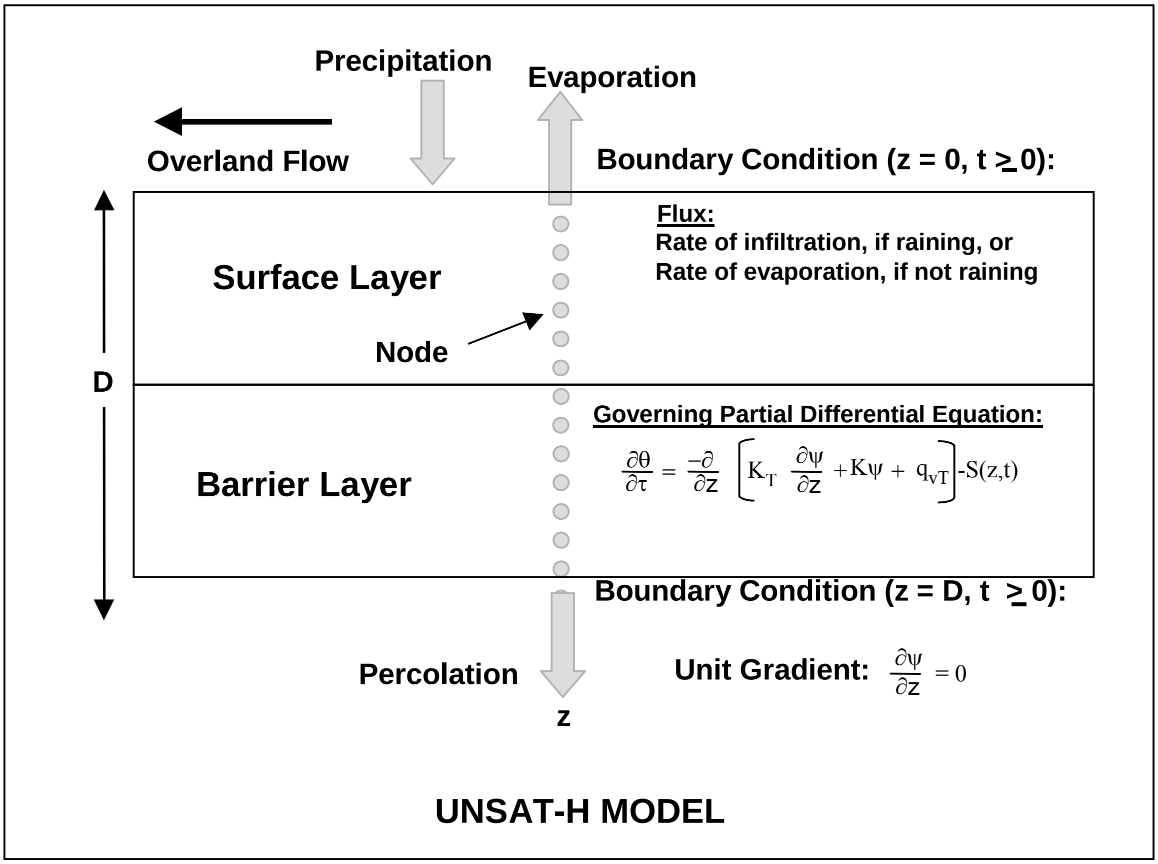


Figure 6.2-1. Schematic representation of water balance computation by UNSAT-H (modified from Khire 1995)

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:

$$T_p = PET\,[a + b\,(LAI)^c] \quad \text{where } d \le LAI \le e \qquad \textbf{Equation 6.1}$$

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:

$$RLD = a \exp(-b\,z) + c \qquad \textbf{Equation 6.2}$$

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.

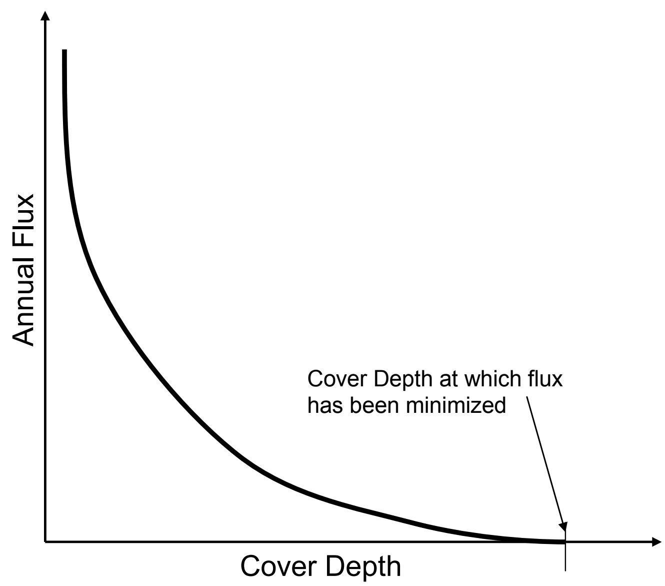


Figure 7.2-1. Annual flux vs. cover soil depth

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.

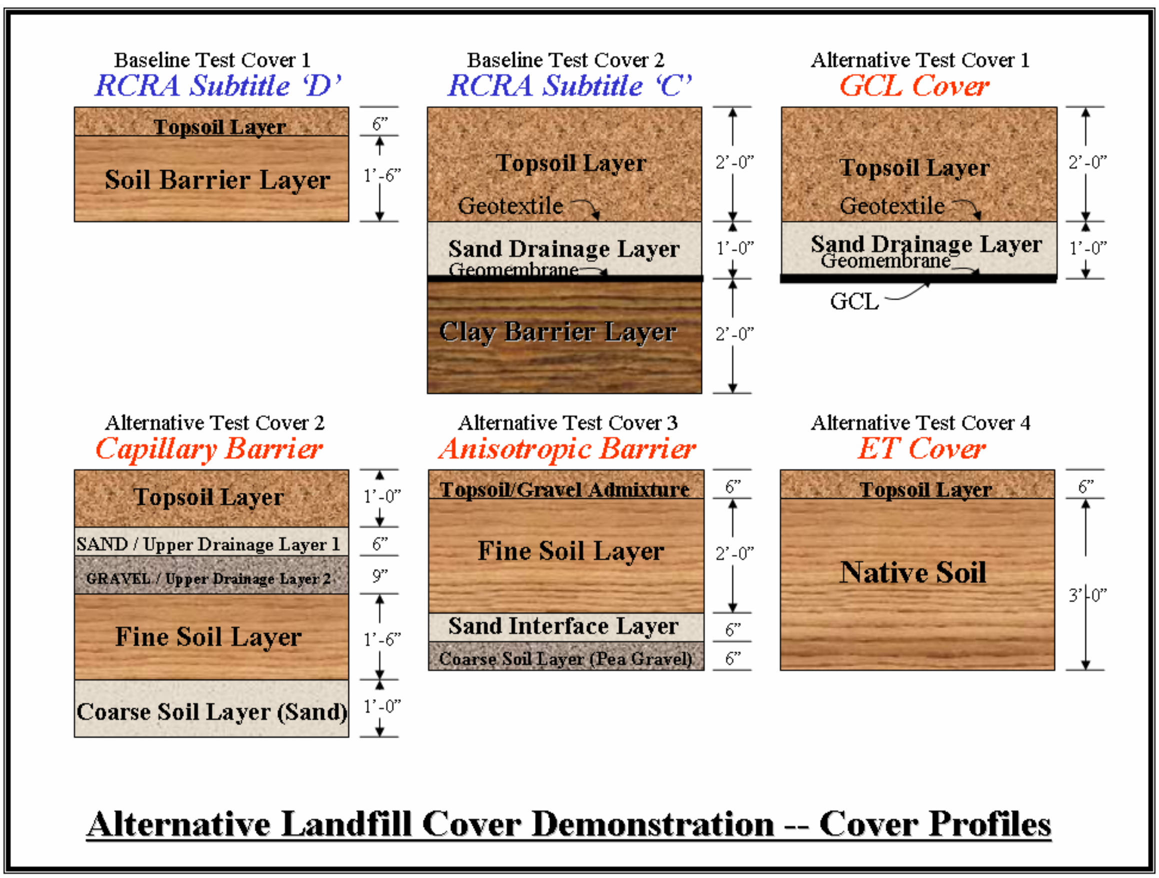
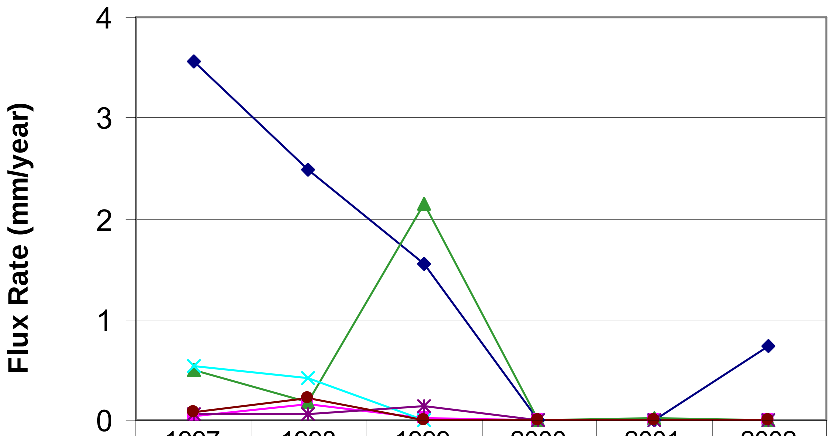


Figure 7.3-1. Profile of test covers (Dwyer 2003)

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.

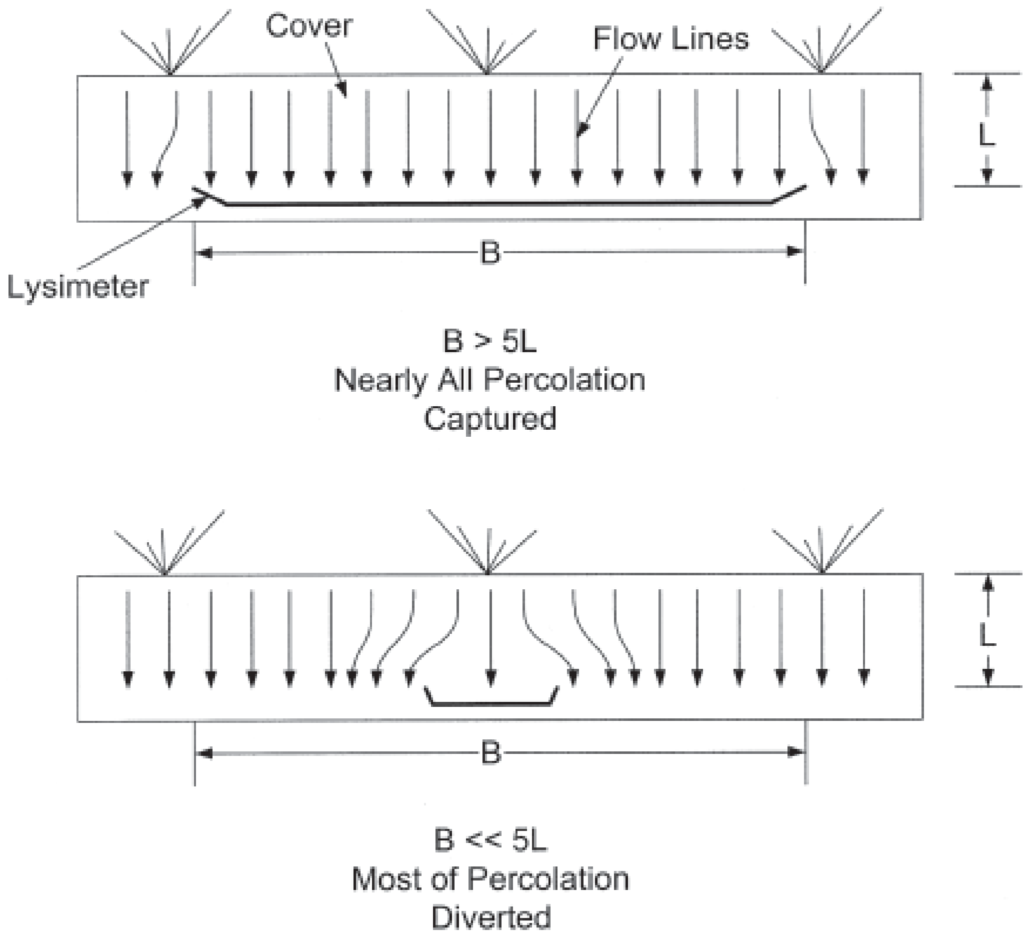


Figure 8.2-1. Effect of lysimeter width on diversion of percolation (modified from Benson et al. in press)

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

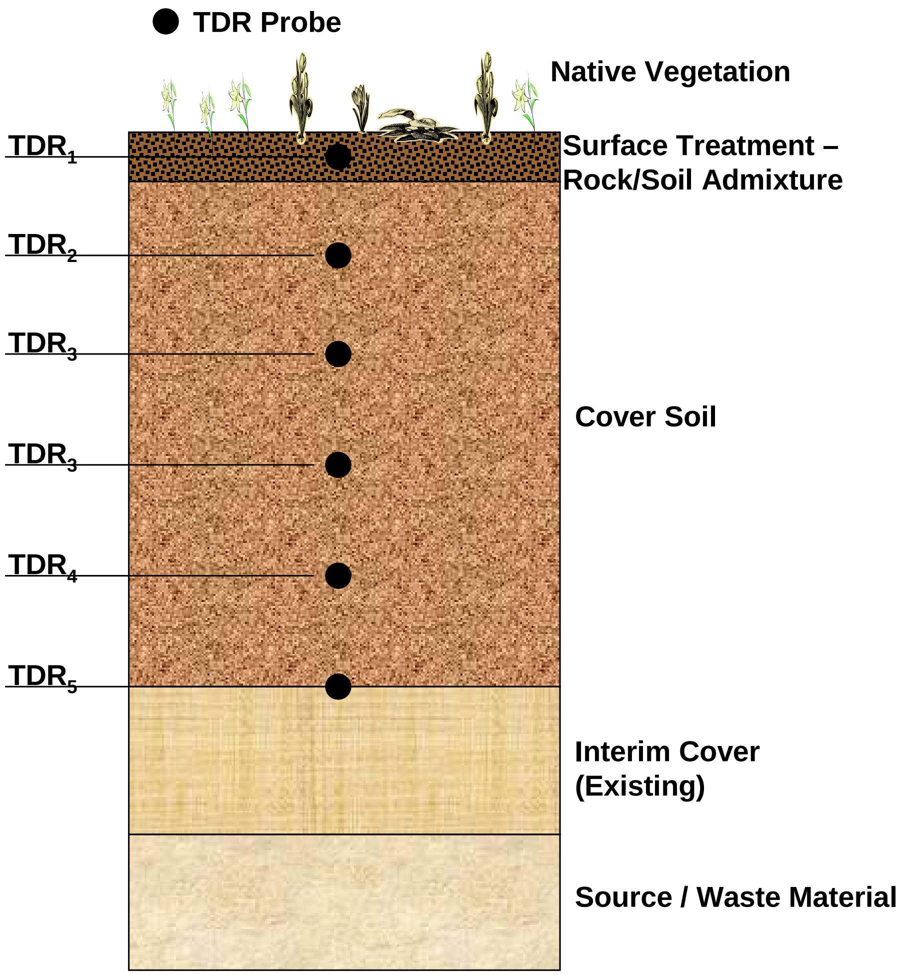


Figure 8.2-2. Example locations of TDR probes

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).

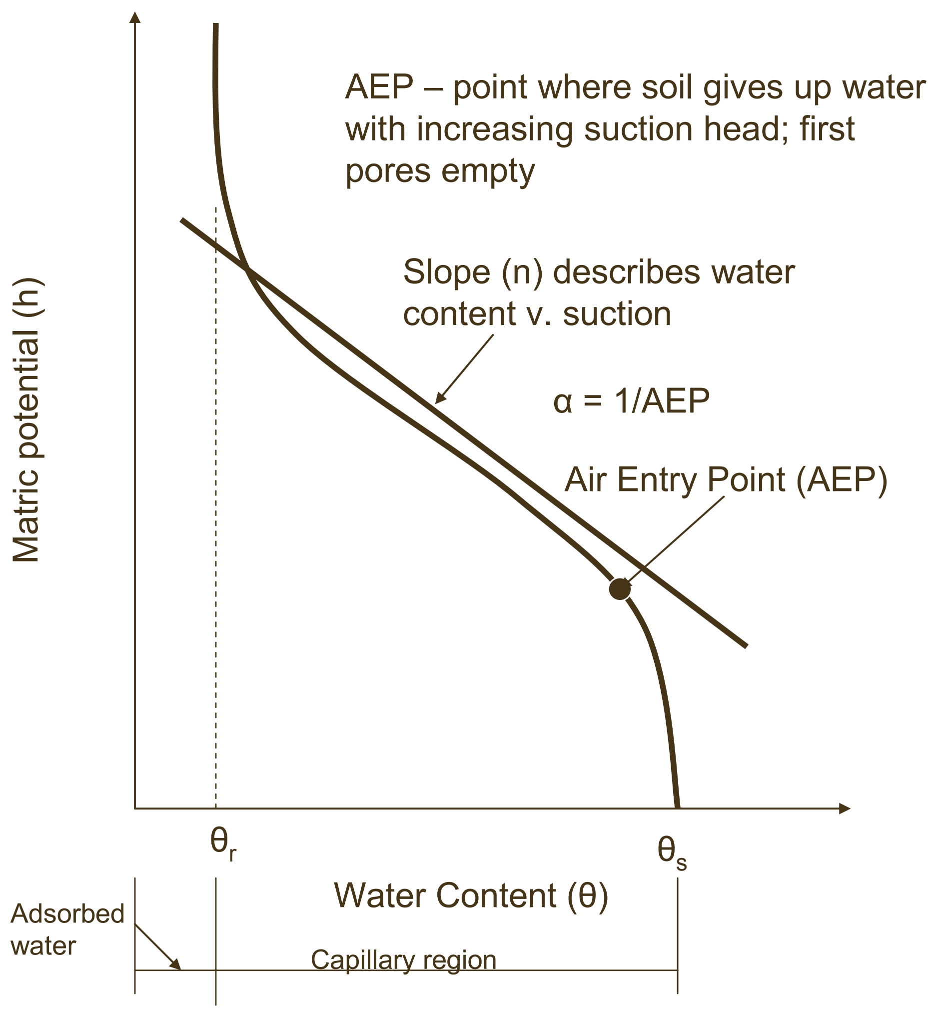


Figure 8.2-3. Moisture characteristic curve

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

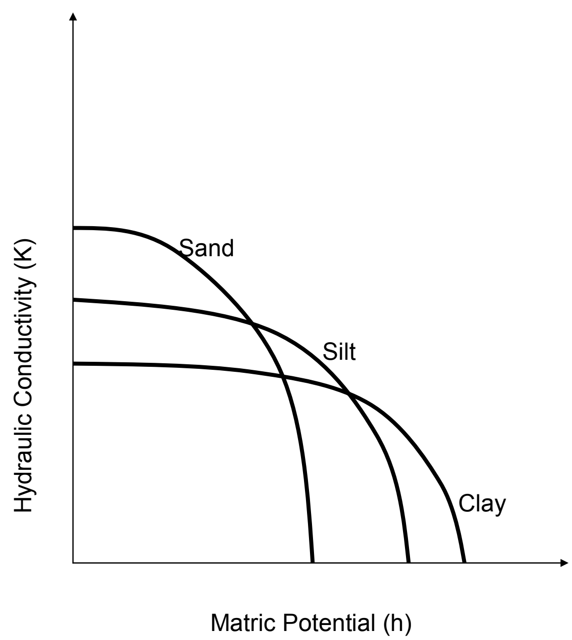


Figure 8.2-4. Hydraulic conductivity as a function of matric potential

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.

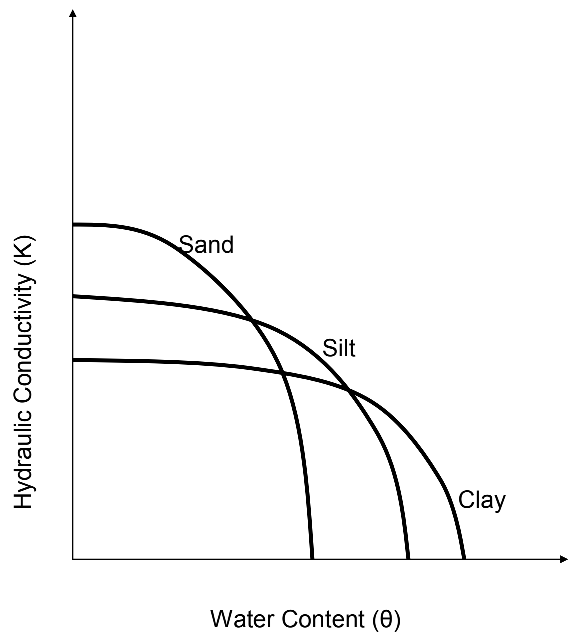


Figure 8.2-5. Hydraulic conductivity as a function of water content

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.

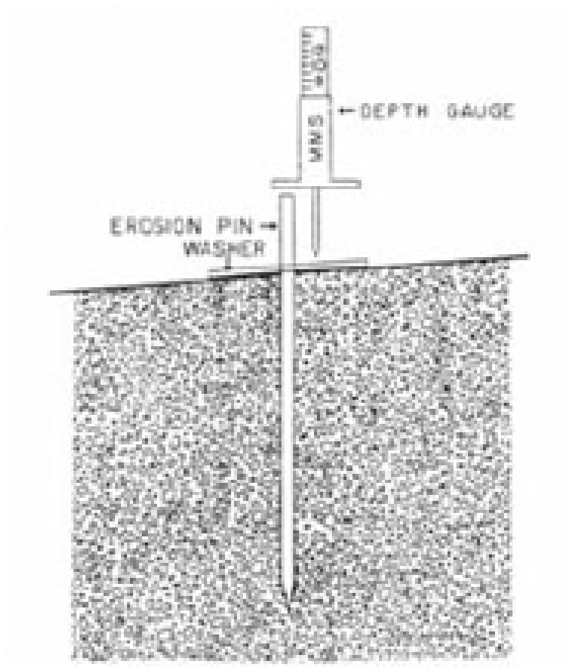


Figure 8.2-6. Typical erosion pin measurement system

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.

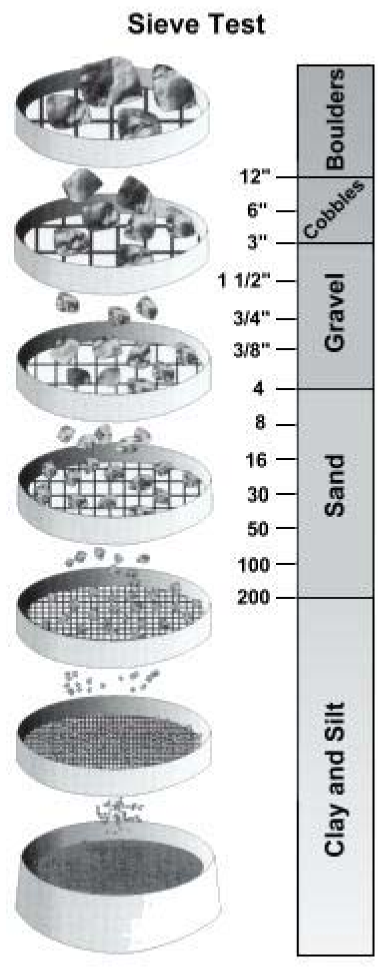


Figure 9.2-1. Soil particle size distribution

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.

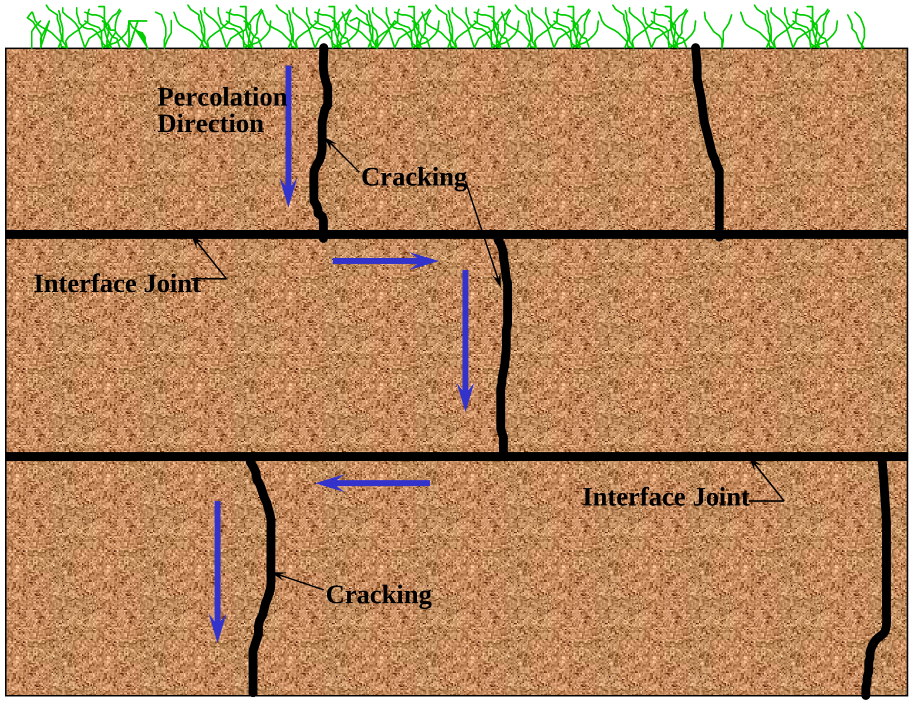


Figure 9.2-2. Preferential flow due to desiccation crack/interface joint

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 B-2

Evapotranspiration Landfill Cover Systems Fact Sheet

Evapotranspiration Landfill Cover Systems Fact Sheet

INTRODUCTION

Alternative final cover systems, such as evapotranspiration (ET) cover systems, are increasingly being considered for use at waste disposal sites, including municipal solid waste (MSW) and hazardous waste landfills when equivalent performance to conventional final cover systems can be demonstrated. Unlike conventional cover system designs that use materials with low hydraulic permeability (barrier layers) to minimize the downward migration of water from the cover to the waste (percolation), ET cover systems use water balance components to minimize percolation. These cover systems rely on the properties of soil to store water until it is either transpired through vegetation or evaporated from the soil surface. Compared to conventional cover systems, ET cover systems are expected to be less costly to construct. While ET cover systems are being proposed, tested, or have been installed at a number of waste disposal sites, field performance data and design guidance for these cover systems are limited (Benson and others 2002; Hauser, Weand, and Gill 2001).

This fact sheet provides a brief summary of ET cover systems, including general considerations in their design, performance, monitoring, cost, current status, limitations on their use, and project-specific examples. It is intended to provide basic information to site owners and operators, regulators, consulting engineers, and other interested parties about these potential design alternatives. An on-line database has been developed that provides more information about specific projects using ET covers, and is available at *http://cluin.org/products/altcovers*. Additional sources of information are also provided.

The information contained in this fact sheet was obtained from currently available technical literature and from discussions with site managers. It is not intended to serve as guidance for design or construction, nor indicate the appropriateness of using ET final cover systems at a particular site. The fact sheet does not address alternative materials (for example, geosynthetic clay liners) for use in final cover systems, or other alternative cover system designs, such as asphalt covers.

Online Database:
http://cluin.org/products/altcovers

BACKGROUND

Final cover systems are used at landfills and other types of waste disposal sites to control moisture and percolation, promote surface water runoff, minimize erosion, prevent direct exposure to the waste, control gas emissions and odors, prevent occurrence of disease vectors and other nuisances, and meet aesthetic and other end-use purposes. Final cover systems are intended to remain in place and maintain their functions for an extended period of time.

In addition, cover systems are also used in the remediation of hazardous waste sites. For example, cover systems may be applied to source areas contaminated at or near the ground surface or at abandoned dumps. In such cases, the cover system may be used alone or in conjunction with other technologies to contain the waste (for example, slurry walls and groundwater pump and treat systems).

The design of cover systems is site-specific and depends on the intended function of the final cover – components can range from a single-layer system to a complex multi-layer system. To

This fact sheet is intended solely to provide general information about evapotranspiration covers. It is not intended, nor can it be relied upon, to create any rights enforceable by any party in litigation with the United States. Use or mention of trade names does not constitute endorsement or recommendation for use.

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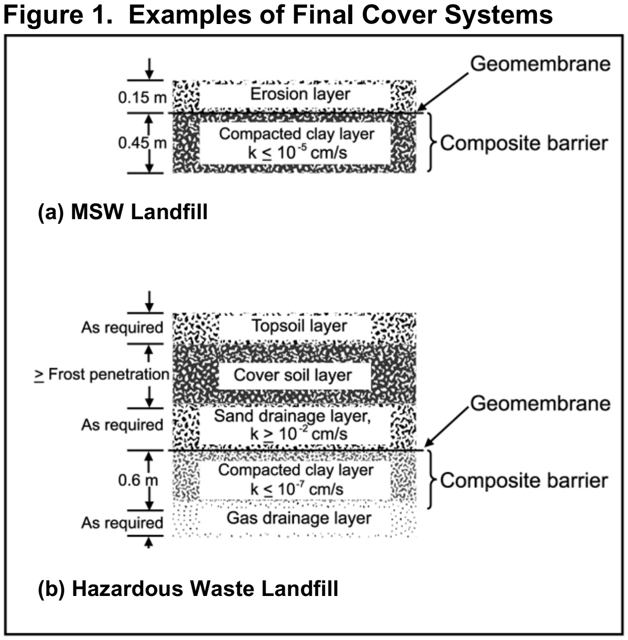
minimize percolation, conventional cover systems use low-permeability barrier layers. These barrier layers are often constructed of compacted clay, geomembranes, geosynthetic clay liners, or combinations of these materials.

Depending on the material type and construction method, the saturated hydraulic conductivities for these barrier layers are typically between $1x10^{-5}$ and $1x10^{-9}$ centimeters per second (cm/s). In addition, conventional cover systems generally include additional layers, such as surface layers to prevent erosion; protection layers to minimize freeze/thaw damage; internal drainage layers; and gas collection layers (Environmental Protection Agency [EPA] 1991; Hauser, Weand, and Gill 2001).

Regulations under the Resource Conservation and Recovery Act (RCRA) for the design and construction of final cover systems are based on using a barrier layer (conventional cover system). Under RCRA Subtitle D (40 CFR 258.60), the minimum design requirements for final cover systems at MSW landfills depend on the bottom liner system or the natural subsoils, if no liner system is present. The final cover system must have a permeability less than that of the bottom liner system (or natural subsoils) or less than $1x10^{-5}$ cm/s, whichever is less. This design requirement was established to minimize the "bathtub effect," which occurs when the landfill fills with liquid because the cover system is more permeable than the bottom liner system. This "bathtub effect" greatly increases the potential for generation of leachate. Figure 1 shows an example of a RCRA D cover at a MSW landfill with a 6-inch soil erosion layer, a geomembrane, and an 18-inch barrier layer of soil that is compacted to yield a hydraulic conductivity equal to or less than $1x10^{-5}$ cm/s (EPA 1992).

Figure 1. Examples of Final Cover Systems



For hazardous waste landfills, RCRA Subtitle C (40 CFR 264 and 265) provides certain performance criteria for final cover systems. While RCRA does not specify minimum design requirements, EPA has issued guidance for the minimum design of these final cover systems. Figure 1 shows an example of a RCRA C cover at a hazardous waste landfill (EPA 1989).

The design and construction requirements, as defined in the RCRA regulations, may also be applied under cleanup programs, such as Superfund or state cleanup programs, as part of a remedy for hazardous waste sites such as abandoned dumps. In these instances, the RCRA regulations for conventional covers usually are identified as applicable or relevant and appropriate requirements for the site.

Under RCRA, an alternative design, such as an ET cover, can be proposed in lieu of a RCRA design if it can be demonstrated that the alternative provides equivalent performance with respect to reduction in percolation and other criteria, such as erosion resistance and gas control.

DESCRIPTION

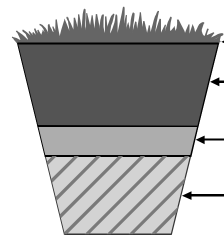
ET cover systems use one or more vegetated soil layers to retain water until it is either transpired through vegetation or evaporated from the soil surface. These cover systems rely on the water storage capacity of the soil layer, rather than low hydraulic conductivity materials, to minimize percolation. ET cover system designs are based on using the hydrological processes (water balance components) at a site, which include the water storage capacity of the soil, precipitation, surface runoff, evapotranspiration, and infiltration. The greater the storage capacity and evapotranspirative properties, the lower the potential for percolation through the cover system. ET cover system designs tend to emphasize the following (Dwyer 2003; Hakonson 1997; Hauser, Weand and Gill 2001):

- Fine-grained soils, such as silts and clayey silts, that have a relatively high water storage capacity
- Native vegetation to increase evapotranspiration
- Locally available soils to streamline construction and provide for cost savings

In addition to being called ET cover systems, these types of covers have also been referred to in the literature as water balance covers, alternative earthen final covers, vegetative landfill covers, soil-plant covers, and store-and-release covers.

Two general types of ET cover systems are monolithic barriers and capillary barriers. Monolithic covers, also referred to as monofill covers, use a single vegetated soil layer to retain water until it is either transpired through vegetation or evaporated from the soil surface. A conceptual design of a monolithic cover system is shown in Figure 2. Exhibit 1 provides an example of a full-scale monolithic cover at a MSW landfill.

Figure 2. Conceptual Design of a Monolithic ET Final Cover

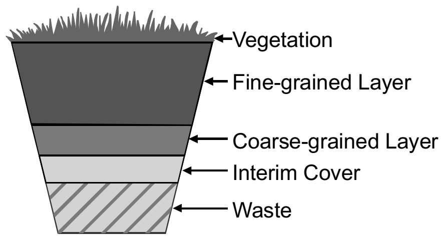


Capillary barrier cover systems consist of a finer-grained soil layer (like that of a monolithic cover system) overlying a coarser-grained material layer, usually sand or gravel, as shown conceptually in Figure 3. The differences in the unsaturated hydraulic properties between the two layers minimize percolation into the coarser-grained (lower) layer under unsaturated conditions. The finer-grained layer of a capillary barrier cover system has the same function as the monolithic soil layer; that is, it stores water until it is removed from the soil by evaporation or transpiration mechanisms. The coarser-grained layer forms a capillary break at the interface of the two layers, which allows the finer-grained layer to retain more water than a monolithic cover system of equal thickness. Capillary forces hold the water in the finer-grained layer until the soil near the interface approaches saturation. If saturation of the finer-grained layer occurs, the water will move relatively quickly into and through the coarser-grained layer and to the waste below. Exhibit 2 provides an example of a capillary barrier field demonstration at a MSW landfill (Dwyer 2003, Stormont 1997).

Exhibit 1. Monolithic ET Cover at Lopez Canyon Sanitary Landfill, Los Angeles, CA

Site type: Municipal solid waste landfill
Scale: Full-scale
Cover design: The ET cover was installed in 1999 and consists of a 3-foot silty sand/clayey sand layer, which overlies a 2-foot foundation layer. The cover soil was placed in 18-inch lifts and compacted to 95 percent with a permeability of less than $3x10^{-5}$ cm/s. Native vegetation was planted, including artemesia, salvia, lupines, sugar bush, poppy, and grasses.
Regulatory status: In 1998, Lopez Canyon Sanitary Landfill received conditional approval for an ET cover, which required a minimum of two years of field performance data to validate the model used for the design. An analysis was conducted and provided the basis for final regulatory approval of the ET cover. The cover was fully approved in October 2002 by the California Regional Water Quality Control Board - Los Angeles Region.
Performance data: Two moisture monitoring systems were installed, one at Disposal Area A and one at Disposal Area ABplus in May and November 1999, respectively. Each monitoring system has two stacks of time domain reflectometry probes that measure soil moisture at 24-inch intervals to a maximum depth of 78 inches, and a station for collecting weather data. Based on nearly 3 years of data, there is generally less than a 5 percent change in the relative volumetric moisture content at the bottom of the cover compared to nearly 90 percent change near the surface. This implies that most of the water infiltrating the cover is being removed via evapotranspiration and is not reaching the bottom of the cover.
Modeling: The numerical model UNSAT-H was used to predict the annual and cumulative percolation through the cover. The model was calibrated with 12 months of soil moisture content and weather data. Following calibration, UNSAT-H predicted a cumulative percolation of 50 cm for the ET cover and 95 cm for a conventional cover over a 10-year period. The model predicted an annual percolation of approximately 0 cm for both covers during the first year. During years 3 through 10 of the simulation, the model predicted less annual percolation for the ET cover than for the conventional cover.
Maintenance activities: During the first 18 months, irrigation was conducted to help establish the vegetation. Once or twice a year, brush is cleared to comply with Fire Department regulations. Prior to the rainy season, an inspection is conducted to check and clear debris basins and deck inlets. No mowing activities or fertilizer applications have been conducted or are planned.
Cost: Costs were estimated at $4.5 million, which includes soil importation, revegetation, quality control and assurance, construction management, and installation and operation of moisture monitoring systems.
Sources: City of Los Angeles 2003, Hadj-Hamou and Kavazanjian 2003.
More information available at http://cluin.org/products/altcovers

Figure 3. Conceptual Design of a Capillary Barrier ET Final Cover



In addition to being potentially less costly to construct, ET covers have the potential to provide equal or superior performance compared to conventional cover systems, especially in arid and semi-arid environments. In these environments, they may be less prone to deterioration from dessication, cracking, and freezing/thawing cycles. ET covers also may be able to minimize side slope instability, because they do not contain geomembrane layers, which can cause slippage (Weand and others 1999; Benson and others 2002; Dwyer, Stormont, and Anderson 1999).

Capillary barrier ET cover systems may also eliminate the need for a separate biointrusion and/or gas collection layer. The coarser-grained layer can act as a biointrusion layer to resist root penetration and animal intrusion, due to its particle size and low water content. The coarser-grained layer also can act as a gas collection layer, because the soil properties and location within the cover system are comparable to a typical gas collection layer in a conventional cover system (Dwyer 2003, Stormont 1997).

LIMITATIONS

ET cover systems are generally considered potentially applicable only in areas that have arid or semi-arid climates; their application is generally considered limited to the western United States. In addition, site-specific conditions, such as site location and landfill characteristics, may limit the use or effectiveness of ET cover systems. Local climatic conditions, such as amount, distribution, and form of precipitation, including amount of snow pack, can limit the effectiveness of an ET cover at a given site. For example, if a large amount of snow melted when vegetation was dormant, the cover may not have sufficient water storage capacity, and percolation might occur (EPA 2000a; Hauser, Weand, and Gill 2001).

Further, landfill characteristics, such as production of landfill gases, may limit the use of ET covers. The cover system may not adequately control gas emissions since typical ET cover designs do not have impermeable layers to restrict gas movement. If gas collection is required at the site, it may be necessary to modify the design of the cover to capture and vent the gas generated in the landfill. In addition, landfill gas may limit the effectiveness of an ET cover, because the gases may be toxic to the vegetation (Weand and others 1999; EPA 2000a).

Limited data are available to describe the performance of ET cover systems in terms of minimizing percolation, as well as the covers' ability to minimize erosion, resist biointrusion, and remain effective for an extended period of time. While the principles of ET covers and

Exhibit 2. Capillary Barrier ET Cover at Lake County Landfill, Polson, Montana

Site type: Municipal solid waste landfill
Scale: Field demonstration under Alternative Cover Assessment Program (ACAP)
Cover designs: The capillary barrier test section was installed in November 1999. From the surface downward, it is composed of 6 inches of topsoil, 18 inches of moderately compacted silt, and 24 inches of sandy gravel. The cover was seeded in March 2000 with a mixture of grasses, forbs, and shrubs, including bluegrass, wheatgrass, alfalfa, and prickly rose shrubs. A conventional composite cover test section was also constructed at the site.
Performance data: Percolation is being measured with a lysimeter connected to flow monitoring systems, soil moisture is being measured with water content reflectometers, and soil matric potential and soil temperature are being monitored with heat dissipation units. From November 1999 through July 2002, the capillary barrier cover system had a cumulative percolation of 0.5 mm. Total precipitation was 837 mm over the 32-month period. Additional field data are expected to be collected through 2005.
Modeling: Numerical modeling was conducted using HYDRUS 2-D, which simulated the wettest year on record over the simulation period of 10 years. The model predicted approximately 0.6 mm of percolation during the first year, and 0.1 mm per year for the remaining 9 years.
Sources: Bolen and others 2001, Benson and others 2002.
More information available at http://cluin.org/products/altcovers

their corresponding soil properties have been understood for many years, their application as final cover systems for landfills has emerged only within the past 10 years. Limited performance data are available on which to base applicability or equivalency decisions (Dwyer 2003; Dwyer, Stormont, and Anderson 1999; Hauser and Weand 1998).

Numerical models are used to predict the performance and assist in the design of final cover systems. The availability of models used to conduct water balance analyses of ET cover systems is currently limited, and the results can be inconsistent. For example, models such as Hydrologic Evaluation of Landfill Performance (HELP) and Unsaturated Water and Heat Flow (UNSAT-H) do not address all of the factors related to ET cover system performance. These models, for instance, do not consider percolation through preferential pathways; may underestimate or overestimate percolation; and have different levels of detail regarding weather, soil, and vegetation. In addition, HELP does not account for physical processes, such as matric potential, that generally govern unsaturated flow in ET covers. Further information about numerical models is provided under the Performance and Monitoring section of this fact sheet (Dwyer 2003; Weand and others 1999; Khire, Benson, and Bosscher 1997).

GENERAL CONSIDERATIONS

The design of ET cover systems is based on providing sufficient water storage capacity and evapotranspiration to control moisture and water percolation into the underlying waste. The following considerations generally are involved in the design of ET covers.

Climate – The total amount of precipitation over a year, as well as its form and distribution, determines the total amount of water storage capacity needed for the cover system. The cover may need to accommodate a spring snowmelt event that causes the amount of water at the cover to be relatively high for a short period of time or conditions during cool winter weather with persistent, light precipitation. Storage capacity is particularly important if the event occurs when local vegetation is dormant, yielding less evapotranspiration. Other factors related to climate that are important to cover design are temperature, atmospheric pressure, and relative humidity (Benson 2001; EPA 2000a; Hauser, Weand, and Gill 2001).

Soil type – Finer-grained materials, such as silts and clayey silts, are typically used for monolithic ET cover systems and the top layer of a capillary barrier ET cover system because they contain finer particles and provide a greater storage capacity than sandy soils. Sandy soils are typically used for the bottom layer of the capillary barrier cover system to provide a contrast in unsaturated hydraulic properties between the two layers. Many ET covers are constructed of soils that include clay loam, silty loam, silty sand, clays, and sandy loam.

The storage capacity of the soil varies among different types of soil, and depends on the quantity of fine particles and the bulk density of the soil. Compaction impacts bulk density, which in turn affects the storage capacity of the soil and the growth of roots. One key aspect of construction is minimizing the amount of compaction during placement. Higher bulk densities may reduce the storage capacity of the soil and inhibit growth of roots (Chadwick and others 1999; Hauser, Weand, and Gill 2001).

Soil thickness – The thickness of the soil layer(s) depends on the required storage capacity, which is determined by the water balance at the site. The soil layers need to accommodate extreme water conditions, such as snowmelts and summer thunderstorms, or periods of time during which ET rates are low and plants are dormant. Monolithic ET covers have been constructed with soil layers ranging from 2 feet to 10 feet. Capillary barrier ET covers have been constructed with finer-grained layers ranging from 1.5 feet to 5 feet, and coarser-grained layers ranging from 0.5 foot to 2 feet.

