INNOVATIVE TECHNOLOGY
Summary Report

DOE/EM-0558

Alternative Landfill Cover

Subsurface Contaminants Focus Area and
Characterization, Monitoring, and Sensor
Technology Crosscutting Program

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INNOVATIVE TECHNOLOGY
Summary Report

Alternative Landfill Cover

OST/TMS ID 10

Subsurface Contaminants Focus Area and
Characterization, Monitoring, and Sensor
Technology Crosscutting Program

Demonstrated at
Sandia National Laboratories
Sandia, New Mexico

INNOVATIVE TECHNOLOGY
Summary Report

Purpose of this document

Innovative Technology Summary Reports are designed to provide potential users with the information they need to quickly determine whether a technology would apply to a particular environmental management problem. They are also designed for readers who may recommend that a technology be considered by prospective users.

Each report describes a technology, system, or process that has been developed and tested with funding from DOE's Office of Science and Technology (OST). A report presents the full range of problems that a technology, system, or process will address and its advantages to the DOE cleanup in terms of system performance, cost, and cleanup effectiveness. Most reports include comparisons to baseline technologies as well as other competing technologies. Information about commercial availability and technology readiness for implementation is also included. Innovative Technology Summary Reports are intended to provide summary information. References for more detailed information are provided in an appendix.

Efforts have been made to provide key data describing the performance, cost, and regulatory acceptance of the technology. If this information was not available at the time of publication, the omission is noted.

All published Innovative Technology Summary Reports are available on the OST Web site at http://ost.em.doe.gov under "Publications."

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SECTION 1
SUMMARY

Technology Summary

Problem

The U.S. Department of Energy (DOE) has many sanitary, hazardous, radioactive, and mixed-waste landfills, as well as mine-spoil and mill-tailings piles, and surface impoundments, which must be closed. Reducing contaminant concentrations to acceptable levels entails some type of remediation, such as: in-place stabilization, capping with an engineered cover; or, a combination of these activities as part of the closure activity. Also, engineered covers may be considered as an interim measure to be placed over a contaminated area until a more permanent solution can be implemented.

Resource Conservation and Recovery Act (RCRA) Subtitles C and D and the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) specify performance standards for engineered covers for hazardous and solid waste landfills. Prescriptive engineered covers are routinely used throughout the United States (U.S.), regardless of regional environmental conditions. They are difficult and expensive to construct and are susceptible to failure, especially under the arid or semi-arid environmental conditions typical in the western U.S. Experience at arid or semi-arid sites has shown that RCRA Subtitle C covers, namely the clay barrier layers, are especially susceptible to failure caused by desiccation and cracking (Landreth et al., 1991; Suter et al., 1993). Deterioration caused by freeze/thaw cycles and biointrusion are often contributing factors.

As determined by the U.S. Environmental Protection Agency (EPA), many landfills have serious problems, such as ground water contamination and adverse impacts to flora and fauna that are caused by landfill leachate being discharged to the environment (EPA, 1988). While not all of these contamination incidents are the result of inadequate landfill covers, many of these problems can be mitigated by capping the entire landfill with a properly designed and constructed (i.e., engineered) cover. To be effective, however, an engineered cover must address regional environmental conditions to ensure proper functioning and reliability.

How It Works

The primary purpose of an engineered cover is to isolate the underlying waste. A key element to isolating the wastes from the environment, engineered covers should minimize or prevent water from infiltrating into the landfill and coming into contact with the waste, thereby minimizing leachate generation. The U.S. EPA construction guidelines for soil hydraulic barriers specify that the soil moisture content and compactive effort may be increased to ensure that the barrier achieves a specified permeability of 1×10^{-7} cm/sec. However, constructing a soil barrier with high moisture content makes the soil more difficult to work and increases the required compactive effort to achieve the specified density, ultimately increasing the construction cost of the barrier.

Alternative landfill cover designs rely on soil physical properties, hydraulic characteristics, and vegetation requirements to lower the flux rate of water through the cover. They can achieve greater reliability than the prescriptive RCRA Subtitle C design, especially under arid or semi-arid environmental conditions. With an alternative cover design, compacted soil barriers can be constructed with a soil moisture content that makes placement and compaction of the soil easier and less expensive. Under these conditions, the soil barrier has more capacity to absorb and control moisture within it, thereby enhancing the reliability of the barrier.

Potential Markets

Any public or private sector site that is considering the use of an engineered cover as part of an interim or final closure action need not use a prescriptive RCRA Subtitle C or Subtitle D cover design, as long as the cover that is installed meets the pertinent performance standards. As documented by the Alternative Landfill Cover Demonstration (ALCD) project, a landfill cover that is more reliable, less expensive, and easier to construct than prescriptive engineered covers can be designed to incorporate site-specific and regional environmental conditions, soil physical properties, hydraulic characteristics, and vegetation requirements to provide a minimum level of performance equivalent to that of the prescriptive RCRA Subtitle C design.

Advantages over Baseline

Alternative landfill covers have the following advantages over the baseline RCRA Subtitle C or D covers:

- easier to construct;
- less expensive; and
- more reliable and effective at preventing infiltration.

Demonstration Summary

The ALCD is being conducted at Sandia National Laboratories (SNL) in Albuquerque, New Mexico. This report covers the period from July 1995 through July 2000. The ALCD is a large-scale field demonstration to compare and document the performance of alternative landfill covers as compared to baseline RCRA Subtitle C and D covers at an arid or semi-arid site (Figure 1). Through side-by-side comparisons of the different cover designs, the ALCD provides the necessary tools (cost, construction, and performance) to enable design engineers to prepare better, regulatory acceptable alternatives to the prescriptive cover designs.

Figure 1. Aerial view of alternative landfill cover demonstration.

The objectives of the ACLD are to:

- demonstrate construction and document cost of the different covers;
- measure the performance of the different cover designs as compared to prescriptive RCRA Subtitle C and D cover designs;
- validate predictive models for long-term performance of the different covers; and
- document the results and provide for technology transfer through presentations, reports, and other publications.

Four alternative-cover designs were demonstrated:

- a geosynthetic clay liner cover;
- a capillary barrier cover;
- an anisotropic barrier cover; and
- an evapotranspiration soil cover.

