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Craig H. Benson

Environmental Geotechnics
Report No. 97-1

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January 1, 1997

EXECUTIVE SUMMARY

A large body of research has been conducted in the last decade relating to design and field hydrologic performance of covers designed with resistive barriers, capillary barriers, and monolayer barriers. A signification portion of this research has consisted of large-scale field demonstrations, some of which are still ongoing. This report provides a summary of these field demonstrations excluding demonstrations conducted in California. Fourteen different demonstrations are described and reviewed. Eight of the demonstrations were conducted in arid and semi-arid climates, and six were conducted in humid climates. These final cover demonstrations include 23 resistive barriers, 41 capillary barriers, and 21 monolayer barriers.

This report also includes a synthesis of principles learned from the field demonstrations. These principles can be summarized as follows:

- Compacted clay barriers will fail if they are not protected against desiccation. In five of the studies that employed compacted clay barriers, the barriers cracked when they desiccated. Afterwards, percolation rates increased substantially regardless of the type of barrier system. These findings suggest that compacted clay barriers used in final covers must be protected against desiccation cracking. Otherwise, the cover will not perform as intended. The only proven method of protection is to cover the clay with a geomembrane and to cover the geomembrane with at least 45 cm of soil. The upper soil layer provides a surcharge that holds the geomembrane in firm contact with the compacted clay.

- Capillary barriers transmit less percolation when the surface layer has lower saturated hydraulic conductivity. However, compromise must be made between low saturated hydraulic conductivity and resistance to desiccation cracking. This compromise is best made using silty sands and sandy silts, which are resistant to desiccation cracking and have reasonably low saturated hydraulic conductivity (~ 10^{-5} cm/sec).

- Rigorous principles must be applied when selecting layer thicknesses for capillary barriers and monolayer barriers. Otherwise, alternative covers are likely to transmit excessive percolation. In most cases a water balance model developed especially for arid and semi-arid climates must be used.

- Capillary barriers and monolayer barriers must have adequate capacity to store water that infiltrates during show melt events or during extended periods when evapotranspiration is low and precipitation is frequent. In many regions, these critical periods occur during the winter months.

- In many situations, an alternative cover must be shown to be equivalent to a prescriptive cover in terms of percolation rate. This comparison can be readily made using rigorous water balance models for sites with prescriptive earthen covers. However, such comparisons are difficult to make when the prescriptive design is a geosynthetic or composite cover, because rigorous methods to simulate flow through these types of covers have not yet been developed. In the absence of rigorous models, the best available field data suggest that the percolation rate from a composite cover is approximately 0.05 cm/yr.

ACKNOWLEDGMENT

This study was sponsored by the City of Glendale, Arizona through a contract with Rust Environment and Infrastructure, Inc. of Phoenix, Arizona. This support is gratefully acknowledged. This report has been reviewed by Rust Environment and Infrastructure and the City of Glendale.

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SECTION ONE

INTRODUCTION

Covers are placed over closed landfills and contaminated soils to minimize percolation into the underlying waste or soil with the objective of preventing generation of leachate. Most covers currently constructed in the United States employ a *resistive barrier* type design (Fig. 1). In this design, a barrier layer having low saturated hydraulic conductivity is used to provide the primary resistance to downward flow. The barrier layer may consist of compacted fine-grained soil, a geomembrane, a geosynthetic clay liner (GCL), or a combination of these materials. A resistive barrier containing only a soil barrier layer is referred to as an *earthen resistive barrier.* Similarly, a resistive barrier constructed only with a geosynthetic barrier layer (e.g., a geomembrane) is referred to as a *geosynthetic resistive barrier,* and a resistive barrier with a composite (geomembrane over soil) barrier layer is a *composite resistive barrier.*

The resistive barrier design may also include a drainage layer above and a gas collection layer below the barrier layer. A vegetated surface layer is also usually included, but in some instances this layer may be replaced by rip rap or gravel for erosion protection. A biota barrier may also be included to prevent plants and burrowing animals from contacting the barrier layer (Benson and Khire 1995, Daniel 1994).

The resistive barrier design is often the *prescriptive* design in the United States. That is, the resistive barrier design is often prescribed by regulation.

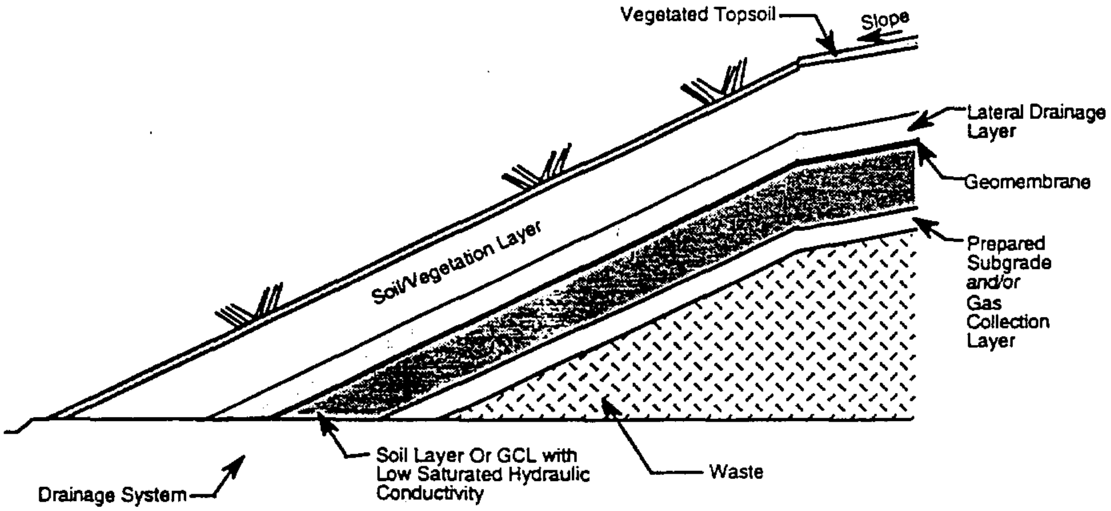


Fig. 1. Schematic of a Cover Employing the Resistive Barrier Design (from Benson and Khire 1995).

Tradition is the primary reason why the resistive barrier design is generally prescribed and frequently used. This tradition was initiated through a series of technical guidance documents issued by the US Environmental Protection Agency (EPA) (e.g., EPA 1983, 1987, 1990). However, little field data exist that show the resistive barrier design is superior or even equivalent to other designs, particularly in semi-arid and arid climates. In addition, recent research suggests that the hydraulic resistance of resistive barrier designs is not related to the saturated hydraulic conductivity of the barrier layers. In fact, the performance of earthen resistive barriers is primarily a function of unsaturated hydraulic properties of the soil layers, layer thicknesses, and the characteristics of preferential flow paths (Khire et al. 1996). In contrast, the performance of geosynthetic and composite resistive barriers appears to be governed by thermally driven vapor flows, which are not a function of saturated hydraulic conductivity (Melchior et al. 1994).

The lack of technical support for the resistive barrier design and the high cost of covers that include resistive barriers has led many investigators to study alternative designs that may be equally effective and less costly. Two types of covers are commonly being considered today: *capillary barriers* and *monolayer barriers*. In some cases, both of these barriers are combined, and on occasion they are also combined with a resistive barrier. In most cases, however, a single type of barrier is used. These barriers may also include biota control layers, drainage layers, and gas collection layers.

A *capillary barrier* can be constructed in various forms, ranging from a simple design consisting of two layers of contrasting particle size to more complex designs that include multiple layers of finer-grained and coarser-grained soils (e.g., Stormont 1995a). In its basic form, however, a capillary barrier consists of a finer-grained layer overlying a coarser-grained layer (Fig. 2a).

The contrast in unsaturated hydraulic properties between the finer- and coarser-grained layers in a capillary barrier restricts movement of water across the interface. Provided the water content remains below the crossing point (Fig. 2b), the coarser soil will have lower unsaturated hydraulic conductivity and the finer soil will have higher matric suction (Fig., 2c), both of which limit migration of water across the interface (Meyer et al. 1996, Khire et al. 1997). As a result, water is stored in the surface layer, or diverted laterally.

Downward flow occurs when the water content of the surface layer approaches the crossing point. Thus, the key aspect of designing a capillary barrier is to ensure that the surface layer is thick enough to store infiltrating water without reaching the crossing point, yet thin enough so that all of the stored water can be removed at a later time via evapotranspiration. As a result, the necessary thickness of the surface is defined by the soil water storage capacity of the surface layer (i.e., how much water can be stored before the crossing point is reached) and the evapotranspiration potential provided by ambient climate and vegetation.

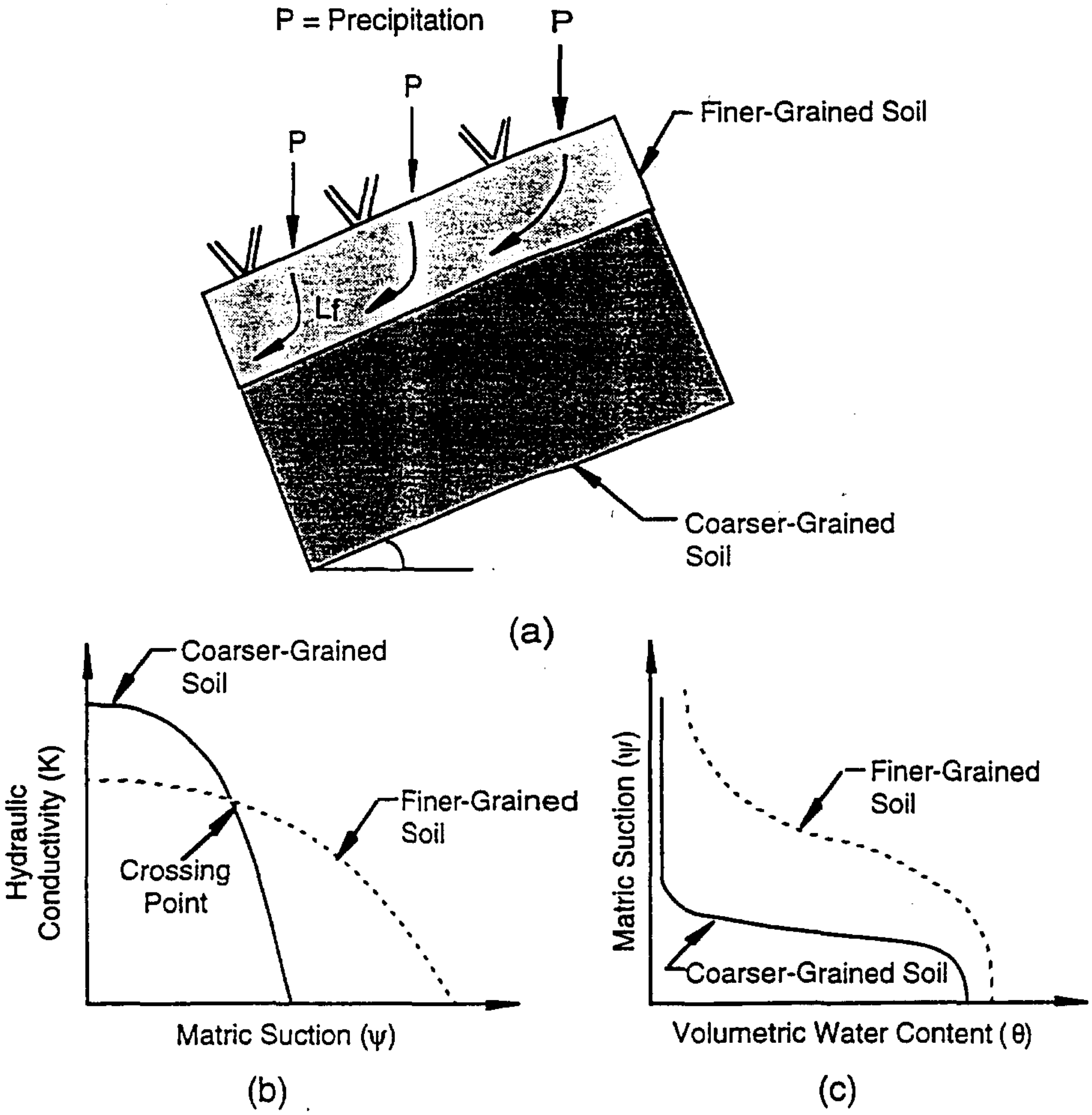


Fig. 2. Schematic of a Capillary Barrier (a), Hydraulic Conductivity Functions Showing Crossing Point (b), and Soil-Water Characteristic Curves (c).

A *monolayer barrier* design employs a thick layer of soil that has adequate soil water storage capacity to retain any water that infiltrates until it can be removed by evapotranspiration (Fig. 3). Sometimes covers with a monolayer barrier design are referred to as *monolithic covers*. Frequently vegetation is employed to enhance the removal of water. However, vegetation is not required in all climates, especially those where evaporation greatly exceeds precipitation and precipitation during the winter months is mild. A monolayer barrier is designed by selecting a thickness which will result in low water contents near the base of the barrier, and limited fluctuations in these water contents (Fig. 3). This condition results in very low unsaturated hydraulic conductivity and a unit gradient condition, which limits percolation to minute amounts.

A large body of research has been conducted in the last decade relating to design and field hydrologic performance of covers designed with resistive barriers, capillary barriers, and monolayer barriers. A signification portion of this research has consisted of large-scale field demonstrations, some of which are still ongoing. This report provides a summary of these field demonstrations. Fourteen different demonstrations are described and reviewed. Eight of the demonstrations were conducted in arid and semi-arid climates, and six were conducted in humid climates. These final cover demonstrations include 23 resistive barriers, 41 capillary barriers, and 21 monolayer barriers. The demonstrations in semi-arid climates are described in Section Two. Section Three contains descriptions of the demonstrations conducted in humid climates.

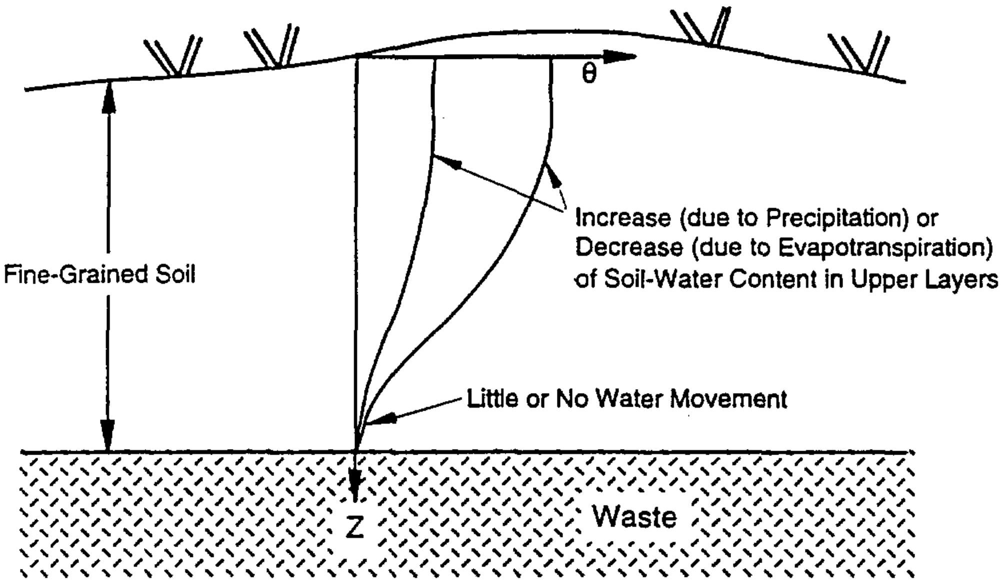


Fig. 3. Schematic of Cover with Monolayer Barrier Design (from Benson and Khire 1995).

The author notes, however, that recent field demonstrations of monolayer barriers that have been conducted in California are not included in this report. These projects are being described in a separate report by another investigator.

This report also includes a synthesis of principles learned from the field demonstrations. These principles, which are described in Section Four, can be used when selecting appropriate types of covers, designing alternative covers, and evaluating equivalency with respect to prescriptive designs.

SECTION TWO

SITES IN ARID AND SEMI-ARID REGIONS

2.1 SANDIA ALTERNATIVE LANDFILL COVER DEMONSTRATION

2.1.1 Project Overview

The Sandia Alternative Landfill Cover Demonstration (ALCD) is being conducted by Sandia National Laboratory of the US Department of Energy at Kirtland Air Force Base in Albuquerque, New Mexico. The objective of the ALCD is to compare the hydrologic performance of five alternative cover designs relative to Resource Conservation and Recovery Act (RCRA) Subtitle C and Subtitle D designs (Dwyer 1995). RCRA Subtitle C contains regulations pertinent to landfilling of hazardous waste. These same regulations are also commonly applied when capping uncontrolled waste sites under the auspices of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), which is also known as Superfund. RCRA Subtitle D contains regulations pertinent to landfilling of non-hazardous waste.