Vegetation types – Vegetation for the cover system is used to promote transpiration and minimize erosion by stabilizing the surface of the cover. Grasses (wheatgrass and clover), shrubs (rabbitbrush and sagebrush), and trees (willow and hybrid poplar) have been used on ET covers. A mixture of native plants consisting of warm- and cool-season species usually is planted, because native vegetation is more tolerant than imported vegetation to regional conditions, such as extreme weather and disease. The combination of warm- and cool-season species provides water uptake throughout the entire growing season, which enhances transpiration. In addition, native vegetation is usually planted, because these species are less likely to disturb the natural ecosystem (Dwyer, Stormont, and Anderson 1999; EPA 2000a).

Soil and organic properties – Nutrient and salinity levels 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, England, and Andraski 2001).

Control layer types – Control layers, such as those used to minimize animal intrusion, promote drainage, and control and collect landfill gas, are often included for conventional cover systems and may also be incorporated in ET cover system designs. For example, a proposed monolithic ET cover at Sandia National Laboratories in New Mexico will have a biointrusion fence with 1/4-inch squares between the topsoil layer and the native soil layer to prevent animals from creating preferential pathways, potentially resulting in percolation. The biointrusion layer, however, will not inhibit root growth to allow for transpiration. At another site, Monticello Uranium Mill Tailings Site in Utah, a capillary barrier ET design has a 12-inch soil/rock admixture as an animal intrusion layer located 44 inches below the surface, directly above the capillary barrier layer.

In addition, a capillary barrier cover demonstration at Sandia National Laboratories has a drainage layer located above the capillary break. A drainage layer consisting of an upper layer of sand and a lower layer of gravel is located directly below the topsoil layer. The sand serves as a filter to prevent topsoil from clogging the drainage layer, while the gravel allows for lateral drainage of water that has infiltrated through the topsoil (Bolen and others 2001, Dwyer 2003).

In more recent applications, several types of ET cover designs also have incorporated synthetic materials, such as geomembranes, which are used to enhance the function of minimizing water into the waste. For example, the Operating Industries Inc. Landfill in California has incorporated a soil layer with a geosynthetic clay liner in the design. The cover system for this site will reduce surface gas emissions, prevent oxygen intrusion and percolation, and provide for erosion control (EPA 2000b).

PERFORMANCE AND MONITORING

Protection of groundwater quality is a primary performance goal for all waste containment systems, including final cover systems. The potential adverse impact to groundwater quality results from the release of leachate generated in landfills or other waste disposal units such as surface impoundments. The rate of leachate generation (and potential impact on groundwater) can be minimized by keeping liquids out of a landfill or contaminated source area of a remediation site. As a result, the function of minimizing percolation becomes a key performance criterion for a final cover system (EPA 1991).

Monitoring the performance of ET cover systems has generally focused on evaluating the ability of these designs to minimize water drainage into the waste. Percolation performance typically is reported as a flux rate (inches or millimeters of water that have migrated downward through the base of the cover in a period of time, generally considered as 1 year). Percolation monitoring for ET cover systems is measured directly using monitoring systems such as lysimeters or estimated indirectly using soil moisture measurements and calculating a flux rate. A more detailed summary on the advantages and disadvantages of both approaches can be found in Benson and others 2001 (EPA 1991, Benson and others 2001).

Percolation monitoring can also be evaluated indirectly by using leachate collection and removal systems. For landfills underlain with these systems, the amount and composition of leachate generated can be used as an indicator of the performance of a cover system (the higher the percolation, the more leachate that will be generated) (EPA 1991).

Although the ability to minimize percolation is a performance criterion for final cover systems, limited data are available about percolation performance for final cover systems for both conventional and alternative designs. Most of the recent data on flux rates have been generated by two federal research programs, the Alternative Landfill Cover Demonstration (ALCD) and the Alternative Cover Assessment Program (ACAP); see Exhibits 3 and 4, respectively, for further information on these programs. From these programs, flux rate performance data are available for 14 sites with demonstration-scale ET cover systems (Dwyer 2003, Benson and others 2002).

In addition, previous studies have been conducted that monitored the performance of ET covers. Selected studies include the following: integrated test plot experiment in Los Alamos, NM, which monitored both types of ET covers from 1984 to 1987 (Nyhan, Hakonson, and Drennon 1990); Hill Air Force Base alternative cover study in Utah, which evaluated three different covers (RCRA Subtitle D, monolithic ET, and capillary barrier ET) over a 4-year period (Hakonson and others 1994); and Hanford field lysimeter test facility in Richland, WA, which monitored ET covers for 6 years (Gee and others 1993).

Additional demonstration projects of ET covers conducted in the 1980's and early 1990's are discussed in the ACAP Phase I Report, which is available at *http://www.acap.dri.edu*.

Exhibit 3. Alternative Landfill Cover Demonstration (ALCD)

The U.S. Department of Energy (DOE) has sponsored the ALCD, which is a large-scale field test of two conventional designs (RCRA Subtitle C and Subtitle D) and four alternative landfill covers (monolithic ET cover, capillary barrier ET cover, geosynthetic clay liner cover, and anisotropic [layered capillary barrier] ET cover). The test was conducted at Sandia National Laboratories, located on Kirtland Air Force Base in Albuquerque, New Mexico, with cover design information available at *http://www.sandia.gov/Subsurface/factshts/ert/alcd.pdf*. The ALCD has collected information on construction, cost, and performance that is needed to compare alternative cover designs with conventional covers. The RCRA covers were constructed in 1995, and the ET covers were constructed in 1996. All of the covers are 43 feet wide by 328 feet long and were seeded with native vegetation. The purpose of the project is to use the performance data to help demonstrate equivalency and refine numerical models to more accurately predict cover system performance (Dwyer 2003).

The ALCD has collected data on percolation using a lysimeter and soil moisture to monitor cover performance. Total precipitation (precip.) and percolation (perc.) volumes based on 5 years of data are provided below. The ET covers generally have less percolation than the Subtitle D cover for each year shown below. More information on the ALCD cover performance can be found in Dwyer 2003.

	1997 (May 1 - Dec 31)		1998		1999		2000		2001		2002 (Jan 1 - Jun 25)	
	Precip. (mm)	Perc. (mm)	Precip. (mm)	Perc. (mm)	Precip. (mm)	Perc. (mm)	Precip. (mm)	Perc. (mm)	Precip. (mm)	Perc. (mm)	Precip. (mm)	Perc. (mm)
Monolithic ET	267.00	0.08	291.98	0.22	225.23	0.01	299.92	0.00	254.01	0.00	144.32	0.00
Capillary barrier ET	267.00	0.54	291.98	0.41	225.23	0.00	299.92	0.00	254.01	0.00	144.32	0.00
Anisotropic (layered capillary barrier) ET	267.00	0.05	291.98	0.07	225.23	0.14	299.92	0.00	254.01	0.00	144.32	0.00
Geosynthetic clay liner	267.00	0.51	291.98	0.19	225.23	2.15	299.92	0.00	254.01	0.02	144.32	0.00
Subtitle C	267.00	0.04	291.98	0.15	225.23	0.02	299.92	0.00	254.01	0.00	144.32	0.00
Subtitle D	267.00	3.56	291.98	2.48	225.23	1.56	299.92	0.00	254.01	0.00	144.32	0.74

Monitoring systems – Lysimeters are installed underneath a cover system, typically as geomembrane liners backfilled with a drainage layer and shaped to collect water percolation. Water collected in the lysimeter is directed toward a monitoring point and measured using a variety of devices (for example, tipping bucket, pressure tranducers). Lysimeters have been used in the ALCD and ACAP programs for collecting performance data for ET cover systems.

Soil moisture monitoring can be used to determine moisture content at discrete locations in cover systems and to evaluate changes over time in horizontal or vertical gradients. Soil moisture is measured using methods to determine relative humidity, soil matrix potential, and resistance. Table 1 presents examples of non-destructive techniques that have been used to assess soil moisture content of ET cover systems. A high soil moisture value indicates that the water content of the cover system is approaching its storage capacity, thereby increasing the potential for percolation. Soil moisture is especially important for capillary barrier ET cover systems; when the finer-grained layer becomes saturated, the capillary barrier can fail resulting in water percolating through the highly permeable layer to the waste below (Hakonson 1997).

Maintaining the effectiveness of the cover system for an extended period of time is another important performance criterion for ET covers as well as conventional covers. Short-term and long-term performance monitoring of a final cover system includes settlement effects, gas emissions, erosion or slope failure, and other factors.

Numerical models – While there are limitations to numerical models, as previously described, they have been used to predict cover performance and assist in the design of ET cover systems. Numerical models have been used to compare the expected performance of ET cover systems to conventional cover systems. By entering multiple parameters and evaluating the design of cover systems, designs can be modified until

Exhibit 4. Alternative Cover Assessment Program (ACAP)

EPA is conducting the ACAP to evaluate the performance of alternative landfill covers. ACAP began in 1998, and cover performance is currently being evaluated at 13 sites. The sites are located in eight states from California to Ohio, and include a variety of landfill types, such as MSW, construction and demolition waste, and hazardous waste landfills. At eight sites, conventional and ET covers are being tested side by side. At the remaining five sites, only ET covers are being tested.

The alternative covers typically were constructed with local soils and native vegetation. At two facilities, however, hybrid poplar trees were used as vegetation. At 11 sites, percolation performance is being evaluated by lysimeters. At the other two sites, performance is being evaluated indirectly by monitoring leachate production. Soil moisture is also being evaluated at all 13 sites. Below is an example of the field data for precipitation (precip.) and percolation (perc.) volumes at 3 of the sites. A summary of field cover performance for all 13 sites through July 2002 is provided in Albright and Benson 2002. More information about ACAP is available on the Desert Research Institute website at *http://www.acap.dri.edu/*.

Site	Cover Design	Start Date	Year 1		Year 2		Year 3	
			Precip. (mm)	Perc. (mm)	Precip. (mm)	Perc. (mm)	Precip. (mm)	Perc. (mm)
Altamont, CA (semi-arid)	Monolithic ET	11/00	225	negligible	300	1.5		
	Composite/ compacted clay	11/00	225	negligible	300	negligible		
Polson, MT (semi-arid)	Capillary barrier ET	11/99	300	0.05	300	0.05	250	0.45
	Composite/ compacted clay	11/99	300	0.5	300	0.5	250	0.5
Omaha, NE (humid)	Capillary barrier ET (thick)	10/00	600	55	200	negligible		
	Capillary barrier ET (thin)	10/00	600	100	200	negligible		
	Composite/ compacted clay	10/00	600	5	200	negligible		

Table 1. Examples of Non-Destructive Soil Moisture Monitoring Methods

Method	Description	Instrumentation
Tensiometer	Measures the matric potential of a given soil, which is converted to soil moisture content	Commonly consists of a porous ceramic cup connected to a pressure measuring device through a rigid plastic tube
Psychrometer	Measures relative humidity (soil moisture) within a soil	Generally consists of a thermocouple, a reference electrode, a heat sink, a porous ceramic bulb or wire mesh screen, and a recorder
Electrical resistance blocks	Measures resistance resulting from a gradient between the sensor and the soil; higher resistance indicates lower soil moisture	Consists of electrodes embedded in a gypsum, nylon, or fiberglass porous material
Neutron attenuation	Emits high-energy neutrons into the soil that collide with hydrogen atoms associated with soil water and counts the number of pulses, which is correlated to moisture content	Consists of a probe inserted into access boreholes with aluminum or polyvinyl chloride casing
Time domain reflectrometry	Sends pulses through a cable and observes the reflected waveform, which is correlated to soil moisture	Consists of a cable tester (or specifically designed commercial time domain reflectrometry unit), coaxial cable, and a stainless steel probe

specific performance results are achieved. The numerical model HELP is the most widely used water balance model for landfill cover design. UNSAT-H and HYDRUS-2D are two other numerical models that have been used frequently for the design of ET covers. HELP and UNSAT-H are in the public domain, while HYDRUS-2D is available from the International Ground Water Modeling Center in Golden, CO *http://typhoon.mines.edu* (Dwyer 2003; Khire, Benson, and Bosscher 1997).

Recent studies have compared available numerical models and found that cover design depends on site-specific factors, such as climate and cover type, and that no single model is adequate to accurately predict the performance of all ET covers. Several of the studies identified are: intercode comparisons for simulating water balance of surficial sediments in semi-arid regions, which compared results of seven numerical models for nonvegetated, engineered covers in semiarid regions; water balance measurements and computer simulations of landfill covers, which evaluated ALCD cover performance and predicted results from HELP and UNSAT-H; and field hydrology and model predictions for final covers in the ACAP, which compared performance results with those predicted by HELP and UNSAT-H (Scanlon and others 2002; Dwyer 2003; Roesler, Benson, and Albright 2002).

COST

Limited cost data are available for the construction and operation and maintenance (O&M) of ET cover systems. The available construction cost data indicate that these cover systems have the potential to be less expensive to construct than conventional cover systems. Factors affecting the cost of construction include availability of materials, ease of installation, and project scale. Locally available soils, which are usually less costly than imported clay soils, are typically used for ET cover systems. In addition, the use of local materials generally minimizes transportation costs (Dwyer 2003, EPA 2000a).

While the construction cost for an ET cover is expected to be less than that for a conventional cover, uncertainty exists about the costs for O&M after construction. Several factors affecting the O&M cost include frequency and level of maintenance (for example, irrigation and nutrient addition), and activities needed to address erosion and biointrusion. In addition, when comparing the costs for ET and conventional covers, it is important to consider the types of components for each cover and their intended function. For example, it would generally not be appropriate to compare the costs for a conventional cover with a gas collection layer to an ET cover with no such layer. Additional information about the costs for specific ET cover systems is provided in project profiles, discussed below under Technology Status.

TECHNOLOGY STATUS

A searchable on-line database has been developed with information about ET cover systems and is available at *http://cluin.org/products/altcovers*. As of September 2003, the database contained 56 projects with monolithic ET cover systems and 21 projects with capillary barrier ET cover systems; these systems have been proposed, tested, or installed at 64 sites located throughout the United States, generally from Georgia to Oregon. Some sites have multiple projects, and some projects have multiple covers and/or cover types.

The database provides project profiles that include site background information (for example, site type, climate, precipitation), project information (for example, purpose, scale, status), cover information (for example, design, vegetation, installation), performance and cost information, points of contact, and references. Table 2 provides a summary of key information from the database for 34 recent projects with monolithic ET or capillary barrier ET covers.

In addition to this on-line database, several ongoing federal and state initiated programs are demonstrating and assessing the performance of ET cover systems. The following programs provide performance data, reports, and other useful information to help evaluate the applicability of ET designs for final cover systems.

- Alternative Landfill Cover Demonstration – See Exhibit 3 for more information or *http://www.sandia.gov/Subsurface/factshts/ert/alcd.pdf*

- Alternative Cover Assessment Program – See Exhibit 4 for more information or *http://www.acap.dri.edu*

- Interstate Technology and Regulatory Council – Published a report called *Technology Overview Using Case Studies of Alternative Landfill Technologies and Associated Regulatory Topics*; March 2003. For further information, see *http://www.itrcweb.org*

Table 2. Selected Sites Using or Recently Demonstrating Evapotranspiration (ET) Covers

Site Name and Location	*Site Type*	*Status of Project*	*Date Installed*
Monolithic ET Covers - Full Scale Projects			
Barton County Landfill, Great Bend, KS	MSW landfill	Installation	NA
Coyote Canyon Landfill, Somis, CA	MSW landfill	Operational	April 1994
Duvall Custodial Landfill, Duvall, WA	MSW landfill	Operational	1999
Fort Carson, Colorado Springs, CO	MSW landfill	Operational	October 2000
Hastings Groundwater Contamination Superfund Site, Hastings, NE	MSW landfill	Design	NA
Horseshoe Bend Landfill, Lawrenceburg, TN	Industrial waste landfill	Operational	1998
Idaho National Engineering and Environmental Laboratory Superfund Site, Idaho Falls, ID	Radioactive waste site	Proposed	NA
Industrial Excess Landfill Superfund Site, OH	Industrial waste landfill	Proposed	NA
Johnson County Landfill, Shawnee, KS	MSW landfill	Installation	NA
Lakeside Reclamation Landfill, Beaverton, OR	Construction debris	Operational	1990
Lopez Canyon Sanitary Landfill, Los Angeles, CA	MSW landfill	Operational	1999
Marine Corps Logistics Base Superfund Site, GA	MSW and hazardous waste landfill	Proposed	NA
Municipal Waste Landfill at Kirtland Air Force Base, NM	MSW landfill	Operational	2002
Operating Industries Inc. Landfill Superfund Site, CA	MSW landfill	Operational	May 2000
Pantex Plant, Amarillo, TX	Construction debris	Operational	2000

Site Name and Location	*Site Type*	*Status of Project*	*Date Installed*
Capillary Barrier ET Covers - Full Scale Projects			
Gaffey Street Sanitary Landfill, Wilmington, CA	MSW landfill	Installation	NA
Hanford Superfund Site, Richland, WA*	Radioactive waste site	Operational	1994
McPherson County Landfill, McPherson, KS	MSW landfill	Operational	2002

Site Name and Location	*Site Type*	*Status of Project*	*Date Installed*
Monolithic ET Covers - Demonstration Projects			
Altamont Landfill, Livermore, CA (ACAP project)	Non-hazardous waste site	Operational	November 2000
Bluestem Landfill #2, Marion, IA (ACAP project)	MSW landfill	Operational	October 2000
Finley Buttes Regional Landfill, OR (ACAP project)	MSW landfill	Operational	November 2000
Green II Landfill, Logan, OH (ACAP project)	MSW and hazardous waste landfill	Operational	2000
Kiefer Landfill, Sloughhouse, CA (ACAP project)	Non-hazardous waste site	Operational	July 1999
Marine Corps Logistics Base, Albany, GA (ACAP project)	MSW and hazardous waste landfill	Operational	March 2000
Milliken Landfill, San Bernadino County, CA (ACAP project)	MSW landfill	Operational	1997
Monterey Peninsula Landfill, Marina, CA (ACAP project)	Non-hazardous waste site	Operational	May 2000
Rocky Mountain Arsenal Superfund Site, Denver, CO	Hazardous waste site	Complete	April 1998
Sandia National Laboratories, NM (ALCD project)	Non-hazardous waste site	Operational	1996

Site Name and Location	*Site Type*	*Status of Project*	*Date Installed*
Capillary Barrier ET Covers - Demonstration Projects			
Douglas County Landfill, Bennington, NE (ACAP project)	MSW landfill	Operational	August 2000
Hill Air Force Base, Ogden, UT	Hazardous waste landfill	Operational	1994
Lake County Landfill, Polson, MT (ACAP project)	MSW landfill	Operational	November 1999
Lewis and Clark County Landfill, MT (ACAP project)	Non-hazardous waste site	Operational	November 1999
Sandia National Laboratories, NM (ALCD project)	Non-hazardous waste site	Operational	1996
Uranium Mill Tailings Repository, UT (ACAP project)	Hazardous waste landfill	Operational	July 2000

Notes:
* Project conducted as Superfund treatability test study with cover constructed over an existing waste site
NA Not Applicable
ALCD Alternative Landfill Cover Demonstration; program supported by DOE
ACAP Alternative Cover Assessment Program; program supported by EPA

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NOTICE

Preparation of this fact sheet has been funded wholly or in part by the U.S. Environmental Protection Agency under Contract Number 68-W-02-034. For more information regarding this fact sheet, please contact Mr. Kelly Madalinski, EPA, at (703) 603-9901 or *madalinski.kelly@epa.gov*.

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Telephone: (513) 489-8190 or (800) 490-9198
Fax: (513) 489-8695

ACKNOWLEDGMENT

Special acknowledgment is given to the following individuals for their review and thoughtful suggestions to support the preparation of this fact sheet: David Carson (EPA), Steve Rock (EPA), Ken Skahn (EPA), Steve Wall (EPA), Greg Mellama (U.S. Army Corps of Engineers), Joey Trotsky (U.S. Navy), Bill Albright (Desert Research Institute), Craig Benson (University of Wisconsin-Madison), Steve Dwyer (Sandia National Laboratory), Glendon Gee (Pacific Northwest National Laboratory), Tanya Goldfield (City of Los Angeles), Charles Johnson (Colorado Department of Public Health), Doug Walters (City of Los Angeles), and Tom Hakonson (Environmental Evaluation Services, LLC).

Appendix B-3

Ecological Revitalization: Turning Contaminated Properties Into Community Assets

ECOLOGICAL REVITALIZATION:

Turning Contaminated Properties Into Community Assets

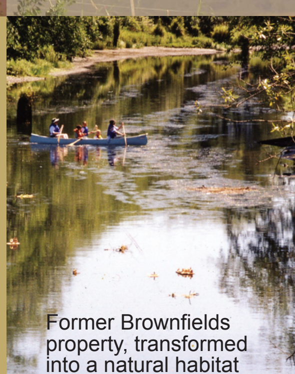
A pocket park at a former service station

Former RCRA Corrective Action facility, restored to a wetland

Constructed wetland on a Superfund landfill site

Former Superfund site restored to natural habitat

Former weapons manufacturing site, now a national wildlife refuge

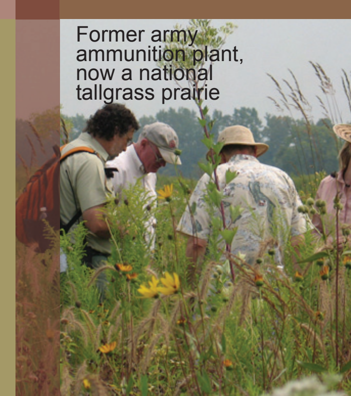


Former Brownfields property, transformed into a natural habitat

Former RCRA Corrective Action facility, now part of the Audubon Trail

February 2009

Former Brownfields property, restored to natural habitat



Former army ammunition plant, now a national tallgrass prairie

About the cover page: Ecological Revitalization in Action

Descriptions are in a clock-wise direction, starting with top right.

1. **Former RCRA Corrective Action facility, restored to a wetland**: Ecological revitalization at the AMAX Metals Recovery Inc. (now Freeport McMoRan) in Braithwaite, Louisiana, where a water retention pond was dewatered to form a wetland that provided a home to alligators relocated due to Hurricane Katrina in 2005. *Photograph courtesy of U.S. Environmental Protection Agency (EPA) Resource Conservation and Recovery Act (RCRA) Corrective Action Program.*

2. **Former weapons manufacturing site, now a national wildlife refuge**: Nearly 27 square miles at Rocky Mountain Arsenal (RMA) in Colorado, one of the worst hazardous waste sites in the country, have been transformed into one of the nation's largest urban national wildlife refuges. The open space surrounding a former weapons manufacturing facility at RMA provides a home for nearly 300 species of wildlife including birds, mammals, reptiles, amphibians, and fish. *Photograph courtesy of EPA Office of Superfund Remediation and Technology Innovation (OSRTI).*

3. **Former RCRA Corrective Action facility, now part of the Audubon Trail**: At England Air Force Base in Louisiana, areas excavated during cleanup became part of the Audubon Trail, provided habitat and a stopping point for migratory birds, and expanded an 18-hole golf course. *Photograph courtesy of EPA RCRA Corrective Action Program.*

4. **Former army ammunition plant, now a national tallgrass prairie**: At the Joliet Army Ammunition Plant (JOAAP) in Illinois, nearly 19,000 acres of land contaminated with explosives and other chemicals were remediated and transformed into the Midewin national tallgrass prairie, one of the first in the country. About a third of Midewin is now open to the public with trails for hiking, biking, or horseback riding, and areas to observe habitat revitalization. *Photograph obtained from a JOAAP brochure titled "From War to Peace" provided by EPA Federal Facilities Restoration and Reuse Office (FFRRO).*

5. **Former Brownfields property, restored to natural habitat**: With assistance from an EPA Brownfields Assessment grant, Lancaster County, Pennsylvania, was able to turn blighted land into natural and recreational greenspace. The 23.5-acre former industrial property has been transformed into hiking trails, picnic grounds, scenic overlooks of the Susquehanna River, and nesting habitat that fostered the reemergence of the Bald Eagle in this area. *Photograph courtesy of EPA Office of Brownfields and Land Revitalization.*

6. **Former Brownfields property, transformed into a natural habitat:** At the Hoquarton Natural Interpretive Trail in Tillamook, Oregon, a former lumber mill was transformed into a recreational and educational greenspace using an EPA Revolving Loan Fund. Weeds and invasive plants were removed, more than two tons of trash was disposed of, and over 2,000 native plants were introduced in riparian areas. A nature trail provided walking and bird watching opportunities. *Photograph courtesy of Oregon Department of Environmental Quality.*

7. **Constructed wetland on a Superfund landfill site**: At the 1.2-acre landfill at the Naval Amphibious Base Little Creek Superfund Site in Virginia Beach, Virginia, 29,000 tons of non-hazardous soil and debris were removed and 6,300 cubic yards of clean fill were imported to convert the landfill to a tidal wetland. Plants were placed along designated elevations to establish tidal wetland vegetation, using the neighboring marsh as a reference. *Photograph courtesy of Bruce Pluta, EPA Region 3, Biological Technical Assistance Groups (BTAG).*

8. **A pocket park at a former service station**: The small West Ogden Pocket Park property in urban Chicago, Illinois, was a former service station that included a derelict building where underground storage tanks (UST) ranging in size from 600 to 10,000 gallons were dumped illegally. At this site, eleven USTs containing gasoline, diesel, heating oil, and used oil were present. UST removal, site cleanup, and revitalization led to the opening of the pocket park in summer of 2001 and added much-needed greenspace to the surrounding neighborhood. *Photograph courtesy of EPA Office of Underground Storage Tanks and Wildlife Habitat Council fact sheet, EPA-510-F-04-007.*

9. (Center) **Former Superfund site, restored to natural habitat:** At the Jacks Creek/Sitkin Smelting & Refining, Inc. Superfund Site in Maitland, Pennsylvania, wetlands were recreated in the riparian corridor along Jacks Creek. Vernal pools were created, woody debris was placed in the wetland as invertebrate habitat, and a wet meadow seed mix was used. *Photograph courtesy of Bruce Pluta, EPA Region 3, BTAG.*

Office of Solid Waste
and Emergency Response

EPA 542-R-08-003
February 2009
www.epa.gov/tio
http://clu-in.org

Ecological Revitalization: Turning Contaminated Properties Into Community Assets

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Notice and Disclaimer

The U.S. Environmental Protection Agency (EPA) funded preparation of this document under Contract No. EP-W-07-078. It was prepared by EPA's Office of Solid Waste and Emergency Response (OSWER) cleanup programs, including the Office of Superfund Remediation and Technology Innovation (OSRTI), Office of Resource Conservation and Recovery (ORCR) (formerly known as Office of Solid Waste), Federal Facilities Restoration and Reuse Office (FFRRO), Office of Brownfields and Land Revitalization (OBLR), and Office of Underground Storage Tanks (OUST).

This document has undergone EPA and external review by subject matter experts. All web links provided in this document were accurate and valid at the time of publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use. If you have questions about this document, please contact Ms. Michele Mahoney, EPA, by phone at 703-603-9057 or via e-mail at mahoney.michele@epa.gov.

To view or download a portable document format (PDF) version of *Ecological Revitalization: Turning Contaminated Properties Into Community Assets* (EPA 542-R-08-003), visit the Hazardous Waste Clean-up Information (CLU-IN) system Web site at www.clu-in.org/download/issues/ecotools/Ecological_Revitalization_Turning_Contaminated_Properties_into_Community_Assets.pdf. A limited number of printed copies are available free of charge and may be ordered via the Web site, by mail, or by fax from:

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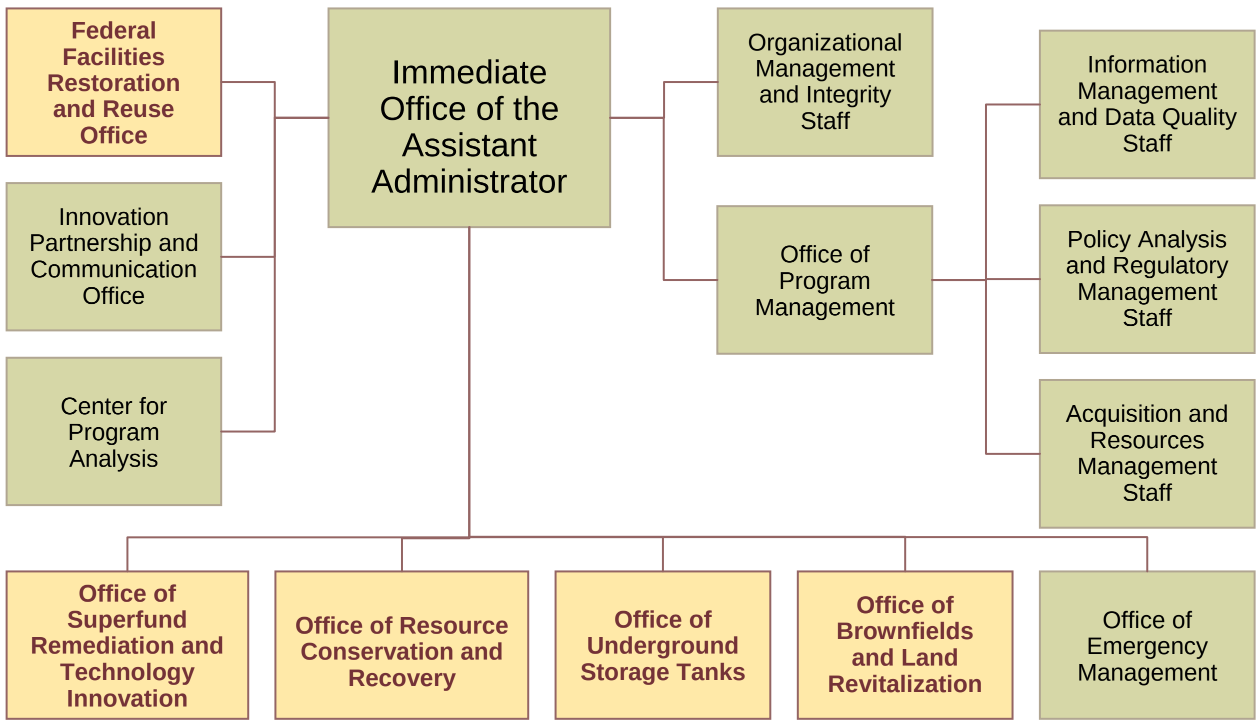
Telephone: 800-490-9198
Fax: 301-604-3408
Web site: www.epa.gov/nscep

EPA Office of Solid Waste and Emergency Response Organizational Chart

(As of January 2009)



Note: Highlighted EPA offices contributed to the development of this document.

Executive Summary

Ecological revitalization refers to the process of returning land from a contaminated state to one that supports a functioning and sustainable habitat. Although the final decision on how a property is reused is inherently a local decision that often rests with the property owner, the U.S. Environmental Protection Agency (EPA) actively supports and encourages ecological revitalization, when appropriate, during and after the assessment and cleanup of contaminated properties under its cleanup programs. This document (1) provides an overview of EPA's cleanup programs and resources available to support ecological revitalization; (2) addresses technical considerations to help cleanup project managers and other stakeholders carry out ecological revitalization at contaminated properties; and (3) presents general planning and process considerations for ecological revitalization of wetlands, streams, and terrestrial ecosystems as well as successful long-term stewardship. Appendix A at the end of the document presents additional case studies on ecological revitalization.

Ecological Revitalization Under EPA Cleanup Programs. Ecological revitalization of contaminated properties is consistent with EPA's mission to protect human health and the environment, and it is an integral component of EPA's cleanup programs. Under its cleanup programs, EPA ensures that (1) ecological revitalization does not compromise the protectiveness of the cleanup and (2) the best interests of stakeholders are considered. EPA's cleanup programs have established initiatives that support ecological revitalization and provide a variety of tools, information resources, and technical assistance. Collaboration and coordination with stakeholders is important for promoting ecological revitalization across EPA's programs.

Technical Considerations for Ecological Revitalization. Technical considerations for ecological revitalization include selecting appropriate cleanup technologies, addressing waste left in place, and minimizing ecological damage during the cleanup. When selecting a cleanup technology, the following may reduce ecosystem impacts during cleanup:

- Preventing access by animals that could cause damage to a cleanup technology
- Locating equipment and utilities to minimize disruption to on-site and surrounding habitat
- Selecting surface vegetation that will thrive and not interfere with the cleanup
- Evaluating the effects of amendments

Excavation and earthmoving equipment can significantly disrupt existing habitat during cleanup. Cleanup project managers are encouraged to consider the following steps to minimize habitat effects and encourage successful ecological revitalization:

- Developing and communicating ecology awareness
- Designing property-wide work zones and traffic plans
- Minimizing excavation and retaining existing vegetation
- Phasing work to stabilize one area of the property before another is disturbed
- Considering property characteristics
- Protecting on-site fauna
- Locating and managing waste and soil piles to minimize erosion
- Designing containment systems with habitat considerations
- Reusing indigenous materials whenever practical
- Controlling erosion and sedimentation
- Ensuring that borrow areas minimize effects on habitat
- Avoiding the introduction of new sources of contamination or undesirable species

For properties where waste is left in place, this document provides solutions and considerations for certain ecological revitalization issues that may arise. These include restoring soils, stabilizing metals, maintaining surface vegetation, and managing attractive nuisance issues.

Wetlands Cleanup and Restoration. Wetlands are of particular concern because in addition to intercepting storm runoff and removing pollutants, they provide food, protection from predators, and other vital habitat factors for many of the nation's fish and wildlife species. Important considerations for planning and designing wetland cleanup and restoration include:

- Evaluating the characteristics, ecological functions, and condition of wetlands
- Determining beneficial wetland functions and structures after the cleanup
- Developing a wetlands design that will achieve the stated ecological functions
- Ensuring that cleanup activities and wetland features have minimal effects on existing wetlands
- Specifying and implementing explicit maintenance requirements

Stream Cleanup and Restoration. Stream cleanups often disrupt stream flow and habitat. Considerations for (1) designing and implementing cleanups that facilitate ecological revitalization of streams and stream corridors and (2) mitigating adverse ecological effects of constructing cleanup features include:

- Stream channel restoration decisions about channel width, depth, cross-section, slope, and alignment
- Streambank stabilization measures (temporary and permanent)
- Streambank vegetation approaches
- Management of watershed processes such as increased runoff or sediment loading from construction

Bioengineering techniques that stabilize the soil or streambank by establishing sustainable plant communities have become an increasingly popular approach to streambank restoration. Stabilization techniques may include using a combination of live or dormant plant materials, sometimes in conjunction with other materials such as rocks, logs, brush, geotextiles, or natural fabrics.

Terrestrial Ecosystems Cleanup and Revitalization. Establishing a plant community that will thrive with minimal maintenance is a critical step in developing a healthy terrestrial ecosystem on cleanup properties. Factors to consider when establishing terrestrial plant communities in disturbed areas include:

- Soil suitability and the need for soil amendments or soil stabilization
- Property-specific plant selection with a preference for native plants
- Protection from disturbances (such as from grazing animals and vehicles)
- Timing to ensure optimal plant establishment

Long-Term Stewardship Considerations. On cleanup completion, operation and maintenance (O&M) activities through responsible stewardship protect the integrity of the cleanup and the functioning of the associated ecosystems. Specifically for properties where waste is left in place, long-term stewardship is necessary to ensure protectiveness of the remedy. When designing a successful O&M program for ecological revitalization, it is important to consider the following:

- Planning early for long-term stewardship
- Incorporating ecological revitalization components into general maintenance activities
- Establishing a monitoring program that incorporates the ecological revitalization components
- Using institutional controls to prevent activities that could potentially interfere or disturb ecologically revitalized areas

1.0 Introduction

Revitalizing properties for ecological purposes helps to achieve U.S. Environmental Protection Agency (EPA)'s goal of restoring contaminated properties to environmental and economic vitality. The term "ecological revitalization" refers to the process of returning land from a contaminated state to one that supports functioning and sustainable habitat. Although the final decision on how stakeholders will reuse a property is inherently a local decision that often rests with the property owner, EPA supports and encourages ecological revitalization as part of the cleanup of contaminated properties across all of its cleanup programs. Ecological revitalization has many positive effects that apply to a variety of stakeholders (see text box below). The objectives of ecological revitalization and those of the remediation process are best accomplished if they are carefully coordinated. To this end, this document provides general information for coordinating ecological revitalization during the cleanup of contaminated properties, as well as technical considerations for implementing ecological revitalization of wetlands, streams, and terrestrial ecosystems during cleanup.

The purpose of this document is to assist cleanup project managers and other stakeholders to better understand, coordinate, and carry out ecological land revitalization at contaminated properties during cleanup. The focus of this document is primarily on planning-level issues, not detailed design approaches, along with technical information and references for executing ecological revitalization activities at contaminated properties. This document highlights (1) several considerations and initiatives under EPA's Office of Solid Waste and Emergency Response (OSWER) cleanup programs that support ecological revitalization, (2) a variety of tools and resources that are available to assist cleanup project managers and other stakeholders, and (3) case studies that provide examples of ecological revitalization at cleanup properties. Another purpose of this document is to help facilitate cross-program networking while planning, designing, and implementing cleanups to help increase valuable ecosystems that are created or improved through ecological revitalization. To that end, Appendix A provides case studies on ecological revitalization approaches taken at various cleanup properties and identifies specific points-of-contact who can provide valuable insights for those interested in implementing ecological revitalization at their properties.

Ecological Revitalization Benefits a Variety of Stakeholders

Cleanup Project Managers. A restored habitat can reduce long-term operation and maintenance (O&M) requirements without compromising the effectiveness of the cleanup action. A restored habitat can also help optimize property engineering controls, such as using vegetation to reduce surface water infiltration or using wetlands as part of stormwater controls.

Potentially Responsible Parties. A valuable restored habitat could enhance a company's image and reputation in the community. Getting a property cleaned up and reused can also ease liability concerns, which in turn may have a positive financial impact.

Local Government. An ecological reuse may increase tourism, tax revenues, property values, and quality of life for residents.

Local Citizen Groups and Individuals. Increasing habitat and passive recreational activities can improve the character of the neighborhood, employment opportunities, and area air and water quality.

Environmental Organizations. Ecological revitalization projects may provide the opportunity to protect or improve local and regional habitats.

The document is organized into the following sections:

- **Section 2** presents an overview of EPA's cleanup programs and their revitalization initiatives, tools, and resources available to support ecological revitalization.
- **Section 3** provides general technical considerations for implementing ecological revitalization, including cleanup technology considerations, cleanup planning and design issues, and considerations for minimizing ecological damage during cleanups.
- **Section 4** provides technical considerations for planning and designing wetland cleanups and restoration efforts.
- **Section 5** provides technical considerations for designing and implementing cleanups that facilitate ecological reuse of streams and stream corridors and for mitigating potential adverse ecological impacts of constructing cleanup features.
- **Section 6** presents factors to consider for establishing terrestrial plant communities in disturbed areas, including general revegetation principles; protecting or creating natural terrestrial ecosystems, meadows, or prairies; and establishing vegetation on semi-arid or arid lands.
- **Section 7** provides considerations for operation and maintenance (O&M) activities to ensure the ongoing integrity of the cleanup and functioning of the associated ecosystems after cleanup completion.

This document was developed by EPA's OSWER cleanup programs, including the Office of Superfund Remediation and Technology Innovation (OSRTI), Office of Resource Conservation and Recovery (ORCR) (formerly known as Office of Solid Waste), Federal Facilities Restoration and Reuse Office (FFRRO), Office of Brownfields and Land Revitalization (OBLR), and Office of Underground Storage Tanks (OUST) (see the OSWER organizational chart, shown on page iii). **Figure 1-1** on the following page identifies specific elements of each OSWER program office's strategic plans, action plans, or program policies that establish support for ecological revitalization. EPA also encourages other public and private interests, including state and local governments and land trusts, land banks, and nonprofit organizations to participate in ecological revitalization activities, particularly in long-term stewardship at cleanup properties. While the scope of this document includes the EPA offices listed above, the information could be useful to a wide variety of additional stakeholders with an interest in the reuse or redevelopment of a cleanup property, specifically to create, restore, improve, or protect ecological resources. Therefore, this document also provides information that can be applicable to cleanup project managers, potentially responsible parties, Resource Conservation and Recovery Act (RCRA) corrective action facility owners/operators, local governments, citizen groups, environmental organizations, and other interested individuals.

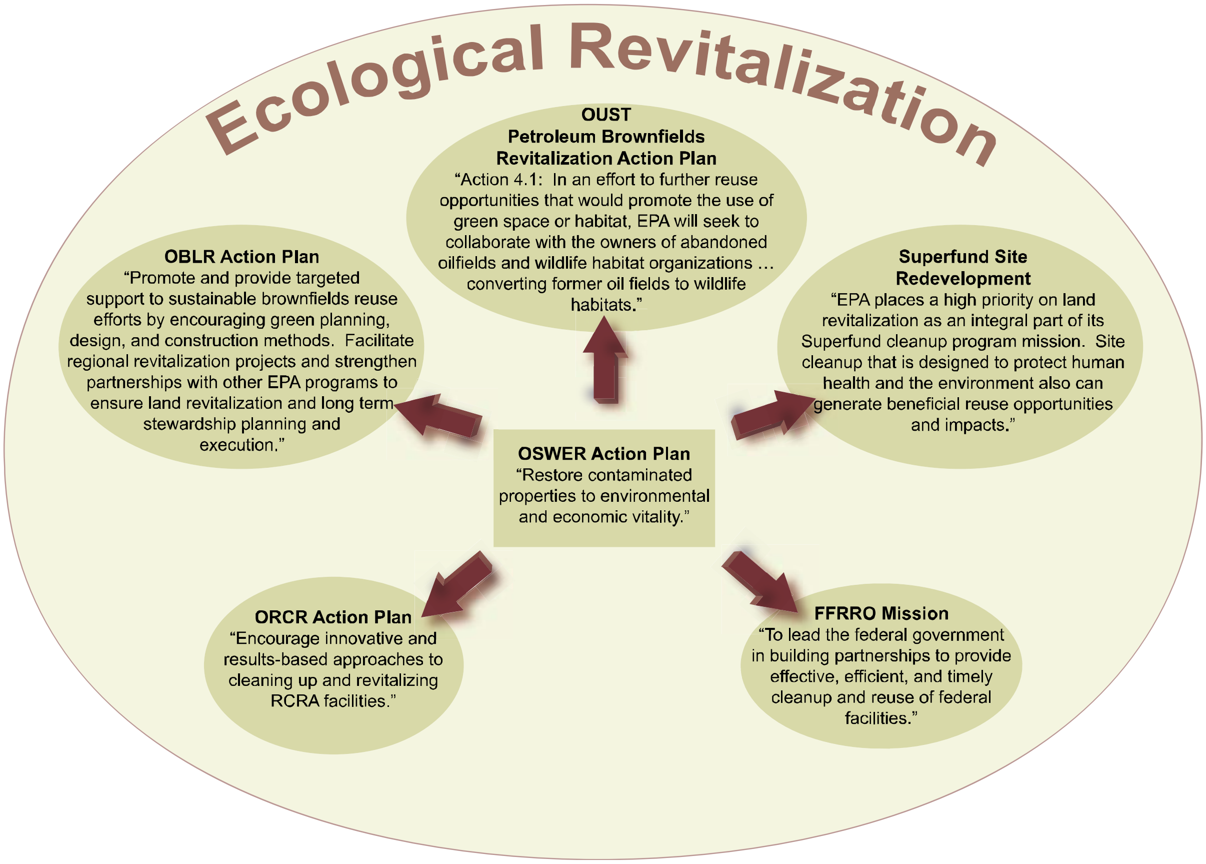
1.1 Ecological Revitalization and Ecological Reuse

The terms "ecological revitalization" and "ecological reuse" are often used interchangeably. However, there is a subtle distinction between the terms. Ecological revitalization refers to *the technical process* of returning land from a contaminated state to one that supports functioning and sustainable habitat. Ecological reuse refers to the *outcome* of a cleanup process and includes those areas where proactive measures (such as a conservation easement) have been implemented to create, restore, protect, or enhance a habitat for terrestrial or aquatic plants and animals (EPA 2006e). In this sense, the process of ecological revitalization of a property can lead to an ecological reuse outcome.