Construction materials were obtained on-site (e.g., native soils) or were fairly common and readily available from local construction-materials suppliers (e.g., bentonite, sand, gravel, and piping). Construction activities used typical construction equipment (e.g., bulldozers, compactors) and standard (American Society of Testing and Materials [ASTM]) geotechnical tests were conducted to classify soil types and monitor soil barrier construction activities. The characteristics of the landfill covers are summarized in Table 1.

Table 1. Landfill cover design characteristics

Landfill Cover Design	Thickness	Layers	Components Description/Thickness
RCRA Subtitle D Cover	60 cm	2	Top vegetation/soil layer -- 15 cm Compacted native soil -- 45 cm
RCRA Subtitle C Cover	150 cm	4	Top vegetation/soil layer -- 60 cm Sand drainage layer -- 30 cm Geomembrane -- 40-mil Compacted bentonite-amended soil -- 60 cm
Geosynthetic Clay Liner (GCL) Cover	90	4	Top vegetation/soil layer -- 60 cm Geotextile filter fabric Sand drainage layer -- 30 cm Geomembrane -- 40 cm Geosynthetic clay liner
Capillary Barrier Cover	140	4	Top vegetation/soil layer -- 30 cm Upper sand drainage layer -- 15 cm Upper gravel drainage layer -- 22 cm Compacted barrier soil layer -- 45 cm Lower sand drainage layer -- 15 cm
Anisotropic Barrier Cover	105	4	Top vegetation/soil layer -- 15 cm Native soil cover layer -- 60 cm Fine sand interface layer -- 15 cm Pea gravel sublayer -- 15 cm
Evapotranspiration Soil Cover	90	2	Top vegetation/soil layer -- 15 cm Compacted native soil layer -- 75 cm

The ALCD was supported by DOE's Office of Science and Technology, Subsurface Contaminants Focus Area and Characterization, Monitoring, and Sensor Technology Crosscutting Program. Alternative landfill-cover design assistance was provided by the following:

Anisotropic Barrier -- Dr. John Stormont, University of New Mexico
Capillary Barrier --Dr. Charles Shackleford, Colorado State University
Evapotranspiration Soil Cover-- Dr. Tom Hakonson, Colorado State University

Evapotranspiration covers have been deployed or designed and permitted at a number of sites in Idaho, California, Arizona, Wyoming, and New Mexico.

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Other

All published Innovative Technology Summary Reports are available on the OST Web site at http://ost.em.doe.gov under “Publications.” The Technology Management System (TMS), also available through the OST Web site, provides information about OST programs, technologies, and problems. The OST/TMS ID for Alternative Landfill Cover Demonstration is 10.

SECTION 2
TECHNOLOGY DESCRIPTION

Overall Process Definition

The performance of six landfill covers was compared at a single demonstration site. Two prescriptive RCRA landfill covers (Subtitle C and Subtitle D) were installed to provide a baseline for comparison of alternative landfill covers designed for arid environments. Four alternative cover designs were demonstrated:

- a geosynthetic clay liner cover;
- a capillary barrier cover;
- an anisotropic barrier cover; and
- an evapotranspiration soil cover.

Each demonstration plot covered an area 13 m wide by 100 m long, with the long dimension crowned in the middle, so that one half sloped to the east and the other half sloped to the west. All layers in the cover designs had a 5% grade. The western slope was monitored under ambient conditions, while a sprinkler system installed on the eastern slope was used to stress-test the covers (active testing). Continuous water balance and meteorological data were collected for a 3-year post-construction period; periodic measurements of vegetative cover, biomass, leaf area index, and species composition were also made.

Construction of each landfill cover plot utilized standard construction practices and equipment. When required, soil lifts were compacted with an 18,200-kg smooth-rolled vibratory compactor. Between lifts of soil, the previous lift was scarified before the next lift was installed to eliminate the potential for a seam between the lifts to develop, which would allow water to pass along it. Soil density and water-content measurements were performed in accordance with ASTM standards to ensure that the soil was within acceptable compaction limits. Native soil used in construction was obtained from on-site borrow areas, while other construction materials were relatively common and readily available from local suppliers.

System Operation

The ALCD constructed and monitored six landfill-cover test plots.

1. **RCRA Subtitle D Cover:** This cover meets the minimum requirements of RCRA Subtitle D, which apply to new sanitary landfills, and has the following general performance standards (Figure 2):

   - soil cover permeability must be less than or equal to the permeability of the bottom liner or subsoil, but no greater than 10^{-5} cm/sec;
   - infiltration must be minimized within a minimum of 45 cm of soil; and
   - erosion must be minimized by using a minimum of 15 cm of soil for plant growth.

The cover installed at SNL is 60-cm thick and is comprised of essentially two layers: a bottom-compacted soil layer 45-cm thick and an upper 15-cm thick layer of loosely-laid topsoil. The bottom-compacted soil layer was constructed using native soil, placed in 15-cm lifts, and compacted at moisture levels sufficient to minimize the saturated permeability of the barrier in accordance with EPA guidelines.

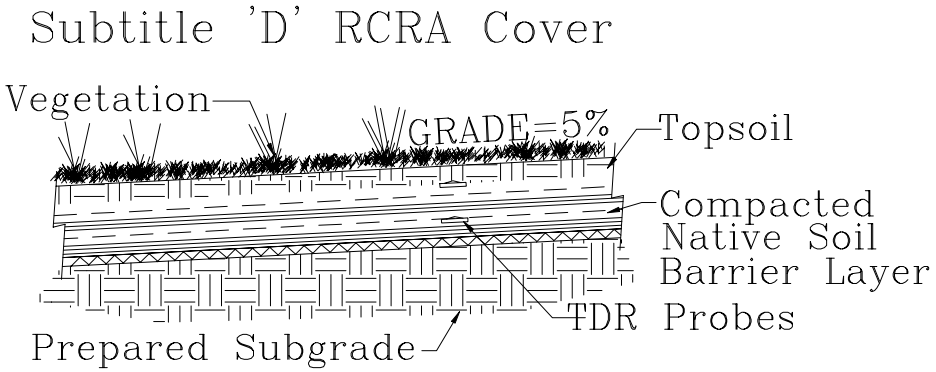

Figure 2. Prescriptive RCRA Subtitle D landfill cover design.