The RCRA Subtitle C and D cover designs are shown in Fig. 4. The Subtitle C design consists of a 60-cm-thick vegetated surface layer underlain by a 30-cm-thick drainage layer (saturated hydraulic conductivity $\geq 10^{-2}$ cm/s), a geomembrane at least 1.0 mm thick and a 60-cm-thick layer of compacted fine-grained soil having saturated hydraulic conductivity $\leq 1\times10^{-7}$ cm/s. This design is also commonly used for final covers at modern composite-lined municipal solid waste (MSW) landfills (i.e., modern "Subtitle D" MSW landfills) and for

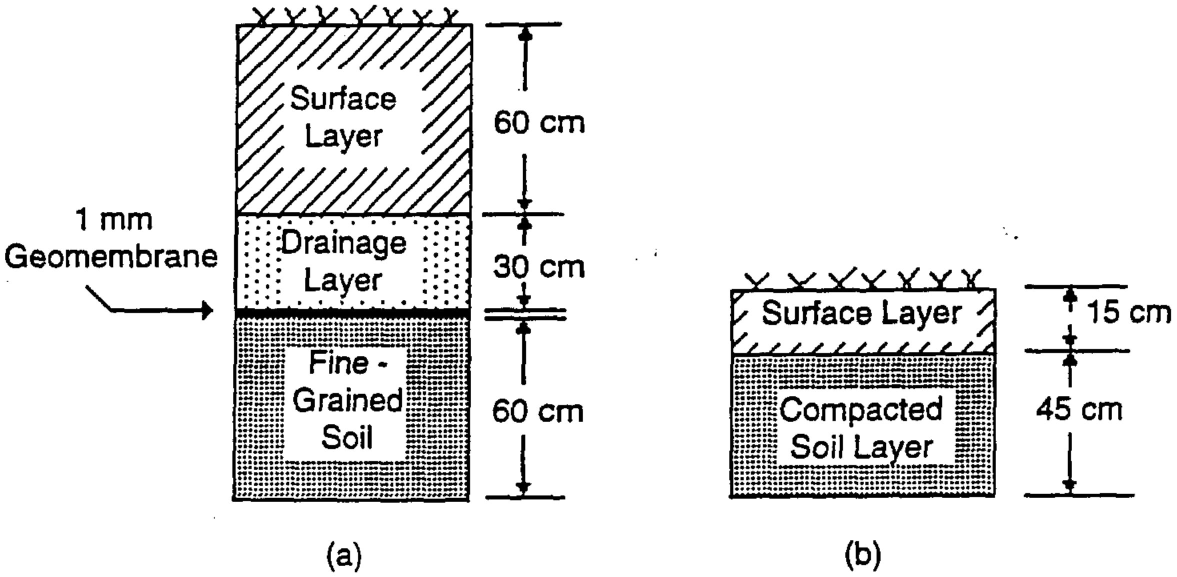


Fig. 4. RCRA Cover Designs Used at the Sandia ALCD: (a) Subtitle C Design and (b) Subtitle D Design (adapted from Dwyer 1995).

remediation of uncontrolled waste sites. The Subtitle D design applicable to many existing US Dept. of Energy landfills is an earthen resistive barrier with a 15-cm-thick vegetated top soil layer underlain by a 45-cm-thick compacted soil layer having saturated hydraulic conductivity $\leq 10^{-5}$ cm/s. It should be noted that this Subtitle D design is for closure of older landfills without lining systems. Modern MSW and hazardous waste landfills employing a composite lining system are required to have a composite cover system similar to the Subtitle C design (Daniel 1994).

The Subtitle C and D test sections constructed for the Sandia ALCD closely follow the Subtitle C and D designs shown in Fig. 4. The drainage layer in the Subtitle C test section at the Sandia ALCD was constructed with sand having a saturated hydraulic conductivity of 0.1 cm/s. The compacted soil layer consisted of a bentonite-amended silty sand having a saturated hydraulic conductivity $\leq 1\text{x}10^{-8}$ cm/sec based on laboratory tests. A 1.5-mm-thick high density polyethylene (HDPE) geomembrane was placed over the bentonite-amended silty sand. The compacted soil layer in the Subtitle D design was constructed with the same soil, but without bentonite. Laboratory tests on the soil without bentonite showed that its hydraulic conductivity is $5.3\text{x}10^{-6}$ cm/s. Field hydraulic conductivity testing is currently being conducted on both compacted soils.

The alternative cover designs consist of the following (Fig. 5): a resistive barrier design identical to the Subtitle C design except a GCL is used in place of the bentonite-amended soil, a traditional capillary barrier, a "anisotropic"

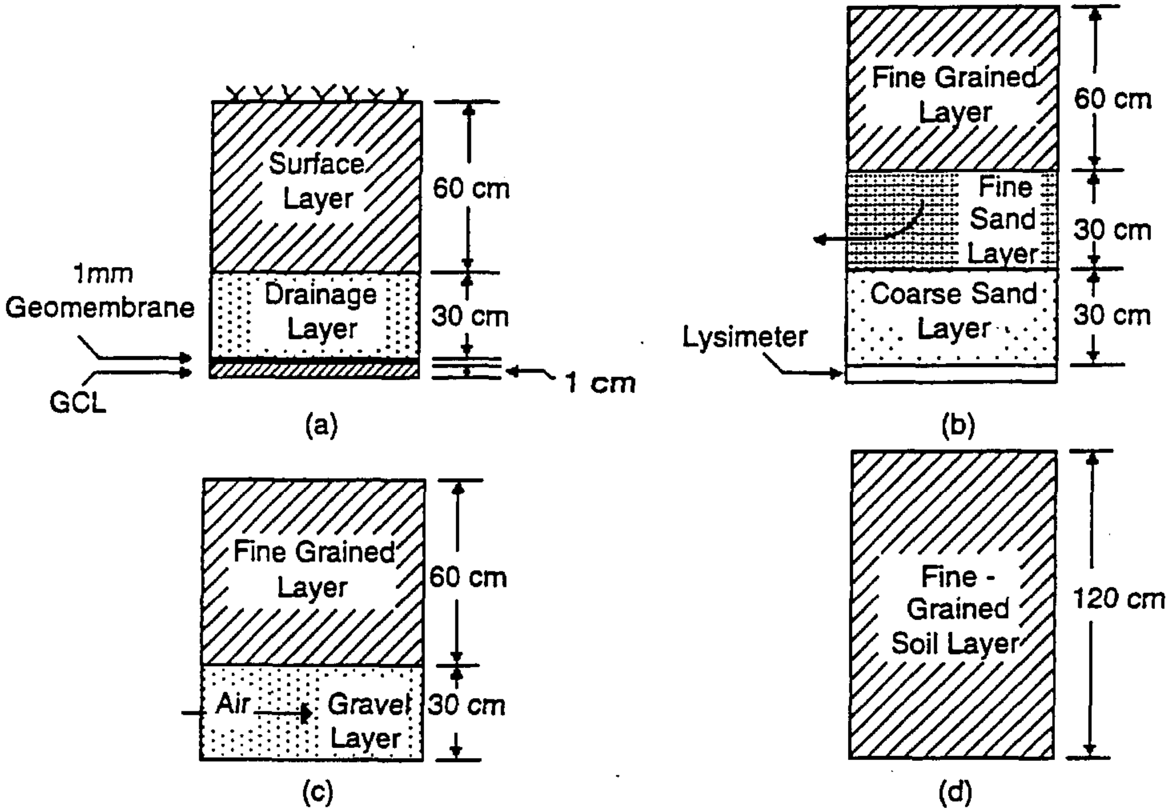


Fig. 5. Alternative Cover Designs at the Sandia ALCD: (a) GCL Subtitle C Design, (b) Anisotropic Capillary Barrier, (c) Dry Barrier, and (d) Monolayer Barrier (after Dwyer 1995).

capillary barrier that diverts flow laterally, a "dry" capillary barrier, and a monolayer barrier. The test section with a GCL was constructed in 1995. The other test sections were constructed in late Summer 1996, and only conceptual information regarding their design has been released (Dwyer 1995).

The anisotropic capillary barrier consists of multiple layers of coarser and finer-grained soils that are arranged so that a finer layer wicks flow laterally. A fine sand is used for the wicking layer, which effectively is an unsaturated drainage layer. The fine sand is sandwiched between a fine-grained vegetated top soil layer and a clean gravel layer. Thus, it actually contains two capillary barriers. Water that passes across the first capillary barrier (top soil-fine sand) moves laterally down slope because of the capillary barrier that exists between the sand and gravel. A description of the theory and application of anisotropic barriers can be found in Stormont (1995 a, b).

The dry barrier is an enhanced capillary barrier that employs air movement through the coarse-grained layer to reduce percolation (Stormont et al. 1994). Air moves through this layer via natural convection induced by vent pipes located at the bottom and top of slope. Convection is induced by a chimney effect caused by the difference in elevation of the upper and lower vent pipes. As drier atmospheric air is drawn into the coarse-grained layer, water in the coarse-grained soil evaporates into the flowing air stream. The evaporated water is then discharged from the cover through the vent at the top of slope. A GCL is also included in the dry barrier beneath the coarse-grained layer as a final barrier against percolation.

2.1.2 Test Section Design

Each test section is 13 m wide and 100 m long. Percolation from each test section is collected in a lysimeter constructed with HDPE geomembrane and a geocomposite drainage layer (Dwyer 1995). Water is routed to the bottom of the slope, where it is collected and then piped to a collection tank. Methods used to measure the flows have not been described. Lateral flow in the drainage layers is measured using a similar system.

Water contents are being monitored with time domain reflectometry (TDR). Thermocouples have been installed to measure soil temperature and a weather station is used to monitor meteorological conditions. A data acquisition and control computer (DACC) is used to control the system and collect the data. The DACC and associated system are similar to the system described in Benson et al. (1994).

An irrigation system has also been installed to irrigate the eastern half of each test section. The test sections are sloped at 5% to the east and west, with the crest at the center. Thus, runoff from the irrigated portion will flow only along the eastern slope. Storms simulating 10-, 50-, and 100-year events will be simulated with the irrigation system.

2.1.3 Water Balance Data

Because the test sections have only recently been constructed, water balance data have not yet been reported by the investigators. Data will be presented this February at the 1997 International Containment Technology Conference in St. Petersburg, Florida.

2.2 INTEGRATED TEST PLOT EXPERIMENT

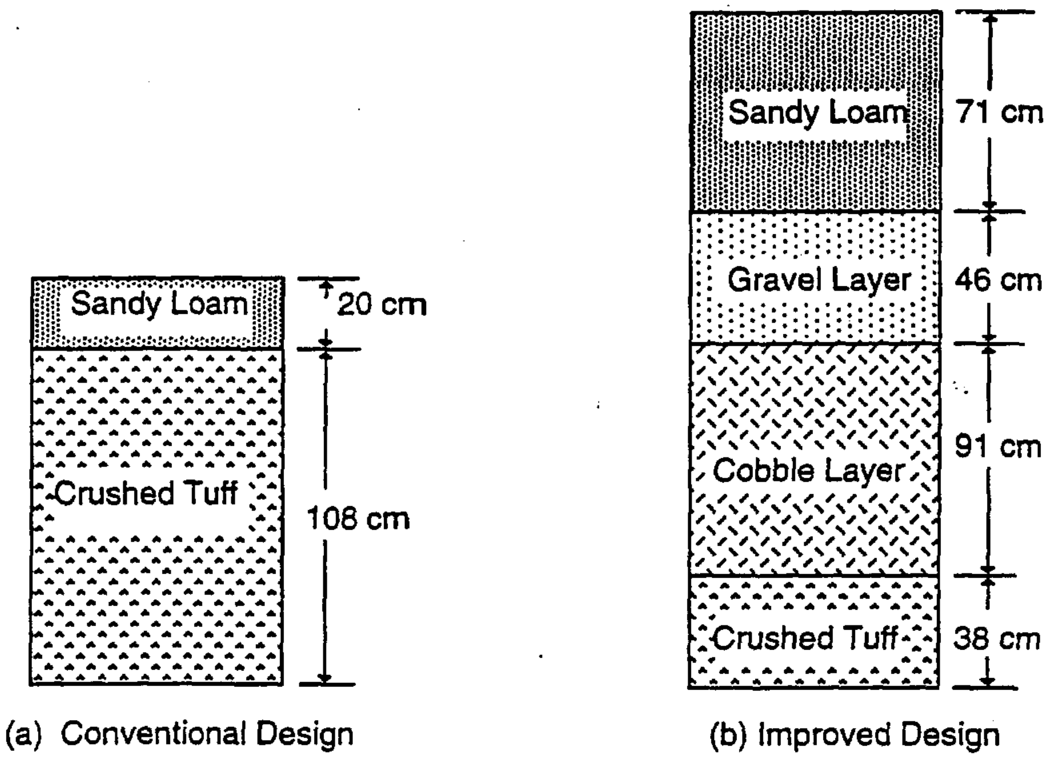
2.2.1 Project Overview

The Integrated Test Plot Experiment (ITPE) was conducted at Los Alamos National Laboratory (LANL) to evaluate potential cover designs for burial trenches containing low level radioactive waste (LLRW). Two designs were considered, a "conventional" design and an "improved design" (Fig. 6). A description of the ITPE can be found in Nyhan et al. (1990).

The conventional design is currently being used at LANL for covering burial trenches. It consists of 20 cm of sandy loam top soil underlain by 108 cm of crushed tuff. In effect, the conventional design is a monolayer barrier with a topsoil cover to promote vegetative growth. The improved design is a capillary barrier consisting, from top to bottom, of 71 cm of sandy loam topsoil, 46 cm of gravel, 91 cm of cobble, and 38 cm of crushed tuff. Crushed tuff was placed at the bottom to simulate the backfill used at LANL when burying LLRW. The cobbles were placed as a biota barrier to prevent the intrusion of roots and burrowing animals. The improved design is a double capillary barrier, with capillary breaks formed at the top soil-gravel and gravel-cobble interfaces.

2.2.2 Test Section Design

Each test section was 3.0 m wide and 10.7 m long. Slopes were less than 0.5% to prevent runoff. Plastic liners 0.15 mm thick were used to collect percolation from the base of each test section. Percolation was then routed via



(a) Conventional Design

(b) Improved Design

Fig. 6. Test Sections Used at ITPE: (a) Conventional Design and (b) Improved Design.

pipes to an outfall point, where flow rates were measured manually using a graduated cylinder and a stop watch.

Water contents were measured using a neutron moisture gage. The gage was inserted into access tubes that were installed laterally across the test sections at depths of 20, 40, 80, and 110 cm. Precipitation was measured using a tipping bucket connected to an analog event recorder.

Each test section was seeded with blue grama and western wheatgrass. Relative plant cover was determined visually on two longitudinal transects. Biomass was also determined by clipping vegetation from ten 100 cm^2 quadrants.

2.2.3 Water Balance Data

Soil water storage in both test sections showed the characteristic seasonal fluctuation found at many arid and semi-arid sites. That is, soil water storage increased during the cooler and wetter winter months, and then decreased due to evapotranspiration during the spring and summer months. Water contents in the surficial soils also indicated that more water was stored near the surface in the improved design, primarily because the capillary barrier impeded downward flow. The additional water stored in the surface layer stimulated vegetative growth on the test sections with the improved design. Biomass on the test sections with the improved design was two to three times greater than on the conventional design (Table 1).

Table 1. Water Balance Data for the ITPE Test Sections (from Nyhan et al. 1990)

Component	**Conventional Design (Monolayer Barrier)**		**Improved Design (Capillary Barrier)**	
Precipitation (cm)	173.7	173.7	173.7	173.7
Soil Water Storage Change (cm)	12.1	9.1	4.2	4.4
Evapotranspiration (cm)	151.7	154.9	169.6	164.7
Lateral Flow (cm)	NA	NA	0.0	1.9
Percolation (cm)	10.6	10.6	0.0	2.6

Percolation was generated each year from the tests plots with the conventional design, but only once from the test plots with the improved design. In addition, percolation was only generated at the end of winter, when snow melt occurred. Calculations showed that evapotranspiration reached a minimum during the snow melt periods.

Percolation occurred during the snow melt because the storage and diversion capacity of the covers was overwhelmed, resulting in downward migration of water. The capacity of the conventional design was overwhelmed each year, whereas the capacity of the improved design was large enough to accommodate the influx of water during all but one very large snow melt. If the layers used in the improved design had been sized for this large snowmelt, percolation probably would have been zero.

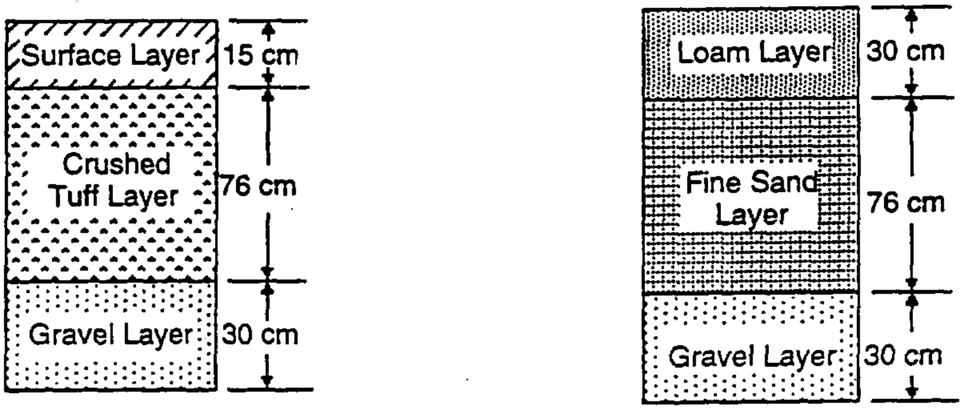
2.3 PROTECTIVE BARRIER LANDFILL COVER DEMONSTRATION

2.3.1 Project Overview

The Protective Barrier Landfill Cover Demonstration (PBLCD) was conducted at Los Alamos National Laboratory (LANL) and is described in Nyhan et al. (1997, 1993). The objective of the study is to compare the hydrologic performance of four landfill cover designs that potentially could be used to cap landfills at LANL. The long-term average annual precipitation at LANL is 32.8 cm.

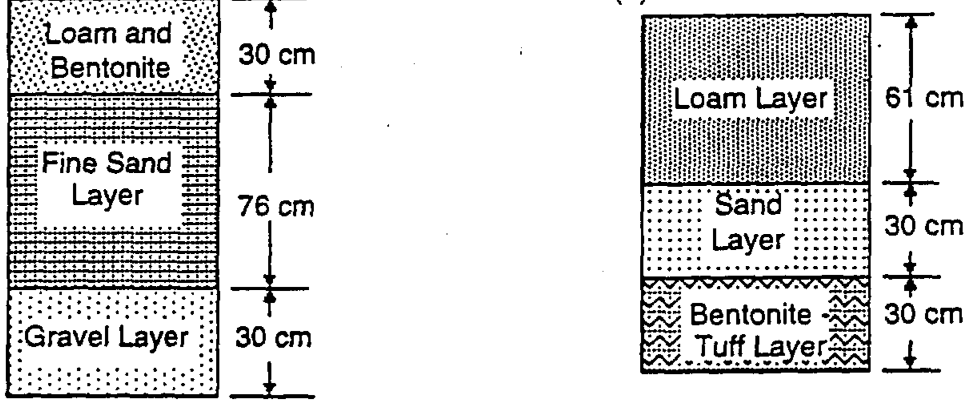
A sketch of each design is shown in Fig. 7. Three designs are alternative earthen covers (Figs. 7a, b, c). The fourth design is a RCRA-type design (Fig. 7d), consisting of a loam top soil layer (61 cm thick), a sand drainage layer (30 cm thick), and a barrier layer consisting of a bentonite-tuff mixture. A geomembrane was not placed on the clayey barrier layer, as called for in the RCRA design, because Nyhan et al. (1997) believed it would not last more than 35 years. Consequently, a design without a geomembrane was thought to better simulate long-term conditions. It should be noted, however, that current research indicates that high density polyethylene geomembranes should have lifetimes in excess of 800 years (Koerner et al. 1990).