Ecological Revitalization and Ecological Reuse

There is a distinction between the terms ecological "revitalization" and "reuse" but they are related. Ecological revitalization returns land to a functioning and sustainable habitat. Ecological revitalization of a site can lead to an ecological reuse, where proactive measures have been implemented to create, restore, protect, or enhance a habitat for terrestrial or aquatic plants and animals (EPA 2006e).

Figure 1-1. Ecological Revitalization as a Component of EPA Cleanup Programs



Ecological reuse is different from greenspace use in that, in addition to habitat, the latter can include parks, playgrounds, and gardens; ecological reuse strives to restore native habitat and does not include active recreation activities. However, low-impact or passive recreation, such as hiking or bird watching, may occur at ecological reuse properties. In addition, ecological revitalization can occur on a portion of a cleanup property adjacent to greenspace use (for example, a golf course with native plant species surrounding the course), commercial operations, or industrial use. Further, ecological revitalization can occur at varying degrees; some areas of a property may be restored to relatively pristine, historic conditions, while other areas may be planted with native or other compatible species. Both degrees of ecological revitalization lead to habitat that one may accurately characterize as ecological reuse.

1.2 General Program Initiatives

EPA's 2006-2011 Strategic Plan (EPA 2006a) restates EPA's commitment to protect human health and the environment, including restoring the nation's contaminated land and enabling communities to return restored properties safely to beneficial economic, ecological, and social use. As part of the strategic plan, EPA established five goals, including:

- Clean Air and Global Climate Change (Goal 1)
- Clean and Safe Water (Goal 2)
- Land Preservation and Restoration (Goal 3)
- Healthy Communities and Ecosystems (Goal 4)
- Compliance and Environmental Stewardship (Goal 5)

> **Interstate Technology and Regulatory Council (ITRC) Collaboration on Ecological Revitalization**
>
> ITRC, a state-led coalition working with the federal government, industry, and other stakeholders to achieve regulatory acceptance of environmental technologies, has compiled a wealth of information on ecological revitalization. ITRC's document "Planning and Promoting Ecological Land Reuse of Remediated Sites" (ITRC 2006) provides recommendations that are applicable to active and inactive properties and all programs. Visit the following Web site for more information: www.itrcweb.org.

Ecological revitalization contributes to each of these goals. For example, EPA's cleanup programs (under Goal 3) have set a national goal of returning formerly contaminated properties to long-term, sustainable, and productive use (EPA 2006a). These programs include Superfund (under authority of the Comprehensive Environmental Response, Compensation, and Liability Act [CERCLA] of 1980, as amended), Corrective Action (under authority of RCRA), Underground Storage Tanks (UST), Federal Facilities Restoration and Reuse, and Brownfields (under Goal 4). In 2003, EPA introduced the Land Revitalization Initiative to (1) promote cross-program coordination on land reuse and revitalization projects and (2) ensure that stakeholders clean up contaminated properties and make them available for productive use. At properties that involve multiple cleanup programs, land revitalization encourages a "one cleanup program" approach to improve consistency, management, and cost-effectiveness of the program. Cleaning up previously contaminated properties for reuse reinvigorates communities, preserves open space, and prevents sprawl. This initiative goes beyond ecological revitalization, and stakeholders can use land in many ways, including new public parks, restored wetlands, and new businesses. For more information on land revitalization, visit the following Web site: www.epa.gov/oswer/landrevitalization/basicinformation.htm.

In 2006, OSWER issued the Interim Guidance for OSWER Cross-Program Revitalization Measures (CPRM) (EPA 2006b, 2006e) to help track land revitalization at the national level. These revitalization measures show how EPA cleanup programs currently track their revitalization activities, as shown in **Table 1-1**.

While all environmental restoration activities that lead to reuse options are beneficial, this document focuses on ecological revitalization, which is becoming even more important as communities are increasingly seeing ecological revitalization as a desirable process to achieve a viable reuse outcome.

1.3 General Process Considerations

Ecological revitalization activities can occur on a wide variety of properties and could be compatible with several types of end uses. When considering ecological revitalization at a property, it may be useful to consider the following:

- It is important to begin the ecological revitalization process early in the cleanup.
- Ecological revitalization is not a short cut for cleanup and can have strict cleanup standards.
- Habitat can be created on an entire property or on a portion of a property, and can be created adjacent to other end uses such as intermodal centers or industrial areas.
- Ecological revitalization is not typically considered an "enhancement," so it can generally be funded by EPA (under the Superfund Program, for example), and may be needed under Section 404 of the Clean Water Act.
- Ecological revitalization provides a variety of environmental, economic, and social benefits.

The remainder of this document further discusses these considerations.

Table 1-1. Cross-Program Revitalization Measures Tracked by Each EPA Cleanup Program

Performance Measures and Indicators	EPA Cleanup Program				
	OSRTI	ORCR	FFRRO	OBLR	OUST
Universe Indicator: The number of contaminated, potentially contaminated, or previously contaminated properties and surface acres for which OSWER's cleanup programs have an oversight role for assessment or response action.	a	b	a	c	d
Protective for People (PFP) measure: The number of acres at which there is no complete pathway for human exposures to unacceptable levels of contamination based on current property conditions.	a	b	a	c	d
Ready for Anticipated Use (RAU) measure: The number of acres at a property that meets the criteria for the PFP measure, as well as (1) all cleanup goals have been achieved for current and reasonably expected land uses and (2) all institutional or other controls have been put in place.	a	b	a	c	d
Status of Use Indicator: How the acres at a property subject to the Universe Indicator are being used at the point in time when the determination is made.	a	**	a	--	--
Type of Use Indicator: For programs, regions, states, local governments, or tribes that are looking for measures they could use to help describe in more detail how contaminated or potentially contaminated properties under their jurisdiction are currently being used. For example, "ecological use" is a type of use under this indicator.	a	**	a	c	--

References: EPA 2007e; f; g and EPA 2009

Notes:

** Reporting of Indicator is voluntary at this time.

-- Indicator not tracked.

a New Land Reuse Module in Comprehensive Environmental Response, Compensation and Liability Information System (CERCLIS) used to track CPRM information, independent of Government Performance and Results Act (GPRA) goals. OSRTI reports "Ready for Reuse" as a GPRA measure (based on status of cleanup and institutional controls [IC]), which equates to both PFP and RAU.

b Through 2008, the RCRA facility Indicator Universe will consist of all RCRA Corrective Action 2008 GPRA baseline facilities. For 2009 and beyond, the RCRA facility Indicator Universe will consist of all RCRA Corrective Action 2020 facilities. The Current Human Exposures Under Control Environmental Indicator (HE EI) will be used to report the PFP measure. A "RCRA RAU Documentation" form has been developed to assist in implementing this performance measure. Status of Use and Type of Use indicators are not being required at a national level. Universe and RAU data elements have been incorporated into the RCRA Information System (RCRAInfo Version 4.0 released in December 2008).

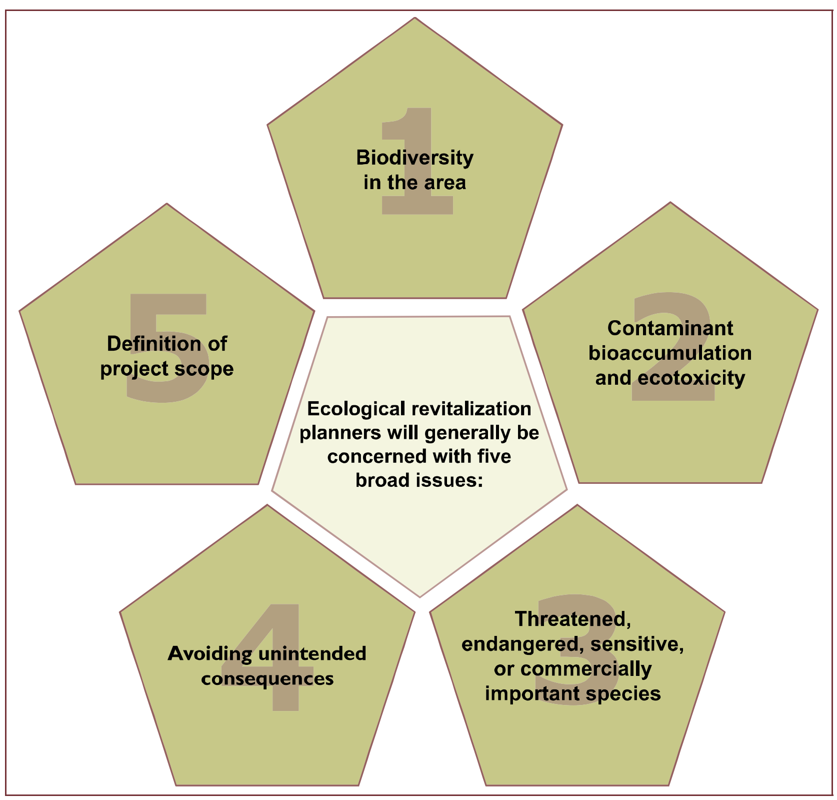
c OBLR is using Property Profile Form data to report on the Universe Indicator (properties and acres where assessment or cleanup are reported as complete for the first time under a Brownfields grant) and Type of Use Indicator (Greenspace, Residential, Commercial, Industrial, and Mixed Use). OBLR is also using their Property Profile Form to collect information on the "Ready for Reuse" measure (based on status of cleanup and IC), which equates to both PFP and RAU measures and is being reported as a Government Performance and Results Act measure by OBLR. Indicator and measure information is being tracked in the EPA OBLR Assessment, Cleanup, and Redevelopment Exchange System (ACRES) database.

d OUST's "Confirmed Release" will equal one site and one acre for the Universe Indicator; OUST's "Cleanup Completed" will equal one acre for both the PFP and RAU performance measures.

Figure 1-2: Before and after photographs of the Bunker Hill Superfund Site in Idaho where contamination was left on-site and capped with biosolids compost and wood ash. A long-term O&M plan was established to ensure that attractive nuisance (see definition on page 3-2) issues did not result. See Appendix A for additional information. *Photographs courtesy of Dr. Sally Brown, University of Washington*.

Ideally, the process of ecological revitalization begins during the assessment or investigation phase of a cleanup rather than after the remedy is underway; this allows for the greatest range of potential options and end uses. As discussed throughout this document, ecological revitalization needs additional considerations to ensure protection of wildlife that could end up inhabiting the cleaned up property, in addition to protecting human health and the environment. Some of these additional considerations are included in **Figure 1-3**.

Figure 1-3: Considerations When Planning for Ecological Revitalization



Ecological revitalization is not a short cut for property cleanup, but rather a viable and productive reuse option that also ensures protection of human health and the environment. Potential challenges to consider early in the process include (1) liability if additional cleanup or maintenance is needed, especially in the long term;

(2) public health and access if the cleanup property is converted to habitat; (3) how ecological revitalization, which can be slower than other reuse alternatives, will impact surrounding areas, and (4) transfer of land and long-term stewardship. Therefore, while ecological revitalization can be considered at all contaminated properties, it may not be appropriate for all properties. There are a variety of considerations needed to ensure protectiveness (further discussed in Section 2), including conducting an ecological risk assessment (ERA), avoiding attractive nuisances (see definition on page 3-2), and bioaccumulation issues. For example, at the Bunker Hill Superfund Site in Idaho (shown in **Figure 1-2**), attractive nuisance issues were taken into account while ecological revitalization was being considered as an option. For additional information on bioaccumulation and EPA's persistent, bioaccumulative, and toxic chemical program, visit the following Web site: www.epa.gov/pbt/index.htm. In addition, ecological revitalization may require other considerations to ensure successful creation of habitat, such as controlling invasive plant species. Technical performance measures (TPM) are available to determine the success of ecological revitalization as part of a cleanup process. For additional information on TPMs, visit the following Web site: www.clu-in.org/products/tpm.

Although commercial, industrial, residential, and some recreational uses are not ecological reuse, habitat can be incorporated as a portion of or adjacent to these redeveloped areas. For example, at the Joliet Army Ammunition Plant (JOAAP), a tallgrass prairie was created among large intermodal centers and other industrial areas. British Petroleum (BP) also plants native vegetation at its refineries adjacent to areas where occasional spills may occur to provide phytoremediation, if necessary. See Appendix A for additional information regarding the JOAAP in Illinois and the BP Former Refinery in Wyoming (a photograph of JOAAP revitalization is also included on the cover of this document).

Ecological revitalization provides a variety of positive environmental, economic, and social impacts. Some positive impacts of ecological revitalization are as follows (Interstate Technology and Regulatory Council [ITRC] 2006; EPA 2006d):

- Repairs damaged land
- Improves soil health
- Supports diverse vegetation
- Reduces erosion
- Sequesters carbon
- Controls landfill leachate
- Protects surface and ground water from potential contamination
- Helps remove stigma associated with prior waste site
- Enhances property values and raises tax revenue (www.epa.gov/superfund/programs/recycle/pdf/method.pdf)
- Provides passive recreational opportunities
- Contributes to a green corridor or infrastructure

Additional environmental, economic, and social impacts are listed in the ITRC's document, "Making the Case for Ecological Enhancements" at www.itrcweb.org/Documents/ECO-1.pdf.

The remainder of this document provides background information on ecological revitalization in relation to EPA's cleanup programs, and technical information and resources to assist in implementing ecological revitalization at contaminated properties.

2.0 Ecological Revitalization Under EPA Cleanup Programs

EPA's mission across its cleanup programs is to protect human health and the environment. Ecological revitalization of contaminated properties is consistent with this mission and is an integral component of EPA's cleanup programs. EPA recognizes the important role that it plays in helping communities and other stakeholders clean up and reclaim contaminated properties, which has led to specific programs and initiatives that support the revitalization and reuse (or continued productive use) of properties as part of their assessment and cleanup. The nature and extent of EPA involvement in supporting ecological revitalization varies from program to program, as well as from property to property. Moreover, the decision on whether and how stakeholders will reuse a property for ecological or other purposes is inherently a local decision that usually rests with the property owner.

This section presents an overview of each cleanup program under EPA OSWER (see the organizational chart on page iii of this document) and its revitalization initiatives, which provides the programmatic context for evaluating and taking steps to support ecological revitalization as part of cleaning up contaminated properties. Section 2.1 provides several considerations that are common to each cleanup program; Sections 2.2 through 2.6 address each program separately.

2.1 General Programmatic Considerations

Depending on the specific circumstances at a contaminated property, EPA's OSWER cleanup programs manage, oversee, or provide assistance with investigation and cleanup under one of several different programs, including the Superfund, Federal Facilities, RCRA Corrective Action, Brownfields, and UST programs. In some cases, individual contaminated properties can be subject to multiple OSWER programs. For example, the Rocky Mountain Arsenal involves the RCRA Corrective Action, Superfund, and Federal Facilities programs (Appendix A provides a case study on this site; a photograph is also included on the cover of this document). As illustrated in **Table 2-1** below, a variety of property types can fall under the purview of one or more programs. With proper planning, these programs can support ecological revitalization as part of, or following, cleanup.

Table 2-1: Property Types Commonly Managed Under EPA Cleanup Programs

Example Property Type	EPA Cleanup Programs				
	Superfund	Federal Facilities	RCRA Corrective Action	Brownfields	UST
Foundry	X		X	X	
Gas Station				X	X
Landfill	X	X	X	X	
Manufacturing Facility	X		X	X	X
Industry/Solvent Use	X		X	X	X
Military Installation	X	X	X		X
Other Federal Facilities*	X	X	X		X
Mining	X	X		X	
Refinery	X		X	X	X
Tannery	X		X	X	

* Non-military use facilities owned or operated by the federal government

Whether being addressed under one or several of EPA's cleanup programs, several factors determine whether and how ecological revitalization can be supported at a specific property. These factors are discussed below.

Ecological Revitalization Cleanup Standards in the Calumet Region, Chicago, Illinois

On the south side of Chicago, Illinois, a roundtable team of federal, state, and local agencies developed the Calumet Area Ecotoxicology Protocol to specifically address ecological revitalization activities in this region (Calumet Ecotoxicology Technical Roundtable Team 2007). The protocol includes cleanup standards that are protective for both human health and ecological receptors, which may be more stringent than federal and state industrial and commercial cleanup goals. Sites being cleaned up in the Calumet Region follow the protocol to ensure protectiveness of human health and the environment as well as streamline the cleanup process.

Protectiveness. An important consideration when evaluating the ecological revitalization of a property is ensuring protectiveness for both human health and the environment. EPA does not lower its standards of protection for a property that will be reused, nor does it allow reuse to reduce effectiveness of cleanup measures. Under its cleanup programs, EPA ensures that contamination is either completely removed, cleaned up to acceptable levels, or managed using protective measures that reduce the possibility of exposure to the contamination. If all contamination is eliminated, then human health and the environment are fully protected and the land or water body is available for ecological or others types of use. Where protective measures are in place for waste that remains after the cleanup, EPA determines whether such measures will continue to provide protection for ecological reuse, or whether that use might impair the protective measures. In some cases, the presence of certain contaminants (for example, persistent pollutants that are readily bioavailable, such as metals and polycyclic aromatic hydrocarbons [PAH]) remaining after the cleanup may preclude ecological revitalization efforts on those portions. Cleanup project managers will make these determinations on a case-by-case basis. One of the key challenges to implementing ecological revitalization under EPA's cleanup programs is that cleanup goals applicable to habitat creation can necessitate complex analyses. Cleanup goals for ecological protection may also need to be more stringent than for protection of human health (see text box above). Another challenge stems from a lack of familiarity with ecological end uses and ways in which to quantify the value of such end uses (EPA 2005).

Enhancement. The extent of EPA's involvement in supporting ecological revitalization at a contaminated property depends on the cleanup program involved, the legal authorities under which the property operates, and the specific property at issue. For example, under the Superfund Program, EPA cannot fund ecological enhancements (that is, activities not necessary for the protection of human health and the environment); rather, it can encourage enhancement activities funded by other stakeholders and can fund aspects of a cleanup project that are necessary for the anticipated future uses of a property. Under the Superfund Program, EPA can fund activities to better understand the reasonably anticipated future land use, which informs remedy selection and implementation and helps support long-term protectiveness. Anticipating the future use of a Superfund site after cleanup completion is of key importance in selecting and designing a remedy that will be consistent with that use. Similarly, EPA's Brownfields Program provides, among other things, technical assistance to communities to support plans for ecological and other "green" enhancements to the cleanup and reuse of properties (for example, designing rain gardens, native landscaping, or green infrastructure), but not the actual revitalization or reuse activities themselves. Other programs, such as RCRA Corrective Action or UST, encourage and support ecological revitalization through their established relationships with states that have delegated programs and through collaborative efforts with governmental and non-governmental organizations. State programs may also have limitations for funding activities that are not directly needed for the protection of human health and the environment. Property owners may see the benefits of supporting the reuse of properties, including the ecological revitalization of the land, particularly when it affects public perception of their business operations and commitment to the environment. Moreover, EPA may

Empire Canyon, Daly West Mine Site, Summit County, Utah

A resort development company has proposed the construction of a hotel, spa, and condominium project at the Daly West Mine Site, to be known as the Montage Resort & Spa. The development will contribute to the cleanup of contamination at this former mining site in Park City, Utah. The developer agreed to participate in EPA's Environmentally Responsible Redevelopment and Reuse (ER3) Initiative for contaminated properties. As an ER3 participant, the Montage Resort & Spa will incorporate extensive "green" features into the design, construction, and operation of the development, including several ecological revitalization components. For example, the project involves treatment of ground water collected by foundation drains using a constructed wetland; a native vegetation management plan to improve ecosystem health and reduce the risk of wildfires around the site; and a conservation easement for 2,800 acres of open space to offset additional density from the project. By incorporating sustainable practices and principles into the project, the developer has minimized the impact of the project on the environment without sacrificing profitability.

be able to offer certain incentives to support ecological revitalization under its initiatives, such as EPA's Environmentally Responsible Redevelopment and Reuse (ER3) Initiative.

In general, most ecological revitalization efforts are not considered enhancements if the activities are necessary for the anticipated future ecological use of the property or to restore ecological function and, therefore, can be considered and incorporated into property cleanup plans. Even costs for extensive revitalization efforts to create or restore the function of an ecosystem can be justified if the revitalization is needed because of environmental stressors or adverse impacts to the property caused by the cleanup. For example, grasses, shrubs, and other native plants serve a practical function of stabilizing soil to prevent erosion, while also improving the property's aesthetics and ecological function.

Other Cross-Cutting Ecological Revitalization Considerations for EPA Cleanup Programs

- ***Liability***: Consider who will be responsible if additional cleanup or maintenance is required, especially in the long-term.
- ***Public Health and Access***: Consider whether the public will safely be allowed to use the property if it is converted to habitat.
- ***Surrounding Areas and Time***: Ecological revitalization can impact surrounding areas because, while ecological revitalization can be a more cost-effective process, the time required to return a property to functioning and stable habitat can take longer than other reuse alternatives.
- ***Transfer of Land and Long-Term Stewardship***: Ensure that institutional controls are in place and operating effectively, and consider who will be the long-term landowner responsible for stewardship of the ecological revitalization and associated natural resources.

Stakeholder Involvement. Regardless of which EPA program is involved in the assessment, cleanup, and revitalization of a contaminated property, numerous stakeholders may have an interest in the actions taken at the property, including the following:

- Other federal, state, local, or tribal agencies
- Parties responsible for the contamination
- Current landowners
- Neighboring property owners and the surrounding community
- Prospective purchasers or future users of the property

With different stakeholders potentially involved at a contaminated property, the ecological revitalization of the property will need to consider the varied interests, objectives, and requirements of those stakeholders. Successful ecological revitalization efforts have typically resulted from well-facilitated processes that encourage open communication and the exchange of information among the stakeholders at a property.

Additional Initiatives That Support Sustainable Cleanup and Reuse. In addition to specific initiatives that are supported by EPA's cleanup programs (and described in the following sections), there are other EPA initiatives that can also support ecological revitalization at contaminated properties regardless of which OSWER program is supporting the cleanup. These initiatives include the following:

EPA's EcoTools Initiative provides a variety of resources for cleanup project managers, especially under the Superfund program. In addition to technical information, the EcoTools Web site provides cleanup project managers access to ecological experts via a technical assistance service. For more information, visit www.clu-in.org/ecotools.

EPA's ER3 Initiative uses enforcement and other EPA-wide incentives to promote sustainable cleanup and redevelopment of contaminated properties. Under the ER3, EPA collaborates with federal, state, public, and private partners to identify, develop, and deliver incentives to encourage developers and property owners to implement sustainable practices during the redevelopment of contaminated properties. The primary components of ER3 are to (1) identify and provide enforcement and EPA-wide incentives to developers and property owners to encourage sustainable cleanup and development; (2) develop partnerships with federal, state, public, and private entities to establish a network of expertise on sustainable development issues; and (3) promote sustainable redevelopment of contaminated properties through education and outreach. For more information on ER3, visit www.epa.gov/compliance/cleanup/revitalization/er3/index.html.

EPA's Five Star Restoration Program brings together students, conservation corps, other youth groups, citizen groups, corporations, landowners, and government agencies to provide environmental education and training through projects that restore wetlands and streams. The program provides challenge grants, technical support, and opportunities for information exchange to enable community-based restoration projects. Visit www.epa.gov/owow/wetlands/restore/5star for additional information about the Five Star Restoration Program.

EPA's GreenAcres Initiative promotes natural and sustainable landscaping practices using native plants and other green landscaping strategies. The GreenAcres Initiative is a component of EPA's Great Lakes National Program Office and its efforts to promote an integrated, ecosystem approach to protect, maintain, and restore the chemical, biological, and physical integrity of the Great Lakes. Under GreenAcres, EPA provides information and resources on using native plants and natural landscape approaches in urban, suburban, and corporate settings. For more information, visit www.epa.gov/greenacres.

EPA's Green Infrastructure Partnership is an initiative to work with partners to promote green infrastructure as an environmentally preferable approach to stormwater management. In January 2008, EPA and its partners released an action strategy for managing wet weather with green infrastructure. The strategy provides a collaborative set of actions that promote the use of green infrastructure and outlines efforts to bring green infrastructure technologies and approaches into mainstream wet weather management. For more information about this partnership and the action strategy, visit http://cfpub.epa.gov/npdes/home.cfm?program_id=298.

EPA's Green Remediation Initiative promotes the use of best management practices (BMP) to maximize the net environmental benefits of cleanup actions. With the help of public and private partners, EPA OSWER is documenting the state of BMPs, identifying ways to improve BMPs, and forming a community of BMP practitioners. Technical assistance is offered to cleanup project managers to find new opportunities for reducing the environmental footprint of cleanup actions. For more information about this initiative, visit www.clu-in.org/greenremediation.

EPA's GreenScapes Program identifies cost-efficient and environmentally friendly solutions for landscaping. Designed to help preserve natural resources and prevent waste and pollution, GreenScapes encourages companies, government agencies, other entities, and homeowners to make more holistic decisions regarding waste generation and disposal and the associated impacts on land, water, air, and energy use. Visit www.epa.gov/greenscapes for additional information on the GreenScapes Program.

2.2 Superfund Sites

EPA's OSRTI carries out the Superfund Program, which addresses contamination from uncontrolled releases at hazardous waste sites that threaten human health and the environment. EPA manages the Superfund Program under the authority of the CERCLA, 1980, as amended. Under the Superfund Program, abandoned, accidentally released, or illegally dumped hazardous wastes that pose a current or future threat to human health or the environment are cleaned up. To accomplish its mission, EPA works closely with communities, potentially responsible parties, and other federal, state, local, and tribal agencies. Together with these groups, EPA identifies hazardous waste sites, investigates the conditions of the sites, formulates cleanup plans, and cleans up sites to ensure that they are protective of human health and the environment.

Superfund cleanups include both long-term and short-term response actions. Long-term cleanups or remedial actions are conducted on sites that, following an evaluation, are listed on the National Priorities List (NPL). Once on the NPL, EPA follows a thorough process to carefully investigate the site and select and carry out a remedy specific to that site. Short-term cleanups called removal actions, fall into three categories: (1) non-time critical responses at sites where on-site activities do not need to be initiated for more than six months; (2) time critical responses at sites where on-site activities must begin within six months; and (3) emergency removal actions at sites that need initiation of on-site activities within hours of the decision that action is necessary. EPA's role and ability to support ecological revitalization may vary across these different site types, as discussed below.

Coordinating Ecological Revitalization Efforts in the Superfund Remediation Process.

OSRTI established the Superfund Redevelopment Initiative (SRI) to ensure that at every Superfund site, EPA and its partners have the necessary tools and information to return the country's most hazardous sites to productive use, including information related to natural resources and ecological revitalization. In addition to cleaning up Superfund sites and making them protective of human health and the environment, communities and other partners are involved in considering future use opportunities and integrating appropriate reuse options into the cleanup process. At previously cleaned sites, communities are also involved to ensure the long-term stewardship of the site remedies. For more information on the SRI, visit the following Web site: www.epa.gov/superfund/programs/recycle.

When investigating, designing, and implementing a cleanup, remedial project managers (RPMs) are encouraged to consider, to the extent practical, anticipated future land uses. With careful planning, many Superfund sites can accommodate ecological revitalization while still meeting the requirements under CERCLA and other federal and state regulations. Stakeholders best accomplish the objectives of ecological revitalization and those of the remediation process through careful coordination. For example, under CERCLA EPA needs to coordinate with all affected Natural Resource Trustees (Trustees) when conducting a remedial investigation (RI). Trustees are designated under Executive Order 12580 and defined under CERCLA as other federal, state, or tribal governments that act on behalf of the public for natural resources under their trusteeship. Trustees often have information and technical expertise about the biological effects of hazardous substances, as well as the location of sensitive species and habitats that can assist EPA in evaluating and characterizing the nature and extent of site-related contamination. Coordination at the investigation and planning stages provides the Trustees early access to information they need to assess injury to natural resources. This assists Trustees in making early decisions about whether sites need restoration in light of the response actions.

Several types of ecological studies, including ERAs and Natural Resource Damage Assessments

Multiagency Coordination at the Atlas Tack Superfund Site, Fairhaven, Massachusetts

Agency coordination is an essential part of the Atlas Tack Superfund Site remediation. As part of planning for the ecological revitalization, EPA coordinated with the U.S. Army Corps of Engineers (USACE) and used the National Oceanic and Atmospheric Administration's (NOAA) Damage Assessment, Remediation, and Restoration Program (DARRP), which acts as a Federal natural resource trustee. NOAA contributed to the development of site-specific sediment remedial goals and the wetland removal plan, and greatly assisted in the design of the mitigation resulting in ecological revitalization at no additional cost to EPA. USACE and NOAA jointly designed separate fresh and salt water marshes to outcompete an invasive species at the site. Using remedial funding, three Federal agencies worked cooperatively to create an effective, natural remedy for the site. For more information, see Appendix A and visit www.epa.gov/ne/superfund/sites/atlas.

(NRDAs), support cleanup and ecological revitalization decisions at a Superfund site. EPA utilizes an ERA as part of its process for assessing the risks of site-related contamination. ERAs are usually conducted during the Remedial Investigation/Feasibility Study (RI/FS) phase of the Superfund response process and inform RPMs about the risk associated with the site. While physical impacts of site cleanup activities are assessed during the FS, ERAs specifically evaluate the likelihood that adverse ecological effects are occurring or may occur because of exposure to chemical (for example, release of hazardous substances) stressors at a site. These assessments often contain detailed information regarding the interaction of these "stressors" with the biological community at the site. Part of the assessment process includes creating exposure profiles that describe the sources and distribution of harmful entities, identify sensitive organisms or populations, characterize potential exposure pathways, and estimate the intensity and extent of exposures at a site. The National Oceanic and Atmospheric Administration (NOAA), a natural resource trustee, and the U.S. Army Corps of Engineers (USACE) played an important role in remediation of the Atlas Tack Superfund Site in Massachusetts, including conducting a site-specific ERA (EPA 2008h) based on the cleanup goals that were established for this site (see text box on this page and **Figure 2-1**). Additional information about this remedy is available at http://www.clu-in.org/download/newsltrs/tnandt1208.pdf.

Trustees also conduct NRDAs, at sites with viable responsible parties, to calculate the monetary cost of restoring natural resources injured by releases of hazardous substances. They evaluate damages to natural resources by identifying the functions or "services" provided by the resources, determining the baseline level of the services provided by the injured resource(s), and quantifying the reduction in service levels because of the contamination. ERAs form the basis for establishing cleanup goals and may contain important information that EPA, Trustees, and risk assessors can use to evaluate ecological revitalization at a site.

While property owners and communities generally conduct land use planning with input from stakeholders, it is important for EPA to understand the anticipated future uses for the site when planning and implementing the remedy. Establishing remediation goals for ecological receptors can be challenging if there is limited data on toxicity, effects on receptor species, and contaminant bioavailability. These challenges can be overcome by planning ahead and collecting appropriate ecotoxicological data (such as contaminant bioavailability and site-specific toxicity), reviewing the open literature and previous ERAs for data, and coordinating with stakeholders to identify site-specific receptors and past incidents of exposure. Uncertainties that cannot be addressed may be documented as part of the site-specific ERA and considered when selecting the site remedy or reuse. Stakeholders have the greatest reuse flexibility if remediation and reuse plans are coordinated *prior* to cleanup. EPA plays an important role in the planning process by communicating key information about the nature of contamination at the site, remedy options, and long-term protectiveness issues.

Stakeholders can still implement ecological revitalization even after the cleanup is complete. In 2004, EPA developed the Return to Use (RTU) Initiative to remove barriers to appropriate reuse at the hundreds of Superfund sites where cleanup has been completed. A focus of RTU has been on establishing partnerships with communities and other stakeholders to address potential obstacles to reuse. Through site-specific partnerships, referred to as demonstration projects, EPA is working with key stakeholders at RTU sites to identify potential reuse barriers and appropriate solutions for those obstacles (EPA 2008a). For more information on the RTU, visit www.epa.gov/superfund/programs/recycle/activities/rtu.html.

Coordinating Ecological Revitalization Efforts in the Superfund Removal Action Process. EPA has prepared a reuse assessment guidance for non-time critical removal actions (see Reuse Assessments Directive, OSWER 9355.7-06P, at www.epa.gov/superfund/programs/recycle/policy/reuse.html); however, guidance is not currently available regarding reuse assessment for time-critical and emergency removal actions. The accelerated and time sensitive nature of these cleanups creates a challenge, as removal teams often complete their activities before there is an opportunity to consider reuse. In some cases, cleanup project managers can quickly conduct an ERA for a removal action, if there is an eminent threat to ecological receptors. However, these instances are rare and the removal action ERA follows the same process outlined for long-term ERAs conducted during the RI/FS. Because the time critical removal process is much faster than the remedial process, implementing reuse planning involves creating a targeted, expedited approach so that reuse can inform the removal action. For example, at the Calumet Container Superfund Site in Hammond, Indiana, EPA conducted a time critical removal action where ecological revitalization drove the reuse strategy for the site. In addition to contaminated soil removal, the removal action also included restoring wetlands and planting native plants. EPA worked successfully and expeditiously with stakeholders to determine future anticipated use of the site (see Appendix A for additional information about this site.)

Tools and Resources. The Superfund Program has developed and made available a variety of tools and resources supporting site reuse in general and ecological revitalization in particular (see www.epa.gov/superfund/programs/recycle/tools/index.html for a list of specific tools and resources that are available). In general, site managers can use SRI guidance documents to create and integrate reuse processes at sites undergoing either a remedial and removal action. SRI has also developed a community involvement process to advance reuse at remediation sites, which could be helpful at removal sites.

The Superfund Program has also developed several resources for site managers, consultants, and others interested in restoring disturbed sites. The Ecotools Web site (www.clu-in.org/ecotools) provides information on soil health, principles of ecological land reuse, and links to various federal, state, academic, and nonprofit agencies and organizations that support ecological revitalization. Through the Ecotools Web site, technical assistance is available for Superfund sites on various ecological revitalization topics, including ecological reuse of contaminated sites, use of soil amendments, use of native plants, control of invasive species, and re-vegetation. Fact sheets and Web-based seminars that focus on tools, methods, and technologies for implementing ecological reuse are also available. Answers to frequently

Technical Assistance for Ecological Revitalization at Superfund Sites

Regardless of the scope of the revitalization project, technical assistance can be obtained from the EPA's regional Biological Technical Assistance Groups (BTAG) (EPA 1991; see Appendix B for links to regional BTAG Web sites), EPA's Emergency Response Team (www.ert.org), EPA's Office of Superfund Remediation and Technology Innovation (OSRTI; www.epa.gov/tio), EPA's Ecotools Web site (www.clu-in.org/ecotools), and the U.S. Department of Agriculture's Natural Resources Conservation Service (www.nrcs.usda.gov).

Figure 2-1: Before and after photographs of the Atlas Tack Superfund Site in Massachusetts where the remedy resulted in preservation of wetland sediment and created a functioning wetland. See Appendix A for additional information. *Photographs courtesy of Elaine Stanley, EPA Region 1.*

asked questions related to ecological revitalization, re-vegetating landfills and waste containment areas, and attractive nuisance issues are available online at www.clu-in.org/pub1.cfm (EPA 2006c, d; EPA 2007c). The Green Remediation Web site (www.clu-in.org/greenremediation) provides various resources for cleanup project managers interested in incorporating green remediation strategies into cleanup actions. Resources include information on the use of BMPs; contracting and administrative toolkits; decision-making tools; links to initiatives involving green remediation applications; technical resources; and site-specific case studies. Technical assistance is also available for cleanup project managers in answering general inquiries about green remediation and for Superfund RPMs to build site-specific green remediation strategies. A useful resource available through this Web site is a technology primer on Green Remediation (EPA 2008j) that outlines the principles of green remediation and describes opportunities to reduce the carbon footprint of cleanup activities throughout the life of a project.

In addition, groups such as regional Biological Technical Assistance Groups (BTAG), which are typically composed of biologists, ecologists, and ecotoxicologists from EPA, and agencies such as the U.S. Fish and Wildlife Service (USFWS), NOAA, and state environmental departments, could provide assistance during cleanup of a site to support ecological revitalization efforts.

2.3 Federal Facilities

EPA's FFRRO works with other EPA offices and federal entities to facilitate faster, more effective, and less costly cleanup and reuse of federal facilities. The federal facilities universe includes NPL sites and certain Base Realignment and Closure (BRAC) facilities (each subject to their respective provisions of CERCLA). The main difference between federal facilities and private Superfund sites is that at federal facilities, EPA has an oversight role rather than primary cleanup authority, which falls to the other federal agency. Many of the site-specific considerations for Superfund sites listed in Section 2.2 also apply to the federal facilities listed on the NPL as well as federal facilities not listed on the NPL (non-NPL sites). Additional challenges that might apply to federal facilities include special circumstances based on the contamination at that facility, such as munitions constituents.

FFRRO and Interagency Coordination

In addition to EPA, FFRRO works with the following federal agencies to coordinate initiatives related to the cleanup of federal properties:

- Federal Aviation Administration
- Defense Logistics Agency
- National Aeronautics and Space Administration
- National Guard
- Small Business Administration
- U.S. Air Force
- U.S. Army
- U.S. Army Corps of Engineers
- U.S. Coast Guard
- U.S. Department of Agriculture
- U.S. Department of Defense
- U.S. Department of Energy
- U.S. Department of Interior
- U.S. Department of Transportation
- U.S. Navy

FFRRO's BRAC Program develops policies, plans, and initiatives to expedite the cleanup and reuse of closing military installations. Since 1993, the BRAC Program has worked with U.S. Department of Defense (DoD), state environmental programs, local governments, and communities to achieve its goal of "making property environmentally acceptable for transfer, while protecting human health and the environment." For more information, visit the following Web site: www.epa.gov/fedfac/about_ffrro.htm.

To implement congressionally mandated actions, EPA issued guidance on how to transfer federal facilities contaminated with hazardous wastes before cleanup completion. In the past, contaminated federal facilities had to undergo complete cleanup at least one year before transfer if hazardous waste was released from, disposed of, or stored on-site. Now, federal agencies can transfer properties prior to cleanup, as long they meet certain conditions. By transferring property that poses no unacceptable risks, communities benefit from faster reuse and redevelopment (EPA 2008c).

Ecological revitalization is a part of many Department of Energy (DOE) and DoD facility reuse projects. Examples include Pease Air Force Base, JOAAP, Rocky Mountain Arsenal, Fernald, and Rocky Flats, which all have major ecological reuse components. See Appendix A for additional information on these case studies; the cover of this document includes a photograph of JOAAP.

Coordinating With Other EPA Offices and Programs. In carrying out its mission, FFRRO works closely with other EPA headquarters offices, including OSRTI, which manages the Superfund Program; ORCR, which manages the RCRA Corrective Action Program; and the Federal Facilities Enforcement Office (FFEO), which oversees compliance with environmental laws and guidance. EPA's Regional offices are also key partners in accomplishing EPA's federal facilities mission. RPMs and

Midewin Tallgrass Prairie at the Joliet Army Ammunition Plant, Will County, Illinois

After working with the community and other stakeholders, the remediation team cleaned up contaminated soil through excavation and bioremediation. More than 19,000 acres of land was transferred to the Forest Service to create the Midewin Tallgrass Prairie, the first national tallgrass prairie in the country. While it will take years to fully restore the land, about a third is now open for the public to observe ongoing habitat restoration, as well as to hike, bike, or ride horseback on interim trails. For more detailed information about this example, see Appendix A.

A Wildlife Refuge at the Rocky Mountain Arsenal in Commerce City, Colorado

EPA is partnering with the Army, Shell Oil, and the Colorado Department of Public Health and Environment to transform the Rocky Mountain Arsenal facility, one of the worst hazardous waste sites in the country, into one of the largest urban national wildlife refuges. The partnership is addressing contaminated ground water, surface water, soils, and buildings. Under the management of the U.S. Fish and Wildlife Service (USFWS), 27 square miles of open space surrounding the manufacturing facility is home to nearly 300 species of wildlife. After the cleanup is complete, the property will become a permanent part of the National Wildlife Refuge System (EPA 2008b). For more detailed information about this example, see Appendix A.

Community Involvement Coordinators (CICs), as well as toxicologists; attorneys; and reuse, tribal, and environmental justice coordinators based in each regional office work closely with EPA headquarters staff to coordinate site-specific cleanup activities. For issues requiring specialized expertise, FFRRO also collaborates with related EPA headquarters offices on a project-specific basis. Additionally, FFRRO co-chairs the Federal Facilities Leadership Counsel (FFLC), a coordinating body within EPA that provides direction and leadership on federal facility cleanup efforts. The FFLC is a forum for addressing a wide spectrum of federal facility cleanup issues, including compliance, technical, enforcement, financial, budgeting, and legislative issues. The FFLC includes EPA regional federal facility program and project managers, regional counsels, and headquarters staff from FFRRO and FFEO.

Coordinating With Other Agencies. FFRRO's partners include governmental and non-governmental groups that are involved in federal facilities cleanup. FFRRO works directly with other federal agencies, primarily DoD and DOE, to coordinate initiatives related to cleanup of federal properties.

FFRRO partners also include state, local, and tribal governments; community groups; environmental justice communities; and advocacy organizations. Local stakeholders include individuals, community groups and any other entities that might be affected by contamination, cleanup activities, or both. FFRRO encourages early and meaningful community involvement at all federal facilities.

Tools and Resources. FFRRO provides a variety of information resources about its programs, policies, and partners. The following Web sites provide access and information about its resources:

Visit www.epa.gov/fedfac/info.htm for access to EPA FFRRO’s publications, newsletters, information centers, and other information resources.

Visit www.epa.gov/swerffrr/policy.htm for access to federal facilities related laws, regulations, policies, and guidance.

Visit FFRRO’s comprehensive, searchable library of resources related to federal facility restoration and reuse topics at http://cfpub.epa.gov/fdrl/index.cfm.