2. **RCRA Subtitle C Cover:** This cover was designed and constructed to meet the requirements for closure of hazardous and mixed-waste landfills, as promulgated in 40CFR Parts 264 and 265, Subpart N. Under these regulations, a low-permeability landfill cover must be constructed to minimize the migration of liquids into the waste and must meet the following performance standards:

- minimize liquid migration;
- promote drainage while controlling erosion;
- minimize maintenance;
- have a permeability equal to or less than that of the natural subsoil;
- address freeze/thaw effects; and
- accommodate settling and subsidence to ensure maintenance of the cover's integrity.

To meet these performance standards, EPA guidelines recommend the following cover design (Figure 3):

- a bottom low hydraulic-conductivity geomembrane or soil layer constructed of natural or amended soil with a maximum saturated hydraulic conductivity of 1×10^{-7} cm/sec, overlain by a geomembrane at least 40-mil in thickness;
- a middle sand-drainage layer at least 30-cm thick, with a minimum saturated hydraulic conductivity of 1×10^{-2} cm/sec, or a geosynthetic material with the same characteristics; and
- a top vegetation/soil layer at least 60 cm in thickness and graded at a slope of 3 to 5 percent.

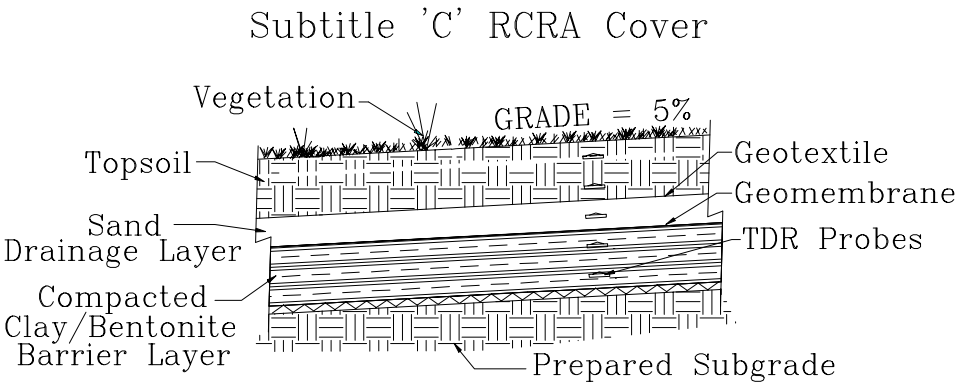

Figure 3. Prescriptive RCRA Subtitle C landfill cover design.

The cover installed at SNL is 150-cm thick and is comprised of a 60-cm thick low hydraulic-conductivity bottom layer, a 40-mil thick geomembrane, a 30-cm thick sand-drainage layer, and a 60-cm thick upper soil layer to provide for vegetative growth.

- The bottom soil layer was constructed of native soil with sodium bentonite added (Figure 4), installed in 15-cm lifts, and compacted with a soil moisture content sufficient to minimize saturated permeability, in accordance with EPA guidelines.

Figure 4. Adding sodium bentonite to native soil, RCRA Subtitle C.

- This compacted soil layer is immediately overlain by a 40-mil thick synthetic geomembrane with welded seams and in intimate contact with the underlying soil layer (Figure 5 and 6).

Figure 5. Geomembrane placement with spreader-bar attachment, RCRA Subtitle C.

Figure 6. Welding seams of geomembrane panels, RCRA Subtitle C.

- The non-compacted sand-drainage layer was installed directly on top of the geomembrane, has a saturated hydraulic conductivity of 1 x 10^{-1} cm/sec, and is overlain by a non-woven, polyester, needle-punched geotextile fabric.
- The top layer is a 60-cm thick, non-compacted soil layer to provide for vegetation growth and is comprised of 45-cm of native soil-fill covered by 15-cm of topsoil.

3. **Geosynthetic Clay Liner (GCL) Cover:** This cover is identical to the RCRA Subtitle C cover, except that the compacted low hydraulic-conductivity soil layer was replaced with a geosynthetic clay liner (GCL) (Figure 7). This cover is 90-cm in thickness and is comprised of:

- a bottom GCL layer (a GCL membrane covered by 40-mil geomembrane),
- a middle 30-cm thick sand-drainage layer covered by a geotextile-filter fabric, and
- an upper 60-cm thick vegetation soil layer.

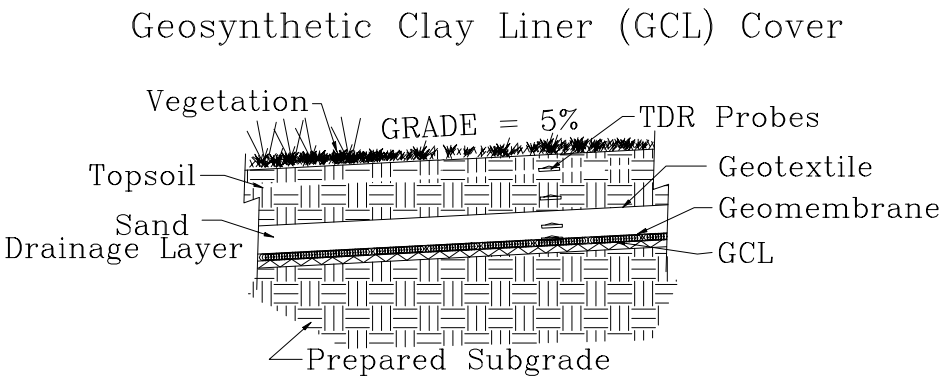

Figure 7. GCL cover design.

At SNL, the GCL layer was laid out on a prepared sub-grade in accordance with the manufacturer's recommendations (Figure 8). All GCL panel seams were overlapped, with no physical seaming between the panels. The GCL was then overlain by a 40-mil thick geomembrane, with welded seams, which comprised the GCL layer. The remainder of the cover is identical in construction to the RCRA Subtitle C cover.

Figure 8. GCL installation.