The three alternative designs are all variations on capillary barriers. The conventional design (Fig. 7a) is the cover design currently being used at LANL; it consists of a loam surface layer (15 cm thick), a layer of crushed tuff (76 cm thick), and a gravel layer (30 cm thick). The capillary break in the conventional design occurs due to the contrast between the crushed tuff and the medium



(a) Conventional Design

(b) Alternative - Loam



(c) Alternative - Loam and Bentonite

(d) RCRA Design

Fig. 7. Schematic of Test Sections Evaluated in the PBLCD: (a) Conventional Design, (b) Capillary Barrier with Loam Surface Layer, (c) Capillary Barrier with Loam-Bentonite Surface Layer, and (d) RCRA Design.

gravel. The other two alternative designs (Figs. 7 b, c) include a fine sand wicking layer instead of the crushed tuff. The fine sand layer is designed to promote lateral drainage above a sand-gravel capillary break. In addition, these designs include a thicker surface layer constructed of loam or loam mixed with bentonite (Figs. 7 b, c). In effect, the capillary barriers shown in Figs. 7 b and c have two capillary breaks, one at the loam-sand interface and the other at the sand-gravel interface. None of the designs include vegetation.

Saturated and unsaturated hydraulic properties were measured for each of the soils that were used (Table 2). However, apparently no calculations were made to determine the storage or diversion capacity of the capillary barriers. That is, the layer types and thicknesses were not selected to ensure percolation near zero for the meteorological conditions at LANL.

2.3.2 Test Section Design

Four test sections of each design were constructed on different slopes (5, 10, 15, and 25%) to investigate how slope angle affects hydrologic performance. It was expected that slope angle would affect run off and lateral flow. *Orientation of the test sections (i.e., relative to north) is not mentioned.*

Each test section was 1.0 m wide (cross-slope) and 10 m long (down slope). A welded steel underdrain was placed beneath the gravel in each test section to collect seepage. Welded steel collection basins were also installed at the down slope end of the RCRA design and the two capillary barriers with sand layers to capture lateral flow.

Table 1. Hydraulic Properties of Cover Soils (from Nyhan et al. 1997).

Soil	α (1/cm)	n	θ_r	θ_s	K_{sat} (cm/s)
Loam Topsoil	0.0271	1.539	0.0692	0.4209	5.7×10^{-3}
Clay Loam	0.0100	1.548	0.0730	0.4839	2.5×10^{-4}
Fine Sand	0.0334	5.472	0.0700	0.4180	1.2×10^{-2}
Medium Sand	0.0288	3.766	0.0376	0.4184	1.3×10^{-1}
Crushed Tuff	0.0104	1.707	0.0031	0.4079	8.2×10^{-4}
Clay-Tuff Mix	0.00014	3.992	0.0000	0.4415	6.3×10^{-8}
Medium Gravel	Not Available	Not Available	Not Available	Not Available	2.0

Note: α and n are van Genuchten parameters.

Data were collected from the test sections using a data acquisition and control computer (DACC) conceptually similar to the DACC described in Benson et al. (1994). Water contents were measured non-destructively using time domain reflectometry (TDR) and percolation rates were measured by collecting percolation in tanks and monitoring the tank levels using an ultrasonic level sensor. Precipitation was measured on-site with a tipping bucket and solar radiation was measured with a pyranometer.

2.3.3 Water Balance Data

Water balance data for the test sections are summarized in Table 3. The data illustrate that the conventional design had the greatest percolation, whereas the RCRA design had the lowest percolation. In addition, percolation was greater from the test sections with shallower slope. Runoff was a relatively small fraction of the water balance, comprising only 2-3% of precipitation. The dominant component of the water balance was evaporation, comprising 81% (conventional design with shallow slope) to 96% (capillary barrier with bentonite-loam surface layer, 25% slope) of precipitation.

The long-term average run off was slightly greater for the test sections with greater slope, although no difference in run off could be attributed to slope on a storm-by-storm basis. Slope had a much greater impact on evaporation, with greater evaporation occurring from the designs with steeper slopes. Greater evaporation on the steeper slopes was attributed to higher solar radiation on these slopes during the critical winter months. The steepest slopes

Table 3. Water Balance Data from the PBLCD (from Nyhan et al. 1997).

Cover Design and Slope	Water Balance Component (cm)				
	Evapotrans-piration	Lateral Flow	Percolation	Runoff	Δ Soil Water Storage
Conventional					
5%	138.9	9.86	17.40	3.04	2.52
10%	143.8	15.12	8.16	3.19	0.45
15%	152.8	10.05	8.60	3.32	-4.57
25%	161.7	6.72	3.09	4.34	-5.69
RCRA					
5%	154.1	17.07	0.00	1.83	-1.12
10%	154.1	16.02	0.00	1.73	0.00
15%	154.4	15.10	0.00	3.94	-2.23
25%	154.4	12.95	0.00	6.14	-2.27
Loam Cap. Barrier					
5%	143.0	14.59	9.64	1.41	2.09
10%	137.9	20.62	3.61	4.65	3.87
15%	150.6	17.85	0.00	3.37	-0.59
25%	155.9	10.69	0.00	5.66	-2.08
Clay Loam Cap. Barrier					
5%	149.5	10.71	5.59	2.95	2.03
10%	152.5	12.77	0.00	4.44	1.06
15%	156.9	6.83	0.00	6.19	0.21
25%	163.7	1.50	0.00	7.43	-1.39

typically received 200 MJ/m^2 more short-wave solar radiation during the winter months than the shallowest slopes. Interlayer flow was not greatly affected by slope angle.

Changes in soil water storage exhibited similar behavior in each of the test sections. Data from the conventional design (5% slope) are shown in Fig. 8. The data exhibit seasonal fluctuations characteristic of arid and semi-arid regions, with the greatest storage occurring in winter and spring of each year. If the layering of the test sections had been selected to accommodate the required soil water storage during the winter and spring months, percolation probably would have been much lower (or even zero) for each of the alternative covers.

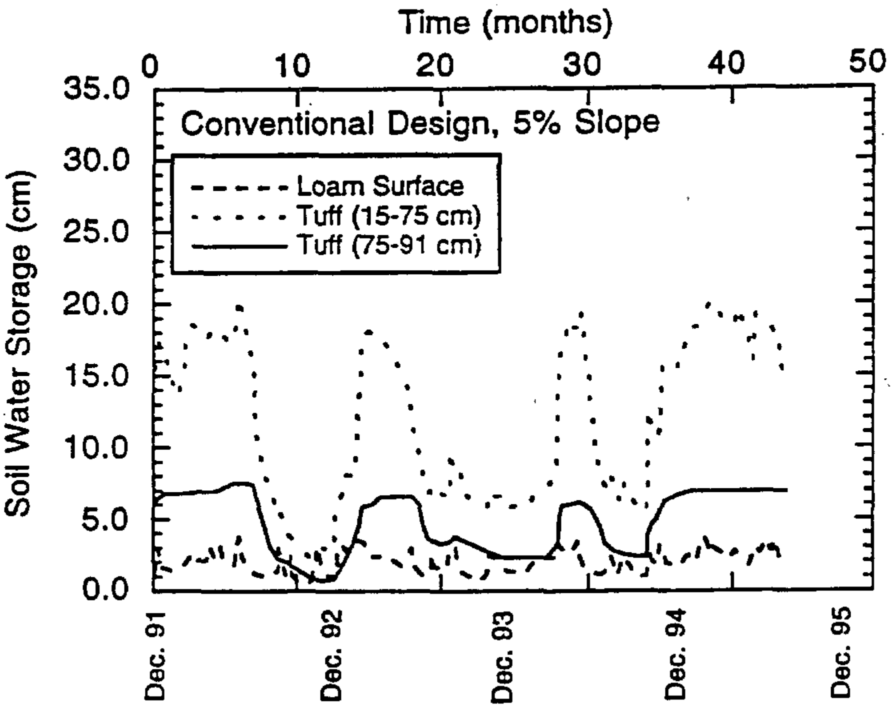


Fig 8. Soil Water Storage for the Conventional Design (from Nyhan et al. 1997).

2.4 IDAHO NATIONAL ENGINEERING LABORATORY CAP STUDY

2.4.1 Project Overview

The Idaho National Engineering Laboratory (INEL) Cap Study was conducted to assess the potential for using vegetated monolayer barriers to store and then deplete soil moisture and thus prevent infiltration from reaching underlying waste buried in shallow trenches. In particular, the investigators intended to identify barrier thickness necessary to store water during the winter months, when soil water storage accumulates, and the type of vegetation needed to remove the stored water during the growing season. The study is described in Anderson et al. (1990).

2.4.2 Description of Test Sections

Ten test sections were constructed, each 3 m x 10.7 m. Construction of a test section consisted of covering a simulated trench with native clayey silt loess to a depth of 2.4 m. Vegetation was then established on eight of the ten test sections using monocultures of crested wheatgrass, great basin wildrye, streambank wheatgrass, and big sagebrush. That is, four different monocultures were established, with two replicates of each. The remaining two test sections were treated with herbicide to prevent vegetative growth.

Six neutron access tubes were installed in each test section for monitoring water content using a neutron gage. Water content was measured manually at un-specified intervals. However, the data presented suggest that measurements were made monthly March through September. Soil water storage was determined by integrating the water content profiles.

Evapotranspiration was assumed to be the difference between precipitation and soil water storage. Runoff was assumed to be zero because the test sections were not sloped. Percolation was assumed to be zero, but no independent measurements were made to confirm this assumption.

2.4.3 Water Balance Data

The water balance data showed that each of the plant species was effective in removing soil moisture. However, the crested wheatgrass removed the most water (extraction occurring to a depth of 1.6 m) and the sagebrush removed the least (maximum depth of extraction 1 m). In contrast, the bare test sections lost very little water to evaporation. In fact, water contents at the base of the un-vegetated test sections increased throughout the study. Percolation undoubtedly emanated from these bare test sections.

The investigators used the computed evapotranspiration data to determine the thickness of a vegetated monolayer cover necessary to store and then release the maximum annual precipitation on record at INEL. Their calculation excluded precipitation that fell during June through September, which was assumed to be immediately removed by evaporation. Based on this analysis, a 2-m-thick monolayer was selected.

Unfortunately, a critical flaw exists in the approach used by the investigators to determine the required thickness of the monolayer. Because water content data were collected infrequently, it is highly probable that water drained and became percolation between monitoring events. The critical periods for water content monitoring are the wettest periods, during which significant changes in water content can occur in short periods of time. These critical periods are also the least desirable periods for making manual measurements (i.e., the weather is bad). In addition, even if water content measurements were made frequently, deep percolation due to preferential flow would not be captured (Khire et al. 1996), because percolation was not measured directly.

2.5. PROTECTIVE CAP BIO-BARRIER EXPERIMENT

2.5.1 Project Overview

The protective cap bio-barrier experiment (PCBBE) is being conducted at the Idaho National Engineering Laboratory (INEL) to assess whether earthen caps can be designed that are more effective than a RCRA-type cap. For the PCBBE, a RCRA cap is a cap that includes a composite (geomembrane-clay) barrier layer, but does not include a drainage layer. The experiment is described by Limbach et al. (1994). Four different cap designs are being tested: a RCRA design, a thick monolayer design, and two capillary barriers (Fig. 9).

Twelve test sections have been constructed, comprised of three replicates of each design. Each test section is 24 m x 16 m, and is divided into six sub-sections. The sub-sections are being used to evaluate different vegetation types and irrigation schemes. The irrigation schemes consist of low, intermediate, and high irrigation rates, with low being ambient precipitation and high being two times the long-term weekly precipitation.

The test sections simulating a RCRA design (Fig. 9a) consist of 0.9 m of vegetated clay loam loess, a geomembrane (thickness or polymer not identified), and a compacted clay layer (0.6 m thick). The monolayer design (Fig. 9b) consists of 2.0 m of the same loess used for the surface layer of the RCRA design. The capillary barriers consist of a 0.5 m (Fig. 9c) or 1 m (Fig. 9d) layer of loess, underlain by a 0.1-m-thick layer of 1 cm gravel, 0.3 m of river cobble (particles 10 to 20 cm in diameter), another 0.1 m of gravel, and finally

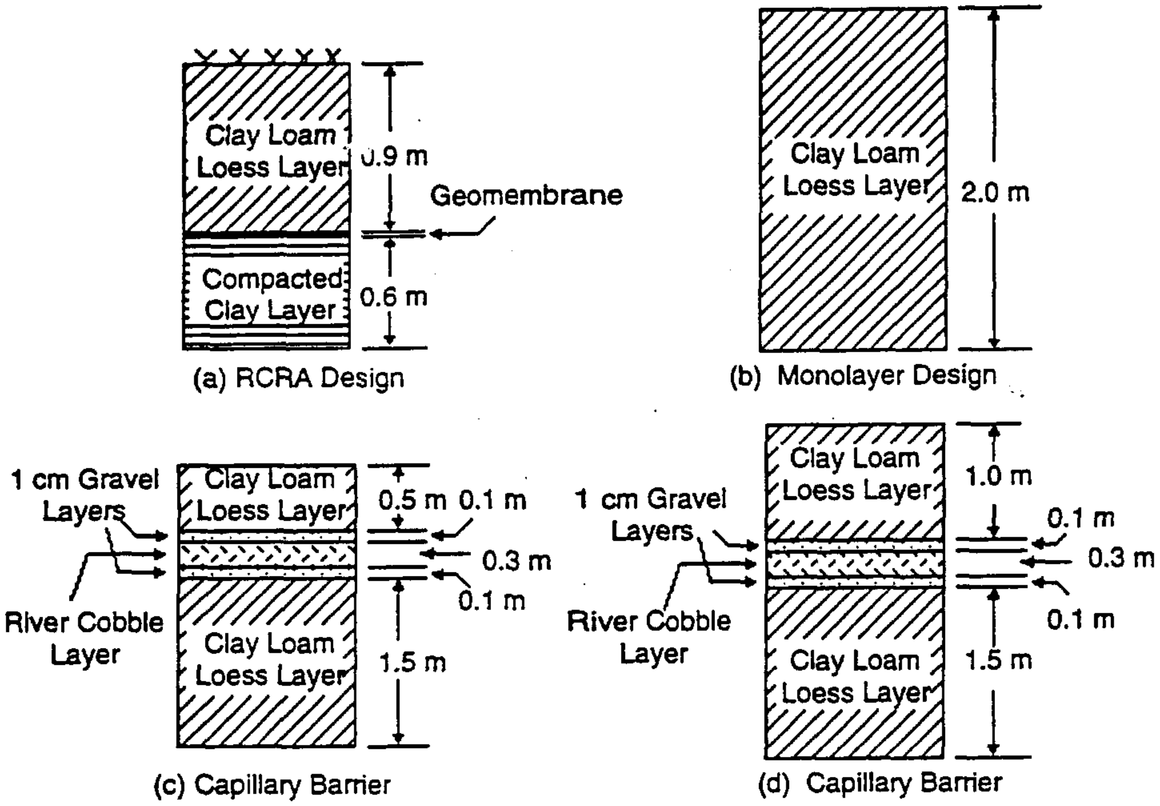


Fig. 9. Schematic of Cover Designs Tested at PCBBE: (a) RCRA Design, (b) Monolayer Design, (c) Capillary Barrier, and (d) Capillary Barrier with Thicker Surface Layer (after Limbach et al. 1994).

1.5 or 1 m of loess.

The investigators did not intend that the capillary barrier test sections behave as capillary barriers. Instead, the coarse-grained layers were installed to act as biota barriers in the loess. Nevertheless, the layering scheme in these test sections consists of two capillary breaks, the upper break at the loess-gravel interface and the lower break being at the gravel-cobble interface. Thus, regardless of the intentions of the investigators, these two designs are capillary barriers that will retard downward moisture movement by forcing moisture to be retained in the topmost fine-grained layer. It is also important to point out that an inverted capillary barrier exists at the lower gravel-loess interface. This barrier will likely prevent removal of water from the coarse-grained layers. during spring and summer. That is, water that passes through the coarse-grained layers will probably become percolation.

Two vegetation schemes will be tested: native-mixed and monoculture. The native-mixed scheme consists of 12 different plant species including shrubs, perennial grasses, and forbs. The monoculture is crested wheatgrass.

2.5.2 Test Section Design

Water balance quantities for each test section are being automatically measured and recorded using a DACC nearly identical to the one described in Benson et al. (1994). Water contents in each test section are being monitored using a neutron gage inserted in access tubes. TDR is being used in one test section of each design as a replicate measurement technique. Percolation is being collected from the base in galvanized steel collection pans. PVC pipe connected to the each pan routes percolate to a tipping bucket, which records the flow rate. Meteorological data are also being collected at the test sections.

2.5.3 Water Balance Data

Limbach et al. (1994) provide no water balance data because the PCBBE project was just constructed when their paper was published. Recent results of the study will be published this February at the 1997 International Containment Technology Conference in St. Petersburg, Florida.

2.6 WENATCHEE ALTERNATIVE COVER DEMONSTRATION

2.6.1 Project Overview

The Wenatchee Alternative Cover Demonstration was conducted to compare the performance of a capillary barrier cover relative to the resistive barrier prescribed by the Washington Department of Ecology. Two test sections were constructed as part of capping activities at the Greater Wenatchee Regional Landfill in East Wenatchee, Washington (Fig. 10). The average annual precipitation in East Wenatchee is 23 cm, and primarily occurs in late fall and winter as rain or snow. Snowfall typically comprises 30% of annual precipitation (Khire et al. 1997).