2.4 RCRA Corrective Action Facilities

EPA’s ORCR regulates all household, industrial, and commercial solid and hazardous waste under RCRA, 1981, as amended. One important objective of EPA’s RCRA Program is to protect the public from the management and disposal of hazardous wastes that RCRA facilities generate as part of normal operations. Examples of RCRA facilities include metal finishing operations, auto body repair shops, dry cleaners, chemical manufacturers, foundries, locomotive and railcar maintenance operations, and steelworks. In some cases, these facilities are no longer operational, have no significant activity, or are now vacant. Accidents or activities by hazardous waste generators or at hazardous waste treatment,

BP Former Refinery, Casper, Wyoming

Under a RCRA Corrective Action Consent Decree, BP and the Wyoming Department of Environmental Quality (DEQ) cleaned up this 4,000-acre former refinery located along the banks of the North Platte River and incorporated several ecological revitalization components, creating wildlife habitat and allowing recreational reuse of the facility. Soda Lake, which was once used to dispose of waste water from the refinery, has been revitalized. BP worked with local citizens and the Audubon Society to design a bird sanctuary and resting ground for migrating birds. The reuse plan also incorporated a wetland treatment system into the design of a golf course constructed on the facility. The team planted more than 2,000 a trees as part of phytoremediation approach for cleaning up of portions of the property (EPA 2007a). This facility is a good example of how ecological revitalization measures can be incorporated at a facility with ongoing manufacturing activities. For more detailed information about this facility, see Appendix A.

storage, and disposal facilities regulated under RCRA may release contaminants into the environment. The RCRA Corrective Action Program ensures that regulated facilities that accidentally or otherwise release hazardous waste investigate and clean up such hazardous releases. The RCRA Corrective Action Program differs from Superfund in several ways. First, RCRA facilities often have viable owners and operators and on-going operations. As such, how best to use/reuse the property is ultimately the decision of the property owner, including whether to incorporate ecological revitalization elements on the facility. Second, EPA has delegated the RCRA Program to 43 states and territories that directly manage and oversee the Corrective Action Program; EPA implements the program in other unauthorized states.

In 1998, EPA established the RCRA Reuse and Brownfields Prevention Initiative to encourage the reuse of facilities subject to corrective action under RCRA so that contaminated or otherwise under-used land

Figure 2-2: Before and after photographs of England Air Force Base in Louisiana where contaminated areas were excavated and became part of the Audubon Trail, providing habitat and a stopping point for migratory birds. See Appendix A for additional information. *Photographs courtesy of RCRA Corrective Action Program*.

transitions back into productive use or greenspace (EPA 2008a). Several activities under this initiative support the ecological revitalization of RCRA facilities. One such activity is a cooperative agreement between EPA and the Wildlife Habitat Council (WHC). Under this agreement, the WHC works with EPA and other stakeholders to incorporate ecological revitalization into the cleanup design for end uses, hence providing wildlife habitat (WHC 2008). For example, corrective action at the Ford Rouge Center in Dearborn, Michigan, included ecological components to minimize impacts to the Rouge River. The cleanup team restored or created new wildlife habitat, including hedgerow wildlife corridors and wetland and grassland restoration. In addition to wildlife habitat, the project included other sustainable elements, such as installing a vegetated roof, using pervious pavement, and including phytoremediation. Because many aspects of the project involved ecological enhancement activities, the Ford Motor Company funded most of the activities on the property, with some additional funding provided through a state grant (for a stormwater swale) and an EPA grant to the Dearborn Public Schools System under its Five Star Restoration Grants Program (to support wetlands restoration activities). See Appendix A for a case study regarding this facility.

DuPont-Remington Arms Facility, Lonoke, Arkansas

The DuPont-Remington Arms Facility continues to manufacture munitions on 385 acres of the 1,116-acre facility. The company manages the remaining 731 acres as a wildlife habitat. In cooperation with Ducks Unlimited, the cleanup team constructed a 20-acre moist soil impoundment for waterfowl habitat (EPA 2007b). See Appendix A for more detailed information about this facility.

EPA introduced RCRA Cleanup Reforms in 1999 (EPA 1999b) and additional Reforms in 2001 (EPA 2001) to more effectively meet the goals of the RCRA Corrective Action Program and speed up the pace of cleanups. One initiative of the 2001 Cleanup Reforms is capitalizing on the redevelopment potential of RCRA Corrective Action facilities. In addition, the RCRA program issued guidance to tailor cleanups to facility-specific end uses, including ecological end uses, while maintaining the ultimate goal of protecting human health and the environment. The "Guidance on Completion of Corrective Action Activities at RCRA Facilities" 68 FR 8757 (Feb 25, 2003) describes how corrective actions can be completed with contaminants remaining, using controls tailored to protection for a specific end use for the property (EPA 2005).

In most cases, facilities that are subject to RCRA corrective action continue their operations throughout the cleanup process. Although operations continue at these facilities, opportunities to incorporate ecological revitalization measures still may exist at parts of the property where there are no ongoing operations (see the DuPont-Remington Arms Facility text box). Facilities that are no longer continuing their current industrial or waste management operations may also provide opportunities for ecological revitalization. Some examples include the Ford Rouge Center in Michigan, the BP Oil facility in Lima, Ohio, and the Hopewell Plant (Honeywell) in Hopewell, Virginia. See Appendix A for additional information on these case studies. In

Reuse at RCRA Corrective Action Facilities

In Spring 2001, a survey to determine trends in reuse potential of the 155 RCRA federal lead corrective action facilities in EPA Region 5 identified that 32 percent of all facilities (a total of 49) have potential for habitat or natural area restoration as a sole option or in combination with other reuses (EPA 2002b). While current, nationwide data is not available for ecological reuse of RCRA facilities, at least two regions (EPA Regions 3 and 10) recently conducted studies regarding their RCRA facilities' status and type of use. The results show that, even though most land use on RCRA facilities is industrial, as stakeholders reuse more RCRA facilities, a broader range of use is occurring. Visit the following Web site to review the results from EPA Region 3's study: www.epa.gov/region03/revitalization/R3_land_use_final/data_results.pdf.

some cases, especially with large properties, parcels of the property may provide special reuse opportunities (for example, riverfront location, road or rail access, or community reuse interest). In particular, many large RCRA facilities are federal facilities that may include large tracts of land that could be suitable for ecological revitalization or conservation easements. Stakeholders may be able to reuse uncontaminated parcels or those parcels on a shorter cleanup schedule more quickly than the entire facility (EPA 2008e). For example, at the former England Air Force Base in Alexandria, Louisiana, areas excavated as part of a remedial action became part of the Audubon Trail, providing habitat and a stopping point for migratory birds (see **Figure 2-2**). See Appendix A for additional information on this case study.

Tools and Resources. ORCR provides a variety of information resources about its programs, policies, and partners. The following Web sites provide access and information about its resources:

Visit www.epa.gov/epawaste/hazard/correctiveaction/bfields.htm for information on the RCRA Brownfields Prevention Initiative and case study examples of successes under the initiative.

Visit www.epa.gov/epawaste/hazard/correctiveaction/resources/index.htm for guidance and other information about RCRA corrective action.

2.5 Brownfields Properties

EPA's OBLR manages the Brownfields Program under the authority of Small Business Liability Relief and Brownfields Revitalization Act of 2002 (the "Brownfields Law"). EPA designed its Brownfields Program to empower states, communities, and other stakeholders to work together in a timely manner to prevent, assess, safely clean up, and sustainably reuse brownfields properties.

Brownfields are real property[1], the expansion, redevelopment, or reuse of which may be complicated by the presence or potential presence of a hazardous substance, pollutant, or contaminant. Included in the definition of Brownfields properties are sites contaminated with petroleum that represent a relatively low risk, including properties where the contamination resulted from an UST (Section 2.6 provides information on EPA's UST Program). An estimated 450,000 brownfields properties are located throughout the country (www.epa.gov/brownfields/about.htm). Cleaning up and reinvesting in these properties relieves development pressures on undeveloped, open land while both improving and protecting the environment.

The Brownfields Program is a grant-based program that promotes green, ecological, and open space uses as part of its competitive grants process. These grants support revitalization efforts by funding environmental assessment, cleanup, and job training activities. Brownfields funds can support sustainable remediation measures and planning for ecological revitalization (as the reuse of the property), but typically not actual revitalization or reuse activities. EPA's grant review process generally favors grant proposals that include ecological reuse as part or all of the ultimate reuse goals, especially with respect to greenspace and sustainable use criteria. The ultimate decision on

Sequim Bay Estuary,
Jamestown S'Klallam Tribe, Washington

The Jamestown S'Klallam Tribe used an EPA Brownfields Cleanup grant to clean up and restore estuary function to 82 acres of Sequim Bay. Cleanup activities included removing pilings, contaminated soil, and solid waste from the shoreline and riparian wetlands. The bay now provides clean sediment and habitat for shellfish, salmon, and other species. See Appendix A for more detailed information about this case study.

[1] "Real property" is a legal term indicating a property consisting of lands and of all appurtenances to lands, as buildings, crops, or mineral rights (distinguished from personal property).

Figure 2-3: Before and after photographs of the Grace Lease Property in Pennsylvania, where a former industrial area was revitalized to natural habitat. See Appendix A for additional information. *Photographs obtained courtesy of Office of Brownfields and Land Revitalization.*

whether a brownfields property will include ecological revitalization remains with the community receiving the grant. Although data specifically on the ecological revitalization of brownfields properties are not available, data reported by grantees on reuse measures for OBLR from fiscal year (FY) 2003 to FY2007 indicated that an estimated 4,756 acres were ready for reuse, and more than 507 acres of greenspace or open space were created (EPA 2008i). The Grace Lease property in Pennsylvania (see **Figure 2-3**) is an example of a restored Brownfields property, which had been dormant for nearly a century and was then converted into a natural habitat. A Brownfields Assessment Grant allowed stakeholders to study contaminant levels at the blighted property, remove uncertainties associated with property contamination, and transform the dormant property into usable greenspace for the community.

The Brownfields Program also encourages the incorporation of green infrastructure into brownfields redevelopment projects. Green infrastructure techniques, such as bioswales, green roofs, and rain gardens, present an opportunity to return land to functioning and sustainable habitat. Other green infrastructure practices can also retain, treat, and release stormwater without exposing it to contaminated soils. For more information about this effort, visit www.epa.gov/brownfields/publications/swdp0408.pdf.

Brownfields and Land Revitalization Technology Support Center (BTSC)

Coordinated through EPA's Technology Innovation Program, the BTSC ensures that Brownfields decision makers are aware of the full range of technologies available to make informed or "smart" technology decisions for their properties, including support for ecological revitalization. BTSC provides a readily accessible resource for unbiased assessments and supporting information on options relevant to specific properties, including a technology-oriented review process for investigation and clean-up plans for these properties. The BTSC also provides information about other available support activities, such as those conducted by the Technical Assistance to Brownfields (TAB) Program located at five regional Hazardous Substance Research Centers. Direct support is available to EPA regional staff, state staff, and local governments. For more information, visit www.brownfieldstsc.org.

The Brownfields Program also provides Training, Research, and Technical Assistance Grants to fund projects that explore innovative ideas in the areas of protection of human health and the environment, sustainable development, and equitable development. Each assistance project will receive between $100,000 and $150,000 in annual funding for up to five years. Recipients can use the grants to support a variety of projects including, ecological revitalization, sustainable uses of land, and green jobs in communities. For more information about these grants, visit www.epa.gov/brownfields/trta.htm.

Other initiatives under the Brownfields Program can also contribute to ecological revitalization of brownfields properties. For example, through its partnership with Groundwork USA and the National Park Service Rivers, Trails, and Conservation Assistance Program, OBLR works with communities to improve their environment, economy, and quality of life through local action. This partnership also results in the ecological reuse of brownfields properties through Groundwork Trusts. Visit www.groundworkusa.net/index.html for more information about the Groundwork USA network.

Under the Sustainable Sites Initiative, EPA is currently working with the U.S. Green Building Council to provide a framework for the green development of brownfields properties. The framework is similar to what the Leadership in Energy and Environmental Design (LEED) system has accomplished for green buildings. The framework includes considerations for cleaning or mitigating all hazardous substances from prior use, supporting sustainable landscape principles and practices, and preventing the creation of future brownfields. For more information, see the following document: www.sustainablesites.org/report/SSI_Guidelines_Draft_2008.pdf.

Tools and Resources. OBLR provides a variety of information resources about its programs, policies, and partners. The following Web sites provide access and information about these resources:

Visit www.brownfieldstsc.org for information on strategies, technologies, and technical assistance available to support the investigation and cleanup of brownfields properties.

Visit www.epa.gov/swerosps/bf/toolsandtech.htm for access to a variety of tools and technical resources available to support property reuse.

Visit www.epa.gov/swerosps/bf/initiatives.htm for information on the various EPA and related initiatives that may be applicable at brownfields properties.

Visit www.epa.gov/swerosps/bf/partnr.htm to learn more about the partnerships that EPA has entered in support of brownfields revitalization and reuse.

2.6 Underground Storage Tank Sites

EPA's OUST manages and oversees the UST Program, which seeks to prevent leaks or releases of petroleum or certain hazardous substances from USTs, and ensures that contamination from USTs is cleaned up. OUST manages the program under the authority of several statutes, including Subtitle I of RCRA, as amended by the 1984 Hazardous and Solid Waste Amendments, the 1986 Superfund Amendments and Reauthorization Act, and the Energy Policy Act of 2005. States and territories primarily implement the UST Program, while EPA implements the UST Program in Indian Country. OUST administers the Leaking UST Trust Fund, which provides money for (1) overseeing and enforcing corrective action taken by a responsible party, who is the owner or operator of the leaking UST; and (2) implementing cleanups at UST sites where the owner or operator is unknown, unwilling, or unable to respond, or which need emergency action.

A key provision of the 2002 Brownfields Law allocates 25 percent of funding each year to assess, cleanup, and make ready for reuse petroleum brownfields properties that are relatively low risk. Of the estimated 450,000 brownfields properties in the U.S., approximately half are affected by USTs or some type of petroleum contamination (EPA 2008f). OUST is responsible for promoting the cleanup of sites with leaking USTs and coordinates with OBLR to refine the implementation of the law's petroleum provisions to allow more sites to support appropriate reuse or revitalization (EPA 2008d).

To encourage the reuse of abandoned properties contaminated with petroleum from USTs, OUST created the USTfields Initiative in 2000. USTfields are abandoned or underused industrial and commercial properties where revitalization is complicated by real or perceived environmental contamination from USTs. The purpose of these pilots was to promote the importance of public-private partnerships; the critical role of the state as the primary implementing agency; and the leveraging of private funds to maximize cleanups. Although OUST will not award any new USTfields pilots beyond the original 50 pilots, sites may receive funding for similar assessment and cleanup projects through the Brownfields assessment, cleanup, and revolving loan fund grants and through the Leaking Underground Storage Tanks (LUST) Trust Fund.

Pocket Park at a Former Service Station, Chicago, Illinois

A former service station in Chicago was transformed into a small pocket park using native plantings. This pocket park initiative is a joint effort by BP, the City of Chicago, and the local community. The contaminants of concern at the site were benzene, toluene, xylenes, and ethylbenzene (BTEX) at levels above maximum contaminant levels (MCLs) but not at levels that would pose a risk to the surrounding community. Once the site received "no further remediation" letters and was considered cleaned up, the team planted native species to create pockets of habitat for wildlife, expand greenspace for the community, and reduce stormwater runoff by reducing paved surfaces. See Appendix A for more detailed information about this example; this document's cover also includes a photograph of this pocket park.

Coordinating with Other Agencies. A major component of OUST's efforts to support the revitalization of contaminated sites caused by leaking USTs is collaboration with federal, state, and local agencies, and tribal and private partners to foster the revitalization and reuse of petroleum-contaminated sites. OUST also works with numerous grant recipients to enhance their efforts to revitalize petroleum brownfields. For example, OUST collaborated with the Indiana Brownfields Trails and Parks Initiative, which uses EPA grant funding to provide environmental assessments to local governments and non-profits for brownfields properties (including petroleum brownfields) where parks, trails, or other green uses are planned (see www.in.gov/ifa/brownfields/files/TPI_Fact_Sheet_6-18-08.pdf for more information on this state program). OUST is also partnering with EPA's Office of Policy, Economics, and Innovation (OPEI) to utilize several assistance mechanisms, such as the SmartGrowth America National Vacant Properties campaign. This campaign provides local planners with the information needed to consider viable reuse options, such as green or open spaces, at abandoned or under-utilized service stations and other petroleum brownfields.

OUST entered into a cooperative agreement with the WHC to help maximize the ecological benefits of reusing petroleum brownfields. One goal of the agreement is to demonstrate how federal, state, and local governments, tribal partners, industry, and community groups can use ecological revitalization to facilitate the restoration of petroleum brownfields for a variety of uses, including wildlife habitat. Under the agreement, the WHC will demonstrate the use of the latest technologies for applying ecological enhancements to site cleanups. Specific objectives for the partnership include: (1) achieving greater regulatory flexibility and support for ecological enhancements; (2) developing a strategy for obtaining constructive and meaningful stakeholder involvement; (3) ensuring sound scientific and technical support for ecological enhancement practices; and (4) promoting the value of ecological enhancements through a broad range of communication tools. OUST works with the WHC to identify opportunities to include ecological enhancements in end use plans at petroleum-contaminated sites. The pocket park project highlighted in the text box on the previous page is one of several successes resulting from this collaboration. WHC documents and provides case studies on a variety of programs on the following WHC Web site: www.wildlifehc.org/brownfield_restoration/lust_pilots.cfm.

OUST collaborated across all levels of government and with private industry to develop a Petroleum Brownfields Action Plan that improves stakeholder communications; expands technical assistance to states, tribes, and local governments; explores potential policy changes; and builds upon existing successes by expanding partnerships and testing new and innovative approaches to petroleum brownfields revitalization (EPA 2008d). The Action Plan provides a comprehensive framework for enhancing revitalization efforts at petroleum brownfields and promoting information sharing from both public and private sector efforts to revitalize petroleum brownfields. Four initiatives outlined in the Action Plan cover broad areas and can further EPA's collective efforts to highlight all applicable reuse options. Tasks within three of those initiatives are applicable to ecological revitalization and include the following:

- **Action Item 1.3** provides a basis for developing a "petroleum reuse/options catalogue" that could help compile and update information on reuse options and associated partnerships, as well as provide insights for interested parties to consider when addressing comparable sites.
- **Action Item 2.3** provides a framework to help eligible entities develop voluntary inventories of petroleum brownfields that complement local end use planning efforts.
- **Action Item 4.2** promotes the use of greenspace or wildlife habitat through collaboration with wildlife habitat organizations and property owners (of abandoned oil fields or urban petroleum brownfields) to support converting these properties to wildlife habitats.

OUST does not currently track the indicators listed in **Table 1-1** related to the status and type of end use. However, OUST is committed to tracking the mandatory measures and has developed the OUST Cross-Program Measures commitment memorandum (EPA 2007e). Petroleum brownfields sites are difficult to track and coordinate because of their small size, scattered distribution, variable ownership, and associated uncertainties in cleanup costs and liability. Continued coordination with organizations, such as the WHC, could help to provide a consistent means of tracking site reuse. Revitalizing petroleum sites also remains a local endeavor, and by enhancing public-private coordination, OUST intends to promote the appropriate use of petroleum brownfields sites to help meet community, end user, and stakeholder needs. Ultimately, though, local organizations drive the end use of each site.

Tools and Resources. OUST provides a variety of information resources about its programs, policies, and partners. The following Web sites provide access and information about its resources:

Visit www.epa.gov/swerust1/pubs/index.htm for publications that support the investigation and cleanup of leaking USTs.

Visit www.epa.gov/swerust1/rags/ustfield.htm to learn more about the USTFields Initiative and to access case studies on the pilot projects for examples and lessons learned associated with the reuse of former UST properties.

More information about the issues and opportunities associated with petroleum or UST brownfields cleanups is also available at www.nemw.org/petroleum%20issue%20opportunity%20brief.pdf (Northeast-Midwest Institute 2007; EPA 2008e).

3.0 Technical Considerations for Ecological Revitalization

There are several technical considerations for implementing ecological revitalization while cleaning up a property that are common to each of the cleanup programs discussed in Section 2.0. The objectives of ecological revitalization and those of the cleanup process are best accomplished if they are coordinated carefully. This section summarizes technical considerations for common cleanup and revitalization technologies that stakeholders can use during planning and design with the intent to minimize ecological damage during cleanups. Specifically:

- Section 3.1 presents factors to consider when selecting cleanup technologies for ecological revitalization.
- Section 3.2 addresses issues that may occur when waste is left in place at a cleanup property, how they could affect ecological revitalization, and potential approaches to mitigate these issues.
- Section 3.3 identifies ways to minimize ecological disruptions during cleanups.

3.1 Considerations When Selecting Cleanup Technologies for Ecological Revitalization

When designing and implementing any cleanup action at a contaminated property, it is necessary to consider certain factors related to natural resources or ecological revitalization (see text box below). Numerous *in situ* cleanup technologies can be used to ensure that contaminated properties are managed in a manner that protects human health and the environment; complies with federal, state, and local cleanup requirements; and allows for safe ecological revitalization. These cleanup technologies can include source control treatment (for example, soil vapor extraction and bioremediation), source control containment (for example, caps and barriers), institutional controls, and monitored natural attenuation. For additional information on a variety of cleanup technologies, visit EPA's CLU-IN Web site (www.clu-in.org/techfocus) and the Annual Status Report (www.clu-in.org/asr). These cleanup technologies can affect ecosystems such as wetlands, streams, and upland areas such as meadows, prairies, and woodlands; therefore, it is important to consider their possible effects during ecological revitalization. While many of these effects are technology and property-specific, some general considerations apply, including the following:

- **Amendments**: Some *in situ* treatments involve adding amendments to the contaminated media. Project managers could evaluate their effects in the subsurface, their potential for eventual transport to surface waters, and their possible subsequent adverse effects on plant and animal communities. Some examples of soil amendments include organic matter additions such as biosolids, compost, manures, digestates, pulp sludges, yard wastes, and ethanol production by-products; lime; wood ash; coal combustion products; foundry sands; steel slag; dredged materials; and water treatment residuals. At the California Gulch Superfund Site in

When designing and implementing a cleanup action, it is important to consider the following:

- Physical and biological condition of the property and its location in relation to local and regional plant and animal species
- Regulatory requirements governing cleanup and protection or creation of ecologically significant areas
- Temporary and long-term ecological impacts
- Types of habitats that are to be protected, restored, or created at the property

Colorado, the remediation team applied lime and municipal biosolids to reduce the acidity of mine tailings and to reduce the bioavailability of heavy metals at the site (see **Figure 3-1**). For additional information on soil amendments, see the following document: www.clu-in.org/download/remed/epa-542-r-07-013.pdf.

- **Regulatory requirements**: Federal and state regulations may apply to organic amendments such as biosolids, manures, and pulp sludges. State and local regulations apply to pH-adjusting amendments such as lime and wood ash as well as mineral amendments, such as foundry sand and dredged materials. For additional information, see the following document: www.clu-in.org/download/remed/epa-542-r-07-013.pdf (EPA 2007d).

- **Attractive nuisance**: An attractive nuisance is an area, habitat, or feature that is attractive to wildlife, where waste or contaminants that have been left on site after a property is cleaned up that may be harmful to plants or animals. One objective of cleaning up such a property is to remove the pathway from a contaminant to a receptor. Some cleanup technologies, such as amended covers, are designed to prevent contact exposure, but they are not a barrier against burrowing animals. Preventing burrowing animals that could cause damage to a cleanup technology from entering the area, through fencing or other means, would help to keep the remedy intact, and protect the animals from coming in contact with the waste left on site. For additional information, see the following document: www.clu-in.org/s.focus/c/pub/i/1438.

- **Equipment and utility location**: Equipment generally needs periodic maintenance and monitoring. The cleanup team can maximize potential for habitat formation and biodiversity, and minimize disruption, by carefully considering the location of equipment. This might mean placing equipment near the edge, rather than in the middle, of a valuable habitat. For example, confining property disturbance to areas within 15 feet of roadways.

- **Hydrology and surface water management**: Cleanup technologies that could affect hydrology need to be designed carefully to avoid adverse effects on existing and anticipated habitat. For example, over pumping by ground water pump and treat (P&T) systems can cause dewatering of wetlands because over pumping lowers the water table (EPA 1993). Alternatively, discharging process water to surface waters and wetlands changes water depth, turbidity, circulation, and temperature. The use of settling basins and other such measures can help moderate discharges to wetlands and streams.

- **Surface vegetation**: Cleanup project managers are encouraged to consult technical experts to determine appropriate surface vegetation that will thrive but not interfere with the cleanup. For example, revegetation designed to emulate the native plant communities in the surrounding area would increase chances of success. However, vegetation growing near equipment related to a cleanup technology, such as a diversion wall, may prevent access to the equipment for maintenance and could cause performance issues. In addition, it is important to consider ecological succession when determining appropriate vegetation. Plant communities will naturally shift toward a climax community unless periodic maintenance is performed. When the cleanup technology, such as phytoremediation, employs vegetation, the plants selected to phytoremediate can also serve as a buffer to control runoff or stabilize soil or streambanks. Stakeholders can obtain technical assistance through a variety of sources, including EPA's regional BTAG (www.epa.gov/oswer/riskassessment/ecoup/pdf/v1no1.pdf), EPA's Emergency Response Team (www.ert.org), and EPA's Ecotools Web site (www.clu-in.org/ecotools).

The considerations mentioned above, in addition to others shown in **Table 3-1** at the end of this section, play a role in addressing cleanup planning and design issues when considering ecological revitalization at properties where waste is left in place.

Figure 3-1: Before and after photographs of the California Gulch Superfund Site in Colorado where site managers used high rates of lime amendment to neutralize the acidity of the mine tailings and applied municipal biosolids directly into the tailings along the Upper Arkansas River. See Appendix A for additional information. *Photographs courtesy of Michael Holmes, EPA Region 8.*

3.2 Cleanup Planning and Design Issues and Ecological Revitalization

The text box at the right outlines some general steps when planning and carrying out ecological revitalization projects during cleanup planning and implementation. However, a number of issues associated with the application of a cleanup technology can alter the effectiveness of the cleanup or the ecological revitalization of a property. **Table 3-1** at the end of this section presents several issues that may occur when waste is left in place at a cleanup property, how they could affect ecological revitalization, and potential approaches to mitigate these issues. By carefully accounting for these issues at the outset, cleanup project managers can ensure the long-term success of the cleanup and minimize the potential negative effects of the cleanup approach on future uses of the property.

General steps when planning and implementing an ecological revitalization project

- Determine pre-disturbance and reference conditions
- Conduct a property inventory
- Establish revitalization goals and objectives
- Evaluate revitalization alternatives
- Develop a property-specific ecological design
- Prepare specifications for construction contractors
- Construct habitat features
- Conduct maintenance and monitoring activities

3.3 Minimizing Ecological Damage During Cleanups

Cleanups that include excavation and require earthmoving equipment can disrupt the surface area of a property and cause considerable loss of existing habitat as well as erosion, sedimentation, and colonization by invasive plants. These disruptions may also cause sedimentation or otherwise adversely affect ground water and nearby surface waters. To minimize the effects on habitat and encourage successful ecological revitalization, cleanup project managers may take steps to minimize excavation and other surface disruptions, avoid erosion and sedimentation, and protect the existing flora and fauna, by considering the following approaches (EPA 1993; Natural Resources Council [NRC] 1992; Kent 1994):

Develop and Communicate Ecology Awareness and Procedures. The process of ecological revitalization begins in the assessment or investigation phase, not after the remedy has been designed and is underway. Contractors and construction engineers are often not cognizant of sensitive ecological areas or aware that they can minimize disturbance and protect the ecology. Cleanup project managers can articulate a preservation policy and distribute it to everyone involved with on-site activities. Cleanup project managers can also incorporate requirements to protect habitat or species into construction plans, specifications, and contracts, as appropriate.

Design a Property-Wide Work Zone and Traffic Plan. The cleanup project manager can delineate staging areas, work zones, and traffic patterns to minimize unnecessary disruption of sensitive areas and existing habitat on or near a property. The cleanup team can delineate areas not requiring surface disruption and areas off-limits to disturbance, such as steep slopes, sensitive habitats, and clean stream corridors, with fences, tape, or signs to avoid disturbance by property workers and equipment.

Minimize Excavation and Retain Existing Vegetation. Earthmoving can destroy the roots of trees and other plants as well as disturb vegetation in uncontaminated areas. In addition, compaction of soil is also damaging to roots. These activities can be restricted to areas essential for the cleanup and avoided in all other areas. Some areas with low contamination levels or immobile contaminants posing no unacceptable risk to human health or the environment may be better off left undisturbed, if the disruptive effects of excavation outweigh the benefits of further cleanup, especially in valuable habitats (EPA 1998). Treatment and monitoring technologies are less invasive cleanup measures than excavation.

Myers Property Superfund Site, New Jersey

At the Myers Property Superfund site in Hunterdon County, New Jersey, (see case study in Appendix A), RPMs are saving select trees in areas with low levels of contamination by hand digging around the roots to a level of six inches. Excavated soil will be replaced with clean topsoil from off site. The site will be monitored in case large trees fall and expose soils deeper than six inches.

Phase Site Work. Sometimes cleanup project managers can phase construction by stabilizing one area of the property before disturbing another. This approach can reduce total soil erosion for the entire property and allows for revegetation or redevelopment of some areas immediately after cleanup. The cleanup project manager can also schedule construction to minimize the area of soil exposed during periods of heavy or frequent rains, and avoid sensitive periods (breeding, nesting, etc.) of certain species. For example, project managers at the Rocky Mountain Arsenal site (see case study in Appendix A and a photograph on the cover of this document) suspended cleanup activities during certain seasons to avoid disturbing the nesting and breeding of the bald eagle and other sensitive species.

Consider Property Characteristics. During the ecological revitalization of a property and to increase chances of successful revitalization, it is important that ecologists consider the following property characteristics: property size, existing habitat, proximity to undisturbed areas, topography, natural water supply, access, biodiversity (preserved by establishing connections between habitats or enlarging habitats), contaminant bioaccumulation (assessed during an ERA [EPA 1998, 1999a]), health of

Rocky Mountain Arsenal, Colorado

At the Rocky Mountain Arsenal, project managers recognized that cleanup-related traffic and road building could have major effects on the existing habitat at the 27-square-mile property. To facilitate reuse of the property as a wildlife refuge, they developed a property-wide traffic plan that routed traffic around valuable habitat and sensitive areas, minimized the potential for erosion and sedimentation, and used existing roads wherever possible. See the Rocky Mountain Arsenal case study in Appendix A for additional details.

species and ecosystems, and threatened and endangered species (usually involves the assistance of a professional biologist or ecologist). Consider surrounding habitat when selecting native species for revegetation to increase chances of success. Urban properties pose additional challenges because they are typically small and may be subject to heavy runoff containing pollutants.

Protect On-Site Fauna. In some cases, the project team may temporarily relocate on-site fauna that is being protected. Relocation may involve humane trapping and release, but less disruptive techniques may also be effective. For example, to relocate beavers and alligators at the French Limited Superfund Site in Crosby, Texas (see case study in Appendix A), project managers reduced their food supply in areas to be treated and increased the food supply in other suitable areas of the property. To protect fauna such as snakes, turtles, and some nesting birds that prefer edge habitat, it is necessary to consider careful use and parking of construction equipment in sensitive areas. For example, using construction equipment on edge habitat, or even using it to store equipment or fill material can adversely affect these species.

Locate and Manage Waste and Soil Piles to Minimize Erosion. Property cleanup may include the creation of temporary waste or soil piles to store contaminated soil for treatment or to store treated soil before redeposition. To minimize disruption of the local habitat, the cleanup project manager can structure stockpiles to minimize runoff; locate them away from steep slopes, wetlands, streams, or other sensitive areas; place them away from tree root zones to avoid soil compaction; and cover or stabilize them to control erosion and dust.

Design Containment Systems with Habitat Considerations. Building containment systems usually removes existing biota but can greatly improve the habitat, especially if the contamination present has severely degraded the area. While revegetation over containment areas or treatment systems must not detract from the effectiveness of the cleanup, cleanup project managers can design the cleanup components with ecological revitalization in mind. Cleanup project managers may also want to consider the type of contaminants, their stability, the media through which they travel, and the anticipated future land use. In addition, they may choose to avoid features that could damage the containment system or create an attractive nuisance. Where feasible, plan to allow enough soil above the protective cover to support the root systems of the intended vegetation. The use of fencing, removing access to potential food sources, or providing sufficient soil cover over the contaminated material can discourage wildlife from coming into contact with the contaminated material or from damaging a containment area.

Reuse Indigenous Materials Whenever Practical. Reusing logs, rocks, brush, or other materials found on site can provide logistical and ecological advantages as well as cost savings. Topsoil from on-site sources is usually well suited to support native vegetation. Treated soil and other materials can also be used as backfill, reducing the need for borrow areas for clean fill. Green waste, such as logs and branches can be used on site, to a limited degree, to create structure within the new habitats. Excess woody material can be shredded, composted, and used as a soil amendment. For example, at Loring Air Force Base in Northeastern Maine (see case study in Appendix A), boulders and cobbles, larger than 15 centimeters in diameter, were removed from the streambed and nearby trees during cleanup and later used in stream reconstruction, after completion of cleanup activities. Reuse of native materials at this property significantly reduced the need for additional materials and thereby achieved cost savings.

Control Erosion and Sedimentation. Revitalization areas usually need erosion and sedimentation control measures to avoid disturbing sensitive areas, even when state or local regulations do not require them. These measures can include retaining sediment on the property and managing runoff using filters, such as compost or other organic materials.

Ensure that Borrow Areas Minimize Impact on Habitat. Borrow areas, locations where cleanup teams excavate clean soil for use elsewhere during a cleanup, may be located and used with ecological revitalization objectives in mind. For example, borrow areas can be located in low-value areas to create or improve habitat and be designed, contoured, and vegetated to meet aesthetic and habitat considerations. Based on consultations with the USFWS, project managers at the Rocky Mountain Arsenal (see case study in Appendix A and a photograph on the cover of this document) designed borrow areas to establish the habitat of a planned wildlife refuge.

Avoid Introducing New Sources of Contamination. If not properly managed, cleanup activities can introduce new sources of contamination that may affect habitat and ecological receptors. Contamination can result from materials used on the property, fugitive dust emissions, and operations of equipment and sanitation facilities. Materials that can cause contamination include pesticides, herbicides, fertilizers, petroleum products, treatment agents, and solid wastes. To avoid introducing these new sources, storage areas can be sheltered from the elements, lined with plastic sheeting, surrounded by berms, and regularly inspected for releases. In addition, equipment maintenance can be done in suitable staging areas and adequate sanitation facilities for property workers can be provided away from streams, wetlands, and other sensitive areas.

Prevent the Introduction of Undesirable Species. Non-native plant species can invade and destroy native species. To prevent introducing undesirable species, monitor barren and disturbed areas, which are susceptible to colonization by undesirable plants, and remove undesirable species where necessary. In addition, equipment operators can wash trucks and equipment before entering a property to avoid introducing invasive plant seeds. Clothing and shoes can also be managed to avoid introducing invasive plant seeds.

TABLE 3-1: Cleanup Planning and Design Issues When Waste is Left on Site and Other Considerations for Ecological Revitalization

Issue	Property Type[2]	Potential Impact	Solution/Consideration
Attractive Nuisance Issues: An area, habitat, or feature that is attractive to wildlife and has, or has the potential to have, waste or contaminants left on site that are harmful to plants or animals after a property is cleaned up	Landfill Mining Site Brownfield Military Installation Foundry Gas Station Metal Plating Facility Refinery Tannery	• Harm wildlife if (1) an exposure pathway exists from contaminants left on site that could directly harm wildlife or travel up the food chain; or (2) wildlife interfere with the cleanup, thereby creating an exposure pathway	• Consider potential ecological risks throughout the cleanup process • Conduct a thorough ecological risk assessment to avoid potential attractive nuisance issues • Carefully consider plant species and the type of animals that those species will attract; protect newly planted species until they are established • For additional information, refer to EPA's fact sheet titled "Ecological Revitalization and Attractive Nuisance Issues" (EPA 2007c)
Managing Gases: Depending on the waste composition, some containment sites have the potential to generate gas	Landfill	• Provide fuel for fire or explosions • Stress vegetation • Damage cover system • Infiltrate nests or other wildlife homes • Create other health or safety hazards	• Determine ability of waste to generate gas during planning stage (EPA 1991) • Build gas collection systems • Place components where they (1) do not interfere with planned uses, (2) minimize noise and odors, and (3) are not easily accessible to trespassers or wildlife • For additional information, refer to the EPA fact sheet "Reusing Cleaned Up Superfund Sites: Commercial Use Where Waste is Left On Site" (EPA 2002a) and "Landfill Gas Control Measures" (www.atsdr.cdc.gov/HAC/landfill/PDFs/Landfill_2001_ch5.pdf)
Restoring Soil: Soils, especially those found in urban, industrial, mining, and other disturbed areas suffer from soil toxicity, too high or too low pH, lack of sufficient organic matter, reduced water-holding capacity, etc.	Mining Site Manufacturing Facility Metal Plating Facility Brownfield Refinery Tannery	• Decrease ability to support vegetation, which can lead to increased erosion and offsite movement of contaminants by wind and water	• Consider appropriate soil amendments (inorganic, organic, or a mixture) to limit contaminant bioavailability and restore appropriate soil conditions for plant growth by balancing pH, adding organic matter, restoring soil microbial activity, increasing moisture retention, and reducing compaction

[2] See Table 2-1 for EPA Programs that can apply to each property type.

TABLE 3-1: Cleanup Planning and Design Issues When Waste is Left on Site and Other Considerations for Ecological Revitalization, Continued

Issue	Property Type[2]	Potential Impact	Solution/Consideration
Settlement: The consolidation of subsurface materials at closed-in-place sites due to compaction or degradation	Landfill	• Rate and magnitude of settlement may affect the type of habitats that will be successful • Damage containment systems, alter slopes, cause gullies to form, and disturb other property features • Municipal landfills can settle up to 30 percent of the landfill depth over 15 to 30 years	• Consult with geotechnical engineer during cleanup planning to estimate settlement magnitude, distribution, and rate • If necessary, delay ecological revitalization until settlement has largely ceased, but under long-term settlement scenarios, vegetation will likely adapt to the changing property conditions • Use a nurse crop like oats, to control erosion and provide greenspace • Use construction techniques, such as preloading, vibrocompaction, and dynamic compaction, to accelerate settlement (these approaches will not affect settlement caused by biodegradation); however, do not compact topsoil because over-compaction of topsoil will result in vegetative failure
Stabilizing Metals: Some property soils contain toxic levels of metals that can be harmful to plants or animals	Mining Site Metal Plating Facility Brownfield Refinery Tannery	• Metals taken up by plants which are eaten by animals causing a potential attractive nuisance • Metals leach into ground water	• Use soil amendments to chemically precipitate or sequester metals that are present in the soil; this can reduce metal availability to plants and metal leaching into water • Select plant species based not only on availability but also on their ability to establish and grow in a newly created root zone and the species' inability to uptake metals
Surface Vegetation: Used to limit soil erosion, promote evapotranspiration and surface water management, and, in some cases, may be a component of the cleanup (for example, phytoremediation)	Landfill Mining Site Brownfield Military Installation Foundry Gas Station Metal Plating Facility Refinery Tannery	• Not all plants are well-suited to property conditions • Roots can physically damage equipment for a cleanup treatment technology, such as a barrier or well	• For wetlands, study the proper hydrology, tidal elevation, and height of a newly constructed wetland profile; these factors are of great importance to allow the new wetland (both saline and fresh) to flourish • When selecting plants, consider Executive Order (EO) 13148, which promotes use of native species • Place equipment away from areas where deep-rooted vegetation will be planted • Choose native plants found in the surrounding natural areas because they have the most chance of success, require the least maintenance, and are the most cost-effective in the long term • Ensure the waste containment system is properly designed and implemented to maintain system integrity while supporting a variety of plants • For additional information, refer to EPA's fact sheet titled "Revegetating Landfills and Waste Containment Areas Fact Sheet" (EPA 2006d)

[2] See Table 2-1 for EPA Programs that can apply to each property type.

TABLE 3-1: Cleanup Planning and Design Issues When Waste is Left on Site and Other Considerations for Ecological Revitalization, Continued

Issue	Property Type[2]	Potential Impact	Solution/Consideration
Surface Water Management: Includes a variety of activities that protect the natural functions and beneficial uses of surface waters	Landfill Mining Site Brownfield Military Installation Foundry Gas Station Metal Plating Facility Refinery Tannery	• Affects nearby vegetation, streams, lakes, and wildlife migration routes through erosion or sedimentation • Runoff controls and water diversions implemented as part of a cleanup influence water tables and the rate of flow into streams or wetlands • Erodes the top layer of a cover system • Percolates into a cap	• Design protective caps to prevent precipitation from infiltrating into the subsurface and grade the cap to establish an effective slope (usually 3-5 percent) • Route runoff through settling basins to collect sediment to reduce impacts to property hydrology and construct runoff controls to reduce the volume and rate of runoff to low-lying areas, wetlands, or streams • Use rerouted runoff to create new wetland habitat or enhance existing habitat to provide natural controls and reduce contaminant transport • Build drainage channels and swales and design diversions where possible to minimize changes to natural drainage patterns or the quantity of surface water flows to wetlands or streams • For additional information, refer to EPA's fact sheet titled "Controlling the Impacts of Remediation Activities in or Around Wetlands" (EPA 1993)
Timing: The time at which ecological revitalization is considered during the remedial planning process	Landfill Mining Site Brownfield Military Installation Foundry Gas Station Metal Plating Facility Refinery Tannery	• The longer planning is delayed, the greater the possibility that fewer reuse options will be available	• Begin revitalization planning as early as possible • Begin developing a revitalization project on parts of a property before a cleanup is completed, if possible • Consider advice from a restoration ecologist to determine the proper season to plant grasses, shrubs, and trees • Consider breeding seasons and other timing issues to avoid affecting sensitive species when scheduling remedial or revitalization activities
Utilities: Can include sanitary sewers, water, telecommunications, natural gas, and electricity	Brownfield Landfill Manufacturing Facility Military Installation Foundry Gas Station Metal Plating Facility Refinery Tannery	• Act as a conduit for gas migration • Facilitate water infiltration into a waste containment area • Require excavation into a waste containment area and contaminated material if utility repairs are necessary • Increase the quantity of leachate generated if sewer lines below a waste containment area begin to leak • Can be damaged by settlement	• Include special provisions to ensure utilities do not hinder the effectiveness of the cleanup or ecosystem functions; for example, avoid burying a utility line in a protective cap or placing it in an area where trees will be planted • For additional information, refer to the following EPA report: "Reusing Cleaned Up Superfund Sites: Commercial Use Where Waste is Left On Site" (EPA 2002a)

[2] See Table 2-1 for EPA Programs that can apply to each property type.

4.0 Wetlands Cleanup and Restoration

Wetlands are of particular concern for cleanups because in addition to intercepting storm runoff and removing pollutants, they provide food, protection from predators, and other vital habitat factors for many of the nation's fish and wildlife species (EPA 2008g). Section 3.0 discusses the general considerations that apply during planning and design of a wetland cleanup and restoration. This section summarizes wetland cleanup and restoration, focusing on specific considerations during planning and design.

Whether a cleanup involves restoring an existing wetland or creating a new one, a cleanup project manager must typically take the following steps (EPA 1988; USFWS 1984):

- Evaluate the characteristics, ecological functions, and condition of wetlands related to the property
- Determine the type of wetland functions and structures that would be beneficial in the area after the cleanup
- Develop a wetland design that will achieve the stated ecological functions
- Design the cleanup and wetland features to ensure that cleanup activities have minimum effect on existing wetlands and other ecosystems and do not create an attractive nuisance (see **Table 3-1** for additional information on attractive nuisance issues)
- Specify and implement maintenance requirements

Once it has been determined that a cleanup will affect a wetland, several key factors need to be considered, including the following:

Wetland Characteristics. The cleanup project manager may wish to determine wetland characteristics to develop a thorough understanding of the role of the wetland in the overall ecosystem and the relationships between the various plant and animal species within the wetland. It is also important to determine if any endangered, sensitive, or commercially important wetland species are present.