4. **Capillary Barrier Cover:** This cover design utilizes the differences in pore-size distributions and the corresponding differences in capillary (suction) forces, under unsaturated conditions, to retain water in the upper soil layer (Figure 9). This condition will persist as long as the contrast in the unsaturated soil properties, as indicated by soil-moisture characteristic curves and unsaturated hydraulic conductivities, is sufficiently large. To be effective, the upper soil layer must have a significantly larger suction than the underlying soil layer at the same water content. Consequently, a capillary barrier is created when a relatively fine-grained soil overlies a relatively coarse-grained soil. For any appreciable flow to occur into the lower soil layer (i.e., drainage layer), capillary forces in the fine-grained upper soil layer must approach zero, which occurs only under saturated conditions.

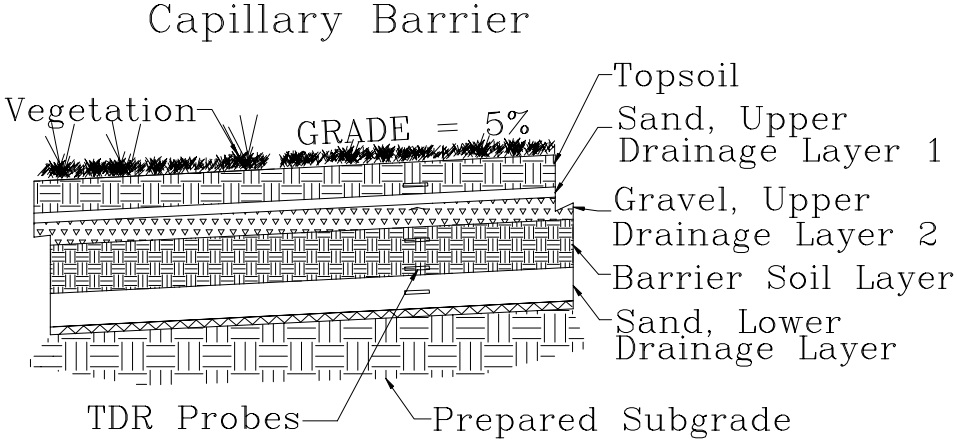

Figure 9. Capillary barrier cover design.

The capillary barrier cover installed at SNL is approximately 140 cm thick and is comprised of the following layers:

- a lower non-compacted sand-drainage layer at least 30 cm in thickness;
- a 45-cm thick compacted-barrier soil layer;
- a graded upper-drainage layer that consists of a 15-cm thick, non-compacted fine-grained sand overlying a 22-cm thick clean pea-gravel layer; and
- a 30-cm thick top vegetation/soil layer (Figure 10).

Figure 10. Capillary barrier installation.

5. **Anisotropic Barrier Cover:** This cover limits the downward migration of water, while encouraging the lateral movement of water through drainage layers. The cover is composed of layers with different capillary forces that have been enhanced, through variations in soil properties and compaction techniques, to provide the anisotropic properties of the cover (Figure 11).

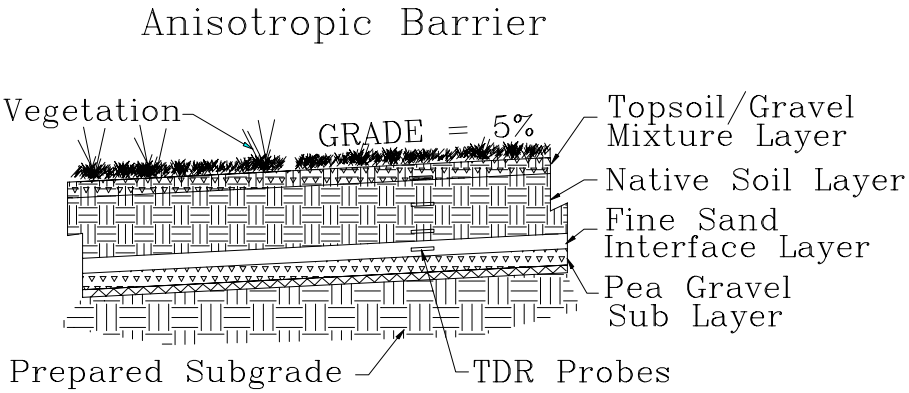

Figure 11. Anisotropic barrier cover design.

The cover installed at SNL is 105-cm in thickness and is comprised of the following layers:

- a 15-cm thick pea-gravel sub (drainage) layer;
- a non-compacted, 15-cm thick, fine-grained sand interface layer;
- a non-compacted, 60-cm thick native soil layer that was installed in six-inch lifts; and
- a 15-cm thick top vegetation/soil layer comprised of a mixture of local topsoil and pea-gravel (Figure 12).

The construction of the top vegetation layer includes pea-gravel (about 25% by weight) to enhance evapotranspiration and vegetative growth, while reducing surface erosion potential. The native soil layer serves as a rooting medium for the surface vegetation and provides increased water retention (storage) that will eventually be available for evapotranspiration. The interfaces between the native soil layer and the fine-grained sand layer and the fine-grained sand layer and the underlying pea-gravel layer, both serve as capillary breaks to the downward migration of liquids.

Figure 12. Anisotropic barrier installation.

6. **Evapotranspiration (ET) Soil Cover:** This cover limits the downward migration of water by capturing and diverting that water for use by the surface vegetation. This single 90-cm thick soil layer is comprised of a 75-cm thick layer that was installed in 15-cm thick compacted layers and a 15-cm thick topsoil layer that was loosely placed (Figure 13). The ET cover consists of an optimum mix of soil texture, soil thickness, and vegetative cover species that maximize utilization of any incident precipitation throughout the year (Figure 14).