The prescriptive cover is a resistive barrier with a 60-cm-thick layer of low plasticity silty clay, covered with a vegetated silty surface layer 15 cm thick. The capillary barrier is a 75-cm-thick layer of medium uniformly graded sand overlain by 15 cm of un-compacted vegetated silt. Properties of the soils are described in Table 4. Khire et al. (1997) and Benson et al. (1994) describe the test sections in detail.

2.6.2 Test Section Design

Each test section is 30m x 30m, of which a 18.3 m x 12.2 m region is used for monitoring. The test sections are instrumented for continuous monitoring of meteorological data, overland flow, soil water content, and percolation using a DACC. Benson et al. (1994) describe the data acquisition system. Percolation is collected using a lysimeter 12.2 m wide x 18.3 m long

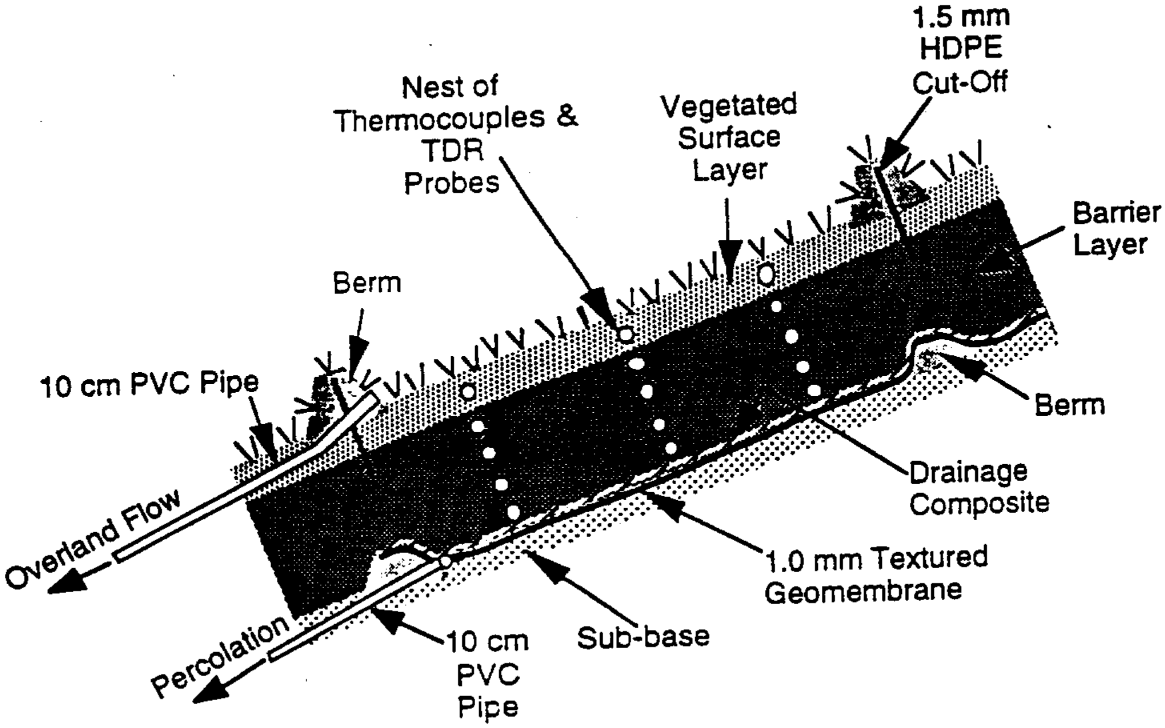


Fig. 10. Schematic of Test Section (adapted from Khire et al. 1997).

Table 4. Haverkamp Parameters for Unsaturated Hydraulic Properties (from Khire et al. 1997).

Test Section	Layer	K_s (cm/s)	θ_s	θ_r	Haverkamp Parameters			
					Matric Suction		Hydraulic Conductivity	
					α	β (1/cm)	A	B (1/cm)
Resistive	Surface	4.5×10^{-5}	0.40	0.06	80	0.6	300	2.2
Resistive	Barrier	2.2×10^{-7}	0.36	0.05	72	0.6	400	1.3
Capillary	Surface	2.7×10^{-4}	0.42	0.015	650	1.0	90	2.2
Capillary	Sand	2.9×10^{-3}	0.40	0.01	35000	2.9	105	2.9

Note: the Haverkamp functions are:

$$\frac{\theta-\theta_r}{\theta_s-\theta_r} = \frac{\alpha}{\alpha + \psi^{\beta}} \qquad K_{\psi} = K_s\left(\frac{A}{A + \psi^{B}}\right)$$

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Resistive	Barrier	2.2×10^{-7}	0.36	0.05	72	0.6	400	1.3
Capillary	Surface	2.7×10^{-4}	0.42	0.015	650	1.0	90	2.2
Capillary	Sand	2.9×10^{-3}	0.40	0.01	35000	2.9	105	2.9

Note: the Haverkamp functions are:

$$\frac{\theta-\theta_r}{\theta_s-\theta_r} = \frac{\alpha}{\alpha + \psi^{\beta}} \qquad K_{\psi} = K_s\left(\frac{A}{A + \psi^{B}}\right)$$

(Fig. 1) constructed from high density polyethylene geomembrane and a geocomposite drain. Runoff flow is collected via diversion berms. Time domain reflectometry (TDR) is used to measure soil water content.

Soil water storage is computed by integrating soil water contents over the depth of the test sections. Evapotranspiration (E) is computed by subtracting daily overland flow (O), percolation (P_r), and the change in the soil water storage (ΔS) from daily precipitation (P). Lateral flow (L) is assumed zero when computing E. Because the soils have relatively low hydraulic conductivities and are saturated only for a small period of time, lateral flow is expected to be less than 0.01% of total precipitation (Khire 1995).

2.6.3 Water Balance Data

Water contents in both test sections followed the periodic behavior characteristic of semi-arid and arid sites. An increase in water content occurs in fall and winter, followed by reductions in spring and summer. This periodicity is reflected in the soil water storage (Fig. 11). An increase in soil water storage occurs in fall and winter, followed by reductions in spring and summer. At Wenatchee, precipitation is higher in fall and winter, moderate during spring, and fairly low during summer. Conversely, evapotranspiration is low during fall and winter and higher during spring. As a result, soil water storage in the resistive and capillary barriers increases during fall and winter (low evapotranspiration), which is followed by a large decrease in spring and moderate decrease in summer.

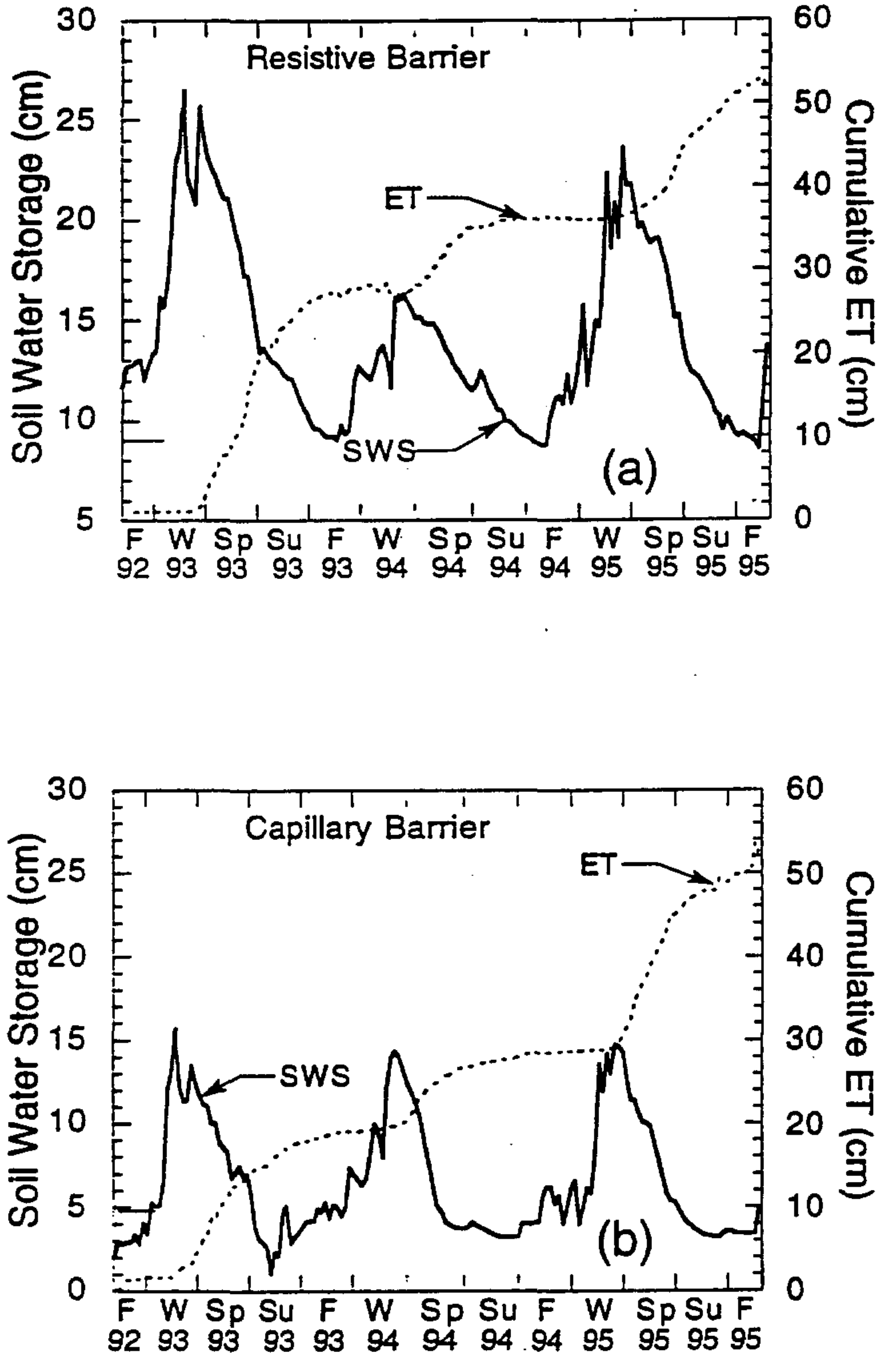


Fig. 11. Soil Water Storage and Evapotranspiration for Resistive (a) and Capillary (b) Barriers.

Evapotranspiration is the most significant component of the water balance at this semi-arid site (~80% of precipitation). Evapotranspiration is a function of soil water storage and energy available to evaporate soil water. Evapotranspiration is low during fall and winter, due to low air temperatures and solar radiation. During spring, as solar radiation and air temperature increase and the growing season begins, evapotranspiration increases rapidly. Evapotranspiration ceases when the water supply in the barrier is exhausted (Fig. 2). For example, evapotranspiration persisted into fall in 1993 and 1995 because water was available. In 1994, however, less water was available and evapotranspiration ceased in mid-summer.

Percolation for the resistive and capillary barriers is shown in Fig. 12. During the three year monitoring period, the resistive barrier transmitted 3.3 cm of percolation (5.1% of precipitation), whereas the capillary barrier transmitted 0.5 cm of percolation (0.8% of precipitation). Significant percolation from the capillary barrier occurred only during Winter 1993, when the record snow fall was received. When the snow melted, the storage capacity of the surface layer was overwhelmed and percolation was generated. If the surface layer of the capillary barrier had been thicker (i.e., providing additional water storage capacity), percolation from the capillary barrier would have been nearly zero (Khire 1995).

Percolation from the resistive barrier in 1993 and 1994 occurred when the wetting front reached the base of the test section towards the end of winter. At the end of Winter 1995, however, percolation occurred before the wetting front

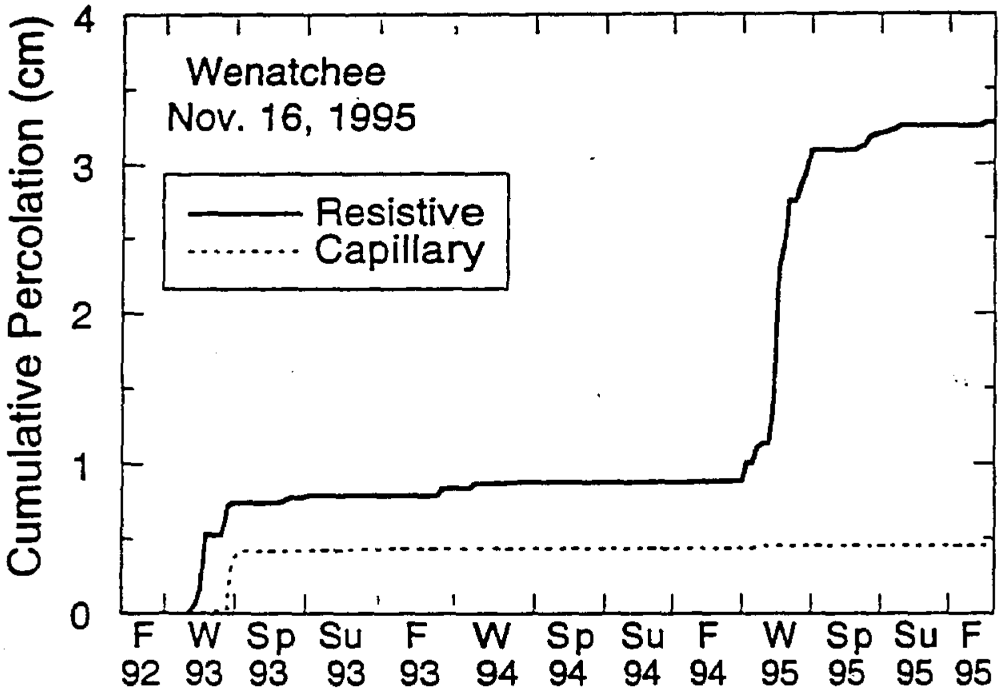


Figure 12. Percolation from the Resistive and Capillary Barriers

reached the base (Khire et al. 1996). Percolation also increased dramatically in 1995. The primary reason for this change is preferential flow through vertical cracks, which formed as the barrier desiccated the previous summer (Benson and Khire 1995). Animal burrows, found during field reconnaissance in Spring 1995, may also have contributed to the increase in percolation.

2.7 HILL AIR FORCE BASE ALTERNATIVE COVER STUDY

2.7.1 Project Overview

The Hill Air Force Base Alternative Cover Study was conducted to evaluate four potential cover designs for closure of old landfills at Hill Air Force Base, Utah. The four designs considered were a conventional monolayer cover that had been previously used at the site, a RCRA-type cover, and two capillary barriers (Fig. 13). Annual precipitation at Hill Air Force Base is 51 cm, 28% of which is snow. The study is described by Hakonson et al. (1994).

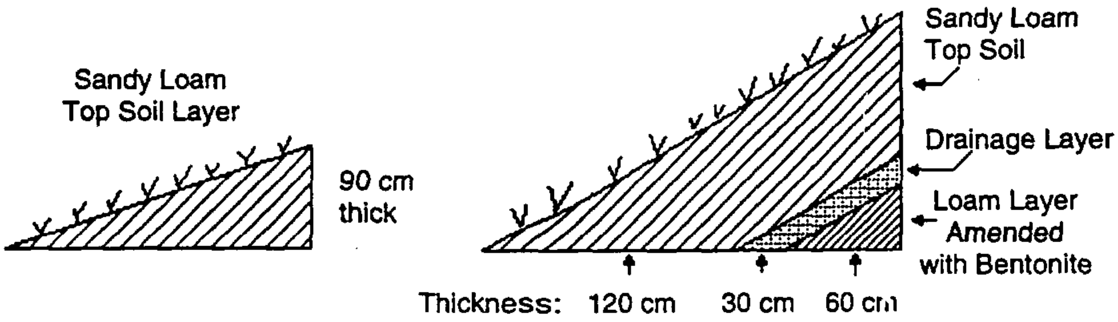
20 in.

35 in

The conventional monolayer consisted of 90 cm of sandy loam top soil having a saturated hydraulic conductivity of $2.8x10^{-4}$ cm/s. The RCRA cover consisted of 120 cm of loam top soil, a 30 cm thick sand drainage layer, and a 60-cm-thick loam barrier layer amended with bentonite. To simulate the very long-term condition, a geomembrane was not placed on top of the barrier layer. However, current research suggests that geomembranes will last at least 800 yr.

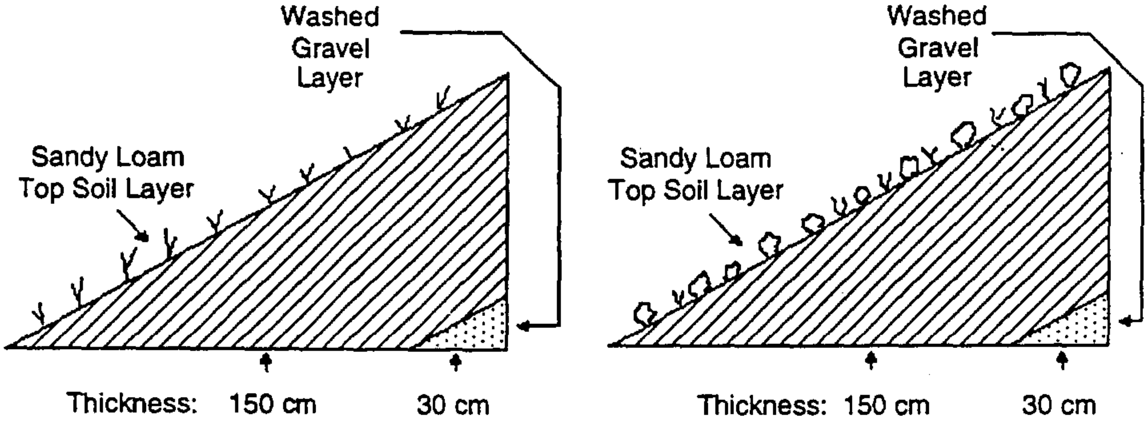
24 in

The bentonite-amended barrier layer had a saturated hydraulic conductivity of $3x10^{-6}$ cm/sec, more than an order of magnitude larger than the maximum saturated hydraulic conductivity prescribed for RCRA covers. The capillary barriers consisted of 150 cm of the sandy loam top soil used in the monolayer design underlain by 30 cm of washed gravel. All of the covers had a 4% slope and were vegetated with native perennial grasses. One of the capillary barriers also was vegetated with rubber rabbitbrush and winged saltbush shrubs.