Wetland Regulatory Requirements. Several regulatory requirements generally apply when a cleanup or reuse project affects wetlands, including Sections 401, 402, 403, and 404 of the Clean Water Act; Section 10 of the Rivers and Harbors Appropriation Act; and the Federal Agriculture Improvement and Reform Act, commonly known as the Farm Bill. Depending on the type of cleanup and the law under which action is taken, permits may be needed prior to conducting any cleanup activities.

Wetland Vegetation and Hydrology. Analyses of hydrologic and soil conditions help define the property's wetland vegetation associations (a known plant community type, uniform habitat conditions, and uniform appearance). Generally, restoring hydrology and re-establishing a previous vegetation association tends to lead to a successful wetland ecosystem. For properties where the historical native vegetation association cannot be determined, use nearby wetlands with similar soil and hydrology

Wetland Mitigation and Ecological Revitalization

Cleanup project managers may consider ecological revitalization part of wetland mitigation depending on the property-specific habitat. However, if the wetland mitigation is part of a contaminant treatment system and is not intended to provide habitat, it cannot be considered ecological revitalization. For additional information on wetland mitigation requirements, go to www.epa.gov/wetlandsmitigation. For additional information on wetlands in general, go to www.epa.gov/wetlands.

as a guide. See example in text box to the right and **Figure 4-1** at the end of this section. For additional information on reference wetlands, visit the Society for Ecological Restoration's Web site under Section 5 of the Ecological Restoration Primer: www.ser.org/content/ecological_restoration_primer.asp. Also, consider water availability and soil type when selecting and placing the vegetation. Where appropriate, seeded species that establish quickly may be planted first, followed by species that are more difficult to establish. Where available, a natural seed bank in existing wetland soils is often adequate for establishing wetland vegetation.

Use of Neighboring Wetlands as Reference at Naval Amphibious Base Little Creek, Virginia Beach, Virginia

After removing a 1.2-acre landfill, the Navy, in partnership with EPA and Virginia Department of Environmental Quality, constructed a tidal wetland in the Chesapeake Bay. The team achieved tidal wetland hydrology by constructing two connecting channels to the nearby Little Creek Cove. In addition, they used a neighboring marsh as a reference wetland to determine appropriate plants to place along designated elevations to establish tidal wetland vegetation. See Appendix A for additional information on this case study.

Wetland Wildlife. Wetlands provide valuable wildlife habitat. The ability of a wildlife species to thrive in a wetland is dependent upon a number of factors, including the minimum habitat area necessary for the species, the minimum viable population of the species, the species' tolerance for disturbance (for example, excavation or installation of ground water pumps), and the wetland ecosystem's functional relationship to adjacent water resources and ecosystems. Thus, three factors will play a major role in determining the effectiveness of a wetland for long-term wildlife use: (1) the size of the wetland, (2) the relationship of the wetland to other wetlands, and (3) the level and type of disturbance (Kent 1994; NRC 1992; EPA 1994).

Wetland Maintenance. A variety of wetland maintenance activities are needed to ensure long-term success, including weed control and management of aggressive exotic species, such as common reed (*Phragmites australis*), purple loosestrife (*Lythrum salicaria*), water hyacinth (*Eichornia crassipes*), and salvinia (*Salvinia molesta*). In addition, installing wire screens or other barriers around the plants or the planted area to control deer, rabbit, or beaver grazing can help protect vegetation until the ecosystem becomes established. Periodic monitoring of the wetland for plant loss, erosion, insect or disease infestations, and litter or debris buildup is also important. For properties near populated areas, public education efforts can help reduce maintenance issues associated with litter or debris dumping, off-road vehicle use, or other human activities that may threaten the long-term success of a wetland project.

Treatment Wetlands. Wetlands created to treat contaminants have some additional considerations regarding ecological revitalization and attractive nuisance issues. Conducting an ERA and monitoring of the treatment wetland until it meets cleanup goals can help to identify any potential attractive nuisance issues. Cleanup project managers are employing this approach on a variety of cleanups. For example, a public-private partnership is installing a series of passive treatment systems, including treatment wetlands, to treat acid mine drainage from abandoned surface and underground coal mines in western Pennsylvania. After passing through a series of limestone-lined ponds to neutralize pH, the water is sent through an aerobic constructed wetland to remove iron hydroxides. The system can even recover metals removed from the water so recovered metal can be sold (see Appendix A for additional information on this case study).

Bunker Hill Superfund Site in the Coeur d'Alene River System in Kellogg, Idaho

At the West Page Swamp area of the Bunker Hill Superfund Site, EPA contractors spread a cap composed of compost and wood ash over the soil to reduce accessibility and bioavailability of the underlying tailings and to restore wetland function.

Figure 4-1: Before and after photographs of Naval Amphibious Base Little Creek in Virginia, where the remediation team converted a landfill into a tidal wetland. See Appendix A for additional information. *Photographs courtesy of Bruce Pluta, EPA Region 3*.

Treatment wetlands are also used as the final polishing treatment step of a remediation scheme. For example, stormwater or effluent from ground water treatment systems can be sent through restored or created wetlands before being released to nearby waterways. This step helps remove suspended solids and other pollutants from the stormwater or effluent.

Ideally, cleanup goals will be met when using a treatment wetland to assist in property cleanup. Once the property meets its cleanup goals, components of the remedy, including a wetland, may no longer be necessary for further treatment. At this stage, coordinating with co-regulatory partners to determine long-term maintenance and stewardship responsibility for the wetland is critical. Section 7.0 discusses long-term stewardship.

For additional information on treatment wetlands, visit the following Web site: www.epa.gov/owow/wetlands/watersheds/cwetlands.html.

5.0 Stream Cleanup and Restoration

Stream cleanup and restoration are important because streams serve as corridors for migratory birds and fish, and they provide habitat to many unique species of plants and animals (EPA 2008g). Cleaning up a stream corridor can be complicated, as cleanups often disrupt the stream flow and habitat. This section provides an overview of considerations for designing and implementing cleanups that facilitate ecological restoration of streams and stream corridors and mitigating adverse ecological impacts of constructing cleanup features. A successful stream cleanup, combined with appropriate restoration strategies can hasten the recovery of degraded stream corridors and begin the natural process of restoring their ecological functions (EPA 1995).

An important first step in cleaning up a stream corridor is to assess the possible sources of disturbance from cleanup activities. Baseline data can be gathered on existing species, in-stream and riparian habitat, soil characteristics, and stream function to characterize potential degradation. Other disturbances to characterize include stream channel alteration, water quality impairment, invasion by exotic species, loss of riparian vegetation, and compaction or undercutting of streambanks. Defining the conditions of the stream corridor prior to the disturbance can help to identify the cause of the disturbance. Another important step is to determine the type of ecosystem that can be established in the stream corridor. When historical records are unavailable, information on undisturbed, nearby stream corridors with similar physical characteristics can help determine the type of ecosystem that will likely be successful at the property. The following considerations are critical to a successful stream cleanup and restoration:

Importance of Stream Corridors

Healthy stream corridors can provide important habitat for fish populations; erosion and sedimentation control; high-quality water for wildlife, livestock, flora, and human consumption; opportunities for recreationists to fish, camp, picnic, and enjoy other outdoor activities; and support for diverse plant and wildlife species.

Stream Channel Restoration. Removing contaminated sediment and soil from stream channels and banks during a cleanup typically results in severe alteration of stream flow. In such instances, reconstruction of stream channels and banks is usually necessary. Decisions about stream channel width, depth, cross-section, slope, and alignment profoundly affect future hydrology (and the resulting ecology) of the stream system. Restoration design typically considers factors such as the physical aspects of the watershed, hydrology, sediment size distribution, average flood flows, and flood frequency. When designing a stream channel restoration, the cleanup project manager can try to anticipate the effects of future land uses on the watershed. For example, the restoration of riverbanks along the Poudre River was designed to accommodate heavy recreational use while providing ecological benefits (see case study in Appendix A). For additional information, refer to resources listed in Appendix B and the following publication at www.clu-in.org/download/newsltrs/tnandt1208.pdf.

Tidal Channels

Stream channel restoration can include tidal channels. After removing contaminated sediment at the Atlas Tack site in Fairhaven, Massachusetts, site managers used coconut coir fiber logs to stabilize the salt marsh tidal channels. See Appendix A for additional information on this case study.

Streambank Stabilization. Disturbed or reconstructed streambanks often need temporary stabilization to prevent erosion. Temporary stabilization can consist of natural materials such as logs, brush, and rocks, and property planners can design it so as not to hinder permanent revegetation. At the Cache La Poudre River Superfund Site, EPA incorporated boulders and snags into the cleanup to stabilize the streambank while providing habitat (see **Figure 5-1** and case study in Appendix A). In

Figure 5-1: Before and after photographs of the Cache La Poudre River Superfund Site in Colorado, where EPA implemented an ecological remedy to preserve the riverine habitat and restore the streambank. See Appendix A for additional information. *Photographs courtesy of Paul Peronard, EPA Region 8.*

some cases, geotextiles, natural fabrics, and bioengineering techniques may be necessary. Revegetating streambanks using seeding or bare root planting techniques will often fail if the stream floods before vegetation is fully established. Consequently, temporary vegetation for stabilizing streambanks may be more successful using anchored cuttings or pole plantings (that is, woody cuttings or poles inserted and anchored into the streambank) taken from species that sprout readily, such as willows. For additional information, refer to resources listed in Appendix B.

Streambank Vegetation. Wherever possible, it is important to protect existing native vegetation, especially mature trees, during cleanup and restoration activities; however, many properties will need some revegetation. Cleanup project managers may select species for revegetation for their ability to establish a long-lasting plant community rather than as quick fixes for erosion or sedimentation problems. For example, fast growing non-native species may quickly stabilize a denuded stream bank, but over the long term, they may end up invading the entire stream corridor to the detriment of desirable native species. Approaches that attempt to establish ecosystems similar to pre-disturbance conditions tend to have more long-term success and need less maintenance than more highly engineered solutions (for example, gabions or riprap) that reduce the amount of viable habitat. For additional information, refer to resources listed in Appendix B.

Watershed Management. The entire watershed ecosystem affects the health and condition of a water body. Therefore, cleanup and revitalization may need to address watershed processes that degrade ecosystems, such as sediment loading from road cuts or construction, increased runoff from impervious areas, and other point and nonpoint sources of

Fort Collins Stream Corridor Restoration

In Fort Collins, Colorado, soil and ground water contamination migrated to the Cache La Poudre River and contaminated the sediments of this wild and scenic river. Cleanup activities included temporarily re-routing the river and excavating the contaminated sediments. The remediated portion of the river was not channelized, and EPA made an effort to create an unobtrusive remedy by consulting ecological restoration experts to create natural stream characteristics. See Appendix A for additional information on this case study.

pollution. Effective watershed management could even eliminate the need for in-stream restoration approaches.

Bioengineering techniques have become an increasingly popular approach to streambank restoration and maintenance. Bioengineering refers to stabilizing the soil or streambank by establishing sustainable plant communities. Stabilization techniques may include using a combination of live or dormant plant materials, sometimes in conjunction with other materials such as rocks, logs, brush, geotextiles, or natural fabrics. Bioengineering techniques can be more labor intensive than traditional engineering solutions and sometimes take longer to control streambank erosion. Nevertheless, over the long term, they often have lower maintenance costs and create important habitat.

Finally, maintenance such as erosion control, reseeding, and soil amendments may be needed after evaluating the initial progress of stream corridor recovery. Allowing natural processes to shape the ecosystem in the stream corridor will generally lead to self-sustaining, long-term recovery of in-stream, riparian, and upland terrestrial habitats in the stream corridor. Because this process takes time, providing short-term riparian and upland habitats may hasten the return of wildlife to the disturbed area. Cleanup project managers may use engineered habitat structures such as weirs, dikes, randomly placed rocks, riffles and pools, fish passage structures, and off-channel pools to enhance in-stream habitat during the short term. Engineered habitat structures are most effective when installed as a complement to a long-term recovery strategy. For additional information on engineered habitat structures, see Section 8G of the Federal Interagency Stream Restoration Working Group's Stream Corridor Restoration Guide at www.nrcs.usda.gov/Technical/stream_restoration/newtofc.htm.

6.0 Terrestrial Ecosystems Cleanup and Revitalization

Grading or earthmoving operations at cleanup properties can seriously disturb terrestrial plant and animal life at properties. The cleanup process can denude some contaminated properties of all vegetation and topsoil. Establishing a plant community that will thrive with minimal maintenance is a critical step in developing a healthy terrestrial ecosystem on these properties. This section discusses factors to consider when planning terrestrial plant communities in disturbed areas. It addresses (1) general revegetation principles and factors to consider in the course of protecting or creating natural terrestrial ecosystems and (2) specific considerations when creating meadows or prairies and establishing vegetation on semi-arid or arid lands. Section 3.1 presents general cleanup planning and design issues that may also be applicable to the revitalization of terrestrial ecosystems.

Native Plantings at College Park Landfill

At the College Park Landfill in Beltsville, Maryland, cleanup project managers used recycled waste materials such as fly ash and animal and plant by-products as land cover as part of the landfill cap. In addition, the vegetative cover includes diverse native plantings. See Appendix A for additional case study information.

General Revegetation Principles. While restoring terrestrial ecosystems, it is recommended that cleanup project managers consider soil type, plant selection, and timing.

Soil Type. Soil testing is generally necessary to evaluate whether the pH, nutrient availability, toxicity, salinity, and organic material content are appropriate for successful plant establishment. Several organizations provide assistance in soil testing, including U.S. Department of Agriculture (USDA)'s Natural Resources Conservation Service (NRCS) and the WHC. The soil can then be prepared or amended, as necessary, to ensure proper soil texture and conditions. Soil amendments, or residuals from other processes that have beneficial properties when added to soil, may be used in areas without adequate topsoil; if fertilizer is needed, it is important to choose a formulation that meets the growing needs of the selected species (EPA 2007d). The cleanup team may also have to stabilize the soil and apply compost to hold seed in place, aid in establishing plants, mitigate the effect of rainfall on newly seeded areas, preserve soil moisture, and control erosion. Soil stabilization methods include mulching with straw or wood-fiber product, or installing synthetic matting. Cleanup project managers may wish to select soil amendments and stabilization techniques for their ability to improve conditions for germination of the selected species. In addition, some types of soil amendments may help adjust the pH of the soil in preparation for seeding (EPA 2007d). Refer to the following document for more information on soil testing: www.nrcs.usda.gov/feature/backyard/pdf/nutrient.pdf.

Plant Selection. Seed mixtures and plants can be adjusted to suit the soil, climate, hydrology, exposure (to both sun and wind), and topography of an area. Local native populations of plant and seed usually result in higher survival rates and maintain the integrity of the local gene pool. As discussed in Section 3.0, cleanup project managers are encouraged to avoid using non-native species. These species can out-compete and displace native species, disrupt ecological processes, and significantly degrade entire plant communities, both on and off the property.

Amending Soils with Biosolids at a Refinery

In Lima, Ohio, a refinery undergoing RCRA Corrective Action is using biosolids to help create prairie habitat with native grasses, flowers, and trees over a soil cover. See Appendix A for additional case study information.

After seeding, cleanup project managers can protect the seeded areas from grazing animals, vehicles, and other disturbances until plants are well established. Techniques for protecting plantings include fencing, clearly marked access roads, animal repellants, trenches or berms to control run-on and runoff (if they are already part of stormwater control features at the cleanup property), and interim surface stabilization methods such as mulching or matting. Cleanup project managers may need to reseed the area within the planting season to replace damaged vegetation or to achieve the desired plant density. For additional information on seed mixtures and plant selection, visit EPA's GreenAcres Web site (www.epa.gov/greenacres), the Plant Conservation Alliance (PCA) Web site (www.nps.gov/plants), and the Bureau of Land Management's Seeds of Success Program (www.nps.gov/plants/sos).

Timing. It is important to seed during the optimum periods for plant establishment, which are property-specific and vary depending on the type of terrestrial habitat that is being restored. Information on seeding techniques and conditions for individual species is available from NRCS technical guides (www.nrcs.usda.gov), university extension offices, and seed suppliers. If planting cannot occur during optimum periods, cleanup project managers may use a nurse crop, such as annual rye or oats, as ground cover until the appropriate planting season.

Meadows and Prairies. A few additional considerations apply when restoring meadows or prairies. Generally, when seeding an area with native grass species, specialized planting equipment, such as a native grass drill, is needed to ensure good seed to soil contact. Seeds need to be certified and purchased on a pure live seed basis. Grass stands usually do not need fertilizer or irrigation. However, they may need periodic maintenance activities, such as controlled burning, mowing, and removing plant litter, to suppress woody growth and encourage vigorous new growth. To maximize benefits to wildlife, conduct these activities outside of the primary nesting season, preferably in late winter or early spring.

Semi-Arid and Arid Areas. Cleanup project managers may consider a number of additional factors when establishing vegetation in semi-arid and arid areas, including the following:

- **Soil treatment** is important because damage to soil structure and function is a common and serious problem in degraded semi-arid and arid areas. Arid soil, compacted soil, and nutrient-poor soil may need to be improved by adding organic amendments, such as leaf and litter compost, composted manure, biosolids, or mulch that is certified contaminant and weed-free. These amendments could help bind recalcitrant organic compounds and metals and increase the much-needed water holding capacity and fertility. Other measures to improve soil structure and function include soil surface treatments, such as creating pits in soil, to improve water retention in arid land and imprinting, to increase soil moisture and gully control to improve plant establishment.
- **Water availability** for plants may improve if the ground is shaped to collect and retain water. Transplanted seedlings may need limited irrigation to survive until established. Species selections can also be adapted to local hydrology. Too much irrigation may encourage invasive weeds, leave salts at the soil surface that kill plants, or cause infiltration into subsurface contaminated materials.
- **Seed selection** for arid areas is hampered by the limited availability of commercial stocks of dry land seeds. If possible, the project manager may hire a commercial seed collector to collect seed from the local area or an area with similar climate. The alternate collection area needs to be within a 100-mile radius and 500 feet of the altitude of the area to be planted; where the average rainfall is within two inches per year of the annual rainfall for the area; and have similar soil characteristics (Department of the Interior [DOI] 1995). Seed testing can help cleanup project managers ensure that the seeds are of high quality. Proper seed storage will also help maintain the seed's viability until sowing. Visit the Plant Conservation Alliance Web site for a directory of restoration experts and native seed suppliers (www.nps.gov/plants).
- **Planting techniques** primarily include direct seeding and transplanting. Direct seeding is generally less expensive. However, in dry areas this technique is more vulnerable to seed loss from exposure to wind, insects, and rodents, as well as declines in germination rates and plant growth because of insufficient rainfall in the months following planting. The installation of an erosion blanket consisting of straw or coco fiber with biodegradable netting can help prevent seed loss and retain moisture while plants are established. Cleanup project managers may also consider using collected seed to grow container plants for drier areas. If container plants are used, additional time will be necessary to allow the plants to germinate and achieve the desired growth in a greenhouse or nursery before planting. Using container plants can be costly and labor intensive. Because plant losses usually occur, it is prudent to budget for monitoring and replacement.

7.0 Long-Term Stewardship Considerations

Cleanups are risk-based and, when waste is left in place, long-term stewardship is necessary to ensure protectiveness of the remedy; therefore, long-term stewardship responsibilities are an integral part of the cleanup process. O&M activities through responsible stewardship protect the integrity of the cleanup and the functioning of the associated ecosystems after cleanup completion. For example, at the Woodlawn Landfill Superfund Site, WHC and Bridgestone Americas Holding, Inc. conducted ecological revitalization activities at the site to create wildlife habitat. Local volunteers manage the site. In addition, Chicago's pocket park project highlighted earlier in Section 2 incorporated (1) ICs and (2) community involvement in site planning and maintenance, which reduced costs and helped ensure the success of ecological revitalization. See Appendix A for case studies regarding these sites.

There are four major components for a successful O&M program:

- Plan early for long-term stewardship
- Identify and complement general O&M activities
- Establish a monitoring program
- Use ICs

Long-Term Stewardship. EPA's co-regulatory partners, including states, local governments, and tribes, have increasing responsibility and oversight for property assessment and cleanup planning. This property knowledge is particularly important for long-term stewardship as state voluntary cleanup programs and property owners typically have primary responsibility for carrying out maintenance of engineering controls and ICs for the long-term. Therefore, it is essential to prepare for safeguarding the effectiveness of the ecological revitalization activities as early in the cleanup planning process as possible. Regardless of who is responsible for O&M, stakeholders can make agreements to have general maintenance tasks as well as those specific to ecological revitalization implemented by property owners, a local government agency, Trustees, or the community. It may be practical to have the same organization undertake general O&M activities as well as those relating specifically to the ecosystem. For example, at the Silver Bow Creek/Warm Springs Ponds Superfund Site in Montana, the Montana Department of Fish, Wildlife, and Parks, a Trustee, conducts many general and specific monitoring and maintenance tasks (see case study in Appendix A).

Cleanup project managers can also enlist a local group or guardian to conduct long-term stewardship of a property. Such groups are committed to follow-through and have knowledge of local conditions. They can also monitor the ecological revitalization component and look for early signs of any emerging issues. Local government agencies can also provide expertise, equipment, supplies, or other resources to help the local community or group conduct long-term stewardship; this can reduce costs, provide interpretive educational benefits, and help encourage a sense of property ownership by the community.

Stakeholder Collaboration at a Former Refinery in Casper, Wyoming

Stakeholders are successfully achieving cleanup of a BP former refinery in Casper, Wyoming through a collaborative process. The group redeveloped the former refinery into a business park and golf course where the wetland treatment system also functions as a golf course water hazard. To reach agreement on the cleanup, BP worked closely with stakeholders, including the local Audubon Society and the community. The Audubon Society used its local expertise to help determine an appropriate shoreline elevation to maintain the wetlands and mud flats. See Appendix A for a case study regarding this site.

General O&M Activities. In some cases, appropriately designed ecosystem revitalization may be self-sustaining and need little or no maintenance after an initial establishment period. In most cases, however, O&M will be necessary. O&M activities depend on the type of cleanup as well as the ecological revitalization component and, depending on the situation, are often necessary for a long period of time (up to 20, 50, or 100 years). O&M for the overall cleanup typically includes inspection, sampling and analysis, routine maintenance and small repairs, and reporting, as necessary. Cleanup project managers can incorporate ecological revitalization measures into each of these tasks.

- **Inspection needs to occur on a regular basis.** Inspectors can also perform non-routine inspections after unusual events such as earthquakes or large storms. Typically, inspectors check for invasive species, erosion, and dead or dying vegetation, among other items, when assessing the ecological revitalization component of the cleanup. For properties with cover systems in place, inspectors also check for settling, burrowing animals, and pooling water. Cleanup project managers typically include performance standards to measure the success of the project, as well as a detailed description of how team members will conduct inspections, sampling, and maintenance activities.
- **Regular sampling and analysis** helps monitor habitat, ground water, and surface water quality. Monitoring habitat indicators such as plant species composition and percentage of cover helps to determine the success of the revitalization measures. In addition, making a determination of the amount of invasive plant species in the area helps to ensure that they are not overtaking the area. Sampling and analysis includes collecting and chemically analyzing water samples from surface water, wetlands, or ground water wells; soil samples may also be collected and analyzed to evaluate soil conditions. For properties with cover systems in place, sampling would include leachate formation and gas release concentrations. The frequency of sample collection can vary widely and needs to be determined on a property-specific basis.
- **Routine maintenance** may consist of simple activities such as burning, using herbicide, or mowing to control invasive species; maintaining a cover; or repairing perimeter fencing. On properties that have operating treatment plants, routine maintenance may be more complex and may need a full- or part-time plant operator. Typical activities include operating ground water and gas treatment systems, repairing erosion damage, and maintaining rainwater collection and diversion systems. Based on inspection results and plant species composition and cover at the revitalization area, reseeding or replanting may be necessary as well as periodic mowing or controlled burns. Manual or natural controls or herbicides or insecticides applications can also control invasive plants and undesirable insects and diseases. For additional information on maintaining a variety of habitat types, review ITRC's Planning and Promoting Ecological Land Reuse of Remediated Sites (ITRC 2006).
- **Reporting** requirements depend on the cleanup program, and cleanup project managers generally write and submit reports to regulatory authorities after both routine and non-routine inspections. The reports typically include information on the general condition of the cleanup measures, test results from samples collected, and operational data from treatment processes (for example, ground water extraction rate, gas flow rate).

Monitoring Program. A monitoring program, established as part of post-cleanup activities, evaluates the effectiveness of the cleanup in restoring ecological function and reducing ecological risks (EPA 1998, 1999a). Information from baseline surveys and ERAs conducted during the planning process can be the starting point for developing the monitoring program. For example, periodic monitoring of sediment contamination and benthic

Loring Air Force Base in Maine

Cleanup project managers for Loring Air Force Base consulted with the U.S. Fish and Wildlife Service (USFWS) to identify useful indicator species such as dragon fly nymphs, midge flies, dace minnow, and brook trout to monitor the recovery of the stream system after remedial activities. These species were selected because they are sensitive to contaminants and are quick to manifest symptoms of exposure. See Appendix A for additional case study information.

communities following the removal of contaminated sediment in a stream can provide indications of the protectiveness of the cleanup features as well as the ecosystem's recovery to a more natural condition. At the Revere Chemical Company Superfund Site in Pennsylvania, ground water and stream monitoring is used to evaluate the risks of heavy metals getting into the ground water and migrating off site. Cleanup project managers also use the monitoring program to help evaluate the recovery of important aquatic species. Monitoring habitat indicators such as plant species composition and percent cover could indicate the success of the revitalization measures. See Appendix A for a case study regarding this site.

Designing and Implementing Institutional Controls

Many factors may influence the design and implementation of ICs, such as state policies, whether the property is a federal facility, or whether regulatory authorities, such as RCRA or CERCLA, are involved. An EPA guide addresses many of these issues (EPA 2000). Visit the following Web site to view the guide: http://epa.gov/superfund/policy/ic/guide/guide.pdf

Institutional Controls. ICs are designed to limit land or resource use, and provide information to help modify or guide human behavior, and complement engineering controls. They can also protect ecological revitalization properties by restricting public access to parts of a property that are particularly sensitive to erosion or contain sensitive or establishing habitats; or to achieve human protectiveness or other revitalization goals. A key to success is to identify and evaluate as much information as possible about the needed ICs early in the planning process. Generally, major considerations with IC use at ecological revitalization properties include the following:

- **Consider what the IC is intended to accomplish and establish clear objectives.** A common IC objective for ecological purposes involves controlling human activities in a particular area that could potentially interfere with sensitive habitats or the ecosystem balance that supports the cleanup features.
- **Consider the appropriate types of ICs.** These can include governmental controls (zoning, building codes, and ground water use restrictions), proprietary controls (easements, covenants, and conservation trusts), enforcement tools (consent decrees and administrative orders), and informational devices (fishing advisories, deed notices, and state registries of contaminated properties). For example, a conservation easement for catch and release fishing and a local health department fishing advisory could accomplish the same IC objective to reduce fish consumption. For information about different types of ICs, see EPA's guide titled Institutional Controls: A Site Manager's Guide to Identifying, Evaluating, and Selecting Institutional Controls at Superfund and RCRA Corrective Action Cleanups at http://epa.gov/superfund/policy/ic/guide/guide.pdf (EPA 2000).
- **Ensure that the specified ICs are effective and remain in place over the long term** through proper implementation, monitoring, and enforcement. For example, at the Silver Bow Creek Superfund Site in Butte, Montana, the Montana Department of Fish, Wildlife, and Parks enforces a fish consumption prohibition. In addition, at the BP Former Refinery in Casper, Wyoming, project managers implemented several ICs including a "use control area" through a resolution to limit use on the property, a ground water restriction area, and a soil management overlay district. Within one of these defined areas, a constructing entity has to contact the state or BP if they have been issued a building permit. See Appendix A for additional information on these case studies.

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Appendices

Appendix A: Ecological Revitalization Case Studies

Appendix B: Additional Ecological Revitalization Resources

Appendix C: Acronyms

Appendix A: Ecological Revitalization Case Studies

Property Name and Location	Property Type	Cleanup Type	Revitalization/Reuse Component	Problems/Issues	Solutions	Point of Contact	Notes/Links*
REGION 1							
Atlas Tack Superfund Site, Fairhaven, MA	Superfund Manufacturing Facility	Ground water contaminated with cyanide and toluene that leached from the site lagoon and soils contaminated with VOCs, heavy metals, pesticides, PCBs, and PAHs were cleaned up by removing buildings, contaminated soil, and sediment.	The cleanup preserved as much of the wetland sediment as possible and provided the necessary mix of fresh and salt water sources to create a functioning wetland, in addition to protecting human health and the environment.	1) The original ROD contained sediment cleanup values that would require complete excavation of the entire marsh. 2) The initial remediation plan included lowering the ground water table to prevent it from flowing through residual contamination.	1) The bioavailability study showed that it was not necessary to remove all sediments, and therefore only necessary sediment was removed, thereby preserving the marsh to the extent possible. 2) The remediation approach was re-evaluated during wetland design, and risks from ground water flowing beneath the site were minimal.	Elaine Stanley, RPM EPA Region 1 1 Congress Street Suite 1100 Mail Code: HBO Boston, MA 02114-2023 617-918-1332 stanley.elainet@epa.gov	http://www.epa.gov/ne/superfund/sites/atlas/
Fort Devens: OU2 Devens Consolidation Landfill, Sudbury, MA	Superfund Military Base	Numerous small historical landfills were remediated and the waste was consolidated in a new state-of-the-art landfill. Soils and debris disposed at the Devens Consolidation Landfill included those contaminated with petroleum, pesticides, PCBs, PAHs, and asbestos. A total of approximately 365,000 cubic yards of waste was disposed of in the new landfill. The historic landfill sites were then backfilled and regraded to restore the sites to pre-construction conditions.	Three of the historic landfills had waste or debris in wetland areas. For these areas, the remedy included waste and debris removal, followed by wetland restoration. The wetlands were restored by backfilling with clean fill and manufactured wetland soil. Materials were stabilized with a custom wetland seed mix, in accordance with a Habitat Restoration Work Plan. The site was monitored and evaluated during the next three growing seasons to ensure it achieved restoration success measures.	Not specified	Not specified	Ginny Lombardo, RPM EPA Region 1 1 Congress Street Suite 1100 Mail Code: HBT Boston, MA 02114-2023 617-918-1754 lombardo.ginny@epa.gov	http://yosemite.epa.gov/r1/npl_pad.nsf/51dc4f173ceef51d85256adf004c7ec8/df7d910ff9a93fab8525691f0063f6c9!OpenDocument&Highlight=0,devens
Fort Devens: OU9 AOC 57, Sudbury, MA	Superfund Military Base	AOC 57 consists of 2 areas that were affected by stormwater runoff and wastes from vehicle maintenance activities at a historic storage yard upgradient of the site. The areas are sloped along Cold Spring Brook. Soils and ground water were contaminated with petroleum hydrocarbons, chlorinated VOCs, PCBs, and arsenic. Contaminated soils were removed and disposed off-site, and ground water will be remediated via MNA.	Soil excavation at one of the areas included excavation within delineated wetland areas along Cold Spring Brook. The remedy required that the wetland areas be restored in accordance with an appropriate mitigation and restoration plan and that the wetland restoration area be monitored for 5 years to ensure that restoration success measures were achieved.	Not specified	Not specified	Ginny Lombardo, RPM EPA Region 1 1 Congress Street Suite 1100 Mail Code: HBT Boston, MA 02114-2023 617-918-1754 lombardo.ginny@epa.gov	http://yosemite.epa.gov/r1/npl_pad.nsf/51dc4f173ceef51d85256adf004c7ec8/df7d910ff9a93fab8525691f0063f6c9!OpenDocument&Highlight=0,devens

* Links valid at time of publication.

Appendix A: Ecological Revitalization Case Studies, continued

Property Name and Location	Property Type	Cleanup Type	Revitalization/Reuse Component	Problems/Issues	Solutions	Point of Contact	Notes/Links*
GE-Housatonic River, Pittsfield, MA	Superfund Manufacturing Facilities	Site remediation involved clean up of Housatonic River sediments and floodplain soils contaminated with PCBs and other hazardous substances. Remediation included excavating and disposing of sediment and soil and full-scale capping of Silver Lake.	GE is providing economic aid to the City of Pittsfield for 10 years and making upgrades to the Housatonic River, its floodplain, and Silver Lake that will have aesthetic value and enhance local habitat.	Issues relating to flood storage compensation are under discussion with EPA.	Not specified	Thomas Hickey, Jr. Pittsfield Economic Development Authority 81 Kellogg Street Pittsfield, MA 01201 413-494-7332 thickey@peda.cc	http://www.epa.gov/region1/ge/redevelopment.html
Industri-Plex Site, Woburn, MA	Superfund Manufacturing Facility	The remedy included remediating approximately 110 acres of soil contaminated with lead, arsenic, and chromium; demolishing onsite buildings; and constructing clay, soil, and synthetic layers, concrete foundations, and asphalt to cover contamination. In addition, gases at a hide pile were collected and treated, and wetlands and open spaces were created.	Wetlands and open space were created adjacent to redeveloped areas, which included a regional transportation center, highway interchange, and land developed for retail and commercial use.	None	None	Joseph LeMay, RPM EPA Region 1 1 Congress Street Suite 1100 Mail Code: HBO Boston, MA 02114-2023 617-918-1323 lemay.joe@epa.gov	http://yosemite.epa.gov/r1/npl_pad.nsf/f52fa5c31fa8f5c885256adc0050b631/1E8F7D6FFCD9B61B85256A0F00067136?OpenDocument
Iron Horse Park, North Billerica, MA	Superfund Manufacturing Facility Landfill	On-site ground water and surface water were contaminated with organic and inorganic chemicals, asbestos, and heavy metals. The soil at the site was contaminated with PCBs, petrochemicals, and heavy metals. Remediation activities included capping on-site landfills and excavating and removing contaminated soil and sediment.	Wetlands were restored.	Not specified	Not specified	Don McElroy EPA Region 1 1 Congress Street, Suite 1100 Mail Code: HBO Boston, MA 02114-2023 617-918-1326 mcelroy.don@epa.gov	http://yosemite.epa.gov/r1/npl_pad.nsf/51dc4f173ceef51d85256adf004c7ec8/e334fff032cee1e78525691f0063f6d0?OpenDocument
Jamaica Island Landfill OU3, Kittery, ME	Superfund Remedial Action Landfill	A variety of organic and inorganic constituents were detected in soil and ground water and included VOCs, SVOCs, PCBs, pesticides, metals, and petroleum hydrocarbons. Remediation included installation of a cap and shoreline erosion controls.	Wetlands were constructed.	Minimizing the effect on existing mudflats in the area and locating appropriate backfill to maximize the potential for success.	Not specified	Fred Evans, RPM Navy Portsmount Naval Shipyard Kittery, ME 03904 610-595-0567 ext.159 evansfj@efane.navfac.navy.mil	http://www.wildlifehc.org/ewebeditpro/items/O57F3078.pdf
Loring Air Force Base, Northeastern ME	Superfund Air Force Base	Ground water contaminated with VOCs and fuel-related compounds and surface water and sediment contaminated with VOCs, PCBs, and heavy metals were remediated. Activities included capping on-site landfills and excavating and removing contaminated soil and sediment.	Boulders and cobbles from the streambed and nearby trees larger than 15 centimeters in diameter that were removed during cleanup were later used in stream reconstruction, after completion of cleanup activities. Reuse of native materials significantly reduced the cost of restoration materials.	Not specified	Not specified	Mike Daly, RPM EPA Region 1 1 Congress Street Suite 1100 Mail Code: HBT Boston, MA 02114-2023 617-918-1386 daly.mike@epa.gov	http://cfpub.epa.gov/supercpad/cursites/csitinfo.cfm?id=0101074

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Appendix A: Ecological Revitalization Case Studies, continued

Property Name and Location	Property Type	Cleanup Type	Revitalization/Reuse Component	Problems/Issues	Solutions	Point of Contact	Notes/Links*
Materials Technology Laboratory, Watertown, MA	Superfund Arsenal	Remediation included removal and off-site disposal of contamination sources related to weapons and ammunition manufacture and storage, and demolition and cleanup of the nuclear reactor, including radiological contamination, PAHs, PCBs, and pesticides.	Wetlands restoration was completed adjacent to the redeveloped area. Fifty-five acres of the property have been used to build the Arsenal Mall, Harvard Community Health Center, Arsenal Apartments, a public park with walking and bike trails, and a playground.	Not specified	Not specified	Christine Williams, RPM EPA Region 1 1 Congress Street Suite 1100 Mail Code: HBT Boston, MA 02114-2023 617-918-1384 williams.christine@epa.gov	http://yosemite.epa.gov/r1/npl_pad.nsf/701b6886f189ceae85256bd20014e93d/d98829ad20e19d6f852568ff005adb08!OpenDocument
Pease Air Force Base, Portsmouth, NH	Superfund Air Force Base	Soils and ground water were contaminated with solvents and fuel.	A wildlife refuge was created in addition to a public airport.	Not specified	Not specified	Mike Daly, RPM EPA Region 1 1 Congress Street Suite 1100 Mail Code: HBT Boston, MA 02114-2023 617-918-1386 daly.mike@epa.gov	http://yosemite.epa.gov/r1/npl_pad.nsf/f52fa5c31fa8f5c885256adc0050b631/9E95FBAD0CEC73E0852568FF005ADB09?OpenDocument
Saco Municipal Landfill, Saco, ME	Superfund Landfill	Soil and ground water contaminated from landfill activities were remediated.	A portion of the site adjacent to the redeveloped area was reserved for a wetland. The site is ready for reuse and the City of Saco plans to develop a community recreation area for hiking, biking, ice skating, and soccer.	Not specified	Not specified	Ed Hathaway, RPM EPA Region 1 1 Congress Street Suite 1100 Boston, MA 02114-2023 617-918-1372 hathaway.ed@epa.gov	http://cfpub.epa.gov/supercpad/cursites/csitinfo.cfm?id=0101010
Tibbetts Road Site, Barrington, NH	Superfund Rural/Farmland	Site soils and ground water were contaminated by chlorinated and non-chlorinated solvents. Remediation included source removal, building demolition, water supply extension, and phytoremediation.	The wooded phytoremediation area is providing increased biodiversity through new wildlife habitat for various birds and small mammals.	Not specified	Not specified	Jerome S. Amber, P.E. Ford Motor Company, retired 248-765-1044 jamber@comcast.net	http://www.wildlifehc.org/ewebeditpro/items/O57F3072.pdf
			REGION 2				
Asbestos Dump, Millington, NJ	Superfund Landfill	Asbestos from 4 sites was collected, consolidated, and treated on-site to prevent release of contaminants. A soil cover was then placed over the site.	A barn was converted into an environmental awareness center. Most of the property will be preserved and will help expand the Great Swamp National Wildlife Refuge.	Not specified	Not specified	Carla Struble, RPM EPA Region 2 290 Broadway New York, NY 10007-1866 212-637-4322 struble.carla@epa.gov	http://yosemite.epa.gov/opa/admpress.nsf/b853d6fe004acebf852572a000656840/3f082ae6d59bb9ac85257165006bc507!OpenDocument
DeRewal Chemical Co., Kingwood Township, NJ	Superfund Chemical Company	Contaminated soil and ground water from chemical spills was cleaned up through excavation and treatment of soil and extraction and treatment of ground water.	The site now contains walking, canoe, and biking trails, and bird watching opportunities. The Kingwood Township also plans to convert a house on the site into a historical, environmental, and recreational center.	Not specified	Not specified	EPA Region 2 290 Broadway New York, NY 10007-1866	http://www.epa.gov/region02/superfund/npl/0200792c.pdf

* Links valid at time of publication.

Appendix A: Ecological Revitalization Case Studies, continued

Property Name and Location	Property Type	Cleanup Type	Revitalization/Reuse Component	Problems/Issues	Solutions	Point of Contact	Notes/Links*
Lipari Landfill, Pitman, NJ	Superfund Landfill	A slurry wall and cap were constructed for the landfill, which accepted wastes contaminated with VOCs and heavy metals. A ground water and leachate P&T system was installed, and contaminated soil and sediment were excavated and treated.	Revitalization included recreational use of a park and lake as well as development of streams and marshes.	In the ROD for OU2, changes in the remedy flow rates, equipment sizes, and estimated costs in design were made to the on-site containment facilities. The ROD for OU3 included changes to the soil and sediment volumes handled and methods for removing sediment.	Changes in the ROD did not change the functionality of the remedies.	Melissa Friedland EPA HQ Ariel Rios Building 1200 Pennsylvania Avenue Mail Code: 5204P Washington, DC 20460 703-603-8864 friedland.melissa@epa.gov	http://cfpub.epa.gov/supercpad/cursites/csitinfo.cfm?id=0200557
Marathon Battery, Cold Spring, NY	Superfund Manufacturing Facilities	The factory and surrounding soils, a nearby marsh, and adjacent river sediments were contaminated with heavy metals. Remediation included excavating, capping, and restoring the marsh; excavating contaminated soils; dredging cove and river sediments; and demolishing the plant.	The marsh is now used for recreational and educational purposes, and the factory grounds are ready for redevelopment.	Difficulties included experienced goose predation, destructive ice flows, invasive plant species, and bare areas due to differential settlement within the marsh.	Each problem was dealt with individually. Some areas were replanted, coir logs were used to encourage natural plant coverage and sediment build-up in bare areas, and beetles were used to retard the growth of invasive species.	Pam Tames, RPM EPA Region 2 290 Broadway New York, NY 10007-1866 212-637-4255 tames.pam@epa.gov	http://www.epa.gov/Region2/superfund/npl/0201491c.pdf
Myers Property Superfund Site, Hunterdon County, NJ	Superfund Manufacturing Facility	Soil and ground water contaminated with VOCs, pesticides, semiVOCs, metals, and dioxins were cleaned up by excavating contaminated soil and sediment, treating soil, and extracting and treating ground water.	RPMs are saving existing trees above a certain size in areas with low levels of contamination by hand digging around the roots to a depth of six inches. Excavated soil will be replaced with clean topsoil from off site.	Subsurface soil contamination remains, so if a tree falls, contaminated soil could be exposed.	The property will be monitored in case large trees fall and expose soils deeper than six inches.	Stephanie Vaughn, RPM EPA Region 2 290 Broadway, 19th Floor New York, NY 10007-1866 212-637-3914 vaughn.stephanie@epa.gov	http://www.epa.gov/region02/superfund/npl/0200774c.pdf
REGION 3							
Army Creek Landfill, DE	Superfund Landfill	Remediation of soil and ground water contaminated with VOCs, chromium, and mercury included a multi-layer protective cover over a municipal and industrial landfill and a ground water treatment system. Army Creek was also contaminated with cadmium, chromium, mercury, iron, and zinc.	Native vegetation was planted to create a bird and wildlife habitat. In addition, discharge pipes from the ground water treatment system were routed to create wetlands to help prevent flooding and create additional habitat.	Not specified	Not specified	Deb Rossi, RPM EPA Region 3 1650 Arch Street Mail Code: 3HS23 Philadelphia, PA 19103-2029 215-814-3228 rossi.debra@epa.gov	http://www.epa.gov/superfund/programs/recycle/live/casestudy_armycreek.html

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Appendix A: Ecological Revitalization Case Studies, continued

Property Name and Location	Property Type	Cleanup Type	Revitalization/Reuse Component	Problems/Issues	Solutions	Point of Contact	Notes/Links*
Avtex Fibers, Front Royal, VA	Superfund Manufacturing Facilities	The principle contaminants found in the ground water were carbon disulfide, ammonia, arsenic, antimony, phenol, and high pH. Arsenic, lead, and PCBs have been identified in soils. PCBs associated with the plant were also detected in the Shenandoah River. Remediation was completed by demolishing or decontaminating onsite buildings, removing and treating onsite hazardous and nonhazardous chemical waste, excavating contaminated soil and debris, and constructing a low-flow wastewater treatment system.	The site was used to create a river conservancy park, active recreation park, and an eco-business park.	Not specified	Not specified	Bonnie Gross, RPM EPA Region 3 1650 Arch Street Mail Code: 3HS23 Philadelphia, PA 19103-2029 215-814-3229 gross.bonnie@epa.gov	http://www.epa.gov/superfund/accomp/success/avtex.htm
Berks Landfill, Berks County, PA	Superfund Landfill	Ground water was contaminated with VOCs and metals. The remedy included ICs, long-term monitoring of ground water, operation and maintenance of the leachate system, and repair to the landfill cap.	The former residential property at the site is being reused as open green space with trees and vegetation. ICs were implemented in order to prevent on-site ground water use and to protect the landfill cap.	Not specified.	Not specified	Kristine Matzko EPA Region 3 1650 Arch Street Mail Code: 3HS21 Philadelphia, PA 19103-2029 215-814-5719 matzko.kristine@epa.gov	http://www.epa.gov/superfund/sites/fiveyear/f05-03018.pdf
Butz Landfill, Monroe County, PA	Superfund Landfill	A former municipal dump contaminated the ground water with a solvent, TCE, and other organic compounds. Nearly 82,720,000 gallons of water were treated using a P&T system.	Revitalization involved creating wetlands to mitigate potential loss of wetlands caused by the P&T system.	Not specified	Not specified	Romuald A. Roman, RPM EPA Region 3 1650 Arch Street Mail Code: 3HS22 Philadelphia, PA 19103-2029 215-814-3212 roman.romuald@epa.gov	http://www.epa.gov/reg3hscd/super/sites/PAD981034705/
Chisman Creek, York County, VA	Superfund Mining site	Ground water and surface water were contaminated with heavy metals from the disposal of fly ash. The cleanup plan eliminated contact with the fly ash and contaminated water, restored ground water, and protected nearby wetlands.	The site is being reused as a recreational complex, including ponds and the County Memorial Tree Grove. The site cleanup also protects nearby ponds, a creek, and an estuary, and it is part of a large water quality improvement that has led to the reopening of the Chisman Creek estuary for private and commercial fishing.	Not specified	Not specified	Andrew C. Palestini EPA Region 3 1650 Arch Street Mail Code: 3HS23 Philadelphia, PA 19103-2029 215-814-3233 palestini.andrew@epa.gov	http://www.epa.gov/superfund/programs/recycle/live/casestudy_chisman.html
College Park Landfill, Beltsville, MD	Superfund Landfill	Remediation included installing a cap over a landfill that accepted household trash, as well as commercial, industrial and some agricultural and research waste.	The vegetative cover will include diverse native plantings.	The stakeholders were concerned about whether the vegetation would be killed by methane from the landfill, and if the vegetation would be able to adequately prevent leachate generation.	A pilot study is being conducted to ensure these concerns are addressed.	Karen Zhang, PhD, PE, RPM USDA 10300 Baltimore Avenue Bldg. 003, Rm. 117 Beltsville, MD 20705 301-504-5557 zhangk@ba.ars.usda.gov	http://www.wildlifehc.org/ewebeditpro/items/O57F3070.pdf

* Links valid at time of publication.