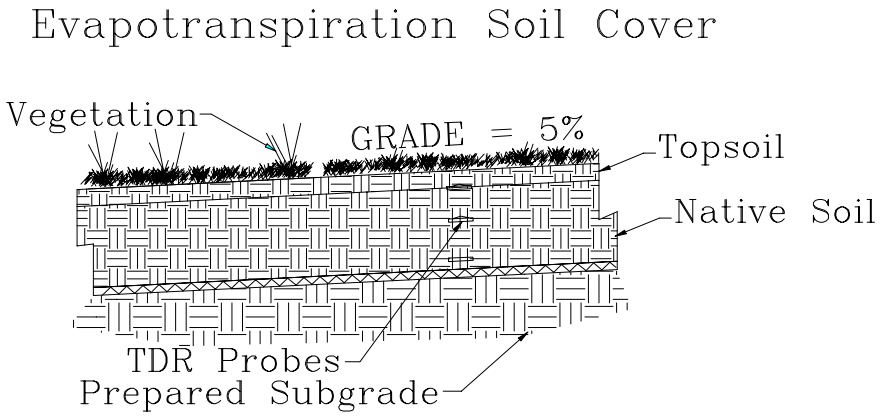

Figure 13. Evapotranspiration cover design.

As constructed at SNL, the vegetative cover consists of both warm and cool-season varieties native to the area and consists primarily of grasses. However, ET covers in other areas should incorporate different growth forms (e.g., grasses, shrubs, and trees) specific to site-specific conditions to ensure maximum growth and water utilization (evapotranspiration) throughout the entire growing season.

Figure 14. Compacting soil in ET cover.

Especially under arid and semi-arid environmental conditions, vegetation can provide a very effective means of controlling or minimizing the subsurface infiltration of water, either as direct precipitation or snow melt. To assist with development of preferred ET cover crops, a separate study was conducted to evaluate different surface treatments and their effect on the establishment and vitality of the surface vegetation.

SECTION 3
PERFORMANCE

Demonstration Plan

Each of the six landfill-cover test plots was constructed as described in Section 2. Performance of each of the covers was then monitored for three years and is ongoing at this time.

Soil properties that were monitored during the demonstration included the following.

- **Soil Moisture** -- Time Domain Reflectometry (TDR) with a data-acquisition system was used to provide a continuous record of soil moisture at different horizontal and vertical locations within each cover.
- **Soil Temperature** -- Thermocouples were installed at strategic locations in each cover to measure soil-temperature variations to support evapo-transpiration calculations and to monitor frost penetration and its effect on soil hydraulic conductivity.
- **Runoff and Erosion** -- Surface runoff was measured on a precipitation-event basis through the use of a gutter and measuring system that automatically collected and quantified the runoff volume, recorded, and stored the data. Sediment was separated from the runoff in a downstream settling tank to provide total soil loss for the event.
- **Percolation and Inter-flow** -- Subsurface flows were measured through the under-drain collection system that was installed at the base of each plot. Water collected by this system was routed to instrumentation that quantifies it and is linked to a data-acquisition system to continuously record the flow events.
- **Meteorology** -- A complete weather station was installed at the ALCD site to automatically record precipitation, air temperature, wind speed and direction, relative humidity, and solar radiation.
- **Vegetation** -- Vegetation attributes were measured seasonally throughout the study to correlate changes in erosion and evapotranspiration (Aguilar et al., 2000). A point frame was used to evaluate cover and leaf area, while biomass was determined by clipping and weighing oven-dried samples collected from subplots within each cover. Species composition was determined using line transects and quadrates.

The performance of each landfill cover used a water-balance approach as the primary evaluation criteria. The water-balance equation was:

$$E = P - I - R - D - \Delta S$$

where evapotranspiration (E), precipitation (P), infiltration or percolation (I), surface runoff (R), lateral drainage (D), and changes in soil-water storage (ΔS) are the variables of interest. The monitoring systems collected data for all of the water-balance equation variables, except for the evapotranspiration term. Automated monitoring systems were used to provide continuous data collection, although manual backup systems were also utilized to verify the accuracy of the automated systems or in case there was a failure of automated systems.

Results

Because of the single-site, side-by-side placement of the six landfill covers, direct comparison of their performance was possible. This information can then be utilized by the lead regulatory agency to consider and approve an alternative landfill-cover design, provided that it meets the required performance standard. While an owner or operator may select an alternative engineered cover on the basis of cost, it is the

comparative performance of the selected cover design to the prescriptive RCRA Subtitle C or D cover design that governs whether or not the regulatory agency will approve its use.

A summary of the flux rates of water through the covers is presented in Table 2. Review of these data indicate that all of the cover designs, with the exception of the RCRA Subtitle D cover, are essentially impermeable. The RCRA Subtitle D cover has the highest flux rate and the Subtitle C cover has the lowest. However, the Anisotropic Barrier Cover Design and the Evapotranspiration Soil Cover Design have efficiencies that are comparable to the RCRA Subtitle C cover design.

Table 2. Flux rates and efficiencies of ALCD covers

Flux Rates (mm/year)							
Year	**Precipitation**	**Subtitle D Cover**	**GCL Cover**	**Subtitle C Cover**	**Capillary Barrier**	**Anisotropic Barrier**	**ET Cover**
1997 (May 1- Dec 31)	154585.46	10.62	1.51	0.12	1.62	0.15	0.22
1998	169048.23	4.96	0.38	0.30	0.82	0.14	0.44
1999	130400.19	3.12	4.31	0.04	0.85	0.28	0.01
2000 (Jan 1-June 25)	28150.74	0.00	0.00	0.00	0.00	0.00	0.00
Average		4.82	1.81	0.13	0.87	0.16	0.19

Efficiency = (Percolation/Precipitation)* 100%						
Year	**Subtitle D Cover**	**GCL Cover**	**Subtitle C Cover**	**Capillary Barrier**	**Anisotropic Barrier**	**ET Cover**
1997	99.97429	99.99635	99.99970	99.99608	99.99963	99.99946
1998	99.98365	99.99876	99.99900	99.99730	99.99955	99.99856
1999	99.98665	99.98158	99.99985	99.99638	99.99881	99.99995
2000	100.00000	100.00000	100.00000	100.00000	100.00000	100.00000
Average	99.98615	99.99417	99.99964	99.99744	99.99950	99.99949

* Efficiency = (1-(percolation volume÷precipitation volume) x 100)

The total percolation for each cover from May 1997 to March 1998 is graphically presented in Figure 15 (Dwyer, 1998). The ALCD is currently over half-way through its five-year test plan and trends in the performance data are still developing. While performance trends are still being evaluated, a brief summary of each covers performance thus far is presented below.