(a) Conventional Monolayer

(b) RCRA Cover



(c) Capillary Barrier - Grass

(d) Capillary Layer - Grass and Shrubs

Fig. 13. Schematics of Cover Designs in Hill Air Force Base Alternative Cover Study: (a) Conventional Monolayer, (b) RCRA Design, (c) Capillary Barrier with Grass, and (d) Capillary Barrier with Grass and Brush.

2.7.2 Test Section Design

The test sections were constructed in modular swimming pools 5 m wide and 10 m long. A system was installed beneath the barriers to collect percolation. The system allowed for flow along the sidewalls of the pools to be separated from flow emanating from the interior of the test sections. An additional system was installed for collecting lateral drainage from the sand layers in the capillary barriers and the drainage layer in the RCRA cover. Water that was collected was routed via PVC pipes to tipping buckets for metering flows.

Soil moisture was measured using a neutron gage. Precipitation was continuously monitored on site. All of the data were collected with a DACC similar to the one described in Benson et al. (1994). Measurements were also made of relative cover, leaf area index, and biomass.

2.7.3 Water Balance Data

The water balance data are summarized in Table 5. Precipitation was 173 cm during the monitoring period. Very little of the precipitation was shed as run off (1.4 - 5.8%), primarily because of the shallow slope of the test sections. Greater run off was obtained from the monolayer and RCRA covers than from the capillary barriers, because the vegetation was better on the capillary barriers. The capillary barriers had better vegetation because they stored more

Table 5. Water Balance of Test Sections at Hill Air Force Base (from Hakonson et al. 1994).

Water Balance Parameter	**Capillary**	**Capillary (Shrubs)**	**Monolayer**	**RCRA**
Run Off (cm)	1.4	2.2	5.8	5.5
Δ Soil Water Storage (cm)	-17	-15	-11	11
Lateral Flow (cm)	20	12	NA	43
Evapotranspiration (cm)	145	144	137	113
Percolation (cm)	24	30	41	0.01
Erosion (Kg)	0.102	0.095	2.374	1.534

water near the surface due to the capillary barrier effect, and therefore more water was available to sustain vegetation.

Soil water storage from the monolayer and capillary barrier test sections increased and decreased periodically, as has been observed at other arid sites (Fig. 14a). The increase in storage represents the accumulation of water during the wetter months when evapotranspiration is low. The decrease in storage represents the release of stored water back to the atmosphere due to evaporation and transpiration. The peak soil water storage in these barriers was approximately the same each year, indicating the barriers reached their storage capacity each winter. Similarly, the minimum soil water storage was also the same each year, suggesting that these barriers dried to residual conditions each summer.

The RCRA cover also showed periodic changes in soil water storage, but the soil water storage gradually increased each year, indicating that the test section was gaining water. Hakonson et al. (1994) report that the water contents measured in the barrier layer were reaching saturation at the end of the monitoring period. That is, the barrier layer was slowly accumulating water, but not releasing it, during the monitoring period. The sand layer above the clay barrier probably prevented the barrier layer from releasing water. In effect, the sand layer created an inverted capillary barrier, which prevented upward movement of water during the summer months.

All of the test sections transmitted percolation (Fig. 14b). The monolayer test section transmitted the most percolation (41 cm) and the RCRA test section

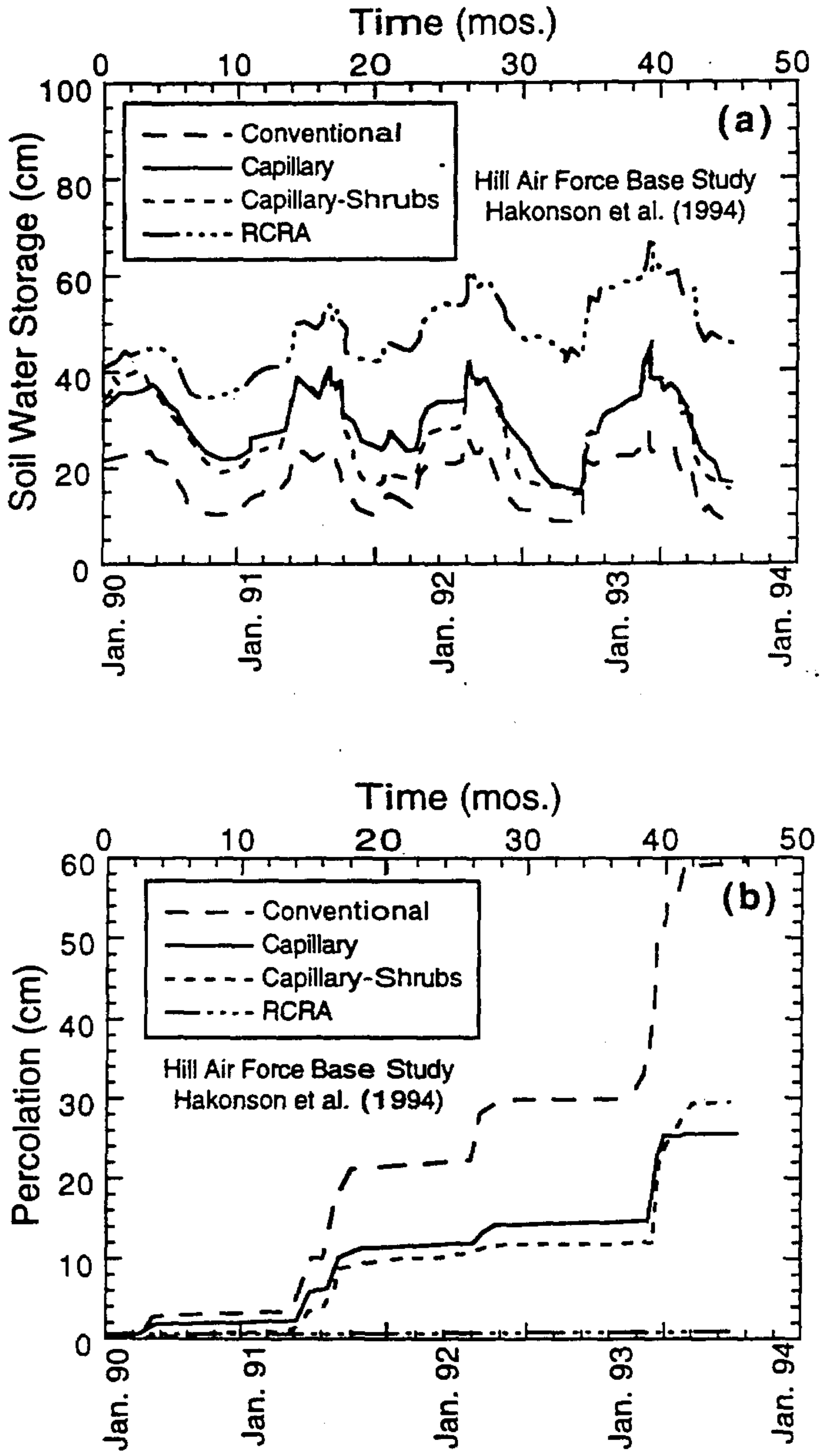


Fig. 14. Soil Water Storage (a) and Percolation (b) at Hill Air Force Base.

the least percolation (0.01 cm). Percolation from the capillary barriers was very similar (24 cm-ordinary vegetation; 30 cm-shrubs). Percolation from the monolayer barrier and the capillary barriers occurred late each winter, when the surficial soils became saturated during snow melt. That is, the surface layers had inadequate soil water storage capacity. Percolation could have been eliminated had the barriers designed with adequate storage capacity, either by using thicker layers or soil having greater storage potential.

Adding shrubs appeared to have no beneficial impact on the capillary barriers. The barrier with shrubs and grasses had less evapotranspiration and greater percolation than the barrier seeded only with grasses. Furthermore, both barriers had similar erosion (Table 5). These results suggest caution against over-reliance on vegetation to enhance the performance of covers.

2.8 HANFORD FIELD LYSIMETER TEST FACILITY

2.8.1 Project Overview

The Hanford Field Lysimeter Test Facility (FLTF) was used to field test 24 lysimeters filled with two different soil layering schemes at the US Dept. of Energy's Hanford facility in Hanford, Washington. Results of the tests were used to design a cap with a design life of 1000 years for covering landfilled radioactive waste at Hanford. Radioactive waste was generated at Hanford as a by-product of plutonium production from the end of World War II through the cold war. A large-scale test section (110 m x 60 m) simulating the cap has recently been constructed (Wing and Gee 1994 a, b), but water balance data from the test section have not yet been reported. Gee et al. (1993) describe the FLTF and associated water balance data.

Twenty of the lysimeters contain capillary barriers. Twelve capillary barriers consist of a 1-m-thick silt loam surface layer overlying a 0.3 1-m-thick medium uniformly graded sand layer. The other eight capillary barriers have a 1.0-m-thick silt loam surface layer. The remaining four lysimeters have a monolayer design consisting of coarse sand. Different vegetation schemes and precipitation events are being applied to yield eleven different possible scenarios ranging from ambient to very wet conditions and un-vegetated to fully vegetated. The annual ambient precipitation is 16.9 cm whereas the "elevated" annual precipitation is 48 cm.

6.6 in

18 in

2.8.2 Lysimeter Design

Each lysimeter is 2 m in diameter and 3 m deep. Beneath the medium sand layer is a graded filter consisting of No. 4 sand, overlying a pea gravel layer and basalt rip rap. Each lysimeter contains a sloping floor and collection point that is used to collect percolation. Access ports are also included for installation of thermocouples, thermocouple psychrometers, tensiometers, and neutron probes. Neutron access tubes are also oriented vertically within the lysimeters. Meteorological data are obtained from the Hanford Meteorological Station located adjacent to the FLTF.

2.8.3 Water Balance Data

When the lysimeters were constructed in 1988, two of the lysimeters with a 1.5-m-thick surface layer were saturated to determine their water storage capacity (the amount of water that can be stored in a capillary barrier before percolation occurs). Results of the experiments showed that the water storage capacity of these capillary barriers is 50 cm.

After the saturation experiments, the lysimeters were exposed to ambient conditions or elevated precipitation for six years. Until 1993, only five of the capillary barriers transmitted percolation (< 0.04 cm/yr), which was attributed to thermal gradients. No percolation occurred from the other 15 capillary barriers.

In winter 1993, record snowfall (1.42 m) was received at the FTLF. In February 1993 the snow melted, which resulted in percolation from five capillary barrier lysimeters, all of which had no vegetation. Percolation from these capillary barriers occurred because the snow melt exceed the 50 cm storage capacity. No percolation was transmitted from the remaining 15 capillary barriers: The following summer, all of the water that entered the capillary barriers was removed by evaporation (un-vegetated barriers) or evapotranspiration (vegetated barriers).

Percolation was transmitted from all of the monolayer covers regardless of whether they were vegetated. The un-vegetated monolayer barriers exposed to ambient precipitation have transmitted 6 cm/yr of percolation, whereas the un-vegetated monolayer barriers exposed to elevated precipitation transmitted 28.5 cm/yr of percolation. Less percolation was transmitted from the vegetated monolayer barriers. However, percolation was transmitted from each monolayer.

SECTION THREE

SITES IN HUMID REGIONS

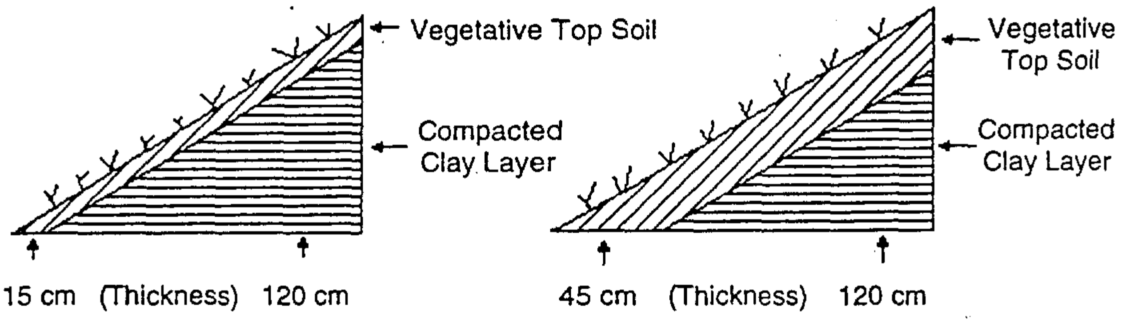
3.1 OMEGA HILLS FINAL COVER STUDY

3.1.1 Project Overview

The Omega Hills Final Cover Study was conducted to evaluate the hydrologic performance of three potential final cover designs. Three test sections were constructed on a side-slope of the Omega Hills landfill near Milwaukee, Wisconsin. Two test sections were earthen resistive barriers, whereas the third test section was a capillary barrier. A description of the test sections can be found in Montgomery et al. (1986) and water balance data can be found in Montgomery et al. (1990). Schematics of the test-sections are shown in Fig. 15. Annual percolation in Milwaukee is 78 cm.

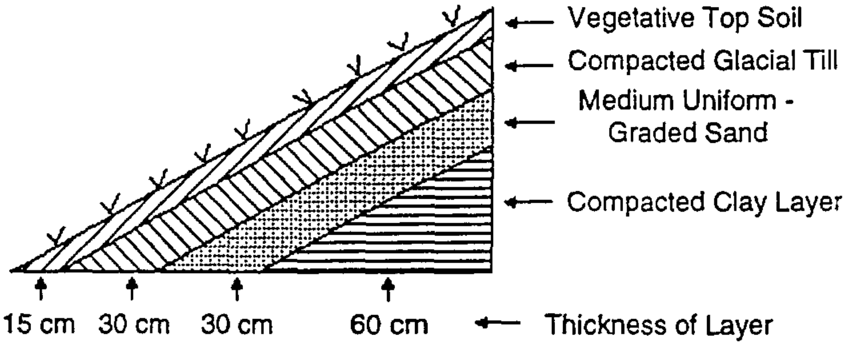
The resistive barriers consisted of a compacted clay barrier layer 120 cm thick constructed with low plasticity glacial till. The saturated hydraulic conductivity of the glacial till is approximately 2×10^{-8} cm/sec. A vegetated top soil layer was placed on the compacted clay layer. One test section had a top soil layer 15 cm thick. The other had a 45-cm-thick top soil layer. The test section with a thinner top soil layer represented the approved final cover for the landfill. The thicker top soil layer was being tested to see if it would yield more evapotranspiration, and thus reduce percolation.

The capillary barrier test section consisted of a layer of vegetated top soil 15 cm thick overlying a layer of compacted glacial till 30 cm thick. A 30-cm-thick



(a) Earthen Resistive Barrier

(b) Earthen Resistive Barrier



(c) Capillary Barrier

Fig. 15. Schematic of Test Sections Used in Omega Hills Final Cover Study: (a) Earthen Resistive Barrier, (b) Earthen Resistive Barrier with Thicker Surface Layer, and (c) Capillary Barrier.

layer of medium uniformly graded sand was placed beneath the compacted clay layer to form a capillary break at the clay-sand interface. A 60-cm-thick layer of compacted clay was placed below the sand. The sand and lower clay layer also form an inverted capillary break, that blocks upward flow of water from the lower clay layer.

3.1.2 Test Section Design

Each test section was 6 m wide and 12 m long and placed on a 33% slope. A lysimeter constructed with a hypalon geomembrane overlain by a geonet and a non-woven geotextile was placed beneath each test section to monitor percolation. Diversion berms were used to direct runoff to a collection swale at the lower end of the test section. Percolation and runoff were piped to collection tanks where volumes were measured indirectly using electronic pressure transducers.

Water contents were measured manually using a neutron probe on a periodic basis. Suctions were monitored using tensiometers equipped electronic pressure transducers. A weather station was installed to collection on-site meteorological data. All of the data, except water contents, were collected automatically using a DACC similar to the one described by Benson et al. (1994).

3.1.3 Water Balance Data

Water balance data from the test sections are summarized in Table 6. Percolation from the test sections is shown in Fig. 16. The data show that evapotranspiration was the most significant portion of the water balance. Also, the sand layer in the capiliary barrier was a very effective means to remove water.

Percolation from the test sections simulating resistive barriers increased significantly during 1988 and 1989. During the summer of 1988, a severe drought occurred, which caused extensive drying of the clay barriers. Test pits excavated adjacent to the test pits revealed extensive desiccation cracking. Cracks 0.5 to 1.0 cm wide and 1.5 m deep were observed. These cracks became preferential flow paths that resulted in increased percolation. Preferential flow was evident in the percolation data. Pulses of percolation lagged behind precipitation events by less than one day, suggesting that flow was occurring through cracks and not the clay matrix. In addition, roots were also found in the cracks, indicating that the cracks provided a readily available source of water.

Percolation from the capillary barrier was relatively constant throughout the monitoring period. Test pits adjacent to the capillary barrier showed that the upper compacted clay layer was extensively cracked. These cracks were responsible for the large lateral flows observed in the sand layer (Table 6). Had these cracks not formed, flows in the sand layer would have been very small. The test pits also revealed that the lower compacted clay layer was moist

Table 6. Summary of Water Balance Data from Omega Hills Test Sections.

Water Balance Variable	1986-87	1987-88	1988-89
Runoff (cm)			
Resistive-Thin	18.0	3.68	4.27
Resistive-Thick	10.9	3.91	4.98
Capillary	9.65	3.68	6.60
Percolation (cm)			
Resistive-Thin	0.15	0.45	5.56
Resistive-Thick	0.68	3.02	5.97
Capillary	4.03	2.21	4.06
Storage (cm)			
Resistive-Thin	0.025	-7.54	7.26
Resistive-Thick	0.025	-9.90	9.78
Capillary	1.65	-7.89	NA
Evapotranspiration (cm)			
Resistive-Thin	71.2	61.2	65.1
Resistive-Thick	77.9	60.7	63.3
Capillary	40.2	48.2	NA
Lateral Drainage (cm)			
Capillary	34.0	11.5	13.2

Note: NA = not available.