Appendix A: Ecological Revitalization Case Studies, continued

Property Name and Location	Property Type	Cleanup Type	Revitalization/Reuse Component	Problems/Issues	Solutions	Point of Contact	Notes/Links*
Craig Farm Drum, Parker, PA	Superfund Landfill	Ground water and soil were contaminated with resorcinol and VOCs, such as benzene and toluene. Site remediation consisted of excavating and stabilizing contaminated soils onsite from two former waste disposal pits.	Wetlands were built on site to replace a smaller area of wetlands lost during construction of the on-site landfill.	Not specified	Not specified	John Epps EPA Region 3 1650 Arch Street Mail Code: 3HS33 Philadelphia, PA 19103-2029 215-814-3144 epps.john@epa.gov	http://www.epa.gov/reg3hscd/super/sites/PAD980508527/
DeSale Restoration, Butler County, PA	Pennsylvania Department of Environmental Protection Mining Site	A passive treatment system was used to capture and treat acid mine drainage and included an anoxic collection system, vertical flow ponds, a settling pond and wetland complex, and horizontal flow limestone bed.	In addition to creating a treatment wetland complex, 11 miles of streams that were once devoid of life because of acid mine drainage are now teeming with fish.	Not specified	Not specified	Scott Roberts Pennsylvania Deparament of Environmental Protection Office of Mineral Resources P.O. Box 2063 Harrisburg, PA 17105-2063 717-783-5338 jayroberts@state.pa.us	http://www.srwc.org/projects/desale.php
E.I. DuPont Nemours & Co., Inc. (Newport Pigment Plant Landfill), Newport, DE	Superfund Landfill	Soils, sediments, ground water, and surface water were contaminated with various metals. Contaminated sediments were excavated, the two landfills were capped, and soil at the ballpark was removed.	The cleanup is protecting Delaware's natural resources and wildlife habitat. Over 35 acres of wetlands and wildlife habitat have been restored as part of the site's overall cleanup.	Ground water appeared to be seeping over the sheet pile wall in several areas of the north landfill. This created a concern regarding possible vapor intrusion into structures above the contaminated ground water plume.	Evaluation of vapor intrusion potential and appropriate mitigation steps was conducted. Ground water table elevation at the north landfill was continuously monitored; water, soil and/or sediment sampling was conducted; and the need for more recovery wells was evaluated.	Randy Sturgeon EPA Region 3 1650 Arch Street Mail Code: 3HS23 Philadelphia, PA 19103-2029 215-814-3227 sturgeon.randy@epa.gov	http://www.epa.gov/superfund/sites/fiveyear/f0503006.pdf
Former Elf Atochem North America (Bensalem Redevelopment), Cornwell Heights, PA	RCRA Corrective Action Manufacturing Facility Refinery	Site soils and ground water are contaminated with chlorinated organics, PAHs, PCBs, pesticides, and arsenic. Remediation included removing contaminated soil and reusing concrete from demolished buildings as fill for basement areas in buildings that had been razed.	The site is planned to be redeveloped as a mixed-use area with greenspace for passive and active recreation along the Delaware River waterfront.	The property is in an area where many industries have downsized or discontinued operations over the last 20 years. Unemployment rates in the area are among the highest in Bucks County.	The redevelopment authority received a grant and loan from the Brownfields Program to help with the cost of the cleanup. A mixed-use area is planned for the site.	Andrew Clibanoff EPA Region 3 1650 Arch Street Mail Code: 3WC22 Philadelphia, PA 19103-2029 215-814-3391 clibanoff.andrew@epa.gov	http://www.epa.gov/reg3wcmd/ca/pdf/elf_atochem.pdf
Grace Lease Property, Lancaster County, PA	Brownfields	A Phase II Environmental Site Assessment found that no contaminants were present at levels above state standards, so cleanup was not necessary.	The area, previously abandoned and unused, now provides natural habitat and recreational greenspace with hiking trails, picnic grounds, and a scenic overlook of the Susquehanna River. In addition, Bald Eagle nesting sites have reemerged on the land.	Site remediation was not necessary.	Not applicable	Andrew Kreider EPA Region 3 1650 Arch Street Mail Code: 3HS51 Philadelphia, PA 19103-2029 215-814-3301 kreider.andrew@epa.gov	http://www.epa.gov/region03/revitalization/newsletter/spring07/Lorax.html

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GSA Southeast Federal Center, Washington D.C.	RCRA Corrective Action Manufacturing Facility	Contamination resulted from shipbuilding and ordnance production activities. Eleven of the 14 buildings were decontaminated and demolished; the remaining buildings will be renovated and reused. Contaminated soil was removed, and ground water is being treated to break down gasoline constituents.	Revitalization includes developing a waterfront park that includes wildlife habitat.	Not specified	Not specified	Barbara Smith EPA Region 3 1650 Arch Street Mail Code: 3LC20 Philadelphia, PA 19103-2029 215-814-5786 smith.barbara@epa.gov	http://www.epa.gov/reg3wcmd/ca/dc/pdf/dc8470090004.pdf
Honeywell (Formerly Allied Signal) Baltimore Works Facility, Baltimore, MD	RCRA Corrective Action Industrial Facility	Manufacturing buildings and associated hazardous waste were removed. The containment area was surrounded by a slurry wall and capped, and ground water is being pumped and treated off site. Chromium and PAH-contaminated soil was removed.	A waterfront park will be constructed and is planned to include wildlife habitat.	Not specified	Not specified	Russell Fish EPA Region 3 1650 Arch Street Mail Code: 3LC20 Philadelphia, PA 19103-2029 215-814-3226 fish.russell@epa.gov	http://www.epa.gov/reg3wcmd/ca/md/pdf/mdd069396711.pdf
Jacks Creek/ Sitkin Smelting & Refining, Inc, Maitland, PA	Superfund Metals Reclamation Facility	The former smelting and precious metals reclamation facility contained several buildings, waste piles, and large areas of soil contaminated with lead, copper, zinc, cadmium, and PCBs. Floodplain wetlands on site and Jacks Creek sediment near the site were contaminated with runoff from the waste piles and soil. The cleanup involved dredging contaminated sediment from the adjacent Jacks Creek, excavating contaminated soil, and removing USTss and drums. Contaminated soil, sediment, and waste piles were consolidated and capped. Drums and waste were removed from the site.	The floodplain remediation required removing vegetation in a segment of the riparian corridor of the creek. Because soil excavation affected existing wetlands on site, wetlands were recreated in the riparian corridor along Jacks Creek. RPMs created vernal pools, placed woody debris in the wetland as invertebrate habitat, and used a wet meadow seed mix. A monitoring plan will help document the effectiveness of the created wetland.	Not specified	Not specified	Rashmi Mathur, RPM EPA Region 3 1650 Arch Street Mail Code: 3HS22 Philadelphia, PA 19103-2029 215-814-5234 mathur.rashmi@epa.gov	http://www.epa.gov/reg3hwmd/risk/eco/restoration/cs/JacksCreek.htm
Hopewell Plant (Honeywell), Hopewell, VA	RCRA Corrective Action Manufacturing Facility	This industrial chemical and fertilizer manufacturing facility is being cleaned up to control ground water releases and current human and ecological exposure to contaminated media.	A portion of the facility has been converted to a wildlife habitat area and has been certified as such by the Wildlife Habitat Council.	Not specified	Not specified	Russell Fish EPA Region 3 1650 Arch Street Mail Code: 3LC20 Philadelphia, PA 19103-2029 215-814-3226 fish.russell@epa.gov	http://www.wildlifehc.org/Registry_CertifiedSites/cert_sites_detail2.cfm?LinkAdvID=95327

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Property Name and Location	Property Type	Cleanup Type	Revitalization/Reuse Component	Problems/Issues	Solutions	Point of Contact	Notes/Links*
Mill Creek Dump, Erie, PA	Superfund Landfill	A former freshwater wetland that was used as a landfill for foundry sands, solvents, waste oils, and other industrial and municipal waste was capped and flatter slopes were created.	The former landfill is now a golf course. Eight acres of wetlands were constructed adjacent to the course.	Not specified	Not specified	Romuald A. Roman, RPM EPA Region 3 1650 Arch Street Mail Code: 3HS22 Philadelphia, PA 19103-2029 215-814-3212 roman.romuald@epa.gov	http://www.epa.gov/reg3hscd/npl/PAD980231690.htm
Morgantown Ordnance Works Disposal Area - OU1, Monongalia County, WV	Superfund Chemical Production Facility Landfill	Remediation activities included constructing a cap, removing soil and sediment contaminated with heavy metals and PAHs, and constructing three wetlands.	Wetlands were constructed and provided leachate treatment.	Contaminated sediment and soil were intended to be cleaned through bioremediation. However, bioremediation did not meet the clean up standards within a reasonable time frame and was not cost effective.	Three consecutive treatment wetlands were constructed to treat landfill leachate. Monitoring was implemented to ensure the effectiveness of wetlands.	Mr. Hilary Thornton, RPM EPA Region 3 1650 Arch Street Mail Code: 3HS23 Philadelphia, PA 19103-2029 215-814-3323 thornton.hilary@epa.gov	http://epa.gov/reg3hwmd/npl/WVD000850404.htm
Naval Amphibious Base Little Creek, Virginia Beach, VA	Superfund Landfill	Approximately 29,000 tons of non-hazardous soil and debris were removed from the landfill and 6,300 cubic yards of clean fill were imported.	The landfill was converted to a tidal wetland. Two connecting channels were constructed to allow tidal inundation into the site from Little Creek Cove. Plants were placed along designated elevations to establish tidal wetland vegetation, using the neighboring marsh as a reference.	Not specified	Not specified	Bruce Pluta EPA Region 3 1650 Arch Street Mail Code: 3HS41 Philadelphia, PA 19103-2029 215-814-2380 pluta.bruce@epa.gov	http://public.lantops-ir.org/sites/public/nablc/Site%20Files/IRhistory.aspx#Site%208
Ohio River Park, Neville Island, PA	Superfund Landfill	A previous municipal landfill operating from the 1930s until the 1950s was capped with a protective cover.	The site will be transformed into a sports complex, with areas of habitat for wildlife; visitors will also be able to enjoy numerous walking, hiking, and biking trails.	Not specified	Not specified	Romuald A. Roman, RPM EPA Region 3 1650 Arch Street Mail Code: 3HS22 Philadelphia, PA 19103-2029 215-814-3212 roman.romuald@epa.gov	http://www.epa.gov/superfund/programs/recycle/live/casestudy_ohioriver.html

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Property Name and Location	Property Type	Cleanup Type	Revitalization/Reuse Component	Problems/Issues	Solutions	Point of Contact	Notes/Links*
Palmerton Zinc Pile Superfund Site, Palmerton, PA	Superfund Mining Site	Former smelting operations resulted in soil and shallow ground water contamination by heavy metals, such as lead, cadmium, and zinc, and created a defoliated area on the adjacent Blue Mountain, a cinder bank, and additional defoliation along Stoney Ridge. Heavy metals were being transported to nearby stream segments through erosion. Biosolids were applied to accelerate revegetation of the defoliated areas, to stabilize the area, reduce soil erosion caused by wind and surface water, and increase evapotranspiration to prevent percolation of water and contaminants to the ground water. In addition, a system was installed to divert surface water around the cinder bank and treat leachate before discharge to the creek.	For the Blue Mountain revegetation, site managers constructed a self-sustaining meadowland because of minimum metal uptake from the plants. Also, ree species with high metal uptake were removed. For the cinder bank revegetation, the team used a grass seed mixture that included a nitrogen-fixing legume to maintain nitrogen fertility without the need for fertilizer.	Attempting to establish forestland at the site was extremely challenging because of competition from grasses, animal grazing, and insects. Some grass species were not desirable because of metals uptake. Use of sludge as a soil amendment caused a negative public perception.	Forestland was ultimately abandoned in favor of meadowland. The types of grass seeds were replaced with those having minimal metals uptake. Sludge application was replaced with mushroom compost.	Charlie Root, RPM EPA Region 3 1650 Arch Street Mail Code: 3HS21 Philadelphia, PA 19103-2029 215-814-3193 root.charlie@epa.gov	http://costperformance.org/pdf/20070522_396.pdf
Resin Disposal, Jefferson Borough, PA	Superfund Landfill	The landfill, which accepted industrial waste including benzene and toluene, was covered with multi-layer cap. Leachate was collected and separated, and oil was recycled as fuel for a nearby plant.	The site now contains native wild flowers and is habitat to migratory birds.	Not specified	Not specified	Rashmi Mathur, RPM EPA Region 3 1650 Arch Street Mail Code: 3HS22 Philadelphia, PA 19103-2029 215-814-5234 mathur.rashmi@epa.gov	http://cfpub.epa.gov/supercpad/cursites/csitinfo.cfm?id=0301042
Revere Chemical, Nockamixon Township, PA	Superfund Waste Processing Facility	The site was contaminated with benzoic acid, VOCs, solvents, and PAHs. Remediation included disposing of debris and solid wastes off-site, cleaning VOC-contaminated soil by vacuum extraction, and installing a slurry wall and cap over an area contaminated with hazardous waste associated with an acid and metal-plating waste processing facility.	Revitalization activities included planting wildflowers and other foliage to attract migratory birds and other wildlife.	Treatment of VOC-contaminated soil by in situ vacuum extraction did not meet requirements of the Pennsylvania Land Recycling and Remediation Standards Act.	Protective levels of contaminant concentrations in ground water were established usingthe Synthetic Precipitation Leaching Procedure to determine the extent of capping. Soil contaminated with VOCs was treated by ex situ vacuum extraction.	Melissa Friedland EPA HQ Ariel Rios Building 1200 Pennsylvania Avenue Mail Code: 5204P Washington, DC 20460 703-603-8864 friedland.melissa@epa.gov	http://cfpub.epa.gov/supercpad/cursites/csitinfo.cfm?id=0300982
Saltville Waste Disposal Ponds, Saltville, VA	Superfund Manufacturing Facility	Elevated mercury levels were present in soil and ground water in the area beneath the former chlorine plant. Remediation activities included constructing a water treatment plant and capping the ponds.	A wildlife habitat area was created on the former disposal ponds.	Not specified	Not specified	Eric Newman 1650 Arch Street Mail Code: 3HS23 Philadelphia, PA 19103-2029 215-814-3237 newman.eric@epa.gov	http://www.epa.gov/reg3hscd/super/sites/VAD003127578/

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Property Name and Location	Property Type	Cleanup Type	Revitalization/Reuse Component	Problems/Issues	Solutions	Point of Contact	Notes/Links*
Seaford Nylon Plant, Seaford, DE	RCRA Corrective Action Site Manufacturing Facility	Wastes include fly ash, corrosives, ignitables, spent halogenated solvents, and discarded commercial chemical products. Ground water contains low levels of metals and VOCs and low pH. Remediation included MNA of ground water with ICs as well as installing a protective cover over solid waste. Fly ash from the site was used as fill at an adjacent golf course.	Reuse includes expansion of the neighboring golf course.	There was concern that the fly ash placed at the golf course may cause a ground water problem.	Evaluations of the ground water at the golf course indicated that the fly ash did not impact the ground water.	Douglas Zeiters Delaware Department of Natural Resources and Environmental Control 89 Kings Highway Dover, DE 19901 302-739-9403 douglas.zeiters@state.de.us	http://www.epa.gov/reg3wcmd/ca/de/pdf/ded002348845.pdf
Site 46 Landfill A, Stump Dump Road, Dahlgren, VA	Superfund Landfill	Ground water and surface water contained contaminants such as cadmium, lead, mercury, and PCBs from municipal waste at the site. Contaminated waste from the site was removed to an appropriate off-site landfill.	The remedial design includes the integration and establishment of tidal wetlands in the low areas of the site.	Uncovering UXO caused a safety issue at the site.	EOD support and screening at all times was required.	Neal Parker 1314 Harwood St., SE Washington Navy Yard Washington, D.C. 20374 202-685-3281 parkernm@efaches.navfac.navy.mil	http://www.wildlifehc.org/eweb editpro/items/O57F3079.pdf
Tybouts Corner Landfill, New Castle, DE	Superfund Landfill	Remediation activities included installing water lines for residents in the area and installing a protective cap over the landfill, which accepted municipal and household waste.	Revitalization included planting wildflowers and other vegetation on the cap to stabilize the ground and prevent erosion.	Not specified	Not specified	Katherine Lose, RPM EPA Region 3 1650 Arch Street Mail Code: 3HS23 Philadelphia, PA 19103-2029 215-814-3240 lose.kate@epa.gov	http://cfpub.epa.gov/supercpad/cursites/csitinfo.cfm?id=0300035
Walsh Landfill, PA	Superfund Landfill	Residential well water off-site was contaminated with chloromethane, chloroform, xylenes, and other VOCs, as well as lead, mercury, and zinc. Remediation included removing waste and installing an evapotranspiration cover system to protect against migration of on site ground water contaminated with mercury, toluene, and other VOCs from former disposal practices.	Revitalization included replanting a vegetative layer of a variety of native hardwood and coniferous trees.	The site was planned for reuse originally. However, because both the site owner and community were unresponsive, the team installed an evapotranspiration cover with trees as an integral part of the remedy. Therefore, reuse options are minimal.	Trees planted as the vegetative layer of the evapotranspiration cover have provided excellent habitat for birds and small mammals. Current plans are for the site to remain as is.	Frank Klanchar, RPM EPA Region 3 1650 Arch Street Mail Code: 3HS22 Philadelphia, PA 19103-2029 215-814-3218 klanchar.frank@epa.gov	http://www.epa.gov/reg3hwmd/super/sites/PAD980829527/index.htm
Wildcat Landfill, Dover, DE	Superfund Landfill	Contaminated soil and ground water from the previous landfill were capped with a protective cover.	A mixture of native plants and wildflowers were planted on the cap, and Kent County is evaluating plans to allocate a part of the site as a greenway, which is an open space for recreational purposes.	Not specified	Not specified	Hilary Thornton EPA Region 3 1650 Arch Street Mail Code: 3HS23 Philadelphia, PA 19103-2029 215-814-3323 thornton.hilary@epa.gov	http://cfpub.epa.gov/supercpad/cursites/csitinfo.cfm?id=0300101

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Property Name and Location	Property Type	Cleanup Type	Revitalization/Reuse Component	Problems/Issues	Solutions	Point of Contact	Notes/Links*
Woodlawn County Landfill, MD	Superfund Landfill	The ground water is contaminated with VOCs, primarily vinyl chloride and 1,2-dichloroethane, and with PAHs, pesticides, and metals, primarily manganese. Initially RPMs installed an impermeable cap and ground water P&T system. Later they replaced the cap with a vegetative soil cap to help sustain naturally occurring bacteria in the soil that degrade the contaminants. In addition to P&T, the remedy included MNA with monitoring of the ground water and the vegetative soil cover. The team planted wildlife enhancements such as trees and native wildflowers after installing the vegetative cap.	The closed landfill was used to create wildlife habitat called "New Beginnings, the Woodlawn Wildlife Habitat Area." It is currently used as a nature and science study area by local schools and as an area for projects by the Boy Scouts and Girls Scouts of America.	Analyses showed contamination of on-site and off-site ground water, soil, and sediment and surface water of a stream that crosses the site. MNA posed a difficulty due the scarcity of its use at the time.	The original remedy included extraction and treatment of contaminated ground water. However, continued monitoring showed that MNA effectively removed or immobilized contaminants from ground water. Two remedial designs were completed in parallel in case the MNA process failed to perform as expected.	James J. Feeney, RPM EPA Region 3 1650 Arch Street Mail Code: 3HS22 Philadelphia, PA 19103-2029 215-814-3190 feeney.jim@epa.gov	http://www.wildlifehc.org/brownfields/woodlawn.cfm
REGION 4							
Black Warrior-Cahaba Rivers Land Trust, AL	Brownfields Mining Site	Soils contaminated with lead and heavy metals. Remediation included a recreational park and community stream cleanup events.	Transformed a former industrial region into a 27-mile greenway with parks and paths along the Five-Mile Creek.	It could take 20 years to complete the entire greenway project.	Many of the targeted former industrial areas have been cleaned up and made available to communities as natural and recreational land.	EPA Region 4 Brownfields Team 61 Forsyth Street, S.W. Atlanta, GA 30303-8960 404-562-8493 www.epa.gov/region4/waste/bf/index.htm	http://www.epa.gov/brownfields/success/fultondale_al_BRAG.pdf
Milan Army Ammunition Plant, Milan, TN	Superfund Ammunitions Plant	Two wetland systems were created, a subsurface flow ground-bed wetland and a surface flow lagoon wetland, to degrade explosives and their byproducts. Specifically, ground water was contaminated with explosives constituents including TNT, RDX, HMX, 2,4-DNT and 2,6-DNT.	Revitalization included creation of wetlands and use of phytoremediation as a remedial technology.	Weather was an obstacle because it affects the efficiency of phytoremediation.	Not specified	Laurie Haines U.S. Army Environmental Center 2511 Jefferson Davis Highway Taylor Building NC3- Arlington, VA 22202-3926 703-601-1590 laurie.haines@us.army.mil	http://www.wildlifehc.org/ewebeditpro/items/O57F3081.pdf
Northwest 58th Street Landfill, Miami, FL	Superfund Landfill	Ground water contaminated with heavy metals and toxic chemicals from previous landfill activities was cleaned up through remediation and closure of the landfill.	Through careful design, a lake was constructed at the site for wading birds; trails were created with lookout centers.	Not specified	Not specified	Bill Denman EPA Region 4 61 Forsyth Street, SW Atlanta, GA 30303 404-562-8939 denman.bill@epa.gov	http://www.epa.gov/region4/waste/reuse/fl/nw58reuse.pdf
Solitron Microwave, Port Salerno, FL	Superfund Manufacturing Facility	Ground water contaminants consist of PCE and its breakdown products. Remediation activities include water line extensions, soil removal, *in situ* chemical oxidation, and natural attenuation.	Six acres at the site have been reserved for wetland areas, an upland preserve for native plant habitat, and a 50-foot natural buffer between the site and surrounding residential areas.	Not specified	Not specified	Bill Denman EPA Region 4 61 Forsyth Street, SW Atlanta, GA 30303 404-562-8939 denman.bill@epa.gov	http://www.epa.gov/Region4/waste/npl/nplfls/solmicfl.htm

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REGION 5							
Allied Chemical & Ironton Coke, Ironton, OH	Superfund Chemical and Tar Manufacturing Facility	Solid wastes and wastewater including crude tar and ammonia contaminated the ground water at this site. Remediation activities included excavating and disposing of contaminated soil, installing containment systems, and constructing a water treatment plant.	This area is being converted into a wetlands system, taking advantage of its natural flooding conditions and predisposition to wetlands-type vegetation.	Not specified	Not specified	Syed Quadri EPA Region 5 77 West Jackson Boulevard Mail Code: SR-6J Chicago, IL 60604-3507 312-886-5736 quadri.syed@epa.gov	http://www.epa.gov/region5/sites/alliedchemical/pdfs/allied-chemical-5yr-review-200409-report.pdf
Bowers Landfill, Circleville, OH	Superfund Landfill	Soil, ground water, and surface water contaminated with VOCs and PCBs. Remediation included removing debris and installing a clay cap.	Wetlands were created around the site to protect the cap from flooding.	The nearby Scioto River was prone to flooding, which could affect the landfill cap.	Wetlands were created in the area between the landfill and river, where clay was taken to create the cap, to control flooding.	Sirtaj Ahmed, RPM EPA Region 5 77 West Jackson Boulevard Chicago, IL 60604-3507 312-886-4445 ahmed.sirtaj@epa.gov	http://www.epa.gov/superfund/programs/recycle/live/casestudy_bowers.html
Calumet Container Site, Hammond, IN	Superfund Industrial Facility	Remediation consisted of cleaning up soil contamination caused by previous drum and pail reconditioning operations at the site.	The area will be restored as a native habitat area with opportunities for passive recreation, including walking trails, and increasing biological diversity of native plants for prairie and wetland habitats.	Not specified	Not specified	Thomas Bloom EPA Region 5 77 West Jackson Boulevard Mail Code: SE-4J Chicago, IL 60604-3507 312-886-1967 bloom.thomas@epa.gov	http://www.epa.gov/region5superfund/redevelop/pdf/Calumet.pdf
Broverman Landfill, Christian County, IL	Illinois EPA Corrective Action Landfill	Cleanup included repair of the protective cap placed over an abandoned municipal landfill.	Prairie plants were seeded to stabilize the soil cover and reduce maintenance requirements.	Deep gullies were eroding down the landfill's sparsely vegetated sides and low areas were holding pools of stagnant water.	The cleanup team filled in large surface irregularities, added rip-rap in drainage ways to deter future erosion, installed vegetation mats, and seeded the area with native grasses and wildflowers. The remedy was cost-effective because nitrogen and phosphorous did not have to be added to the soil, additional topsoil and tilling was not required, and maintenance only included occasional prescribed burns.	Jody Kershaw Illinois EPA 1021 North Grand Avenue East P.O. Box 19276 Springfield, Illinois 62794-9276 217-524-3285 jody.kershaw@epa.state.il.us	http://www.epa.state.il.us/environmental-progress/v25/n1/abandoned-landfill.html
Dupage County Landfill, IL	Superfund Landfill	Ground water contamination associated with the landfill was cleaned up.	The site is now being used as a recreational area with picnic and camping areas, trails, and a lake. The previous landfill is used for sledding during the winter months.	Not specified	Not specified	Thomas Williams, RPM EPA Region 5 77 West Jackson Boulevard Mail Code: SR-6J Chicago, IL 60604-3507 312-886-6157 williams.thomas@epa.gov	http://cfpub.epa.gov/supercpad/cursites/csitinfo.cfm?id=0500606
E-Pond Solid Waste Management Unit, Lima, OH	RCRA Corrective Action Refinery Landfill	Synthetic root barrier and soil cover will be placed over the site, which is contaminated with chromium, antimony, thallium, PCB-1248, benzo(a)pyrene, and dibenz(a,h)anthracene.	Prairie habitat constructed with native plants. Interpretive areas and educational opportunities will be created.	Not specified	Not specified	Thomas Matheson, RPM EPA Region 5 77 West Jackson Boulevard Mail Code: DM-7J Chicago, IL 60604-3507 312-886-7569 matheson.thomas@epa.gov	http://www.epa.gov/epaoswer/hazwaste/ca/curriculum/download/eco-rec.pdf

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Appendix A: Ecological Revitalization Case Studies, continued

Property Name and Location	Property Type	Cleanup Type	Revitalization/Reuse Component	Problems/Issues	Solutions	Point of Contact	Notes/Links*
Fernald, Southwest OH	Superfund Uranium Metal Production	Remediation and closure project addressing uranium contamination in soil and ground water. Remediation included treatment and disposal through an on-site disposal facility and off-site disposal. The treated silos and waste pit materials were all disposed of off-site. The on-site disposal facility contains primarily contaminated soil and building debris.	End use of the entire 1,000-acre site is an educational park focusing on site history and ecology. Deep excavations are being converted to wetland and open water habitat. Excavations into the subsoil are being converted to native grasslands.	The primary problems have been invasive species control, geese and deer browsing, and germination success.	Invasive control was initially implemented through mechanical removal. Selective use of herbicides provides on-going control. Deer exclosures have been installed to fence the deer out of new restoration areas where woody plants were installed. Goose fencing, flagged twine, and coyote decoys have been used to discourage geese. Germination success is being evaluated and in some cases has required reseeding.	Thomas A. Schneider Ohio EPA, Office of Federal Facility 401 East Fifth Street Dayton, OH 45402-2911 937-285-6466 tom.schneider@epa.state.oh.us	http://www.wildlifehc.org/ewebeditpro/items/O57F3069.pdf
Ford Rouge Center, Dearborn, MI	MDEQ/ RCRA Corrective Action Automobile Manufacturing Complex	Remediation included removal of soils contaminated with SVOCs, PCBs, metals, and organics as well as containment strategies.	Ecological enhancements include a vegetated roof, pervious pavement, vegetated drainage swales, hedgerow wildlife corridors, wetland restoration, sunflower plantings, and grassland restoration. When it was built, this was the world's largest green roof at 10 acres in size. Honey bee hives have been added to enhance pollination for new plantings.	Issues encountered included coordinating remediation with ongoing plant expansion activities.	Early negotiations with MDEQ helped the process go smoothly.	Dan Ballnik Ford Motor Company One American Road Dearborn, MI 48126 313-248-8606 dballni1@ford.com	http://www.wildlifehc.org/ewebeditpro/items/O57F3071.pdf
Former Brass Foundry and Eljer Park, Marysville, OH	RCRA Corrective Action Foundry	Remediation included removing soil and stream sediments contaminated with VOCs and metals, demolishing buildings, capping residual areas, and improving site drainage to prevent erosion.	Revitalization included creating a park with athletic fields, playground equipment, a walking trail, and a wetlands area.	Not specified	Not specified	Jan J. Chizzonite, Managing Executive Partner Environmental Strategies Consulting LLC 11911 Freedom Drive Reston, VA 20190 703-709-6500 jan.chizzonite@wspgroup.com	http://www.epa.gov/ne/nationalcaconf/docs/Chizzonite.pdf
Former Ford Michigan Casting Center Landfill, Flat Rock, MI	Brownfields Landfill	A wooded leachate collection/management system was used to treat contaminated soil and ground water.	Wooded phytoremediation area providing increased biodiversity via creation of wildlife habitat for various birds and small mammals.	Not specified	Not specified	Jeff Hartlund Ford Motor Company One American Road Dearborn, MI 48126 313-322-0700 jhartlun@ford.com	http://www.wildlifehc.org/ewebeditpro/items/O57F3059.pdf
Former Gulf Refinery Site, Hooven, OH	RCRA Corrective Action Refinery	Phytoremediation consisting of a vegetative cap was used to treat soil contaminated with a mixture of petroleum hydrocarbons, including PAHs.	Activities at the site include constructing a wetland habitat for wildlife and extending the park planned for the adjacent area by providing community access.	Not specified	Not specified	Lucinda Jackson ChevronTexaco Corporation 100 Chevron Way P.O. Box 1627 Richmond, CA 94802-0627 510-242-1047 luaj@chevron.com	http://www.wildlifehc.org/ewebeditpro/items/O57F3061.pdf
Ilada Energy Company, East Cape Girardeau, IL	Superfund Waste Oil Reclamation Facility	Water and soil were contaminated with VOCs, PCBs, and heavy metals. Remediation activities included the removal of 1,742 cubic yards of soil and 865,700 gallons of water. Oil and sludge were incinerated.	The site is part of an ecological preservation area. The Land Conservancy bought land around the site and planted bottomwood trees adjacent to the site.	Not specified	Not specified	Sam Chummar EPA Region 5 77 West Jackson Boulevard Mail Code: SR-6J Chicago, IL 60604-3507 312-886-1434 chummar.sam@epa.gov	http://www.epa.gov/region5superfund/npl/illinois/ILD980996789.htm

* Links valid at time of publication.

Appendix A: Ecological Revitalization Case Studies, continued

Property Name and Location	Property Type	Cleanup Type	Revitalization/Reuse Component	Problems/Issues	Solutions	Point of Contact	Notes/Links*
Industrial Excess Landfill (IEL), Uniontown, OH	Superfund Landfill	Remediation activities such as extraction and treatment, capping the landfill, and installing a landfill gas extraction system were used to treat ground water contaminated by VOCs.	The site's remedy involves enhancing wildlife habitat and creating greenspace. Almost 10,000 native trees and shrubs were planted.	Not specified	Not specified	Timothy Fischer, RPM EPA Region 5 77 West Jackson Boulevard Mail Code: SR-6J Chicago, IL 60604-3507 312-886-5787 fischer.timothy@epa.gov	http://www.epa.gov/superfund/sites/fiveyear/f2006050001133.pdf
Joliet Army Ammunition Plant, Joliet, IL	Superfund Ammunitions Plant	Remediation included excavation and off-site disposal of soils contaminated with metals and on-site bioremediation of explosives-contaminated soils.	Midewin National Tall Grass Prairie was created for recreational, educational, and agricultural benefits to the public. Also, revitalization activities included restoring native wildlife populations and habitat.	Remediation goals were questioned as possibly not protecting ecological resources of the Midewin National Tall Grass Prairie due to the uncertainty of the risk posed by chemical constituents.	Site representatives are still working to establish proper remediation goals and costs.	Laurie Haines U.S. Army Environmental Center 2511 Jefferson Davis Highway Taylor Building NC3- Arlington, VA 22202-3926 703-601-1590 laurie.haines@hqda.army.mil	http://www.epa.gov/R5Super/npl/illinois/IL0210090049.htm
Petersen Sand and Gravel, Libertyville, IL	Superfund Quarry	The former Petersen quarry was used during the 1950s as a dumping ground for solvents and paints causing extensive contamination. Cleanup activities included removing drums, paint cans, and contaminated soil and surface water.	The cleanup enabled Independence Grove Forest Preserve to create a 115-acre lake and establish an education center at the site.	Not specified	Not specified	David Seeley, RPM EPA Region 5 77 West Jackson Boulevard Mail Code: SR-6J Chicago, IL 60604-3507 312-886-7058 seely.david@epa.gov	http://www.epa.gov/region5superfund/npl/illinois/ILD003817137.htm
Pocket Parks at Former Service Stations, Chicago, IL	IEPA Corrective Action Former Service Station	The sites were contaminated with BTEX, and contaminated soil was removed. Each of the sites received "No Further Remediation" letters through IEPA's Voluntary Cleanup Program.	Greenspace was created to reduce paved areas, which decreased the amount of stormwater that reaches the combined storm sewers.	Local politics favored commercial use over recreational use.	Multiple meetings with community groups helped to achieve consensus.	Kelly Kennoy City of Chicago 30 North Lasalle Street, 25th Floor Chicago, IL 60602-2575 312-744-8692 kkennoy@cityofchicago.org	http://www.wildlifehc.org/ewebeditpro/items/O57F3057.pdf
REGION 6							
AMAX Metals Recovery (Freeport McMoRan), Braithwaite, LA	RCRA Corrective Action Metals Recovery Facility	A UST and waste pile area was cleaned up and designated "ready for reuse."	A water retention pond was dewatered to form a wetland that provided a home to alligators relocated due to Hurricane Katrina in 2005.	Not specified	Not specified	U.S. EPA Region 6 1445 Ross Avenue Suite 1200 Dallas, TX 75202-2733 Louisiana Department of Environmental Quality Galvez Building 602 North Fifth Street Baton Rouge, LA 70802	http://findarticles.com/p/articles/mi_qn4200/is_20080604/ai_n25483065?tag=artBody;col1
Brooks City-Base, San Antonio, TX	RCRA Corrective Action Former Medical Research and Development Facility	A portion of the base was cleaned up by installing soil vapor extraction and ground water P&T systems, removing and installing a cover over garbage and construction debris, excavating contaminated soil, and incorporating ICs.	The former air force base was issued a "ready for reuse" determination, which was the first of its kind issued in Texas and the first for a federal facility nationwide. The remedial process incorporated ecological revitalization into the cleanup plan.	Not specified	Not specified	Jeanne Schulze EPA Region 6 1445 Ross Avenue, Suite 1200 Mail Code: 6PD-F Dallas, TX 75202-2733 214-665-7254 schulze.jeanne@epa.gov	http://enviro.blr.com/display.cfm/id/25919

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Property Name and Location	Property Type	Cleanup Type	Revitalization/Reuse Component	Problems/Issues	Solutions	Point of Contact	Notes/Links*
DuPont Remington Arms Facility, Lonoke, AK	RCRA Corrective Action Manufacturing Facility	Remediation included excavation and treatment of approximately 6,080 cubic yards of contaminated soils.	Remington Arms continues to manufacture ammunition at the facility. The remaining 731 acres are managed as a wildlife habitat. Ecological revitalization efforts include construction of a 20-acre moist soil impoundment for waterfowl habitat in cooperation with Ducks Unlimited.	Not specified	Not specified	Jeanne Schulze EPA Region 6 1445 Ross Avenue, Suite 1200 Mail Code: 6PD-F Dallas, TX 75202-2733 214-665-7254 schulze.jeanne@epa.gov	http://www.epa.gov/epaoswer/hazwaste/ca/success/rem11-07.pdf
England Air Force Base, LA	RCRA Corrective Action Air Force Base	A portion of the former air force base was cleaned up by removing contaminated soil, incorporating ICs, and instituting MNA of contaminated ground water. The site was designated "ready for reuse."	Areas excavated as part of a remedial action became part of the Audubon Trail, providing habitat and a stopping point for migratory birds, and an expanded 18-hole golf course.	Not specified	Not specified	Louisiana Department of Environmental Quality Public Records Center Galvez Building, Room 127 602 N. Fifth Street Baton Rouge, LA 70802	http://www.epa.gov/region6/ready4reuse/england_rfr.pdf
French, Ltd., Crosby, TX	Superfund Industrial Waste Storage	Remediation included treating soil and ground water contaminated with VOCs and heavy metals and creating 23 acres of new wetlands.	Wetlands and surrounding habitat can be used as recreation for outdoor enthusiasts and as habitat for vegetation and wildlife.	Not specified	Not specified	Ernest Franke, RPM EPA Region 6 1445 Ross Avenue Suite 1200 Mail Code: 6SFRA Dallas, TX 75202-2733 214-665-8521 franke.ernest@epa.gov	http://cfpub.epa.gov/supercpad/cursites/csitinfo.cfm?id=0602498
Heifer International New World Headquarters, Little Rock, AR	Brownfields Industrial Facility	Petroleum contaminated soil was removed from the site.	Activities at the site included the creation of retention ponds and a wetland habitat.	The primary issue at this site was funding.	Support from federal, state, and local sources, along with existing funds allowed cleanup.	Gerald Cound Director of Facilities Management Heifer International 1 World Avenue Little Rock, AR 72202 501-907-2965 gerald.cound@heifer.org	http://www.wildlifehc.org/ewebeditpro/items/O57F5385.pdf
REGION 7							
3-D Investments, Inc., Alda, NE	RCRA Brownfields and Superfund Former Gas Station, Battery Cracking and Lead Recovery Facility	The 3.65-acre site was investigated under RCRA authority. The facility went bankrupt and cleanup costs exceeded monies in the facility's trust fund, so EPA RCRA referred the facility to Region 7 EPA Superfund. Region 7 Superfund evaluated the site and conducted removal activities of lead-contaminated soils. The site was cleaned up to residential or near residential standards.	EPA sent a letter stating the facility was cleaned up, and the property was deeded to the Crane Meadows Nature Center, a nonprofit organization dedicated to natural resource education and the preservation of Sandhill cranes.	During the cleanup response, EPA discovered areas of contamination that were previously unknown. Neighbors and Crane Meadows Nature Center also had a concern regarding excess tree removal.	EPA Region 7 RCRA received a RCRA Brownfields Prevention Initiative Targeted Site Effort grant to assist with characterization, public involvement and other activities. EPA worked with neighbors and Crane Meadows Nature Center to alleviate their concerns about removing perimeter trees. Crane Meadows Nature Center wanted perimeter trees to remain to serve as a wind-break. EPA obliged this request. Mulch from some of the trees was also left onsite.	Andrea R. Stone EPA Region 7 901 North Fifth Street Mail Code: ARTDRCAP Kansas City, KS 66101 913-551-7662 stone.andrear@epa.gov	http://www.epa.gov/swerosps/rcrabf/html-doc/tsefac03.htm

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Appendix A: Ecological Revitalization Case Studies, continued