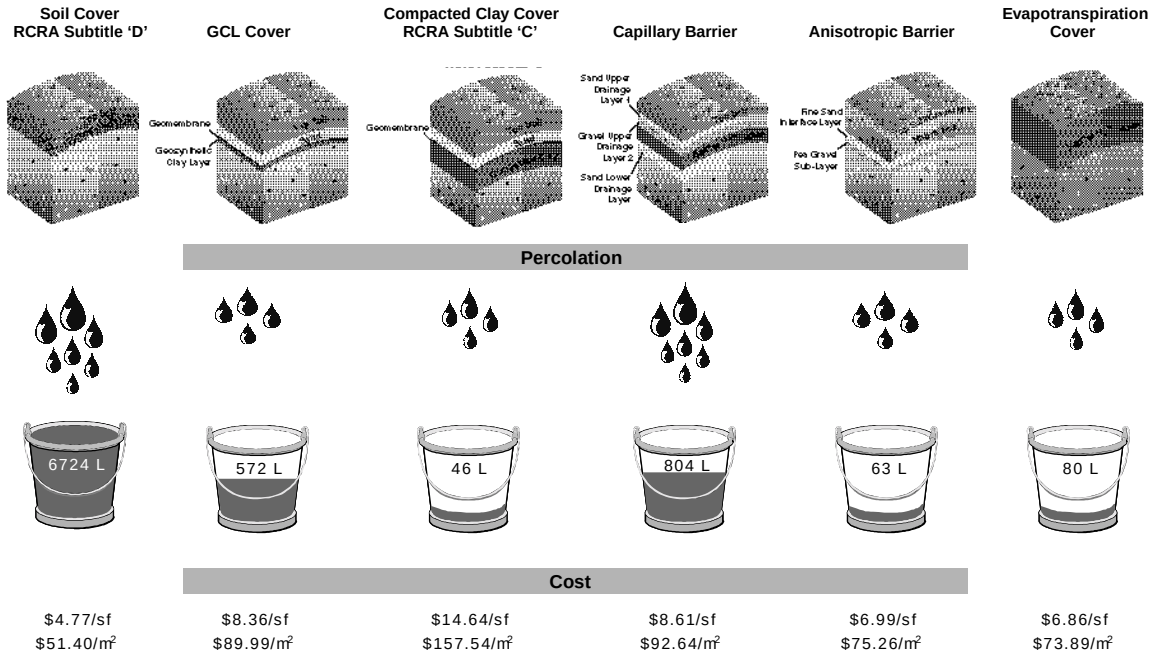

Figure 15. Schematic representation of water balance between May 1997 and March 1998 for the six landfill covers at the ALCD site at SNL.

- **RCRA Subtitle D Cover** -- This design performed poorly the first year, although the flux rate has decreased over time. Field observations showed that desiccation cracking and freeze/thaw effects, plus root penetration, earthworm activity, and insect activity may have contributed to its poor performance. The reduction in the flux rate over time may be attributable to the shift from capillary to hydraulic forces as the cover became saturated.
- **RCRA Subtitle C Cover** -- There was little percolation during the first year, and variation in percolation became evident in subsequent years. The soil barrier has exhibited an increase in soil moisture content, partly because of the bentonite, but also because it is covered by a geomembrane. The geomembrane inhibits drying of the barrier layer by evaporation, consequently as additional moisture infiltrates the barrier layer, it eventually creates percolation. Also, as moisture moves through the geomembrane (either by diffusion or defects), it infiltrates the barrier layer.
- **GCL Alternative Cover** -- This cover did not perform as well as expected. Eight 1-cm^2 defects were placed in the geomembrane to simulate heavy equipment damage that may occur during placement of cover soil. It is possible that as moisture moves through the geomembrane (either through defects or diffusion), it runs through the seams of the GCL before the seams can hydrate and swell shut. The GCL could also have been damaged during construction, the bentonite could be leaching from it, or it could have been damaged by root intrusion.
- **Capillary Barrier Alternative Cover** -- While the percolation rate for the first year was higher than expected, it slowed significantly in later years. The 5% slope in the cover design may be a problem, because the moisture will accumulate in the fine layer to a level where it finally breaks through into the coarse layer. Later-year observations have shown that the percolation rate is slowing as the vegetation on the surface thickens with the growth of native grasses and shrubs, which are removing moisture from the surface soil layer, thereby increasing the ET rate.

- **Anisotropic Barrier Alternative Cover** -- This cover is performing well. The percolation rates decreased after the first year as a result of increased transpiration from the vegetation. Observed percolation rates are comparable to the RCRA Subtitle C Cover design.
- **Evapotranspiration Soil Cover --** This cover is performing well, with observed percolation rates that are comparable to the RCRA Subtitle C Cover.

SECTION 4
TECHNOLOGY APPLICABILITY AND ALTERNATIVES

Competing Technologies

RCRA Subtitle C and Subtitle D covers are the standards for hazardous and sanitary landfills, respectively. As provided by RCRA, the lead regulatory agency may consider and approve alternative landfill cover designs, so long as they meet the following performance standards, as contained in 40 CFR Parts 264 and 265, Subpart N:

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

In addition, the cover must function effectively throughout the 30-year post-closure care period.

Other than the prescriptive landfill cover designs, other covers that might meet the closure performance standards include manmade covers (e.g., concrete, asphalt) or *in situ* modification (e.g., vitrification, chemical stabilization).

Technology Applicability

Alternative engineered cover designs can be applied to any landfill or other waste site where there is a regulatory requirement to minimize the infiltration of surface water. Demonstration of the enhanced performance of an alternative design as compared to the baseline RCRA Subtitle C and D standards for a specific site may be required by the appropriate regulatory agency. While the ALCD focused on developing cover designs for arid and semi-arid environments, the same approach can be applied to cover designs to accommodate other environmental conditions.

Patents/Commercialization/Sponsor

A patent for the Anisotropic Barrier was received by Sandia National Laboratories in 1997. The sponsor of this work has been the DOE Office of Science and Technology within the Office of Environmental Management.