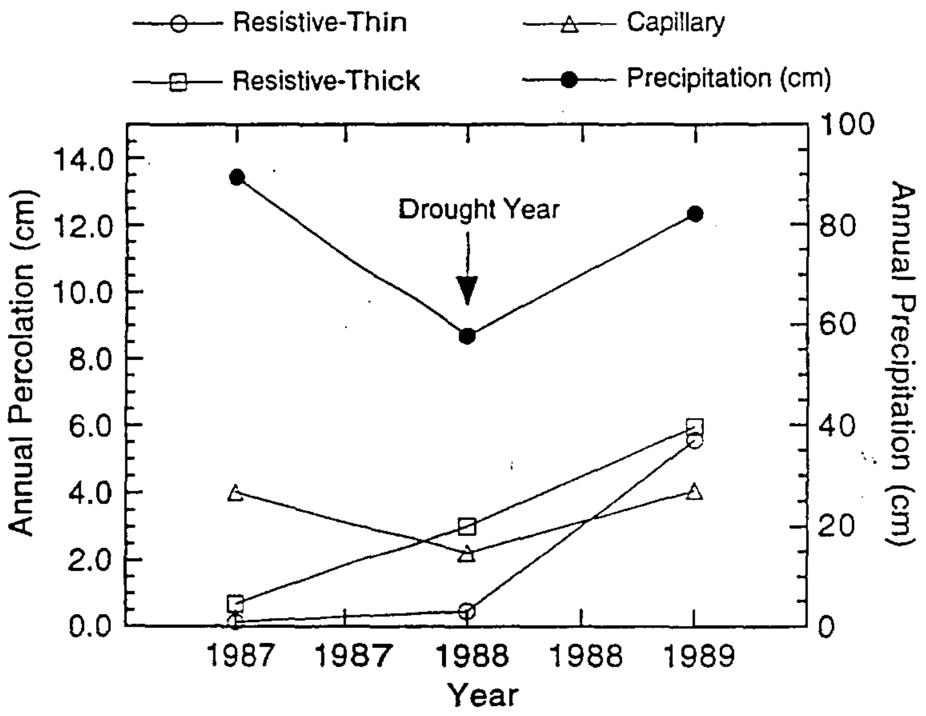


Fig. 16. Precipitation and Percolation Data from Omega Hills Test Sections.

and un-cracked. Apparently the capillary barrier formed by the sand-lower clay interface prevented upward migration of water during the summer months, and thus prevented the lower clay layer from cracking. That is, although the upper capillary break failed due to cracking of the clay, the lower capillary break performed as intended.

The water balance data also show evapotranspiration from both resistive barriers was essentially the same. That is, the thicker surface layer did not enhance evapotranspiration. In addition, percolation from the resistive barrier with a thicker surface layer was always greater than from the barrier with a thinner surface layer. Thus, it appears there was little benefit of increasing the surface layer thickness.

3.2 GREDE FOUNDRIES ALTERNATIVE COVER STUDY

3.2.1 Project Overview

The Grede Foundries Alternative Cover Study is a field demonstration where an alternative earthen resistive barrier has been proposed that is constructed with waste foundry sands. The demonstration is being conducted at a landfill owned and operated by Grede Foundries, Inc., and is described by Vierbicher Associates (1996). The landfill is adjacent to the Grede ductile iron foundry in Reedsburg, Wisconsin.

The prescriptive cover now required for the site consists of a 60-cm-thick of compacted clay barrier layer, overlain by a 90-cm-thick protection layer, and a 15-cm-thick vegetated top soil layer. Grede foundries has proposed an alternative cover constructed with a 60-cm-thick layer of waste foundry sand, a 90-cm-thick foundry sand protection layer, and a 15-cm-thick vegetated top soil layer. Foundry sand has been proposed for the barrier and protection layers because it is primarily a mixture of uniform fine sand and 10% sodium bentonite, and thus should have very low hydraulic conductivity. The foundry sand is also believed to be resistant to frost and desiccation cracking. In addition, the foundry believes that adequately low hydraulic conductivity can be achieved with little moisture conditioning of the sand and low or moderate compactive effort. Also, since foundry sand is a industrial by-product of the Reedsburg foundry, it can be obtained without cost.

The Wisconsin Department of Natural Resources (WDNR) was receptive to the proposed alternative cover, but was concerned with the following issues:

the saturated hydraulic conductivity of the foundry sand, (2) frost and desiccation resistance of the foundry sand, and (3) the quality of leachate that might be generated by percolation emanating from the foundry sand. To address these issues, Grede Foundries constructed ten large-scale test sections to assess field performance of the alternative and prescriptive designs. Five different layering schemes were considered, and two types of vegetation.

A schematic of the five layering schemes is shown in Fig. 17. Test Section A represents the cover required by the last permit issued for the foundry landfill. It consists of a 15 cm top soil layer overlying 60 cm of compacted clay, having hydraulic conductivity less than 1×10^{-7} cm/s. Test Section B represents the new cover design required by WDNR. Test Section B has a 90-cm-thick un-compacted earthen protection layer between the topsoil and compacted clay layers. Test Section C is an alternative design that is a modified version of Test Section B, where the 90 cm un-compacted earthen protection layer is replaced with a 90 cm un-compacted foundry sand layer. Test Section D is similar to Test Section C, but the barrier layer is 90 cm thick and consists of compacted foundry sand. Test Section E is a modified version of Test Section D, and contains a 240-cm-thick un-compacted foundry sand protection layer and a 150-cm-thick compacted foundry sand barrier layer. Test Sections D and E are also alternative designs.

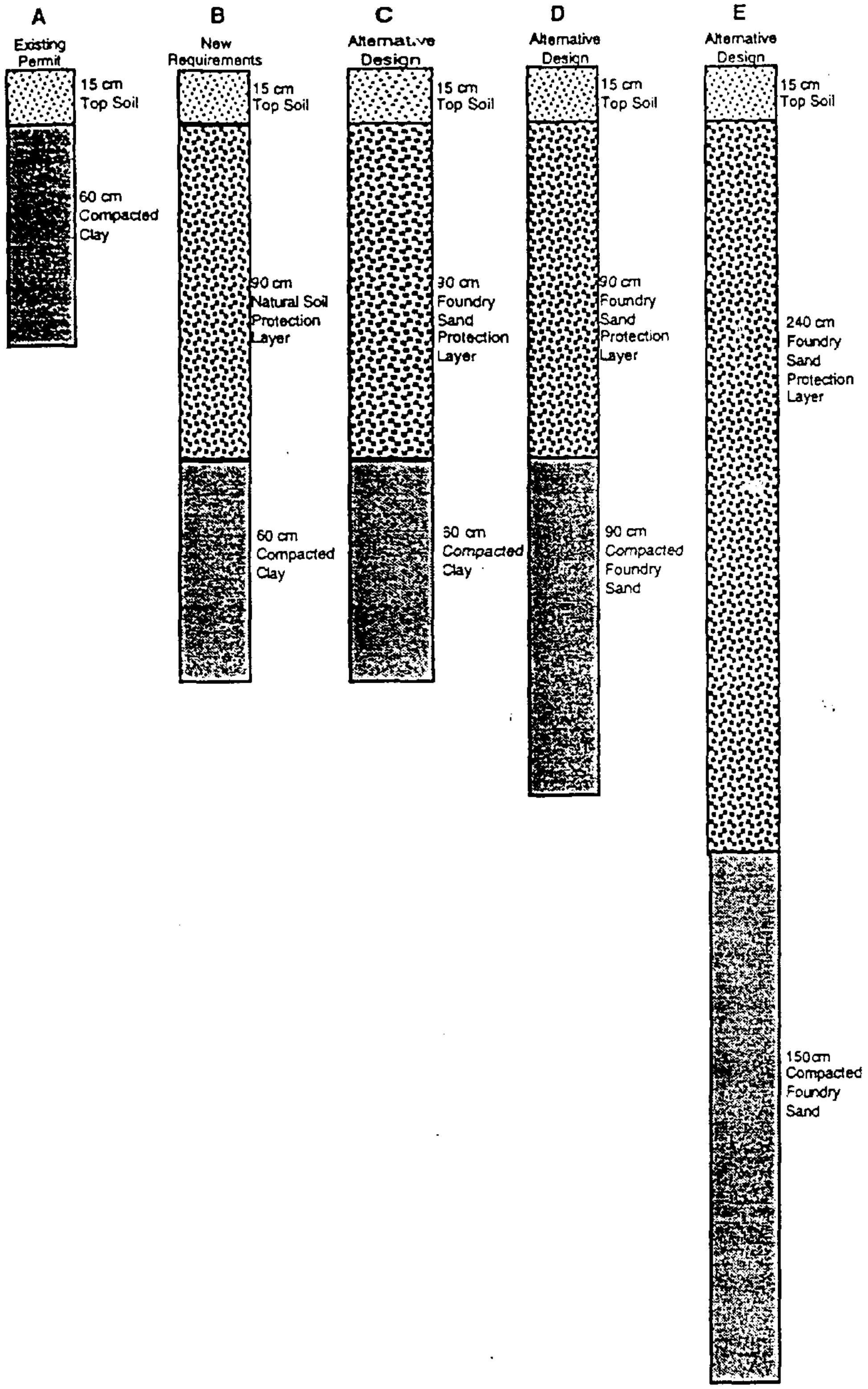


Fig. 17. Layering Used in Alternative Cover Test Sections - Grede Foundries, Reedsburg, Wisconsin.

3.2.2 Test Section Design

The test sections were constructed in May 1992. Prior to placing the soil layers, a lysimeter was constructed for each test section using PVC geomembrane and a gravel collection layer. The lysimeters were leak tested prior to soil placement.

Soil layers for each test section were placed using methods employed during construction of full-scale covers. Quality assurance sampling and testing was performed during construction in accordance with WDNR requirements. Quality assurance testing included index testing on grab samples and hydraulic conductivity testing of undisturbed specimens. Results of the index tests showed that the soil used for the clay barrier layer classifies as a moderately plastic clay (CL-CH), whereas the foundry sand classifies as a clayey sand (SC). All of the undisturbed specimens (clay and foundry sand) had hydraulic conductivity less than $1x10^{-7}$ cm/s.

3.2.3 Percolation Data

Percolation emanating from the test sections has been monitored since construction. Detailed data can be found in Vierbicher Associates (1996). Average annual percolation through March 1996 is shown in Fig. 18 for each test section. The percolation rates in Fig. 18 are the average percolation rates for the two different vegetation schemes. Vegetation had no distinct effect on percolation rate.

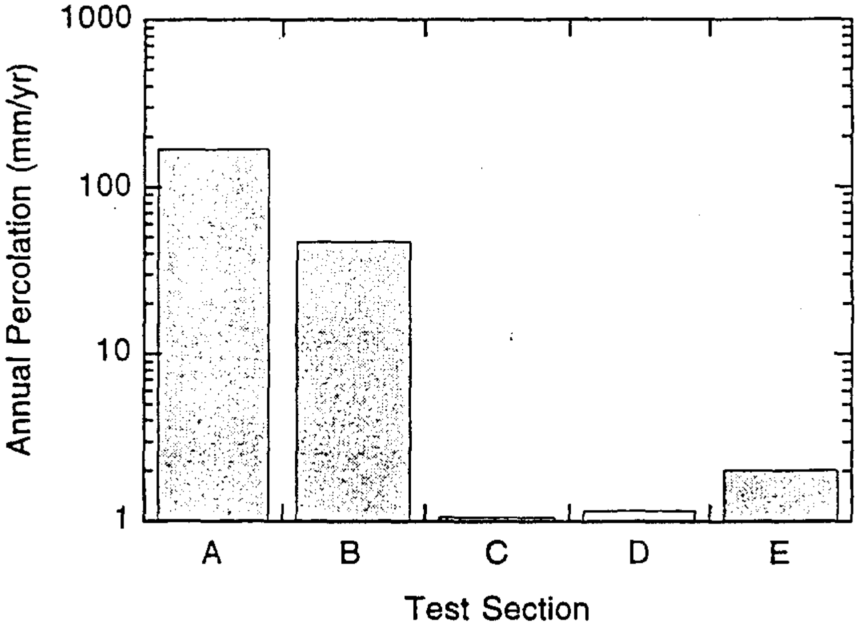


Fig. 18. Average Annual Percolation from Grede Test Sections.

There are two distinct characteristics of the percolation data. First, percolation rates for the test sections constructed with foundry sand (C, D, and E) are approximately two orders of magnitude lower than percolation rates for the test sections constructed with clay (A, B). This is true regardless of whether the foundry sand is used as the un-compacted protection layer (C) or the compacted barrier layer (D, E). Second, percolation rates for the test sections with foundry sand barrier layers are similar, regardless of the thickness of the barrier layer or thickness of the protection layer. These findings suggest that covers constructed with Grede foundry sand are likely to perform better than those constructed with compacted clay, regardless of whether the foundry sand is compacted or loosely placed.

In Spring and Summer 1996 soil structural analyses were conducted to determine why the test sections constructed with clay performed poorly. The analyses showed that the compacted clay in Test Sections A and B was extensively cracked due to frost action and desiccation (Albrecht 1996). In contrast, the system sand layers in Test Sections A, B, and C were devoid of cracks or other macropores that would readily conduct flow.

Cracks in the clay barrier layers were apparently responsible for the high percolation rates measured in Test Sections A and B. Mineral deposits were found on the smooth fracture surfaces. The fractures also had a moist surface, but the intact clay between the fractures was dry. In addition, roots were found within the fractures, but not in the intact clay between the fractures. Each of these observations suggests that water was flowing preferentially in the fractures.

Large (30-cm-diameter) block specimens were removed from the clay barrier in Test Section A to assess the field hydraulic conductivity of the barrier layer (Albrecht 1996). The hydraulic conductivity of the clay was found to be 5×10^{-5} cm/s, on average, which is more than two orders of magnitude higher than the as-compacted hydraulic conductivity. The high hydraulic conductivities were the result of preferential flow through cracks. An extensive crack network was observed when trimming the block specimens.

3.3 NUCLEAR REGULATORY COMMISSION STUDY ON COVERS FOR LOW-LEVEL RADIOACTIVE WASTE

3.3.1 Project Overview

The US Nuclear Regulatory Commission (NRC) is currently evaluating four potential cover designs for disposal facilities containing low-level radioactive waste (O'Donnell et al. 1994, Schulz et al. 1995). The designs are a thick vegetated monolayer, an earthen resistive barrier, a capillary barrier, and a bio-engineered cover. Schematics of the test sections are shown in Fig. 19. Test sections simulating each cover design have been constructed at a field site near Beltsville, Maryland. Annual precipitation in Beltsville is 106 cm.

The thick vegetated monolayer was constructed of 4 m of "native soil" and was seeded with fescue grass (Fig. 19a). Characteristics of the soil are not reported. However, photographs in Schulz et al. (1995) show lush vegetation growing on the cover of the monolayer. Thus, the "native" soil is probably a silty sand which is suitable for sustaining vegetation.

Two earthen resistive barriers were constructed. Each test section contains a layer of compacted Christiana clay 45-60 cm thick. Hydraulic and index properties of the clay are not reported. A gravel drainage layer approximately 30 cm thick is placed on the compacted clay layer. The drainage layer is overlain by vegetated top soil (Fig. 19b) or rip rap (Fig. 19c).

The capillary barrier design is essentially the same as the earthen resistive barrier with vegetated top soil, except two coarse-grained layers are placed beneath the compacted clay layer. The upper coarse-grained layer is a

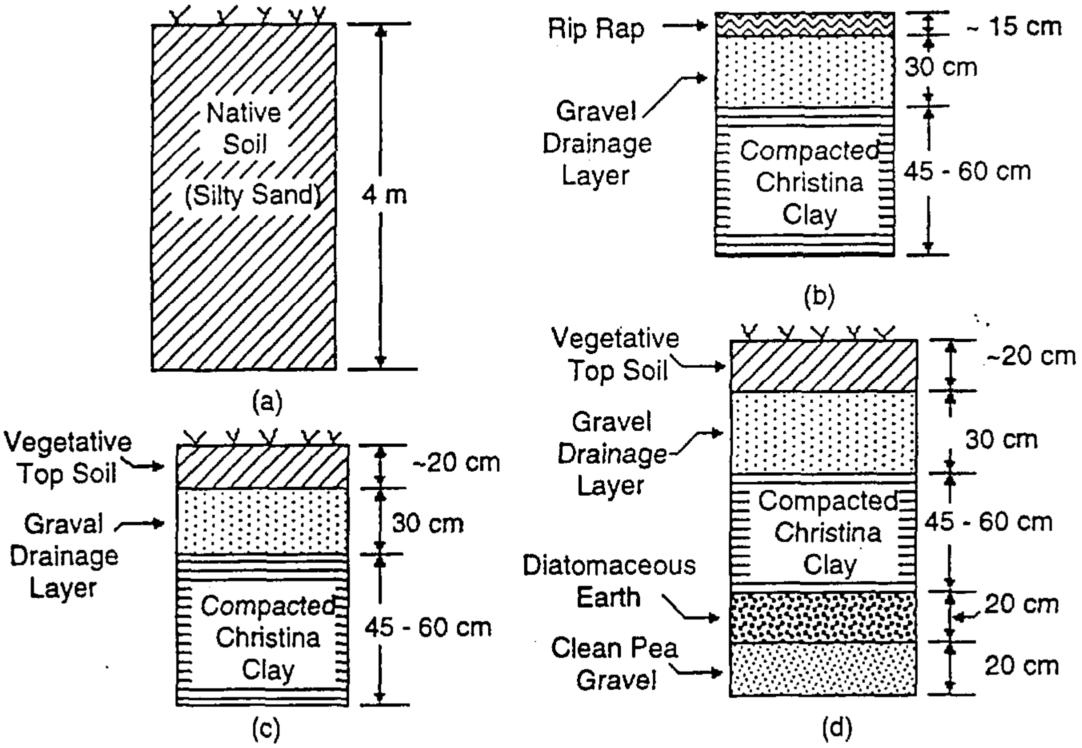


Fig. 19. Schematics of Vegetated Monolayer (a), Earthen Resistive Barrier with Rip Rap Surface (b), Earthen Resistive Barrier with Vegetated Top Soil (c), and Capillary Barrier (d).