Property Name and Location	Property Type	Cleanup Type	Revitalization/Reuse Component	Problems/Issues	Solutions	Point of Contact	Notes/Links*
Cherokee County, Galena, KS	Superfund Mining Site	Remediation consisted of burying surface mine wastes contaminated with lead, mercury, and cadmium in abandoned mine pits, subsidence areas, and mine shafts on site; diverting streams away from waste piles; recontouring land surface; and revegetating with native prairie grasses to control runoff and erosion.	Native prairie grassland habitat encouraged the return of wildlife.	Potential for cave-in of filled mine shafts after heavy rain or freezing and thawing cycles.	Avoided development in the areas with potential for cave-in or collapse.	David Drake, RPM EPA Region 7 901 North Fifth Street Mail Code: SUPRFFSE Kansas City, KS 66101 913-551-7626 drake.dave@epa.gov	http://www.epa.gov/superfund/programs/recycle/live/casestudy_cherokee.html
Times Beach, Times Beach, MO	Superfund Contaminated Urban Area	A temporary incinerator was installed to burn soil contaminated with dioxin. The waste ash from the treated soil was buried on site. People were relocated and all homes and businesses were demolished.	A state park now exists on the site and acts as a bird sanctuary.	Numerous problems and issues resulted from this contentious Superfund site. See the Web site provided under "Notes/Links" for more information.	See the Web site provided under "Notes/Links" for more information.	Bob Feild, RPM EPA Region 7 901 North Fifth Street Mail Code: SUPRMOKS Kansas City, KS 66101 913-551-7697 feild.robert@epa.gov	http://cfpub.epa.gov/supercpad/cursites/csitinfo.cfm?id=0701237
Wheeling Disposal Service Co, Inc. Landfill, Amazonio, MO	Superfund Landfill	Soil contaminated with municipal and industrial wastes was remediated by upgrading the existing landfill cap with a clay and soil cover. Ground and surface water were monitored.	During the cleanup, the owner dug a pond and planted native wild grasses and other foliage that would attract birds and wildlife.	Not specified	Not specified	Amer Safadi, RPM EPA Region 7 901 North Fifth Street Mail Code: SUPRMOKS Kansas City, KS 66101 913-551-7825 safadi.amer@epa.gov	http://cfpub.epa.gov/supercpad/cursites/csitinfo.cfm?id=0700780
REGION 8							
BP Former Refinery, Platte River Commons, Casper, WY	RCRA Corrective Action Former Petroleum Refinery	Cleanup included removal of trash and waste from the river to contain the flow of contaminated ground water, excavation of contaminated soils, addition of P&T wells and construction of a wetland treatment system. Nearly 2,000 trees were planted to assist with phytoremediation.	After the river was cleaned up, a recreational kayak course was created. A portion of the site was used to create an 18-hole golf course. Wetlands were incorporated into the golf course design to assist in treating contaminated ground water. Trees were planted for phytoremediation.	Not specified	Not specified	Vickie Meredith WDEQ Solid & Hazardous Waste Division, Hazardous Waste Permitting and Corrective Action Program 250 Lincoln Street Lander, WY 82520 vmered@state.wy.us 307-332-6924 Tom Aalto, EPA Region 8 1595 Wynkoop Street Mail Code: 8P-HW Denver, CO 80202-1129 aalto.tom@epa.gov 303-312-6949	http://www.epa.gov/waste/hazard/correctiveaction/pdfs/casper11-07.pdf

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Property Name and Location	Property Type	Cleanup Type	Revitalization/Reuse Component	Problems/Issues	Solutions	Point of Contact	Notes/Links*
Cache La Poudre River Superfund Site, Fort Collins, CO	Superfund	Soil and sediments in the Poudre River, and ground water were contaminated with gasoline mixed with coal tar. Cleanup activities included sediment excavation and temporary re-routing of the Poudre River, a vertical sheet pile barrier to stop ground water flow, and ground water treatment.	EPA completed an intact but unobtrusive remedy of the Poudre River to preserve the riverine habitat.	Beavers ate about half of the tree plantings.	Site managers used wire on the first 6 to 8 feet of tree plantings, and painted the wire to be easily visible.	Paul Peronard, OSC EPA Region 8 1595 Wynkoop Street Mail Code: 8EPR-SR Denver, CO 80202-1129 303-312-6808 peronard.paul@epa.gov	http://www.clu-in.org/conf/tio/ecocasestudies_080207/
California Gulch Superfund Site, Upper Arkansas River Operable Unit, Leadville, CO	Superfund Mining Site	The mining district's soil, surface water, and sediments were heavily contaminated with lead, zinc, and other heavy metals from mine tailings. Biosolids and lime were applied directly to the tailings along Upper Arkansas River.	The area along the river has been restored and supports vegetation and wildlife, and is available for agricultural use and recreational use such as hiking and fishing.	Tailings could not be excavated because of the risk of tailings entering the river and the difficulty of finding a repository for the contaminated soil. Also, replacement of topsoil would be costly. Mobilizing materials to the site was difficult due to the elevation of the site. Water was also scarce due to low rainfall and high elevation.	Biosolids were spread over the tailings, reducing the potential for tailings to migrate to the river.	Rebecca Thomas, RPM EPA Region 8 1595 Wynkoop Street Denver, CO 80202-1129 303-312-6552 thomas.rebecca@epa.gov Mike Holmes, RPM EPA Region 8 1595 Wynkoop Street Denver, CO 80202-1129 303-312-6607 holmes.michael@epa.gov	http://www.epa.gov/superfund/programs/recycle/pdf/cal_gulch.pdf
East Helena Site, Helena, MT	Superfund Smelting Site	Ground water, surface water, and soil contamination from decades of lead smelting activities was cleaned up by removing waste, treating soil, and capping the area.	In addition to mixed commercial and residential use, portions of the site are being used for a neighborhood park, a baseball field, and some wetlands redevelopment.	Not specified	Not specified	Scott Brown EPA Region 8 Montana Operations Office Federal Building 10 West 15th Street Suite 3200 Mail Code: 8MO Helena, MT 59626 406-457-5035 brown.scott@epa.gov	http://cfpub.epa.gov/supercpad/cursites/csitinfo.cfm?id=0800377
Kennecott North and South Zone Sites, Salt Lake County, UT	Superfund Mining Site	Soil and ground water were contaminated with mining wastes, including sulfates and heavy metals. Soil was removed, and ground water was pumped and treated in the mine's tailings slurry line.	Open space, wetlands, and wildlife habitat were created. A residential area was also created.	Not specified	Not specified	Rebecca Thomas, RPM EPA Region 8 1595 Wynkoop Street Mail Code: 8EPR-SR Denver, CO 80202-1129 303-312-6552 thomas.rebecca@epa.gov	http://www.epa.gov/superfund/programs/aml/tech/kennecott.pdf
Milltown Reservoir Sediments, Milltown, MT	Superfund Mining Site	Six million cubic yards of mining waste that had piled up at the base of the Milltown Dam was poisoning the reservoir and affecting drinking water. A new drinking water system was installed at the site.	In addition to adding a new drinking water system, 2.5 miles was added to existing hiking trails in Missoula to complete a loop around the University of Montana and Missoula's waterfront.	Not specified	Not specified	Scott Brown EPA Region 8 Montana Operations Office Federal Building 10 West 15th Street Suite 3200 Mail Code: 8MO Helena, MT 59626 406-457-5035 brown.scott@epa.gov	http://cfpub.epa.gov/supercpad/cursites/csitinfo.cfm?id=0800445

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Property Name and Location	Property Type	Cleanup Type	Revitalization/Reuse Component	Problems/Issues	Solutions	Point of Contact	Notes/Links*
Monticello Mill Superfund Site, Monticello, UT	Superfund Former DOE Processing Facility	A cover system was constructed to contain radioactive material removed from the site. The cover design mimics and enhances the natural ground water balance and uses a capillary barrier. Native vegetation was planted to maximize evapotranspiration.	The native vegetation chosen was designed to emulate the structure, function, diversity, and dynamics of native plant communities in the area.	Not specified	Not specified	Mark Aguilar EPA Region 8 1595 Wynkoop Street Mail Code: 8EPR-F Denver, CO 80202-1129 303-312-6251 aguilar.mark@epa.gov	http://www.clu-in.org/PRODUCTS/NEWSLTRS/ttrend/view.cfm?issue=tt0500.htm
Rocky Flats Plant, Golden, CO	Superfund Former DOE Weapons Facility	At one time the site stored more than 14 tons of plutonium. All special nuclear materials were packaged and shipped to licensed repositories. Over 800 structures were cleaned up, as necessary, and removed. 690 tanks were decontaminated and removed, and onsite landfills were covered. Three contaminated ground water plume barriers and passive treatment systems were installed. Finally, wastes and contaminated soils were removed and shipped to permitted facilities.	Part of the site that has been remediated has been transferred from DOE to DOI and the USFWS to manage as a National Wildlife Refuge.	Not specified	Not specified	Mark Aguilar EPA Region 8 1595 Wynkoop Street Mail Code: 8EPR-F Denver, CO 80202-1129 303-312-6251 aguilar.mark@epa.gov	http://www.epa.gov/region8/superfund/co/rkyflatsplant/index.html
Rocky Mountain Arsenal, Commerce City, CO	Superfund Army-Lead Remedial Action Ammunition Plant	P&T systems were installed to remediate ground water contaminated with wastes from production of chemical warfare agents, industrial and agricultural chemicals, and pesticides.	Congress passed the Rocky Mountain Arsenal National Wildlife Refuge Act, requiring the site to become part of the national wildlife refuge system once cleanup is complete.	Not specified	Not specified	Greg Hargreaves, RPM EPA Region 8 1595 Wynkoop Street Mail Code: 8EPR-F Denver, CO 80202-1129 303-312-6661 hargreaves.greg@epa.gov	http://www.rma.army.mil/cleanup/clnfrm.html
Silver Bow Creek and Warm Springs Ponds, Butte, MT	Superfund Mining Site	Remediation included excavating sediment contaminated by copper mining activities and installing a water treatment system.	Extensive wetlands are now home to a variety of wildlife. Nesting platforms were built to protect birds. The wetlands are also used for recreation such as fishing, hiking, and biking.	Not specified	Not specified	Ron Bertram, RPM EPA Region 8 1595 Wynkoop Street Mail Code: 8EPR-F Denver, CO 80202-1129 406-441-1150 bertram.ron@epa.gov	http://cfpub.epa.gov/supercpad/cursites/csitinfo.cfm?id=0800416

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Property Name and Location	Property Type	Cleanup Type	Revitalization/Reuse Component	Problems/Issues	Solutions	Point of Contact	Notes/Links*
Summitville Mine, CO	Superfund Mining Site	Gold mining released cyanide and acidic mine water to the Alamosa River. Cleanup activities include permanently stabilizing the site and reversing the effects of mining on the river.	The Alamosa River and tributaries flow through wetlands, forested and agricultural land, and into the Terrace Reservoir, which supplies irrigation water to livestock and farms. The site has been revegetated with grasses that promote the recolonization of native plants. The river, which was void of life because of contamination, now supports some types of aquatic life.	Not specified	Not specified	Victor Ketellapper, RPM EPA Region 8 1595 Wynkoop Street Mail Code: 8EPR-F Denver, CO 80202-1129 303-312-6578 ketellapper.victor@epa.gov	http://cfpub.epa.gov/supercpad/cursites/csitinfo.cfm?id=0801194
REGION 9							
Atlas Asbestos Mine, Fresno County, CA	Superfund Mining Site	The remedy included the removal of contaminated material, stabilization of erosion-prone areas, and structural improvements to clean up the asbestos contaminated soil and water.	The site is a wildlife sanctuary and a popular recreational area for hikers, campers, and hunters.	At the Atlas Mine Area, the road to the Rover Pit/Channel A is likely to fail sometime in the future due to an active landslide. In addition, the road to Pond A may also fail in the future due to erosion.	Alternate access roads to the Rover Pit/Channel A and to Pond A will be identified prior to failure of the existing roads.	Anna Lynn Suer EPA Region 9 75 Hawthorne Street Mail Code: WTR-2 San Francisco, CA 94105 415-972-3148 suer.lynn@epa.gov	http://www.epa.gov/superfund/sites/fiveyear/f2006090001092.pdf
A West Coast Refinery, Location not provided	EPA Research Technology Development Forum Site Refinery Effluent Treatment System	A phytoremediation demonstration was conducted at the site, which was contaminated with hydrocarbons. The remediation also included enhancing and planting wetlands, and installing a vegetation cap.	The site includes a clean stormwater holding basin. Natural vegetation was planted over the 90-acre vegetation cap.	Selenium was identified on site and in bird eggs, which can be harmful to the wildlife, especially bird embryos.	The site was turned into a treatment zone and habitat zone. Birds were discouraged from the treatment zone where selenium was to be removed. After testing, selenium was found to be greatly reduced in bird eggs.	Kim Beman Chevron 6001 Bollinger Canyon Road San Ramon, CA 94583, KBGS@chevron.com	http://www.wildlifehc.org/ewebeditpro/items/O57F3055.pdf
Alameda Naval Air Station, Alameda, CA	Superfund Landfill, Lagoon	Remediation included using dredged sediment from the lagoon as part of a landfill cap for parts of the site that were contaminated with PCBs, heavy metals, and PAHs.	A golf course is being planned in the landfill area, and a marina will be constructed in the lagoon area.	Not specified	Not specified	Anna Marie Cook EPA Region 9 75 Hawthorne Street Mail Code: SFD-8-3 San Francisco, CA 94105 415-972-3029 cook.anna-marie@epa.gov	http://www.epa.gov/oerrpage/superfund/programs/recycle_old/pilot/facts/r9_38.htm
REGION 10							
American Crossarm & Conduit Co., Chehalis, WA	Superfund Wood Treatment Facility	Remediation activities include removing contaminated site material, disposing of the site facilities, removing lagoon sediment, and excavating soil. The contaminants of concern are carcinogenic polyaromatic hydrocarbons, PCP, and dioxin/furans.	Wetlands restoration.	Not specified	Not specified	Anne McCauley EPA Region 10 1200 Sixth Avenue Mail Code: ECL-113 Seattle, WA 98101 206-553-4689 mccauley.anne@epa.gov	http://www.epa.gov/superfund/sites/fiveyear/f04-10004.pdf

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Property Name and Location	Property Type	Cleanup Type	Revitalization/Reuse Component	Problems/Issues	Solutions	Point of Contact	Notes/Links*
Commencement Bay, Tacoma, WA	Superfund Industrial Activities	Industrial activities resulting in hazardous waste contamination of the waterways within Commencement Bay were addressed.	In addition to navigational improvements to the port, nine acres of wetlands were restored as a result of the cleanup. EPA also worked with Washington Department of Environment to create seven acres of essential mud flats habitat where fish, birds, wildlife, and plant species thrive.	Not specified	Not specified	Chris Bellovary EPA Region 10 1200 Sixth Avenue Mail Code: ECL-111 Seattle, WA 98101 206-553-2723 bellovary.chris@epa.gov	http://cfpub.epa.gov/supercpad/cursites/csitinfo.cfm?id=1000981
Harmony Mine and Mill, Baker, ID	Superfund Mining Site	A diversion ditch was created and pipes laid to divert Withington Creek from tailings piles. After they were dry, 10,000 cubic yards of tailings were excavated and hauled to a repository location. A sedimentation pond was also constructed below the tailings pile to catch any runoff that occurred. Tailings were then capped with a 2-foot layer of compacted rock followed by a one-foot layer of uncompacted rock.	Where the tailings were removed, the area was graded, a stable creek bed with the ability to withstand large debris flow was constructed, and disturbed areas were seeded. Withington Creek is a designated cold water community and salmonid spawning habitat for the endangered chinook salmon.	Not specified	Not specified	Greg Weigel EPA Region 10, Idaho Operations Office 1435 North Orchard Street Boise, ID 83706 208-378-5773 weigel.greg@epa.gov	http://epaosc.net/site_profile.asp?site_id=10BN
Hoquarton Natural Interpretive Trail, Tillamook, OR	Brownfields Lumber Mill	Using an EPA Revolving Loan Fund, contaminated soil was excavated and treated.	The former lumber mill was transformed into a recreational and educational greenspace. Volunteers removed weeds and invasive plants, disposed of over two tons of trash, and planted over 2,000 native plants in riparian areas. A trail was also installed to provide walking and bird watching opportunities.	It was unclear how long-term maintenance of the park would be achieved.	Long-term maintenance of the park was supported by school groups and other volunteers.	Mike Slater EPA Region 10 805 SW Broadway Mail Code: OOO Portland, OR 97205 503-326-5872 slater.mike@epa.gov	http://www.landcurrent.com/contemporary/landscape_design.php?in=Hoquarton&work=public
Old Jensen Texaco Station, Rosalia, WA	OUST Abandoned Gas Station	Through the USTFields Pilot Program, this abandoned gas station site was remediated by removing five USTs and contaminated soil to make the site ready for future reuse. Contaminated soil treated and disposed of off-site. Additional contamination is being addressed through ground water monitoring and possible MNA.	Stakeholders plan to convert the former gas station site into a visitor and community center with green infrastructure. They plan to incorporate native plant communities that are part of the the distinctive Palouse ecosystem, including grasslands, scrub thickets, ridges, and slope communities. The community center could be used to educate visitors about the unique geology and ecology of the region.	Additional contamination could not be removed without destroying the historic building this project was intended to restore. *In situ* treatment options have been considered but will not be pursued until additional ground water data is evaluated. MNA of the remaining contamination may prove to be an adequate and appropriate cleanup alternative.	Not specified	Wildlife Habitat Council 8737 Colesville Road, Suite 800 Silver Spring, MD 20910 301-588-8994 whc@wildlifehc.org	http://www.wildlifehc.org/ewebeditpro/items/O57F7008.pdf

* Links valid at time of publication.

Appendix A: Ecological Revitalization Case Studies, continued

Property Name and Location	Property Type	Cleanup Type	Revitalization/Reuse Component	Problems/Issues	Solutions	Point of Contact	Notes/Links*
Port Hadlock Detachment, Jefferson County, WA	Superfund Landfill	Soil, ground water, sediment, and shellfish were contaminated with heavy metals, PCBs, and pesticides. As part of the remediation, the portion of the landfill that had leaked into the surrounding beaches was contained and capped.	Beaches and tribal fishing grounds were re-opened.	None	None	Nancy Harney, RPM EPA Region 10 1200 Sixth Avenue Mail Code: ECL-115 Seattle, WA 98101 206-553-6635 harney.nancy@epa.gov	http://cfpub.epa.gov/supercpad/cursites/csitinfo.cfm?id=1001117
SeQuential Biofuels, Eugene, OR	OUST Fueling Station	USTs from the closed fueling station were removed and contaminated soil was excavated. A Brownfields grant assisted in cleaning up the remainder of the site and getting it ready for reuse.	The new station is bordered with grassy bioswales that help to contain stormwater runoff from the site, remediate contamination biologically before it leaves the site, and slow the flow of stormwater into the storm-sewer system. In addition, green building technologies were used including a vegetated roof, solar panels, purchased wind energy, and use of available natural light through window design to reduce the need for heating and cooling.	Not specified	Not specified	Jim Glass Oregon Department of Environmental Quality 750 Front Street NE, Suite 120 Salem, OR 97301-1039 503-378-5044 glass.jim@deq.state.or.us	http://www.neiwpcc.org/lustline/lustline_pdf/lustline_55.pdf
Sequim Bay Estuary, Clallam County, WA	Brownfields	Cleanup activities involved removing 99 creosote-treated pilings from the estuary and removing 350 tons of contaminated soil and 600 tons of solid waste from an adjacent shoreline and riparian wetlands.	The bay water now provides clean sediment and habitat for shellfish, salmon, and other natural species. The project also has the economic benefits for the Jamestown S'Klallam Tribe with increased revenue from the sale of fish and an expanded tourist area for kayaking and bird watching.	Not specified	Not specified	EPA Region 10 Brownfields Team 1200 Sixth Avenue Seattle, WA 98101 206-553-2100	http://www.epa.gov/brownfields/03grants/sequim.htm
West Page Swamp (Bunker Hill NPL Site), Shoshone County, ID	Superfund Mining Site	Remediation included constructing a cap over soil contaminated with lead and zinc tailings. The cap consisted of biosolids compost and wood ash.	Wetland is now habitat to wildlife.	Stakeholders were concerned that remediation is only a short-term solution because contaminants were not completely removed from site.	Ground water and surface water wells were installed and are being monitored quarterly or annually.	Harry Compton EPA Facilities Rariton Depot 2890 Woodbridge Avenue Mail Code: 101MS101 Edison, NJ 08837-3679 732-321-6751 compton.harry@epa.gov	http://www.wildlifehc.org/ewebeditpro/items/O57F3063.pdf
Wyckoff-Eagle Harbor, Puget Sound, WA	Superfund Wood Treatment Facility	EPA worked with USACE to obtain clean silt to cap contaminated sediments from a previous wood treatment facility and shipyard to stop further release of toxins into Puget Sound. EPA also removed on-site buildings and polluted sediments from the harbor.	After contaminated sediment was removed, EPA and state officials lined the area with gravel to attract mussels and barnacles and created a 2-acre estuarine habitat.	Not specified	Not specified	Ken Marcy EPA Region 10 1200 Sixth Avenue Mail Code: ECL-112 Seattle, WA 98101 206-553-2782 marcy.ken@epa.gov	http://www.epa.gov/superfund/programs/recycle/live/casestudy_wyckoff.html

* Links valid at time of publication.

Appendix B: Additional Ecological Revitalization Resources

Section 1: Introduction

Interstate Technology & Regulatory Council (ITRC): www.itrcweb.org

Land Revitalization Initiative: www.epa.gov/oswer/landrevitalization/basicinformation.htm

U.S. Environmental Protection Agency (EPA) Hazardous Waste Cleanup Information (CLU-IN). Tools for Ecological Land Reuse: www.cluin.org/ecotools

EPA One Cleanup Program Initiative: www.epa.gov/oswer/onecleanupprogram

Section 2: Ecological Revitalization Under EPA Cleanup Programs

Atlas Tack Superfund Site Information: www.epa.gov/ne/superfund/sites/atlas

Brownfields Green Infrastructure Fact Sheet: www.epa.gov/brownfields/publications/swdp0408.pdf

Biological Technical Assistance Groups (BTAG) Regional Web sites:
- EPA Region 3: www.epa.gov/reg3hwmd/risk/eco/index.htm
- EPA Region 4: www.epa.gov/region4/waste/ots/index.htm
- EPA Region 5: www.epa.gov/region5superfund/ecology/index.html
- EPA Region 8: www.epa.gov/region8/r8risk/eco.html

Cross Program Revitalization Guidance:
www.epa.gov/superfund/programs/recycle/pdf/cprm_guidance.pdf

Emergency Response Team: www.ert.org

EPA CLU-IN Publications Search Web site: www.clu-in.org/pub1.cfm

EPA CLU-IN Tools for Ecological Land Reuse: www.cluin.org/ecotools

EPA Guidelines for Ecological Risk Assessment:
http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=12460

EPA Land Revitalization Web site: www.epa.gov/landrevitalization/index.htm

EPA Office of Superfund Remediation and Technology Innovation: www.epa.gov/tio

EPA Region 3—Hazardous Waste Cleanup Sites Land Use & Reuse Assessment, Data Results:
www.epa.gov/region03/revitalization/R3_land_use_final/data_results.pdf

EPA Office of Solid Waste and Emergency Response (OSWER). 1991. ECO Update—The Role of Biological Technical Assistance Groups (BTAG) in Ecological Assessment. Publication number 9345.0-051. September. www.epa.gov/oswer/riskassessment/ecoup/pdf/v1no1.pdf

EPA OSWER. 2008. Green Remediation: Incorporating Sustainable Environmental Practices into Remediation of Contaminates Sites. www.clu-in.org/download/remed/Green-Remediation-Primer.pdf

Federal Facilities Restoration and Reuse Office (FFRRO) Web site: www.epa.gov/fedfac/about_ffrro.htm

Interim Guidance for OSWER Cross-Program Revitalization Measures:
www.epa.gov/landrevitalization/docs/cprmguidance-10-20-06covermemo.pdf

Local native plant societies: www.michbotclub.org/links/native_plant_society.htm

National Oceanic and Atmospheric Administration (NOAA): http://response.restoration.noaa.gov

Superfund Sitewide Ready-for-Reuse Performance Measure:
www.epa.gov/superfund/programs/recycle/pdf/sitewide_a.pdf

Underground Storage Tank (UST) Brownfields Cleanups:
www.nemw.org/petroleum%20issue%20opportunity%20brief.pdf

U.S. Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS):
www.nrcs.usda.gov

Wildlife Habitat Council (WHC) Leaking Underground Storage Tank (LUST) Cleanups Web site:
www.wildlifehc.org/brownfield_restoration/lust_pilots.cfm

Section 3: Technical Considerations for Ecological Revitalization

EPA CLU-IN. The Use of Soil Amendments for Remediation, Revitalization, and Reuse:
www.clu-in.org/download/remed/epa-542-r-07-013.pdf

EPA Tech Trends. Fort Wainwright:
www.clu-in.org/PRODUCTS/NEWSLTRS/ttrend/view.cfm?issue=tt0500.htm

Section 4: Wetlands Cleanup and Restoration

EPA, Office of Water, Office of Wetlands, Oceans, and Watersheds: www.epa.gov/OWOW/wetlands

EPA OSWER. Considering Wetlands at Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) Sites (EPA 540/R-94/019, 1994):
www.epa.gov/superfund/policy/remedy/pdfs/540r-94019-s.pdf

EPA OSWER. Environmental Fact Sheet: Controlling the Impacts of Remediation Activities in or Around Wetlands (EPA 530-F-93-020).

Society of Wetland Scientists (SWS), Wetlands Journal: www.sws.org/wetlands

U.S. Department of Interior (DOI), U.S. Fish and Wildlife Service. National Wetlands Inventory:
www.nwi.fws.gov

U.S. Geological Survey (USGS), National Wetlands Research Center: www.nwrc.gov

Wetlands Research Program and Wetlands Research Technology Center:
http://el.erdc.usace.army.mil/wetlands

Wetland Science Institute, Natural Resources Conservation Service, U.S. Department of Agriculture:
www.wli.nrcs.usda.gov

Section 5: Stream Cleanup and Restoration

EPA Office of Water. River Corridor and Wetland Restoration Web site: www.epa.gov/owow/wetlands/restore

EPA Office of Water and OSWER. Integrating Water and Waste Programs to Restore Watersheds: www.epa.gov/superfund/resources/integrating.htm

EPA OSWER. Contaminated Sediment Remediation Guidance: www.epa.gov/superfund/health/conmedia/sediment/guidance.htm

Federal Interagency Stream Corridor Restoration Guide: www.nrcs.usda.gov/technical/stream_restoration/newgra.html

University of Nebraska-Lincoln: www.ianr.unl.edu/pubs/Soil/g1307.htm

Section 6: Terrestrial Ecosystems Cleanup and Revitalization

Clemants, Stephen. 2002. Is Biodiversity Sustainable in the New York Metropolitan Area? University Seminar on Legal, Social, and Economic Environmental Issues, Columbia University, December 2002.

EPA OSWER. 2008. Green Remediation: Incorporating Sustainable Environmental Practices into Remediation of Contaminates Sites. www.clu-in.org/download/remed/Green-Remediation-Primer.pdf

Handel, Steven N., G.R. Robinson, WFJ Parsons, and J.H. Mattei. 1997. Restoration of Woody Plants to Capped Landfills: Root Dynamics in an Engineered Soil, Restoration Ecology, 5:178-186.

North Carolina Cooperative Extension Service: www.ces.ncsu.edu/depts/hort/hil/hil-645.html

Plant Conservation Alliance: www.nps.gov/plants

Robinson, G.R. and S.N. Handel. 1993. Forest Restoration on a Closed Landfill: Rapid Addition of New Species by Bird Dispersion, Conservation Biology, 7: 271-278.

Society for Ecological Restoration. Ecological Restoration Reading Resources: www.ser.org/reading_resources.asp

USDA, NRCS. Plant Materials Program: http://plant-materials.nrcs.usda.gov

USDA, NRCS. PLANTS Database: http://plants.usda.gov

Weed Science Society of America: www.wssa.net

Section 7: Long-Term Stewardship Considerations

EPA. Superfund – Operation and Maintenance Web site: http://epa.gov/superfund/cleanup/postconstruction/operate.htm

EPA OSWER. 2005. Long Term Stewardship Task Force Report and the Development of Implementation Options for the Task Force Recommendations. www.epa.gov/LANDREVITALIZATION/docs/lts-report-sept2005.pdf.

Institutional Controls: A Site Manager's Guide to Identifying, Evaluating, and Selecting Institutional Controls at Superfund and RCRA Corrective Action Cleanups, available at http://epa.gov/superfund/policy/ic/guide/guide.pdf

Appendix C: Acronyms

ACRES	Assessment, Cleanup, and Redevelopment Exchange System
AOC	Area of Concern
BMP	Best Management Practices
BP	British Petroleum
BRAC	Base Realignment and Closure
BTAG	Biological Technical Assistance Group
BTEX	Benzene, Toluene, Ethylbenzene, and Xylenes
BTSC	Brownfields and Land Revitalization Technology Support Center
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CERCLIS	Comprehensive Environmental Response, Compensation, and Liability Information System
CIC	Community Involvement Coordinator
CLU-IN	Hazardous Waste Clean-up Information
CPRM	Cross-Program Revitalization Measure
DARRP	Damage Assessment, Remediation and Restoration Program
DEQ	Department of Environmental Quality
DNT	Dinitrotoluene
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOI	U.S. Department of Interior
EO	Executive Order
EOD	Explosives Ordnance Disposal
EPA	U.S. Environmental Protection Agency
ER3	Environmentally Responsible Redevelopment and Reuse
ERA	Ecological Risk Assessment
FFEO	Federal Facilities Enforcement Office
FFLC	Federal Facilities Leadership Council
FFRRO	Federal Facilities Restoration and Reuse Office
FS	Feasibility Study
FY	Fiscal Year
GPRA	Government Performance and Results Act
HE EI	Human Exposures Under Control Environmental Indicator
HMX	High Melting Explosive (or Cyclotetramethylenetetranitramine)
IC	Institutional Control
IEPA	Illinois Environmental Protection Agency
ITRC	Interstate Technology & Regulatory Council
JOAAP	Joliet Army Ammunition Plant
LEED	Leadership in Energy and Environment Design
LUST	Leaking Underground Storage Tank
MCL	Maximum Contaminant Level
MDEQ	Michigan Department of Environmental Quality
MNA	Monitored Natural Attenuation
NOAA	National Oceanic and Atmospheric Administration
NPL	National Priorities List
NRC	National Research Council
NRCS	Natural Resources Conservation Service
NRDA	Natural Resource Damage Assessment
O&M	Operation and Maintenance
OBLR	Office of Brownfields and Land Revitalization
OPEI	Office of Policy, Economics, and Innovation
ORCR	Office of Resource Conservation and Recovery
OSC	On-Scene Coordinator
OSRTI	Office of Superfund Remediation and Technology Innovation

OSWER	Office of Solid Waste and Emergency Response
OU	Operable Unit
OUST	Office of Underground Storage Tanks
P&T	Pump and Treat
PAH	Polycyclic Aromatic Hydrocarbon
PCA	Plant Conservation Alliance
PCB	Polychlorinated Biphenyl
PCE	Perchloroethylene (or Tetrachloroethene)
PDF	Portable Document Format
PFP	Protective For People
RAU	Ready for Anticipated Use
RCRA	Resource Conservation and Recovery Act
RDX	Royal Demolition Explosive (or Cyclotrimethylenetrinitramine)
RI	Remedial Investigation
RMA	Rocky Mountain Arsenal
ROD	Record of Decision
RI/FS	Remedial Investigation/Feasibility Study
RPM	Remedial Project Manager
RTU	Return To Use
SRI	Superfund Redevelopment Initiative
SVOC	Semi-Volatile Organic Compound
SWS	Society of Wetland Scientists
TAB	Technical Assistance to Brownfields
TCE	Trichloroethylene
TNT	Trinitrotoluene
TPM	Technical Performance Measure
USACE	U.S. Army Corps of Engineers
USDA	U.S. Department of Agriculture
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
UST	Underground Storage Tank
UXO	Unexploded Ordnance
VOC	Volatile Organic Compound
WHC	Wildlife Habitat Council

Ecological Revitalization:
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Appendix B-4

Postconstruction Changes in the Hydraulic Properties of Water Balance Cover Soils

Postconstruction Changes in the Hydraulic Properties of Water Balance Cover Soils

C. H. Benson[1]; A. Sawangsuriya[2]; B. Trzebiatowski[3]; and W. H. Albright[4]

Abstract: Hydraulic properties of soils used for water balance covers measured at the time of construction and one to four years after construction are compared to assess how the hydraulic properties of cover soils change over time as a result of exposure to field conditions. Data are evaluated from ten field sites in the United States that represent a broad range of environmental conditions. The comparison shows that the saturated hydraulic conductivity (K_s) can increase by a factor of 10,000, saturated volumetric water content (θ_s) by a factor of 2.0, van Genuchten's α parameter by a factor of 100, and van Genuchten's n parameter can decrease by a factor of 1.4. Larger changes occur for denser or more plastic fine-textured soils that have lower as-built K_s, α, and θ_s and higher as-built n, resulting in a reduction in the variation in hydraulic properties that can be attributed to compaction. After two to four years, many water balance cover soils can be assumed to have K_s between 10^{-5} and 10^{-3} cm/s, θ_s between 0.36 and 0.40, α between 0.002 and 0.2 kPa^{-1}, and n between 1.2 and 1.5. The data may be used to estimate changes in hydraulic properties for applications such as waste containment, where long-term maintenance of hydraulic properties in shallow engineered soil layers is important.

DOI: 10.1061/(ASCE)1090-0241(2007)133:4(349)

CE Database subject headings: Hydraulic properties; Hydraulic conductivity; Soil water; Water balance.

Introduction

The hydrology of water balance covers used for waste containment systems is strongly influenced by the hydraulic properties of the cover soils, namely the saturated hydraulic conductivity (K_s), the unsaturated hydraulic conductivity (K_ψ), and the soil-water characteristic curve (SWCC) (the relationship between volumetric water content, θ, and suction, ψ). Cover soils with higher K_s, more gradually varying K_ψ, and a SWCC with higher air entry suction generally transmit less surface runoff and more percolation (drainage from the base of the cover) (Fayer and Gee 1997; Khire et al. 2000; Roesler et al. 2002; Apiwantragoon et al. 2003; Zornberg et al. 2003; Benson et al. 2005).

Hydraulic properties measured during design are often used to determine the required thickness of a water balance cover and as input to models used to predict cover hydrology (Fayer et al. 1992; Khire et al. 1997; Zornberg et al. 2003; Benson and Chen 2003; Benson et al. 2005). During design, however, hydraulic properties are typically determined on laboratory-compacted specimens and may not reflect the condition of cover soils following long-term exposure to local environmental conditions. Postconstruction processes (freezing and thawing, wetting and drying, root growth and death, and burrowing of worms and insects) often form larger pores between existing peds (Buol et al. 1997; Hillel 1998), altering the hydraulic properties of the soil and the hydrology of the cover (Suter et al. 1993; Benson and Othman 1993; Chamberlain et al. 1995; Waugh et al. 1999; Albrecht and Benson 2001; Henken-Mellies et al. 2001; Ayers et al. 2004; Meiers et al. 2006).

When long-term analyses of cover hydrology are made, temporal changes in soil properties are assumed or inferred because few data exist regarding how hydraulic properties change over time (Waugh et al. 1994, 1999; Khire et al. 2000; Zornberg et al. 2003). This paper compares hydraulic properties of cover soils measured at the time of construction and one to four years after construction, provides methods to estimate changes in the hydraulic properties over time, and provides recommendations regarding cover construction methods that will minimize the propensity for change in hydraulic properties. The data were collected from a network of final cover test sections in the Alternative Cover Assessment Program (ACAP) (Albright et al. 2004). Although this comparison spans a relatively short period of time and cannot be considered to represent "long-term" effects, the comparison does provide an indication of how the hydraulic properties of water balance cover soils may change over time and how these changes are related to the type of soil and the placement condition during construction.

[1]Professor and Kellet Fellow, Dept. of Civil and Environmental Engineering, Univ. of Wisconsin, Madison, WI 53706. E-mail: benson@engr.wisc.edu

[2]Civil Engineer, Road and Pavement Design Division, Bureau of Materials, Analysis and Inspection, Dept. of Highways, Bangkok, Thailand. E-mail: sawangsuriya@gmail.com

[3]Engineer, Malcolm Pirnie, Schaumburg, IL 60173. E-mail: btrzebiatowski@pirnie.com

[4]Associate Research Hydrogeologist, Division of Hydrologic Sciences, Desert Research Institute, Reno, NV 89512. E-mail: bill@dri.edu

Note. Discussion open until September 1, 2007. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on January 5, 2006; approved on October 16, 2006. This paper is part of the ***Journal of Geotechnical and Geoenvironmental Engineering***, Vol. 133, No. 4, April 1, 2007. ©ASCE, ISSN 1090-0241/2007/4-349–359/$25.00.

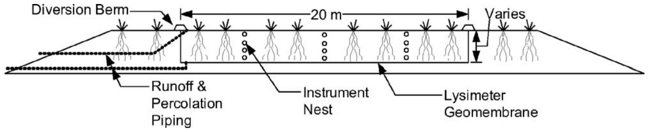

Fig. 1. Typical cross section of ACAP test section along the centerline. The lysimeter is 10 m × 20 m. The top deck of the test section is 30 m long and 20 m wide.

Background

Sample Sources

The ACAP test sections are large-scale lysimeter facilities located at sites throughout the United States that are used to monitor the water balance of prototype covers. A description of the test sections and the monitoring systems can be found in Benson et al. (2001) and Albright et al. (2004). A cross section of a typical test section is shown in Fig. 1. Each test section has a top deck that is 20 m wide and 30 m long, is sloped at 5 or 25%, depending on site-specific issues, and includes a 10 m × 20 m pan lysimeter lined with a geomembrane for monitoring the water balance (Albright et al. 2004). Instruments are included for monitoring runoff, interflow, percolation, soil-water content, soil suction, and meteorological conditions. Construction of all but one of the test sections was completed by 2000 (a test section in Apple Valley, Calif. was constructed in Summer 2002).

Cover soils were placed inside and outside the lysimeters using identical methods in lifts 300–450 mm thick. Methods planned for construction of the full-scale cover at each site were used during construction of the test sections to the greatest extent practical so that full-scale conditions would be simulated. Details of the construction methods can be found in Bolen et al. (2001). Soils were placed with light to moderate compactive effort at water contents dry of optimum with a target dry unit weight corresponding to 85% of maximum dry unit weight for standard Proctor compaction. This target dry unit weight, which is relatively low for engineered fills, was selected so that root growth would not be inhibited (Goldsmith et al. 2001).

Undisturbed samples of the cover soils were collected during construction from randomly selected locations as hand-carved blocks at the in situ water content following the methods described in ASTM D 7015. The samples were trimmed into polyvinyl chloride (PVC) rings (inside diameter and height = 200 mm, wall thickness = 8 mm) that provided lateral confinement as well as protection during transportation. All samples were collected within the boundaries of the lysimeter so that they would be directly applicable to water balance analyses and numerical water balance modeling conducted as part of ACAP. After sampling, the samples were sealed in plastic (while remaining in the PVC rings to provide protection), placed in padded boxes, and shipped to the laboratory for testing. Disturbed samples of the cover soils were also collected simultaneously for measurement of index properties.

Undisturbed samples were also collected in 2002–2004 using the same method. These samples were obtained from randomly selected locations at the near surface (upper 300 mm of the test section), where the greatest changes in properties were expected. Samples were not collected from greater depths so as to avoid disturbance of the test sections. In situ tests to determine hydraulic properties were not conducted so that no water would be added to the test sections other than that received by precipitation or irrigation.

Samples were collected from ten sites representing climatic conditions ranging from humid to arid. Locations of the test sections, climate types, year of construction, and average index properties of the soils are summarized in Table 1. The soils are designated as SM, SC, SC-CL, CL, CL-ML, and CL-CH in the Unified Soil Classification System and all but one of the soils (Apple Valley) are fine-textured. This broad range of locations and materials from test sections representing full-scale conditions is intended to capture the range of changes likely to be encountered in practice. However, because actual final cover test sections were used, a systematic evaluation of specific mechanisms affecting changes in hydraulic properties was not possible.

Anticipated Changes in Hydraulic Properties

In many cases, postconstruction changes in soil structure consist of the formation of larger pores and lower density. Larger pores are formed by biological process such as ingress of plant roots and burrowing of worms and insects. Volume changes caused by wet-dry cycling and frost action can reduce the density of soils and can result in formation of larger pores and a broader pore size distribution (Othman and Benson 1994; Albrecht and Benson

Table 1. Site and Soil Characteristics

Site Location	Climate	Year construction completed	Unified soil classification	Specific gravity	Particle size distribution				Atterberg limits	
					Gravel (%)	Sand (%)	Fines (%)	2 μm clay (%)	Liquid limit	Plasticity index
Apple Valley, Calif.	Arid	2002	SM	2.65	35	52	13	8	NP	NP
Albany, Ga.	Humid	2000	SC	2.65	6	65	29	23	27	12
Altamont, Calif.	Semi-arid	2000	CL-CH	2.66	2	5	93	38	48	22
Boardman, Ore.	Semi-arid	2000	CL-ML	2.70	0	16	84	12	24	4
Cedar Rapids, Iowa	Humid	2000	SC-CL	2.64	2	46	52	26	34	16
Helena, Mont.	Semi-arid	1999	SC	2.59	2	54	44	30	67	47
Marina, Calif.	Semi-arid	2000	SC	2.68	8	60	32	15	28	14
Omaha, Neb.	Humid	2000	CL	2.57	0	2	98	30	45	28
Polson, Mont.	Sub-humid	1999	SM	2.62	6	52	42	5	NP	NP
Sacramento, Calif.	Semi-arid	1999	CL	2.70	2	22	76	19	40	22

Note: Climate classifications are based on definitions described in UNESCO (1979). NP = nonplastic as defined in ASTM D 2487; particle sizes based on definitions in the Unified Soil Classification System (ASTM D 2487): gravel > 4.8 mm, 4.8 mm > sand > 75 μm, fines > 75 μm.

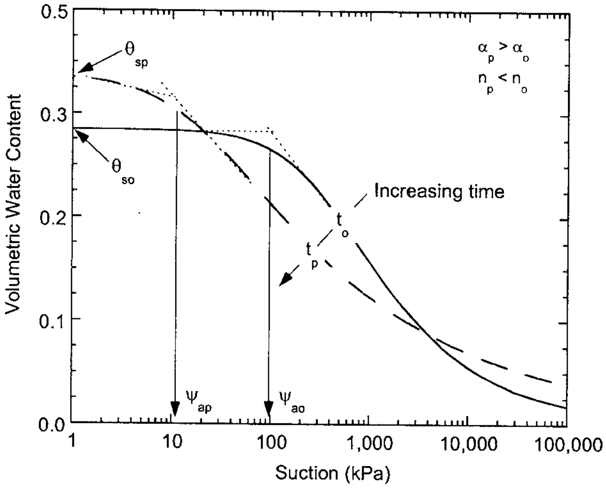

Fig. 2. Changes in SWCC between time of construction (t_0) and a later time $(t_p) > t_0$. Symbols are defined as follows: θ_{s0}=initial saturated water content; θ_{sp}=postconstruction saturated water content; ψ_{a0}=initial air entry suction; ψ_{ap}=postconstruction air entry suction; α_0=initial α parameter; α_p=postconstruction α parameter; n_0=initial n parameter; and n_p=postconstruction n parameter.

2001). Changes in hydraulic properties are anticipated in response to these changes in soil structure (Lin et al. 2006). For example, freeze-thaw and wet-dry cycling result in cracking of soil and increases in the saturated hydraulic conductivity (Benson and Othman 1993; Phifer et al. 1994; Waugh et al. 1994; Waugh and Petersen 1995; Albrecht and Benson 2001; Ayers et al. 2004).

The effect on the SWCC is hypothesized as shown in Fig. 2. The air entry suction (ψ_a) should drop due to formation of larger pores (Hillel 1998) and the saturated volumetric water content (θ_s) should increase due to the reduction in density (i.e., lower dry unit weight corresponds to higher porosity or θ_s). The slope of the SWCC for $\psi > \psi_a$ should also be shallower because of the broader distribution of pore sizes in the soil (Brooks and Corey 1966). A bimodal shape may also occur, but was not observed for any of the SWCCs measured in this study.