SECTION 5
COST

Methodology

Cost information for the different cover designs was collected during the construction phase for each plot. Each cover was designed independently and the construction was competitively bid, with award to the low bidder under a firm fixed-price contract. Design costs included the common construction costs (e.g., mobilizing, demobilizing, and sub-grade preparation), materials costs, and labor. Material and construction costs were carefully allocated to each cover to ensure a common basis for comparison.

Cost Analysis

Construction costs and schematics for each of the landfill covers are summarized in Figure 16. These unit costs represent only the actual materials and construction costs and do not include monitoring equipment and instrumentation costs, or other costs associated with the testing of the covers.

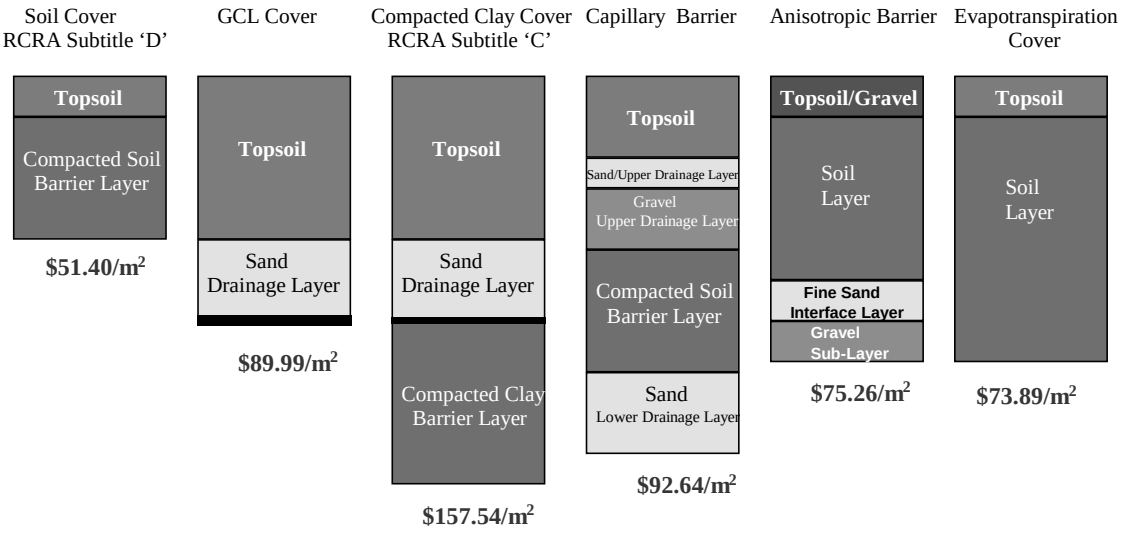

Figure 16. Summary of construction costs.

The RCRA Subtitle C Cover had the highest unit cost per square meter, primarily due to the use of the compacted clay barrier and geomembrane as the hydraulic barrier. The Capillary Barrier Cover was the next highest cost, followed by the GCL Cover. Both the RCRA Subtitle C and the Capillary Barrier Covers required the careful placement of different grades of sand and pea-gravel and a compacted soil-barrier, which increased the complexity and difficulty of construction and thus increased the cost of construction. Both the Anisotropic Barrier and Evapotranspiration Soil Covers employed a less complex, and therefore, less costly construction, while the RCRA Subtitle D Cover had the simplest and most straightforward construction requirements.

Because the ALCD demonstrated that the ET cover is a preferred alternative to the standard baseline cover, the ET cover was selected to be deployed at the Mixed Waste Landfill at SNL. MSE conducted a cost analysis of this project, comparing the ET cover to the RCRA "C:" cover as the baseline. Total capital cost for the baseline cover is estimated to be $3.55M, while the estimated capital cost for the ET cover is $1.76M. Operating and maintenance costs for the baseline cover are estimated at $12.36M cumulative costs over 30 years, whereas the operating and maintenance costs for the ET cover are estimated at $2.07M. The differences between the baseline and the proposed alternative are summarized as follows:

- Initial activities: Costs associated with characterization and design can be assumed to be the same.
- Mobilization: Costs for the alternative are less than for the baseline due to the use of on-site native soils for construction.
- Emplacement: Costs for the alternative are less than half of those for the baseline technology.
- ES&H and Assurance: These costs include safety oversight, permitting, project management, and quality assurance. The alternative cover costs are less due to reduced labor costs associated with the shorter schedule for installation.
- Operation and Maintenance: The primary cost is for long-term monitoring. The baseline technology requires groundwater monitoring wells and laboratory analysis of samples collected in the field. The alternative uses fiber-optic moisture sensors that do not require laboratory analysis and are thus much less expensive.

Overall cost savings for the alternative ET cover as compared to the baseline are estimated to total $7.6M over a 30-year period at the Mixed Waste Landfill Site. However, the deployment has not yet occurred and costs have been escalating since the beginning of the project. Actual cost savings will likely be less than originally predicted.

Cost Conclusions

Although the RCRA Subtitle D cover was the least expensive to construct, its performance was not satisfactory and thus it was ranked as the least preferable cover design to use at a site similar to that at SNL. Recommended designs must integrate both the construction cost and the overall performance of the cover. As a result of the above analysis, the Evapotranspiration Cover and the Anisotropic Barrier Cover rank as the most preferable designs, when comparing the six covers tested at the ALCD.

SECTION 6
REGULATORY AND POLICY ISSUES

Regulatory Considerations

From its inception, the ALCD was committed to getting regulatory and public acceptance for the project. Preliminary cover designs were independently reviewed by industry experts to ensure their technical validity. After reviewer comments were incorporated into the designs, the revised test plan was sent to environmental regulatory agencies in most of the western states for their review. Comments were then incorporated into the test plan. Working through the Western Governors Association, more than 1000 stakeholders were provided information on the ALCD project.

Regulatory approval of landfill and other waste site covers is governed by RCRA Subtitle C requirements that include the following:

- minimize liquid migration/infiltration;
- promote drainage while controlling erosion;
- minimize maintenance/erosion;
- have a permeability equal to or less than that of the natural subsoil or bottom liner;
- address freeze/thaw effects; and
- accommodate settling and subsidence to ensure maintenance of cover integrity.