20-cm-thick layer of diatomaceous earth. The lower layer is a 20-cm-thick layer of clean pea gravel.

The bio-engineered cover is constructed from panels of fiberglass sheet underlain with 4 m of native soil. A gap exists between each sheet in which Pfitzer junipers are planted. The junipers are used to extract any water that passes by the fiberglass sheets.

3.3.2 Test Section Design

Few details are provided by O'Donnell et al. (1994) and Schulz et al. (1995) regarding how water balance measurements are being made. A lysimeter consisting of a PVC geomembrane and a layer of gravel is placed beneath each test section. Deep percolation is measured by pumping water from the lysimeter through a vertical riser. Surface runoff and lateral drainage are collected in gutters and discharged to a metering system. A neutron probe is used for measuring soil water contents.

3.3.3 Water Balance Data

Water balance data for the test sections is summarized in Table 7. Deep percolation has been zero for the earthen resistive covers and the bio-engineered cover. Percolation from the monolayer cover has typically been about 20% of precipitation. Percolation from the capillary barrier (0.13 cm) was measured only once, in 1994. It is important to note, however, that the method

Table 7. Water Balance Data from NRC Test Sections.

Cover Design	1990	1991	1992	1993	1994
Evapotranspiration (% precipitation)					
Monolayer	75	71	81	64	53
Resistive-Soil Surface	68	65	75	60	59
Resistive-Rip Rap Surface	30	28	26	24	26
Capillary	92	75	78	60	60
Bio-Engineered	30	32	39	40	40
Runoff (% precipitation)					
Monolayer	5	1	6	4	13
Resistive-Soil Surface	32	35	25	40	41
Resistive-Rip Rap Surface	70	72	74	76	74
Capillary	8	25	22	40	>39
Bio-Engineered	70	68	61	40	60
Percolation (% precipitation)					
Monolayer	20	28	13	32	34
Resistive-Soil Surface	0	0	0	0	0
Resistive-Rip Rap Surface	0	0	0	0	0
Capillary	0	0	0	0	<1
Bio-Engineered	0	0	0	0	0

Note: Water balance calculations ignore soil water storage.

used to measure percolation in this study (pumping water from lysimeters up a riser) is relatively inaccurate. The resolution is probably 0.5 cm/yr. From this perspective, the earthen resistive barriers and the capillary barrier performed similarly.

3.4. HEATHE STEEL WASTE ROCK PROJECT

3.4.1 Project Overview

The Heathe Steel Waste Rock Project was conducted to evaluate a capillary barrier design for use as a cap over acid-generating mine tailings at the Heathe Steel Mine near Newcastle, New Brunswick, Canada. The project is described in Yanful et al. (1993 a, b) and Woyshner and Yanful (1995). Annual precipitation in Newcastle is 96 cm.

Unlike other cover designs, the capillary barrier described in this project was designed to limit percolation and oxygen flux. Minimizing oxygen flux is critical when capping mine tailings, because oxygen is required for the tailings to oxidize and generate acidic leachate laden with heavy metals. If oxidization is minimized, percolation passing through the tailings does not become significantly contaminated.

Test sections simulating two earthen cover designs were tested (Fig. 20). Both designs included a 60-cm-thick layer of compacted fine-grained till acting as the barrier against percolation and oxygen diffusion. A 40-cm-thick layer of well-graded sand was placed above the till layer in both test sections. One test section contained a 50-cm thick layer of uniformly graded coarse sand directly beneath the till layer. The other test section contained a 30-cm-thick layer of coarse sand. Both test sections also include a 10-cm-thick surface layer of gravel for minimizing erosion.

To minimize oxygen diffusion, it is necessary that the barrier layer remain nearly saturated so that the air phase in the soil remains occluded. To maintain

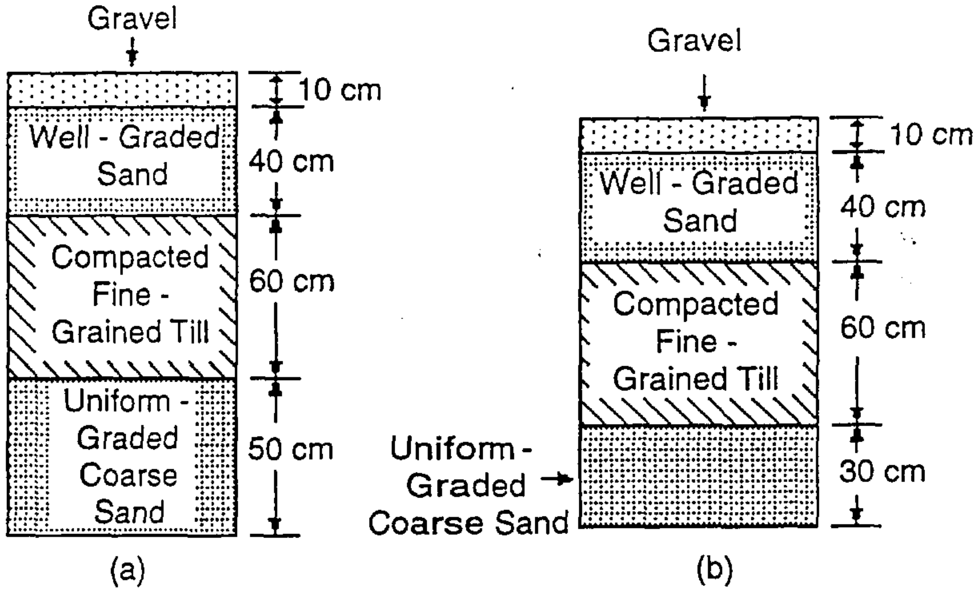


Fig. 20. Cross-Section of Test Sections at Heathe Steel Waste Rock Project: (a) Thick Layer of Coarse Sand, (b) Thin Layer of Coarse Sand.

saturation, downward and upward movement of water (i.e., percolation and evaporation) must be minimized. The sand layers placed on either side of the compacted till layer were expected to limit water movement via the capillary barrier effect. The underlying coarse-sand layer has very low air entry suction, which prevents percolation from the compacted till unless the till is fully saturated. The overlying sand layer also forms a capillary barrier that prevents desiccation of the till. That is, capillary barriers were used to prevent both percolation and evaporation. In addition, the uppermost layer of gravel added for erosion control also functions as an additional capillary barrier that minimizes evaporation.

3.4.2 Test Section Design

The test sections were 20 m by 20 m in plan, and were constructed directly on old tailings. A lysimeter 2.2 m^2 constructed from HDPE was placed underneath each test section to collect percolation. TDR probes were installed in each layer for monitoring water content and heat dissipation sensors were used to measure soil suctions. Gaseous oxygen was monitored in the soil layers by extracting samples from 6-mm-diameter stainless steel tubes placed at various depths and measuring the oxygen concentration with a portable meter. Thermocouples were installed to assess temperature changes due to oxidation of the tailings. Tailings oxidation is an exothermic reaction, i.e., it generates heat. All of the data were collected manually.

.3 Performance Data

Data collected from the test sections indicates that the covers performed intended. Oxygen levels in the tailings decreased from 20% before acement of the cover to less than 3% after covering. Temperatures in the lings also decreased after the cover was installed. Water contents easurements showed that the upper and lower-coarse grained layers typically e nearly dry, whereas the till layer is essentially saturated. Percolation from e barriers has ranged between 2 and 4% of percolation, with most of the erc tion occurring as a result of snow melt and spring rains.

The compacted clay layer was constructed with highly plastic Mercia Mudstone (liquid limit = 53, plasticity index = 30). For the non-engineered test sections, the compaction water content was 6.6% wet of optimum water content and the relative compaction was 92.6%. For the engineered test sections the compaction water content was 6.3% wet of optimum and the relative compaction was 96.5%. Practically none of the measurements of water content and dry unit weight feel wet of the line of optimums (percent wet of line of optimums ranged from 0 to 12%). From a practical perspective, there is no apparent difference between the compaction condition of the non-engineered and engineered compacted clay layers.

The saturated field hydraulic conductivity of each clay layer was measured with four sealed double ring infiltrometers. Saturated field hydraulic conductivities ranged from $6.8\text{x}10^{-7}$ to $5.0\text{x}10^{-6}$ cm/sec for the non-engineered clay layer and $1.5\text{x}10^{-6}$ cm/sec to $2.3\text{x}10^{-5}$ cm/sec for the engineered clay layers. The low percentage of compaction data falling wet of the line of optimums is responsible for the high field hydraulic conductivities. That is, each clay barrier was compacted dry of the line of optimums, which is known to yield high field hydraulic conductivity (Benson and Boutwell 1992, Benson 1994).

3.5.2 Test Section Design

The test sections were 8 m wide and 15 m long. Each test section contained three lysimeters 2 m wide by 5 m long to collect percolation. The lysimeters were constructed from HDPE geomembrane 2.0 mm thick overlain by a geocomposite drain, 0.6 m of quartz gravel, and a non-woven needle-punched geotextile. Water collected from the lysimeters was piped by gravity to a collection point where a tipping bucket was used to measure flows. Surface runoff and lateral drainage were collected using a similar system, but were measured with a single tipping bucket. Thus, it was not possible to separate flow dues to run off and lateral drainage.

Each test section was equipped with eight neutron access tubes for water content measurements. A tensiometer nest was also installed in each test section containing six tensiometers at depths of 30, 70, 90, 110, 130, and 150 cm. A weather station was also installed to measure on-site meteorological conditions. All of the data were recorded automatically using a computerized data acquisition system. Details of the system were not described.

3.5.3 Water Balance Data

Percolation data reported in Rust (1996) are summarized in Table 8. Problems with the data acquisition system preclude comparison of the remaining water balance data. Percolation from each of the test sections was fairly low, relative to percolation rates measured at other sites with similar covers and climate (e.g., the Omega Hills study, Sec. 3.1). The low percolation rates may be an artifact of the measurement system. The gravel used for the lysimeters was probably unsaturated, and stored significant quantities of water. This would make the percolation rates appear too low.

Table 8. Percolation Data from the Little Packington Landfill Final Cover Study.

	Percolation: Non-Engineered (cm)		Percolation: Engineered (cm)	
Slope	10%	20%	10%	20%
1992-93	0.1	0.12	0.27	0.12
1993-94	0.64	0.71	0.51	0.12

Percolation from three of the four test sections was significantly higher in 1993-94. During the summer of 1993, the clay layers desiccated significantly, which probably induced desiccation cracking. Flow monitored subsequent to the summer of 1993 showed a brief time lag between flow in the lysimeter and precipitation events (Rust 1996), which suggests that preferential flow was occurring. Thus, preferential flow through desiccation cracks is the likely cause of the increased percolation rates observed in 1993-94.

3.6 GEORGSWERDER LANDFILL COVER STUDY

3.6.1 Project Overview

The Georgswerder Landfill Cover Study was conducted to evaluate the field performance of three potential cover designs for use in remediating old uncontrolled landfills in Germany. The project was conducted at Georgswerder Landfill in Hamburg, Germany and is described by Melchior and Miehlich (1989, 1994) and Melchior et al. (1994). Annual precipitation in Hamburg is 83 cm.

Three cover designs were evaluated (Fig. 21). Each test section contained a vegetated surface layer 75 cm thick consisting of top soil underlain by a sand drainage layer 25 cm thick. The barrier systems were directly beneath the sand drainage layer. Two test sections contained resistive barriers consisting of a compacted layer of glacial till 60 cm thick or a composite barrier consisting of compacted glacial till (60 cm thick) overlain by a 1.5-mm-thick HDPE geomembrane. The third test section was a capillary barrier consisting of a 40-cm-thick layer of compacted glacial till, overlying a layer of fine sand and a layer of fine gravel. In effect, the capillary barrier test section contained three capillary breaks (top soil-sand drainage layer, glacial till-fine sand, and fine sand-gravel).

3.6.2 Test Section Design

Design of the test sections is described in Melchior and Miehlich (1989). Each test section was 10 m wide and 50 m long and had two slopes (4% and

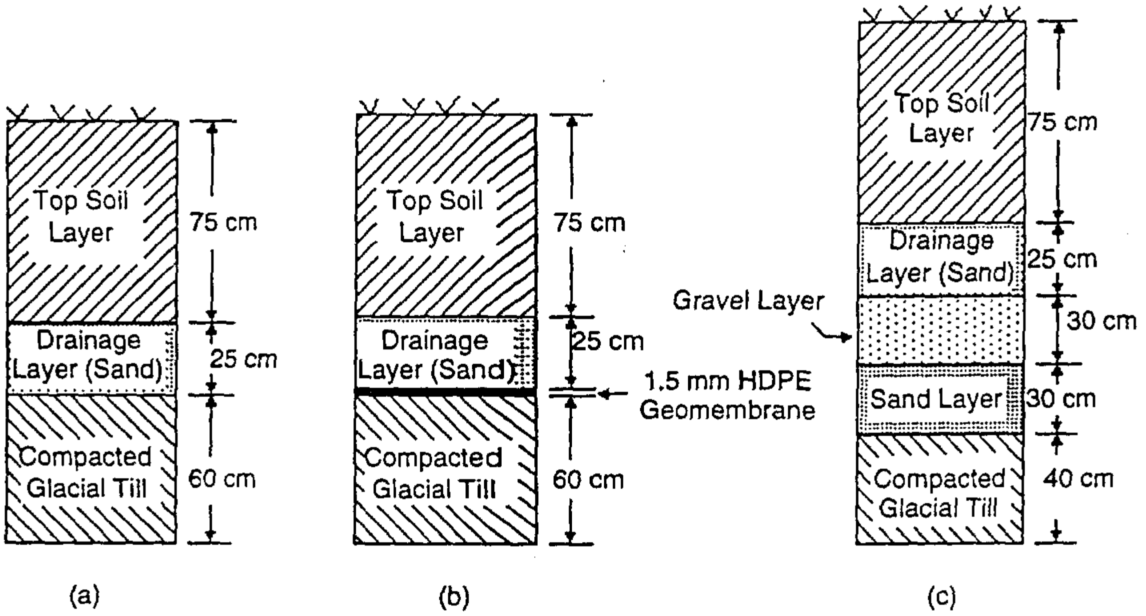


Fig. 21. Cross-Section of Test Sections at Georgswerder Landfill Cover Study: (a) Earthen Resistive Barrier, (b) Composite Resistive Barrier, (c) Capillary Barrier.

20%). A lysimeter constructed from HDPE geomembrane and fine sand was placed underneath the extent of each test section to collect percolation (Fig. 22). The barrier systems were constructed directly on top of the lysimeters. Water collected from the lysimeter and from "gutters" collecting lateral drainage was piped by gravity to collection tanks. Flows were measured using three techniques: tipping buckets (low flows), paddlewheel flow meters (high flows), and float gages in the collection tanks (Melchior and Miehlich 1994).

Water contents were measured manually on a periodic basis with a neutron gage in 24 different neutron tubes. Suctions were monitored continuously using 531 tensiometers equipped with electronic pressure transducers. A weather station was installed to collect automatically collect on-site meteorological data. All of the data, with exception of the water content measurements, were collected automatically with a computer system.

3.6.3 Water Balance Data

Water balance calculations showed that most of the precipitation was shed as evapotranspiration and lateral drainage. During the first three years of the study, evaporation was 64% of precipitation and lateral drainage was 34%. of precipitation, on average. That is, percolation was at most 2% of the water balance during the first three years of the study.

A drought occurred during the third summer, which caused extensive desiccation and cracking of the compacted glacial till layers. Thereafter, percolation from the resistive barrier containing only a clay barrier layer and the

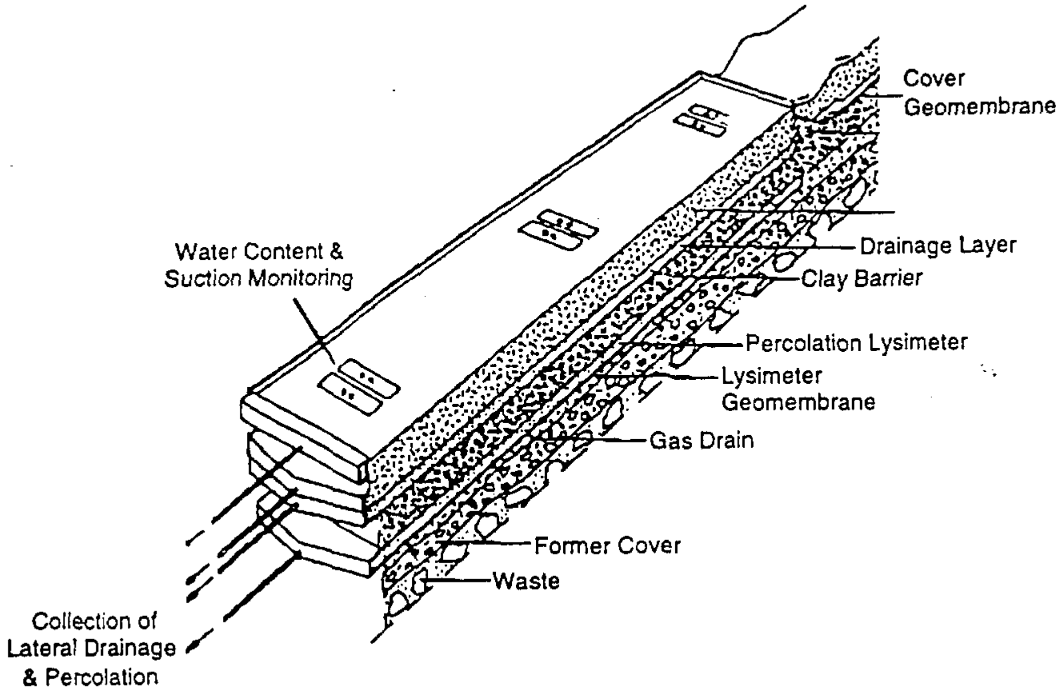


Fig. 22. Schematic of Test Section Used in Georgswerder Landfill Cover Study (adapted from Melchior and Miehlich 1989).

capillary barrier (Fig. 23) increased dramatically. Excavations in Spring 1993 showed that cracks formed during the drought in the compacted glacial till layers in the earthen resistive barrier and the capillary barrier. These cracks, which contained a sheen of water during the excavation, were preferential conduits for flow. Flow through cracks in the earthen resistive barrier immediately became percolation. In the capillary barrier, the glacial till formed the uppermost layer of the barrier. When the glacial till cracked, excessive quantities of water were transmitted into the fine sand wicking layer, resulting in the fine sand becoming saturated. As a result, water moved downward into the fine gravel and became percolation.