A variety of equations can be used to describe SWCCs parametrically (Leong and Rahardjo 1997). The most common function used to describe SWCCs is the sigmoidal van Genuchten equation (van Genuchten 1980)

$$\theta = \theta_r + (\theta_s - \theta_r)[1 + (\alpha\psi)^n]^{n/n-1} \quad (1)$$

where ψ=suction; θ=volumetric water content; θ_r=residual water content; and α and n=fitting parameters. Eq. (1) is used in this study for parametric description of the SWCCs because of its widespread use (other functions could have been used, but they are less common). The parameters α and n in Eq. (1) describe the shape of the SWCC. The parameter α is inversely related to the air entry suction and the parameter n is directly related to the slope of the SWCC (van Genuchten 1980; Leong and Rahardjo 1997; Tinjum et al. 1997). Soils with lower air entry suction have larger α and SWCCs having shallower slope have smaller n. Thus, α and θ_s should increase, and n should decrease, as larger pores and a broader pore size distribution develop in the soil.

Testing Methods

Saturated Hydraulic Conductivity

All samples were trimmed into test specimens having a diameter of 150 mm and height of 200 mm for saturated hydraulic conductivity testing. Care was taken to minimize disturbance of the soil structure. For example, root matter and other biomass was left in the specimens during testing to prevent damage to the pore structure and to represent the field condition as faithfully as practical.

The hydraulic conductivity tests were conducted in flexible-wall permeameters in general accordance with ASTM D 5084, *Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible-Wall Permeameter* (ASTM 2004). The falling head water-rising tail water procedure was followed (Method C). The average effective stress was 14 kPa to simulate the stress within a cover profile, the back-pressure was 207 kPa, and the average hydraulic gradient was 10. All tests were conducted until the hydraulic conductivity was steady and inflow equaled outflow.

Soil-Water Characteristic Curve

SWCCs were measured using methods described in ASTM D 6836, *Standard Test Methods for Determination of the Soil-Water Characteristic Curve for Desorption Using a Hanging Column, Pressure Extractor, Chilled Mirror Hygrometer, and/or Centrifuge* (ASTM 2004). Only drying SWCCs were measured due to the difficulties associated with measuring wetting curves for fine-textured soils (Fredlund and Rahardjo 1993; Tinjum et al. 1997). A pressure plate extractor (Method B) was used for suctions between 0 and ≈1 MPa; a chilled mirror hygrometer (Method D) was used for higher suctions. Data from both tests were combined to form a SWCC, even though the pressure plate extractor (PPE) applies matric suction (ψ) and the chilled mirror hygrometer (CMH) measures total suction (ψ_t). However, at higher suctions the osmotic component of suction is relatively small, rendering $\psi \approx \psi_t$ (Andraski 1996; Burger and Shackelford 2001; Wang and Benson 2004).

Test specimens for the PPE tests were trimmed from the same specimens tested for saturated hydraulic conductivity using a stainless-steel ring with a sharp bevel until the soil filled the retaining ring. Excess soil on the top and bottom of the ring was removed using a spatula. The trimmed specimens had a diameter of 73 mm and a height of 25 mm, which is a typical size for SWCC tests (Topp et al. 1993; Wang and Benson 2004). The appropriate specimen size needed to represent field conditions for SWCCs has not been determined for compacted fill soils in engineered systems. However, SWCCs measured in the laboratory on specimens of this size are comparable to SWCCs determined in situ at the ACAP sites using co-located water content and suction sensors (Benson et al. 2004; Bohnhoff 2005). Li et al. (2005) also found that SWCCs measured in the laboratory on specimens having similar size to those used in this study were comparable to SWCCs measured in situ in a Hong Kong slope constructed from decomposed granite.

After trimming was complete, the gravimetric water content of the excess soil was measured and the specimen was saturated using a vacuum chamber filled with de-aired water as described in ASTM D 6836. After saturation, the test specimen was placed in the PPE and air pressure was applied in increments to obtain a set of ψ-θ measurements. Volumetric water contents were determined at equilibrium from the volume of outflow measured in a capillary

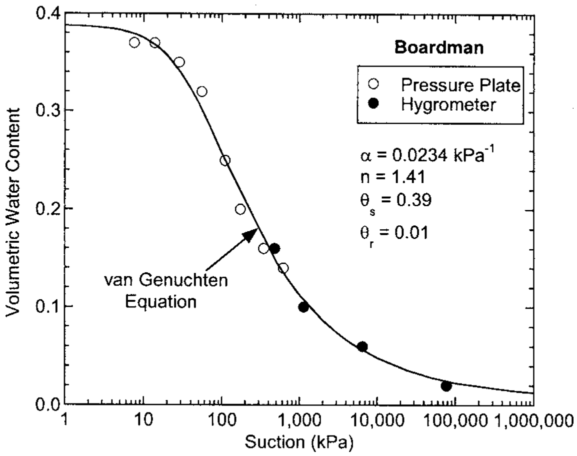

Fig. 3. Typical SWCC measured with a PPE and CMH along with fit of the van Genuchten equation [Eq. (1)] for a specimen from the ACAP site in Boardman, Ore.

tube. Typically eight to ten measurements of ψ-θ were obtained for each PPE test, requiring 1–3 months to complete depending on soil type (longer test times were required for more clayey soils). Oven-dried water contents measured at the end of the PPE tests showed that the difference in θ from the outflow and gravimetric measurements was less than 0.01.

CMH tests were conducted with a WP4 Dewpoint PotentiaMeter (Decagon Devices, Pullman, Wash.), which is similar to the CMHs described in Gee et al. (1992) and Albrecht et al. (2003). Several specimens were trimmed from the specimen used for the PPE extractor test into polyethylene cups (38 mm diameter, 5 mm tall) used in the CMH. The specimens were allowed to air dry to different water contents, and then were sealed for 24 h to promote equilibration. Afterwards, cups containing the specimens were inserted into the CMH to determine ψ_t. Once ψ_t was reported by the CMH, the specimen was removed, the gravimetric water content, mass, and volume were determined, and the corresponding volumetric water content was computed. Typically three to six measurements of ψ-θ were obtained using the CMH.

An example of a typical SWCC obtained using these methods is shown in Fig. 3. The PPE and CMH data overlap in the middle of the SWCC, indicating that $\psi \approx \psi_t$ at higher suctions, as described previously. All SWCCs were fit with van Genuchten's equation [Eq. (1)] using a least-squares optimization procedure. A typical fit is also shown in Fig. 3.

Table 3. Hydraulic Properties after One Year of Service

Location	K_{sp} (cm/s)	α_p (kPa^{-1})	n_p	θ_{sp}	θ_{rp}
Apple Valley, Calif.	3.0×10^{-5}	0.232	1.19	0.26	0.00
	2.8×10^{-5}	0.166	1.21	0.28	0.00
	1.5×10^{-5}	0.289	1.18	0.25	0.00
	3.0×10^{-5}	0.288	1.20	0.26	0.00

Note: K_s=saturated hydraulic conductivity; α and n=van Genuchten parameters; θ_s=saturated volumetric water content; θ_r=residual volumetric water content; and subscript p indicates specimens collected postconstruction.

Results and Analysis

Hydraulic properties corresponding to the as-built condition are summarized in Table 2. Because a large number of tests were conducted during construction, geometric means are reported for K_s and α and arithmetic means are reported for n, θ_s, and θ_r. Geometric means are reported for K_s and α because they are log-normally distributed, whereas arithmetic means are reported for n, θ_s, and θ_r because they are normally distributed (Russo and Bouton 1992; Hills et al. 1992; Benson 1993; Gurdal et al. 2003). Standard deviations (σ) are also reported in Table 2, with standard deviations of $\ln K_s$ and $\ln\alpha$ reported for K_s and α to correspond with the geometric means. Hydraulic properties for samples collected after construction are summarized in Tables 3–6. Because fewer samples were collected during the postconstruction sampling events, K_s, α, n, θ_s, and θ_r are reported for the individual tests in Tables 3–6.

Saturated Hydraulic Conductivity

Saturated hydraulic conductivities for the postconstruction specimens (K_{sp}) are graphed against the as-built saturated hydraulic conductivities (K_{s0}) for the same sites in Fig. 4. If there was no

Table 2. As-Built Hydraulic Properties of Cover Soils

	K_{s0} (cm/s)			α_0 (kPa^{-1})		n_0		θ_{s0}			
Site location	GM	$\sigma_{\ln_{K_s}}$	N_{K_s}	GM	$\sigma_{\ln_\alpha}$	Mean	σ_n	Mean	$\sigma_{\theta s}$	θ_{r0}	N_{SWCC}
Albany, Ga.	1.5×10^{-6}	4.11	6	0.0039	1.38	1.39	0.10	0.34	0.13	0.00	6
Altamont, Calif.	5.3×10^{-7}	2.21	8	0.0043	1.09	1.38	0.10	0.36	0.05	0.00	6
Apple Valley, Calif.	3.1×10^{-5}	0.70	6	0.278	0.08	1.42	0.02	0.26	0.05	0.00	6
Boardman, Ore.	1.2×10^{-5}	1.08	32	0.0159	0.40	1.49	0.06	0.39	0.06	0.00	27
Cedar Rapids, Iowa	9.7×10^{-7}	2.63	8	0.0016	0.55	1.61	0.15	0.33	0.05	0.00	8
Helena, Mont.	1.5×10^{-7}	0.80	16	0.0018	0.28	1.19	0.02	0.34	0.10	0.00	13
Marina, Calif.	8.6×10^{-8}	1.75	16	0.0036	0.47	1.40	0.07	0.31	0.12	0.00	12
Omaha, Neb.	1.6×10^{-7}	2.05	12	0.0014	0.86	1.50	0.18	0.39	0.06	0.00	9
Polson, Mont.	4.2×10^{-5}	0.66	8	0.0010	0.07	1.40	0.01	0.35	0.06	0.00	8
Sacramento, Calif.	3.1×10^{-7}	2.20	16	0.0048	1.21	1.34	0.07	0.29	0.02	0.00	12

Note: GM=geometric mean; σ=standard deviation; N=number of specimens that were tested; K_s=saturated hydraulic conductivity; α and n=van Genuchten parameters, θ_s=saturated volumetric water content; θ_r=residual volumetric water content; and subscript 0 indicates that specimens were collected during construction.

Table 4. Hydraulic Properties after 2 Years of Service

Location	K_{sp} (cm/s)	α_p (kPa^{-1})	n_p	θ_{sp}	θ_{rp}
Albany, Ga.	1.2×10^{-6}	0.0002	1.75	0.29	0.00
	5.6×10^{-5}	0.0200	1.20	0.33	0.00
	1.2×10^{-6}	0.0002	1.94	0.27	0.00
	6.2×10^{-7}	0.0200	1.30	0.23	0.00
Boardman, Ore.	1.4×10^{-5}	0.0200	1.41	0.37	0.02
	5.4×10^{-5}	0.0350	1.32	0.41	0.00
	1.6×10^{-5}	0.0400	1.30	0.38	0.00
Cedar Rapids, Iowa	3.7×10^{-5}	0.0030	1.36	0.29	0.00
	4.6×10^{-4}	0.0400	1.23	0.49	0.00
Omaha, Neb.	1.1×10^{-6}	0.0015	1.41	0.37	0.00
	3.7×10^{-5}	0.0034	1.32	0.40	0.00
Apple Valley, Calif.	1.8×10^{-5}	0.233	1.18	0.26	0.00
	1.4×10^{-5}	0.216	1.22	0.29	0.01
	1.7×10^{-5}	0.126	1.22	0.27	0.01

Note: K_s=saturated hydraulic conductivity; α and n=van Genuchten parameters; θ_s=saturated volumetric water content; θ_r=residual volumetric water content; and subscript p indicates specimens collected postconstruction.

Table 5. Hydraulic Properties after 3 Years of Service

Location	K_{sp} (cm/s)	α_p (kPa^{-1})	n_p	θ_{sp}	θ_{rp}
Altamont, Calif.	1.1×10^{-4}	0.0035	1.46	0.39	0.03
	9.9×10^{-5}	0.0044	1.27	0.34	0.00
	5.8×10^{-6}	0.0105	1.26	0.37	0.00
Boardman, Ore.	2.1×10^{-5}	0.0234	1.41	0.39	0.01
	5.4×10^{-5}	0.0340	1.84	0.43	0.00
	3.3×10^{-5}	0.0344	1.63	0.42	0.05
Cedar Rapids, Iowa	6.0×10^{-4}	0.0548	1.26	0.40	0.00
	7.4×10^{-5}	0.0359	1.21	0.31	0.00
	4.0×10^{-4}	0.0141	1.31	0.47	0.00
	3.8×10^{-4}	0.0651	1.20	0.45	0.00
	6.2×10^{-4}	0.0044	1.53	0.50	0.02
	3.5×10^{-4}	0.0137	1.28	0.48	0.00
Helena, Mont.	1.2×10^{-7}	0.1279	1.13	0.44	0.00
	4.7×10^{-8}	0.0018	1.28	0.43	0.00
Marina, Calif.	6.5×10^{-4}	0.0362	1.27	0.36	0.00
	1.7×10^{-4}	0.3288	1.27	0.61	0.00
	1.1×10^{-4}	0.0291	1.27	0.32	0.00
Omaha, Neb.	2.7×10^{-5}	0.0596	1.22	0.46	0.00
	3.2×10^{-4}	0.0090	1.29	0.45	0.00
	2.1×10^{-5}	0.0097	1.29	0.42	0.00
	9.0×10^{-6}	0.0126	1.24	0.40	0.00
	2.1×10^{-4}	0.0093	1.32	0.46	0.00
	4.8×10^{-4}	0.0050	1.45	0.47	0.03
Polson, Mont.	1.6×10^{-4}	0.1979	1.30	0.38	0.00
	9.9×10^{-5}	0.0900	1.35	0.38	0.00

Note: K_s=saturated hydraulic conductivity; α and n=van Genuchten parameters; θ_s=saturated volumetric water content; θ_r=residual volumetric water content; and subscript p indicates specimens collected postconstruction.

Table 6. Hydraulic Properties after 4 Years of Service

Location	K_{sp} (cm/s)	α_p (kPa^{-1})	n_p	θ_{sp}	θ_{rp}
Helena, Mont.	2.1×10^{-6}	0.0775	1.15	0.45	0.00
	1.1×10^{-4}	0.0451	1.24	0.53	0.00
Polson, Mont.	1.2×10^{-4}	0.0735	1.63	0.40	0.03
	2.8×10^{-4}	0.0524	1.47	0.43	0.00
	1.3×10^{-4}	0.0612	1.85	0.41	0.03
Sacramento, Calif.	3.4×10^{-5}	0.0047	1.44	0.45	0.03
	1.1×10^{-4}	0.0067	1.32	0.41	0.00
	2.6×10^{-5}	0.0129	1.20	0.44	0.00
	1.4×10^{-5}	0.0052	1.28	0.40	0.00

Note: K_s=saturated hydraulic conductivity; α and n=van Genuchten parameters; θ_s=saturated volumetric water content; θ_r=residual volumetric water content; and subscript p indicates specimens collected postconstruction.

change in K_s, the postconstruction data would be scattered around the 1:1 line in Fig. 4. Data falling above the 1:1 line correspond to increases in K_s.

Some of the less permeable soils (i.e., soils with $K_s \approx 10^{-6}$ cm/s or lower) in the as-built condition retained their low hydraulic conductivity for one to three years (e.g., for the Helena site, the as-built $K_{s0}=1.5\times10^{-7}$ cm/s whereas the $K_{sp}=1.2\times10^{-7}$ or 4.7×10^{-8} cm/s after 3 years). However, K_s of other less permeable soils increased by two orders of magnitude or more (e.g., for the Omaha site, the as-built $K_{s0}=1.6\times10^{-7}$ cm/s, whereas $K_{sp}=1.1\times10^{-6}$ or 3.7×10^{-5} cm/s after two years). After 4 years, however, K_s for these soils increased by at least a factor of 10 and, in some cases, by nearly a factor of 10,000 (Fig. 4). In contrast, for those soils that were more permeable ($K_s > 10^{-5}$ cm/s) in the as-built condition, K_s increased only by a factor of 1.8–6.7, and in one case (Apple Valley) K_s decreased slightly. Moreover, regardless of the as-built K_{s0}, after 3–4 years nearly all of the K_{sp} fall in a band between 10^{-5} and 10^{-3} cm/s (labeled "in-service condition" in Fig. 4), and no trend is apparent between K_{sp} and the as-built K_{s0} (Fig. 4).

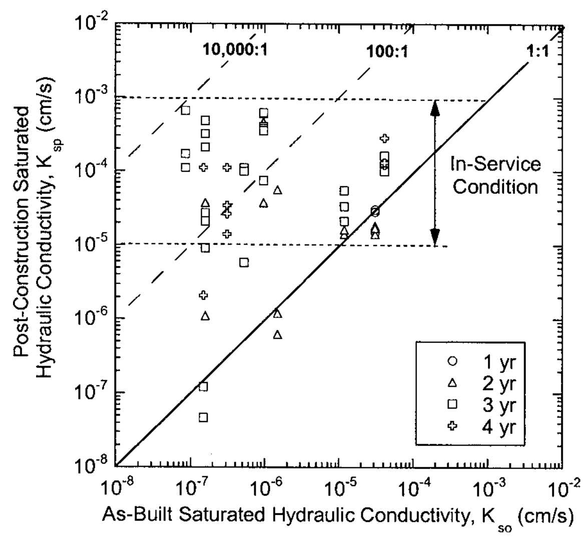

Fig. 4. Postconstruction saturated hydraulic conductivity (K_{sp}) versus as-built saturated hydraulic conductivity (K_{s0}). The band labeled "in service" indicates range for soils after 2–4 years of exposure to site environmental conditions.

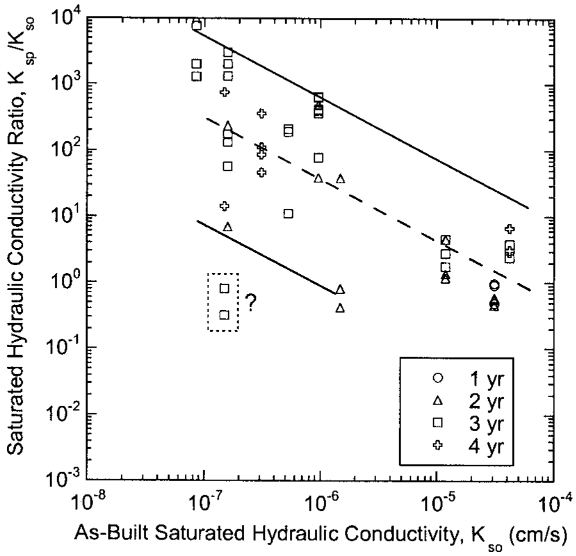

Fig. 5. Ratio of postconstruction saturated hydraulic conductivity relative to as-built saturated hydraulic conductivity (K_{sp}/K_{s0}) versus as-built saturated hydraulic conductivity (K_{s0}). Trend lines drawn by eye. Outliers ("?") are for site in Helena, Mont. (Table 5).

These observations suggest that differences in K_s of fine-textured soils used for water balance covers become smaller over time, with larger changes in K_s occurring for soils that have lower K_{s0} and smaller (or negligible) changes for soils that have higher K_{s0}. Location of the site appears to be less important, as similar changes in hydraulic properties occurred for sites in climates that were humid or semiarid and warm or cool (Tables 5 and 6). The importance of K_{s0} on the magnitude of change in K_s is evident in Fig. 5, where the hydraulic conductivity ratio (K_{sp}/K_{s0}) is graphed versus K_{s0}. The overall trend is decreasing K_{sp}/K_0 with increasing K_{s0}. On average, $K_{sp}/K_{s0} \approx 300$ for $K_{s0} \approx 10^{-7}$ cm/s and $K_{sp}/K_{s0} \approx 0.5$ for $K_{s0} \approx 10^{-4}$ cm/s. Soils with higher K_{s0} typically have less plastic fines or lower dry density, and therefore undergo smaller volume changes during processes such as wetting and drying (Kleppe and Olson 1985; Albrecht and Benson 2001). Consequently, smaller changes in pore structure are likely for soils with higher K_{s0}. At the other extreme, soils with high K_{s0} may also become less permeable over time due to pore filling and crusting by fines (Assouline 2004).

Statistical significance of the trend in Fig. 4 was evaluated by linearly regressing $\ln(K_{sp}/K_{s0})$ on $\ln K_{s0}$, and determining whether the slope of the regression was significant using an F-test. The significance level was 0.05, which is the significance level commonly used for hypothesis testing (Berthouex and Brown 2002). The analysis confirmed that the trend was significant, with an F-statistic of 47.0 and p value <0.0001 (i.e., $p \ll 0.05$, indicating significance).

Soil-Water Characteristic Curve

Changes in the SWCC are reflected in changes in the SWCC parameters θ_s, θ_r, α, and n, as indicated in the discussion of Fig. 2. The change in θ_s is shown in Fig. 6, where the ratio of θ_s postconstruction (θ_{sp}) to the as-built θ_s (θ_{s0}) is graphed versus θ_{s0}. Graphs are not shown for θ_r because, in nearly all cases, θ_r is approximately zero for the as-built and postconstruction conditions (Tables 2–6). Statistical significance of the trend between θ_{sp}/θ_{s0} and θ_{s0} was confirmed by regression ($F=37.1$, p value $<0.0001 \ll 0.05$).

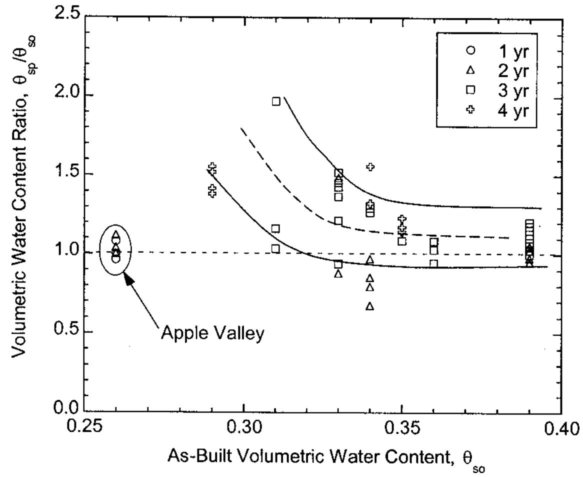

Fig. 6. Ratio of postconstruction saturated volumetric water content to as-built saturated volumetric water content (θ_{sp}/θ_{s0}) versus as-built saturated volumetric water content (θ_{s0}). Trend lines drawn by eye.

Because θ_s is inversely proportional to dry density, θ_{sp}/θ_{s0} is a measure of the postconstruction change in dry density ($\theta_{sp}/\theta_{s0} > 1$ corresponds to a reduction in dry density). As shown in Fig. 6, $\theta_{sp}/\theta_{s0} \approx 1$ for the soils with the largest θ_{s0} (0.36–0.39) or lowest dry density in the as-built condition, and tends to increase as θ_{s0} drops below 0.35. The largest θ_{sp}/θ_{s0} (1.5–2.0) corresponds to the lowest θ_{s0} ($\approx 0.29-0.31$). The exception is the soil from Apple Valley, for which $\theta_{s0}=0.26$ and $\theta_{sp}/\theta_{s0} \approx 1.0$. The Apple Valley soil, a broadly graded alluvium, is coarse-textured (fines content=13%, Table 1) and therefore should undergo smaller changes in volume and density compared to the finer-textured soils when subjected to wet-dry cycling.

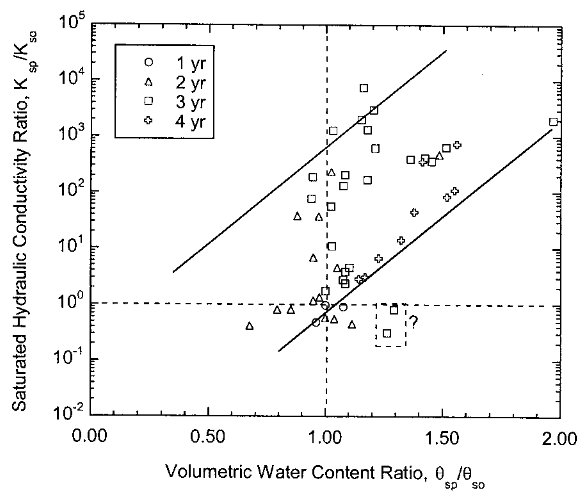

Fig. 7. Ratio of postconstruction saturated hydraulic conductivity relative to as-built saturated hydraulic conductivity (K_{sp}/K_{s0}) versus ratio of postconstruction saturated volumetric water to as-built saturated volumetric water content (θ_{sp}/θ_{s0}). Trend lines drawn by eye. Outliers ("?") are for site in Helena, Mont. (Table 5).

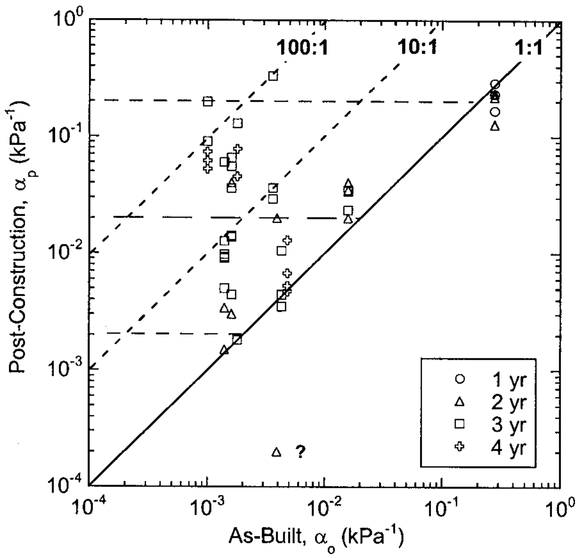

Fig. 8. Postconstruction α parameter measured in 2002–2004 (α_p) versus α in the as-built condition (α_0). Outlier ("?") for site in Albany, Ga. (Table 4).

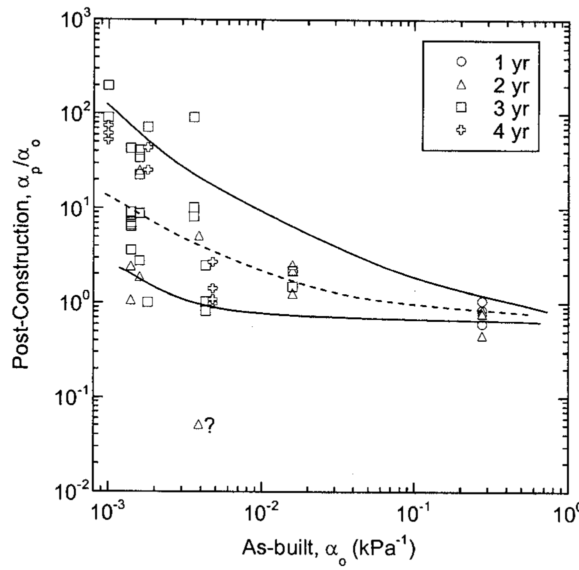

Fig. 9. Ratio of postconstruction α relative to α in as-built condition (α_p/α_0) versus α in as-built condition (α_0). Trend lines drawn by eye. Outlier ("?") for site in Albany, Ga. (Table 4).

There also is a direct correspondence between K_{sp}/K_{s0} and θ_{sp}/θ_{s0}, as shown in Fig. 7. The trend between K_{sp}/K_{s0} and θ_{sp}/θ_{s0} was also confirmed to be statistically significant using regression ($F=19.5$, p value $<0.0001 \ll 0.05$). Larger changes in K_s occur for the fine-textured soils with larger θ_{sp}/θ_{s0}. That is, K_s undergoes a greater change when the soil undergoes a larger change in θ_s (or equivalently a larger change in dry density).

The effect on α is shown in Fig. 8, where postconstruction α (α_p) is graphed versus α in the as-built condition (α_0). As was shown for K_s (Fig. 4), α increased in the four-year period after construction (many of the data points fall above the 1:1 line), with some α increasing nearly two orders of magnitude (the exception is the coarse-textured soil from Apple Valley, for which α decreased). As indicated in the discussion of Fig. 2, formation of larger pores should cause a reduction in ψ_a and an increase in α. Inspection of Fig. 8 also indicates that there is no trend between α_p and α_0 (the data fall in a horizontal band), which suggests that α becomes more similar over time and less related to α_0 (the same was found for K_s, Fig. 4). In particular, α_p ranges between approximately 0.002 and 0.2 kPa^{-1}, regardless of α_0.

Larger increases in α tended to occur for soils having lower α_0 (or, conversely, higher ψ_a), as shown in Fig. 9 in terms of the α ratio (i.e., α_p/α_0) versus α_0. Statistical significance of the trend between α_p/α_0 and α_0 was confirmed using regression ($F=22.5$, p value $<0.0001 \ll 0.05$). Although considerable scatter exists, the average factor increase in α (i.e., the trend passing through the middle of the data) is approximately 10 for $\alpha_0=0.002$ kPa^{-1}, 2 for $\alpha_0=0.02$ kPa^{-1}, and 0.8 for $\alpha_0=0.2$ kPa^{-1}. Formation of larger pores has a more dramatic effect on the network of pores in a soil that initially contains primarily small pores (low α_0) compared to a soil that initially contains both large and small pores (high α_0). In the limiting case of a soil initially dominated by large pores (large α_0), formation of additional large pores will have little effect on the network of pores controlling the initial release of water (i.e., the pores controlling ψ_a) and therefore little effect on α. However, for soils with large pores, pore filling and crusting by fines may cause α to decrease.

The effect on the n parameter is shown in Fig. 10. For many of the soils, the postconstruction n is lower than the as-built n (n_0) (i.e., n_p often falls below the 1:1 line). That is, the slope of the SWCC becomes shallower, which reflects broadening of the pore size distribution. There are a few exceptions, however, where n_p is much larger than n_0 [denoted with a question mark (?) in Fig. 10]. Examination of the SWCCs corresponding to these outlier n provided no explanation for these exceptions to the general trend.

The change in n is also shown in Fig. 11 in terms of the n ratio (n_p/n_0) versus n_0. Significance of the trend in Fig. 11 was confirmed using an F-test ($F=11.2$, p value $=0.002 \ll 0.05$). The change in n is larger when n_0 is larger, ranging from approximately 1 (i.e., no change) for $n_0=1.2$ to approximately 0.75 for $n_0=1.6$, on average. That is, larger changes in n occur when n_0 is larger, which reflects a greater change in pore size distribution for soils that initially have a narrower pore size distribution (i.e., larger n_0).

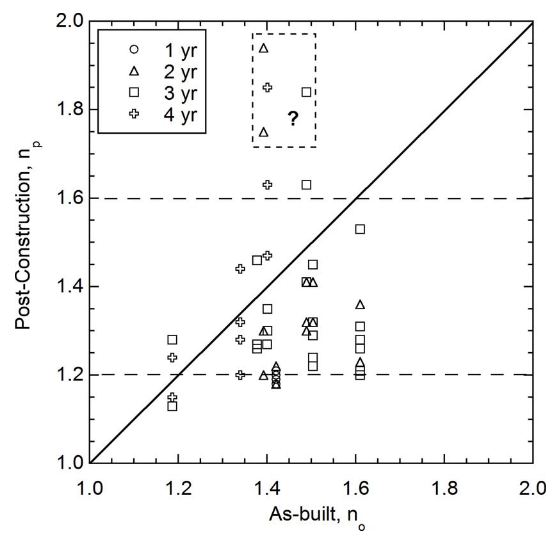

Fig. 10. Postconstruction n parameter (n_p) versus n in the as-built condition (n_0). Outliers ("?") for sites in Albany, Ga. (Table 4), Boardman, Ore. (Table 5), and Polson, Mont. (Table 6).

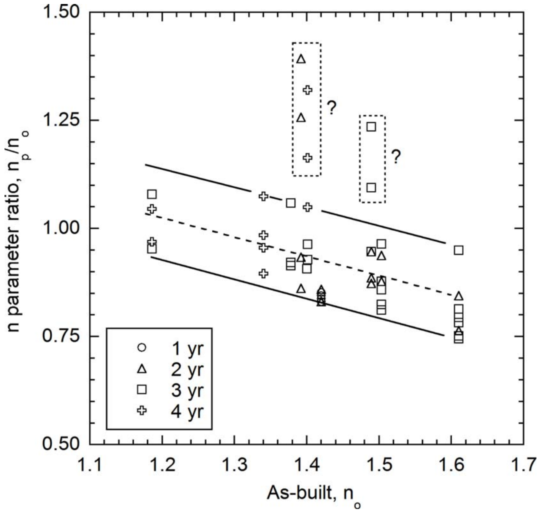

Fig. 11. Ratio of postconstruction n to as-built n (n_p/n_0) versus as-built n (n_0). Trend lines drawn by eye. Outliers ("?") for sites in Albany, Ga. (Table 4), Boardman, Ore. (Table 5), and Polson, Mont. (Table 6).

The changes in n shown in Fig. 11 are small relative to the range over which n can vary. The parameter n often falls between 1 and 2 for fine-textured soils used in covers and liners (e.g., Tinjum et al. 1997; Gurdal et al. 2003), but can be more than 10 for uniformly graded coarse-grained soils with little fines (e.g., Bradford and Abriola 2001). However, the modest change in n shown in Fig. 11 can have a significant effect on the SWCC, as shown illustratively in Fig. 12 for both high and low α (0.002 and 0.23 kPa^{-1}) and high and low n (1.2 and 1.5). Reducing n from 1.5 to 1.2 at $\psi=1,000$ kPa results in a change in θ of approximately 0.1 (29% of the total porosity), regardless of whether α is low or high (Fig. 12).

Influence of Plasticity

Analysis of variance (ANOVA) was conducted to determine if plasticity index of the fine-textured soils affected the changes in K_s, α, n, and θ_s. The Apple Valley soil was excluded from the analysis because of its small fines content. Plasticity index (PI) was selected because it is indicative of the potential for volume change, and therefore should be an index of the potential for change in the pore network (Albrecht and Benson 2001). Data sets for the ANOVA were compiled for K_{sp}/K_{s0}, α_p/α_0, n_p/n_0, and θ_{sp}/θ_{s0} for soils categorized as low plasticity (PI$<$10 or nonplastic), moderate plasticity (10$<$PI$<$20), and high plasticity (PI$>$20). For all analyses, the significance level β was set at 0.05.

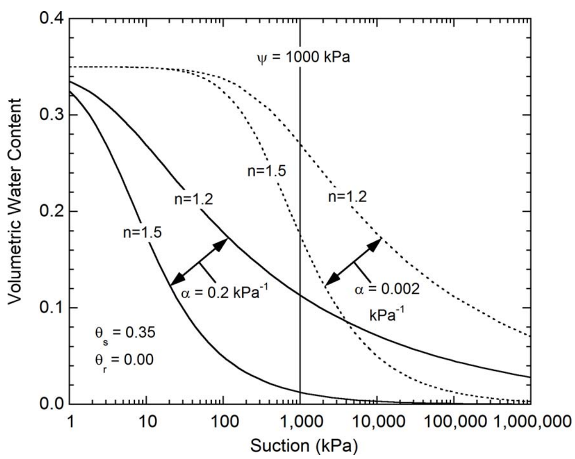

Fig. 12. Effect of n on the SWCC for $\alpha=0.003$ or 0.3 kPa^{-1} and $n=1.2$ or 1.6. For all SWCCs, $\theta_s=0.35$ and $\theta_r=0.00$.

Table 7. Summary of Statistics from ANOVAs

Hydraulic property	ANOVA p-statistic (significant?)	PLSD on plasticity effect (p-statistic; significant?)
K_{sp}/K_{s0}	$<$0.0001 (yes)	Low-medium: $p<0.0001$; yes Low-high: $p<0.0001$; yes Medium-high: $p=0.010$; yes
α_p/α_0	0.00340 (yes)	Low-medium: $p=0.0009$; yes Low-high: $p=0.0083$; yes Medium-high: $p=0.144$; no
n_p/n_0	0.0330 (yes, marginal)	Low-medium: $p=0.0538$; no, marginal Low-high: $p=0.947$; no Medium-high: $p=0.0122$; yes
θ_{sp}/θ_{s0}	0.0524 (no, marginal)	Low-medium: $p=0.0160$; yes Low-high: $p=0.0893$; no Medium-high: $p=0.215$; no

Fisher's protected least significant difference (PLSD) test (Box et al. 1978) was conducted after each ANOVA to provide a direct comparison of each of the data sets. The PLSD test is a t-test between the means in each data set of an ANOVA. For the PLSD, β was also set at 0.05.

Results of the ANOVAs and PLSD tests are summarized in Table 7. The ratios $K_{sp}/K_{s0}$and α_p/α_0 are significantly affected by plasticity (Table 6). Plasticity also has a significant effect on n_p/n_0 and an insignificant effect on θ_{sp}/θ_{s0}, although in both cases the inference is marginal ($p\approx0.05$). The PLSD indicates that both K_{sp}/K_{s0} and α_p/α_0 are significantly different for low plasticity soils relative to other soils, and that K_{sp}/K_{s0} is significantly different for soils categorized as low, moderate, or high plasticity. In contrast, n_p/n_0 is significantly different only for the medium and high plasticity soils and θ_{sp}/θ_{s0} is significantly different only for the low and moderately plastic soils. The more plastic soils typically exhibited larger changes in K_s, α, n, and θ_s (Tables 1–6), which is consistent with the results of the ANOVAs and PLSD tests in Table 7.

Practical Implications

The data presented illustrate that the hydraulic properties of soils used for water balance covers can change over time, and that the magnitude of the change is related to the as-built condition. The ranges of hydraulic properties shown in Figs. 4, 8, and 10 can be used as a starting point for assessing how changes in hydraulic properties may affect the hydrology of water balance covers constructed with fine-textured soils. In particular, after a relatively short period ($<$5 years), fine-textured cover soils are likely to have K_s between 10^{-5} and 10^{-3} cm/s, α between 0.002 and 0.2 kPa^{-1}, and n between 1.2 and 1.5, regardless of the initial properties. Different combinations of these parameters can be used in design to evaluate potential long-term conditions and to make predictions.

Estimates of typical K_{sp}, α_p, n_p, and θ_{sp} can be obtained using the central (dashed) trend lines in Figs. 5, 6, 9, and 11 using values of K_{s0}, α_0, n_0, and θ_{s0} measured during design or construction. For example, consider a soil with the following as-built hydraulic properties: $K_{s0}=10^{-6}$ cm/s, $\alpha_0=0.003$ kPa^{-1}, $n_0=1.5$, and $\theta_{s0}=0.32$. Based on the central trend lines in Figs. 5, 6, 9, and 11, $K_{sp}/K_{s0}=40$, $\alpha_p/\alpha_0=5.5$, $n_p/n_0=0.9$, and $\theta_{sp}/\theta_{s0}=1.2$. Applying these factors yields $K_{sp}=4.0\times10^{-5}$ cm/s, $\alpha_p=0.016$ kPa^{-1}, $n_p=1.35$, and $\theta_{sp}=0.38$. Because the specimens tested in this study were obtained at a shallow depth (upper 300 mm), such estimates probably represent maximum effects. Smaller changes in hydraulic properties may occur at deeper depths. However, more study is needed to assess how changes in hydraulic properties vary with depth.

Inspection of the data suggests that the hydraulic properties of cover soils converge to common values over time, eliminating many of the differences that exist in the as-built condition due to compaction and differences in soil composition. Consequently, for applications where long-term maintenance of hydraulic properties is important, designers should consider designing and constructing covers in a manner that mimics the long-term condition. Soils that are less prone to volume change in response to wetting and drying or freezing and thawing (and therefore less susceptible to changes in pores size) should be selected if possible (e.g., coarse-textured soils with low plasticity fines or less plastic fine-textured soils). Compaction specifications should ensure that the soil is not overly compacted and will have a dry density close to that expected in the long term. One approach to determine a realistic long-term dry density is to measure the dry density of natural vegetated surficial soils of a similar type in the vicinity of the site. The data in Fig. 6 also suggest that θ_s will be in the range of 0.36–0.40 in the long term, which corresponds to a dry density between 1.6 and 1.7 Mg/m^3 for a specific gravity of solids of 2.65. Water content should also be controlled during construction to ensure that cover soils are placed under conditions that minimize remolding of clods and formation of soil with hydraulic properties dominated by microstructure [i.e., compaction should be dry of optimum water content, Benson and Daniel (1990)].

Water balance covers designed and constructed using these principles are less likely to exhibit large changes in hydraulic properties, at least in the short term (<5 years). In addition, vegetation is more readily established and maintained when cover soils are placed with less compaction and a more open pore structure (Goldsmith et al. 2001). Nevertheless, the long-term persistence of conditions similar to those reported in this study remains unknown. For example, the effects of loosening in the short term could be compensated by processes that tend to fill pores (e.g., siltation or calcification). Moreover, for soils that are not processed during construction (e.g., clod size reduction, moisture conditioning), structure remaining in the borrow source may persist in the cover profile. An indication of conditions expected in the long term can be obtained by inspecting existing natural soil profiles having similar composition and layering, such as the profile in the borrow source (Waugh et al. 1994). Other factors besides hydraulic properties may also have an important effect on the long-term performance of water balance covers, such as erosion or eolian deposition, differential settlement, fire, and climate change. Dealing with each of these issues, and the related effects on hydraulic properties, is beyond the scope of this study. A discussion of these factors can be found in Gee and Ward (2004).

Summary and Conclusions

Data collected from ten field sites in the Alternative Cover Assessment Program have been presented to illustrate how the hydraulic properties of soils used in water balance covers can change over time. Comparison of the data collected at the time of construction and 2–4 years hence indicated that the saturated hydraulic conductivity (K_s) can increase as much as 10,000 times, the van Genuchten parameter α as much as 1,000 times, the saturated volumetric water content (θ_s) as much as 2.0 times, and the van Genuchten parameter n to decrease as much as 1.3 times. Larger changes occur for fine-textured soils that have lower K_s, α, and θ_s and higher n in the as-built condition (i.e., denser fine-textured soils with more uniform pores). In addition, at least in the near term, cover soils appear to become more similar over time, eliminating many of the differences that exist in the as-built condition. Changes in hydraulic properties can be limited by using soils less prone to volume change (coarse-textured soils or soils with less plastic fines) and by placing the soil with methods that result in soil structure having less propensity for change (i.e., with lower compactive effort and at water contents dry of optimum). Placement conditions that result in soil having similar characteristics as observed in existing analog soil profiles are likely to result in covers that are less prone to changes in hydraulic performance over time.

The data presented in this paper can also be used to estimate hydraulic properties input to water balance models for assessing the hydrology of water balance covers over time. Ranges of the hydraulic properties identified in this study can be selected for sensitivity analyses and the trend lines that are presented can be used to estimate changes in the hydraulic properties of cover soils based on the hydraulic properties measured at the time of construction.

Acknowledgments

Support for this study was provided by U.S. Environmental Protection Agency (USEPA) through the Superfund Innovative Technologies Evaluation (SITE) Program. Mr. Steven Rock was the program manager for USEPA. This manuscript has not undergone USEPA peer review and the findings and conclusions that are presented are solely those of the writers. Endorsement by USEPA is not implied and should not be assumed. Xiaodong Wang, Preecha Apiwantragoon, and Ho Young Jo conducted the saturated hydraulic conductivity tests in this study. Tayfun Gurdal conducted many of the SWCC tests on specimens collected during construction.

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