Regulatory approval to install an alternative landfill cover requires that it meets or exceeds the required performance standards. The site owner or operator will be required to submit the necessary permits to demonstrate that the alternative design is preferable to the prescriptive design.

Safety, Risks, Benefits, and Community Reaction

Worker Safety

Construction of engineered covers entails the addition of natural and man-made materials on top of the waste cells for construction of the cover. The underlying material is not excavated or encountered; thus, worker exposure is minimal to nonexistent. Consequently, the primary health and safety concerns during construction of an engineered cover are those that are typical of earth-moving projects, i.e., working around large earth-moving equipment and the associated hazards.

Community Safety

The use of a reliable engineered cover ensures isolation of the underlying waste from environmental factors, thereby minimizing the potential for contaminant migration and reducing the potential for community exposure to the contaminants of concern.

Environmental Impacts

Soil used for construction of the covers is typically obtained from nearby borrow areas and proper erosion and sedimentation control practices must be implemented to mitigate potential environmental impacts from these activities. Positive impacts will occur at the site itself.

Socioeconomic Impacts and Community Perception

Construction of site-or regional-specific engineered covers will have minimal impact on the local labor force, although the use of relatively common and readily available construction materials may have a positive impact with local construction-supply companies.

Installation of engineered covers that are specifically designed to accommodate site- or regional-specific environmental conditions provide for a positive community perception, because the design is customized to meet the particulars of the site and is not an adaptation of a standardized design that may or may not work properly.

SECTION 7
LESSONS LEARNED

Implementation Considerations

- The side-by-side nature of the ALCD helped ensure collection of timely and accurate information concerning all aspects of the project. Because the six cover designs were being tested concurrently, and were adjacent to one another, a more direct comparison of cost and performance data was possible, thereby providing a more accurate assessment of the different factors that affect their integrity and functionality.
- Compacting the soil for construction of the hydraulic barrier under increased moisture conditions, in accordance with EPA guidelines, was difficult to achieve. The soil was harder to work, took a longer time, and excessive compactive effort was required to achieve the required saturated hydraulic conductivity, thereby increasing costs.
- Compacting the soil for construction of the hydraulic barrier was possible under lower moisture conditions that improved the workability of the soil and the ease of construction, thereby reducing the cost of this activity.

Technology Limitations and Needs for Future Development

- The ALCD focused on engineered covers that were designed to accommodate the environmental conditions that are specific to the arid or semi-arid western states. The results of the ALCD may not be directly applicable to other sites or regions that have appreciably different environmental conditions (i.e., humid environments).
- A similar demonstration for engineered covers that have been designed to accommodate the site- or regional-specific environmental conditions of other climatic areas (e.g., tropical, subtropical, and temperate) is required.

Technology Selection Considerations

- The ALCD demonstrated that site- or regional-specific environmental conditions affect the functionality and reliability of engineered landfill covers and must be factored into the cover design.
- While an impermeable cover may be the cover of choice in wet environments, an alternative cover based on local soil properties and vegetative moisture requirements may be more effective and less costly in arid or semi-arid environments.
- While construction of the geomembrane liner typically provides an impermeable barrier, damage to the liner, in the form of small tears or punctures, may occur when the protective soil cover is placed over the liner, thereby affecting its integrity and reliability.

APPENDIX A
REFERENCES

Aguilar, R., Stephen F. Dwyer, Gretchen Newman, and Samuel R. Loftin, (2000). Landfill Cover Revegetation Using Organic Amendments and Cobble Mulch in the Arid Southwest, Sandia National Laboratories Report SAND2000-0399.

Dwyer, Stephen F., John C. Stormont, and Clifford E. Anderson (1999). *Mixed Waste Landfill Design Report*, Sandia National Laboratories Report SAND99-2514.

Dwyer, Stephen F. (1998). Alternative Landfill Covers Pass the Test, Civil Engineering Magazine. ASCE Publication. September 1998, pp. 50-52.

Dwyer, Stephen F. (1998). *Construction Costs of Six Landfill Cover Designs*, Sandia National Laboratories Report SAND98-1988.

Dwyer, Stephen F. (1998). *Large-Scale Study of Landfill Covers at Sandia National Laboratories,* Sandia National Laboratories Report SAND98-2021.

Dwyer, Stephen F., Jesus Lopez (1998). Data Quality Management Plan (DQMP) for the Alternative Landfill Cover Demonstration Project. Sandia National Laboratories Report SAND98-2050.

Dwyer, Stephen F. (1998). Construction Overview of Six Landfill Cover Designs. Internal Sandia National Laboratories Report.

Landreth, R. E., D. E. Daniel, R. M. Koerner, P. R. Schroeder, and G. N. Richardson (1991). Design and Construction of RCRA/CERCLA Final Covers, U.S. Environmental Protection Agency Seminar Publication, EPA/625/4-91/025, Government Printing Office, Washington, DC.

Lopez, J., Stephen F. Dwyer (1998). Data Acquisition System for the Alternative Landfill Cover Demonstration (ALCD). Conference Proceedings: 4th International Environmental Geotechnology Symposium, Boston, MA.

Lopez, Jesus, Stephen F. Dwyer, and James N. Swanson (1997*). TDR Calibration for the Alternative Landfill Cover Demonstration (ALCD)*,. Sandia National Laboratories Report SAND97-2317.

Suter, G. W., R. J. Luxmoore, and Ellen D. Smith (1993). *Compacted Soil Barriers at Abandoned Landfills Will Fail in the Long Term*, Journal of Environmental Quality, Volume 22, pages 217-226.

U.S. Environmental Protection Agency, Office of Solid Waste (1988). *Case Studies on Ground Water and Surface Water Contamination from Municipal Solid Waste Landfills*, EPA/530-SW-88-040, Government Printing Office, Washington, DC.

U.S. Environmental Protection Agency Seminar Publication (1991). *Design and Construction of RCRA/CERCLA Final Covers*, EPA/625/4-91/025, Government Printing Office, Washington, DC.

Wentz, C. A. (1989). Hazardous Waste Management, page 374.