Percolation from the composite resistive barrier occurred seasonally throughout the monitoring period, and was essentially the same each year. However, the quantity of percolation was higher than anticipated based on flows expected from defects in the geomembrane. Examination of the data showed that percolation from the composite resistive barrier was primarily thermally driven vapor flow that occurred during the summer months when the thermal gradient was oriented downward. During other parts of the year, percolation from the composite resistive barrier was essentially zero.

It is also important to recognize that the capillary barrier performed as well as the composite resistive barrier before the compacted glacial till layer was cracked by desiccation (Fig. 23). Had the fine-grained surface layer been constructed using a soil resistant to desiccation cracking, the capillary barrier

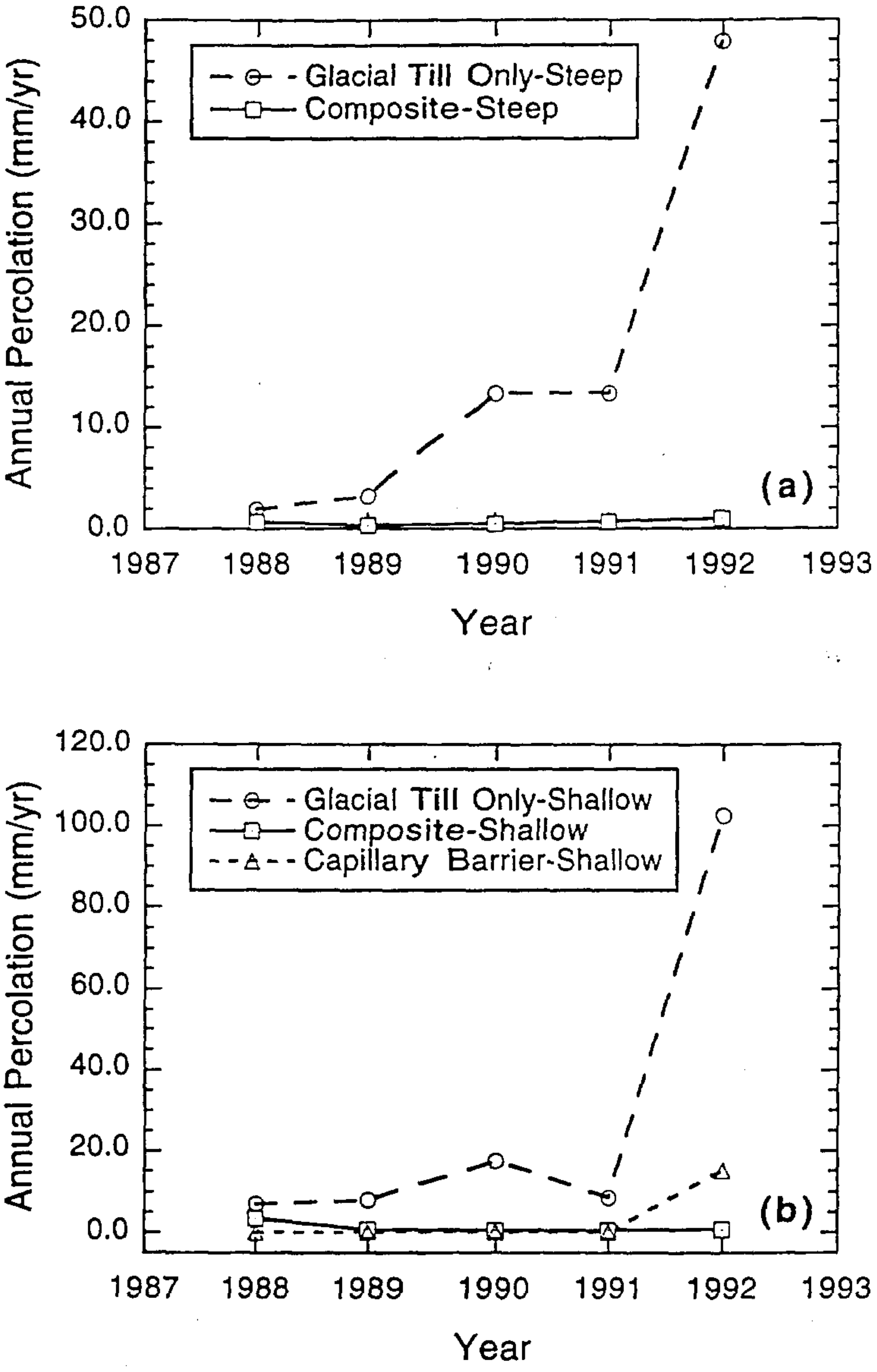


Fig. 23. Percolation from Test Sections at Georgswerder Landfill Cover Study (data from Melchior et al. 1994).

probably would have continued to perform as well as the composite resistive barrier.

Finally, it is important to point out that Melchior et al. (1994) provide the sole source of percolation data from covers designed as composite resistive barriers. Their data suggest that thermally driven vapor flow is primarily responsible for percolation from composite resistive barriers. Their data can also be used to estimate a reasonable average percolation rate for covers designed with composite resistive barriers. Based on their data, a reasonable annual percolation rate is 0.05 cm/yr.

SECTION FOUR

CONCLUSION

This report has described fourteen final cover demonstrations including 85 different final covers. These demonstrations have resulted in a wealth of information regarding the hydrologic performance of final covers in arid, semi-arid, and humid climates. Based on this information, the following conclusions are drawn.

- Compacted clay barriers will fail if they are not protected against desiccation. In five of the studies that employed compacted clay barriers, the barriers cracked when they desiccated. Afterwards, percolation rates increased substantially regardless of whether the compacted clay barrier was used in a resistive barrier or a capillary barrier. More importantly, all of the compacted clay barriers that failed were located in humid climates. More should be expected when un-protected compacted clay barri arid and semi-arid climates.

  It is surprising, however, that two of the earthen resistive barrie in arid regions (i.e., the PBLCD, Sec 2.3; Hill Air Force Base Se did not experience desiccation cracking and increases in pe The reasons why these barriers did not crack is subtle; the constructed with compacted soil-bentonite mixtures, not co Research has shown that soil-bentonite mixtures do not crack in hydraulic conductivity when they desiccate (Albrecht 1996). Had these barriers been constructed with compacted clay, they would have cracked and large increases in percolation rate would have occurred.

These findings suggest that compacted clay barriers used in final covers must be protected against desiccation cracking. Otherwise, the cover will not perform as intended. The only proven method of protection is to cover the clay with a geomembrane and to cover the geomembrane with at least 45 cm of soil (Corser and Cranston 1991). The upper soil layer provides a surcharge that holds the geomembrane in firm contact with the compacted clay.

- The demonstrations show that capillary barriers transmit less percolation when the surface layer has lower saturated hydraulic conductivity. Lower saturated hydraulic conductivity promotes runoff, and prevents excessive infiltration that can overwhelm the soil water storage capacity of the surface layer. However, the surface layer must be resistant to desiccation cracking. If cracks do form, the capillary barrier will fail, as occurred in the Omega Hills Final Cover Study (Sec. 3.1) and the Georgswerder Landfill Cover Study (Sec. 3.6). Unfortunately, the lowest saturated hydraulic conductivities are obtained with compacted clays, which are prone to desiccation cracking. Thus, a compromise between low saturated hydraulic conductivity and resistance to desiccation cracking must be made. This compromise is best made using silty sands and sandy silts, which are resistant to desiccation cracking and have reasonably low saturated hydraulic conductivity (~ 10^{-5} cm/sec).

- The demonstrations show that the capillary barrier effect is realized in the field. However, some of the capillary barriers (e.g., Hill Air Force Base Study, Sec. 2.7) transmitted more percolation than expected, and more percolation than was transmitted by the prescriptive resistive barrier designs. In hindsight, the reason for these apparent "failures" is clear. The surface layer thicknesses used in the field demonstrations often were not selected based on rigorous design principles, but rather were selected arbitrarily. Because the required surface layer thickness (i.e., the required soil water storage capacity) was never determined, the soil water storage capacity was exceeded and significant percolation occurred. Had rigorous principles been used, thicker surface layers would have been selected and percolation would have been small if not zero. In fact, when capillary barriers with thicker surface layers were used in demonstrations (e.g., the Hanford FLTF), virtually no percolation was transmitted.

Rigorous principles were not employed in many of these studies because the design and analysis tools needed for selecting appropriate layer thicknesses were not available when most of the demonstrations were initially formulated. Fortunately, these tools (e.g., water balance models developed specifically for arid and semi-arid regions) are now available (e.g., Khire 1995). As a result, layer thicknesses for capillary barriers *should now be selected* using a rigorous analysis based on sound principles of unsaturated flow.

- The demonstrations conducted at LANL, Hill Air Force Base, Wenatchee, and the Hanford FLTF show that a critical condition for capillary barriers is during snow melt events. During snow melt events, evapotranspiration is low and infiltration is high. As a result, the risk of exceeding the soil water storage capacity is high. Consequently, the design of capillary barriers must include adequate capacity to store water that infiltrates during show melt events.

  A natural extension of this finding is that the critical design period for capillary barriers is when evapotranspiration is low and precipitation is prolonged. This condition also results in a high risk of exceeding the soil water storage capacity of the surface layer. In many regions, this critical period will occur during the winter months (Khire 1995). Capillary barriers must be designed with adequate soil water storage capacity for this critical period.

- Mixed results have been obtained from the demonstrations including monolayer barriers. The NRC Study (Sec. 3.3) shows that the performance of monolayer covers in humid climates is poor. In contrast, the monolayer barriers evaluated in the INEL Cap Study (Sec. 2.4) performed well. However, percolation from base of the INEL monolayer barriers was not measured and thus a definitive conclusion cannot be drawn from the INEL Cap Study. The monolayer barriers evaluated in the ITPE (Sec. 2.2) also did not perform well. It must be noted, however, that none of these covers were engineered. Instead, the layer thicknesses were selected arbitrarily or based on previous practice. Had the monolayer barriers been engineered, much better results would have been obtained. It is expected that the forthcoming data from the PCBBE (Sec. 2.5) and the data from the studies in California will show much better performance, because these caps and covers have been engineered using rigorous analyses.

- In many situations, an alternative cover must be shown to be equivalent to a prescriptive cover in terms of percolation rate. This comparison can be readily made using rigorous water balance models for sites with prescriptive earthen covers. However, such comparisons are difficult to make when the prescriptive design is a geosynthetic or composite cover, because rigorous methods to simulate flow through these types of covers have not yet been developed. In the absence of rigorous models, the data presented by Melchior et al. (1994) provide the best means to characterize percolation rates through geosynthetic and composite covers. In particular, they show that the percolation rate from a composite cover is approximately 0.05 cm/yr.

SECTION FIVE

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APPENDIX

REPRINTS OF SELECTED REFERENCES

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PART 1

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Glendon W. Gee and N. Richard Wing

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further research. Capillary barriers should be studied in greater detail in order to be able to better engineer these systems. The breakthrough at the end of 1992 indicates that effective limitation of the infiltration rate into the capillary layer is essential. The combination of a flexible membrane liner above a capillary liner seems to be a promising concept (see below). In contrast, compacted soil liners that were not protected by a geomembrane were destroyed due to desiccation and shrinkage in the course of a very few summers: the weather was slightly dry in 1989; of average moisture in 1988, 1990, and 1991; and extremely dry in 1992. We can only speculate how liners with a different clay composition or liners better protected by thicker topsoils might have performed. Yet it is impossible to specify how surface liners can be reliably protected against desiccation and shrinkage. The soil liners studied had only a relatively low risk of shrinkage due to their particle size distribution and their clay mineral composition compared to other clay liners. Furthermore, the climatic conditions in Hamburg are far from being very dry and therefore should create a rather more favorable environment for soil liners than would a more arid climate. Therefore, the results of this study indicate a high risk of failure for compacted soil liners in landfill covers in general.

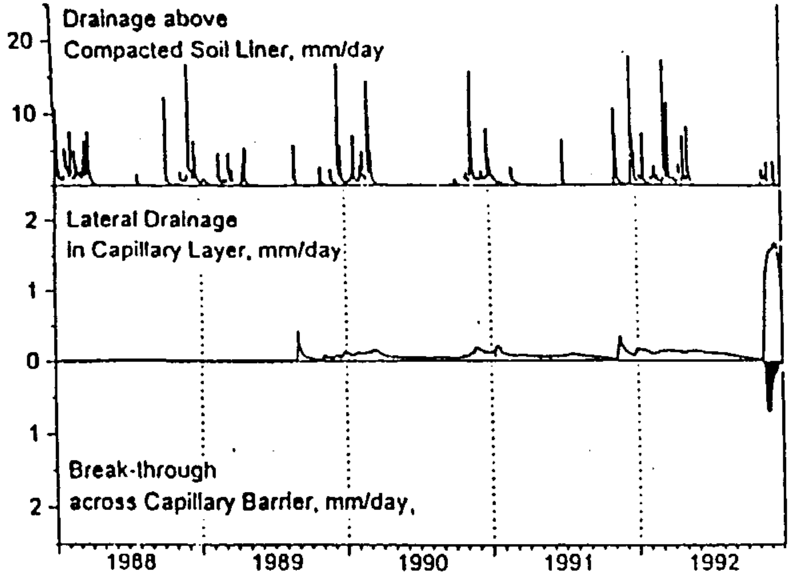

Figure 6. Extended capillary barrier—discharges.

Another disadvantage of compacted soil liners is that maintaining moisture contents at optimum levels during their construction makes their use a very complex, expensive, and time-consuming venture. Furthermore, suitable materials are rare, and the usual quality control programs cannot guarantee the construction of an efficient liner. Direct monitoring is possible only on selected parts of a whole cover by installing test fields that allow direct measurement of liner leakage in large areas. Because of the high costs of such a procedure, it is not commonly practiced. Leak detection and subsequent repair of covers are therefore usually not possible.

Table 3. Extended capillary barrier: Annual drainage rates (mm) above compacted soil liner, annual lateral drainage within capillary layer (mm), and annual breakthrough (mm and % of potential leakage) across capillary barrier.

	Drainage above Compacted Soil Liner	Lateral Drainage within Capillary Layer	Break-through Capillary Barrier	
	mm/yr	mm/yr	mm/yr	%
1988	389.7	8.4	0.0	0.0
1989	233.4	14.2	0.0	0.0
1990	320.5	31.0	0.0	0.0
1991	198.3	32.3	0.0	0.0
1992	277.7	101.2	15.2	3.9

In addition, the results of the study show that compacted soil liners desiccate periodically even below a flexible membrane liner due to thermally induced water transport. This may cause shrinkage and failure of the soil liner even before the projected end of the design life of the flexible membrane liner. Even if this does not happen, the compacted soil component most likely will not be the intended long-term backup system for the flexible membrane liner because of possible shrinkage when the flexible membrane liner no longer averts the capillary rise of water. For all these reasons, the use of compacted soil liners in landfill covers must be questioned as long as they cannot be securely protected occurred through the composite liner—only desiccation of the compacted soil component. The loss of moisture of the soil liner is, however, very small: about 1.5% by volume. The hydraulic gradient is positive at all times but drops significantly below 1 during the dry period. The potentials, however, are not low enough to generate capillary rise of water.

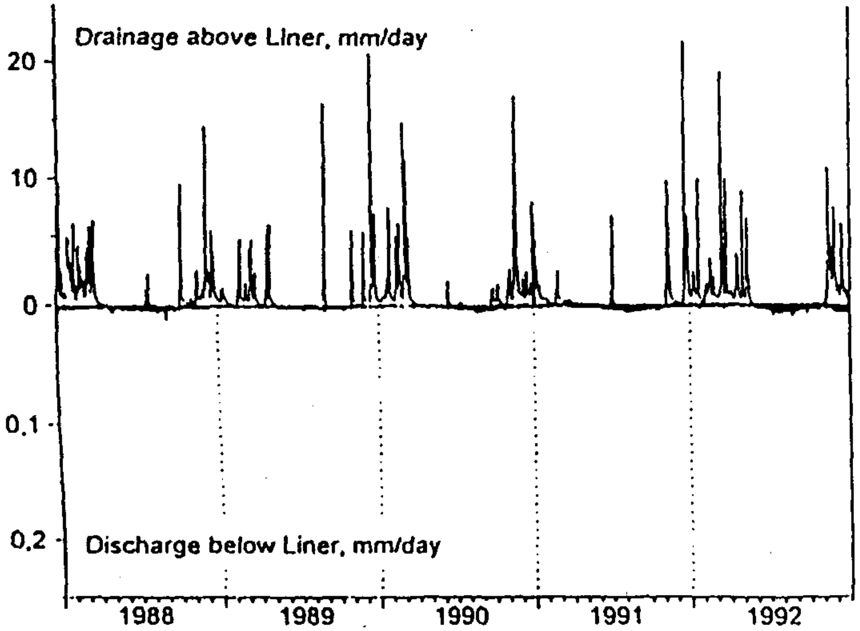

Figure 4. Composite liner—discharges above and below liner.

The moisture loss of the soil liner below the flexible membrane is most likely caused by thermal gradients. Soil temperature varies during the year between 5 and 19°C (Figure 5). Due to the heat of the landfill, the temperature is higher at the bottom of the liner than at its top during fall, winter, and spring. Only during the summer is atmospheric heat input high enough to heat the top of the liner to temperatures that exceed those at its bottom. Comparison of temperature gradients and discharges reveals that discharges below the liner start with the first occurrence of negative gradients (temperature decreasing with depth). The maxima of soil temperature and disch[illegible] intensity also correspond. The discharge intensity decreases slowly after the reversal of the temperature gradient; soil temperature also decreases during that time.

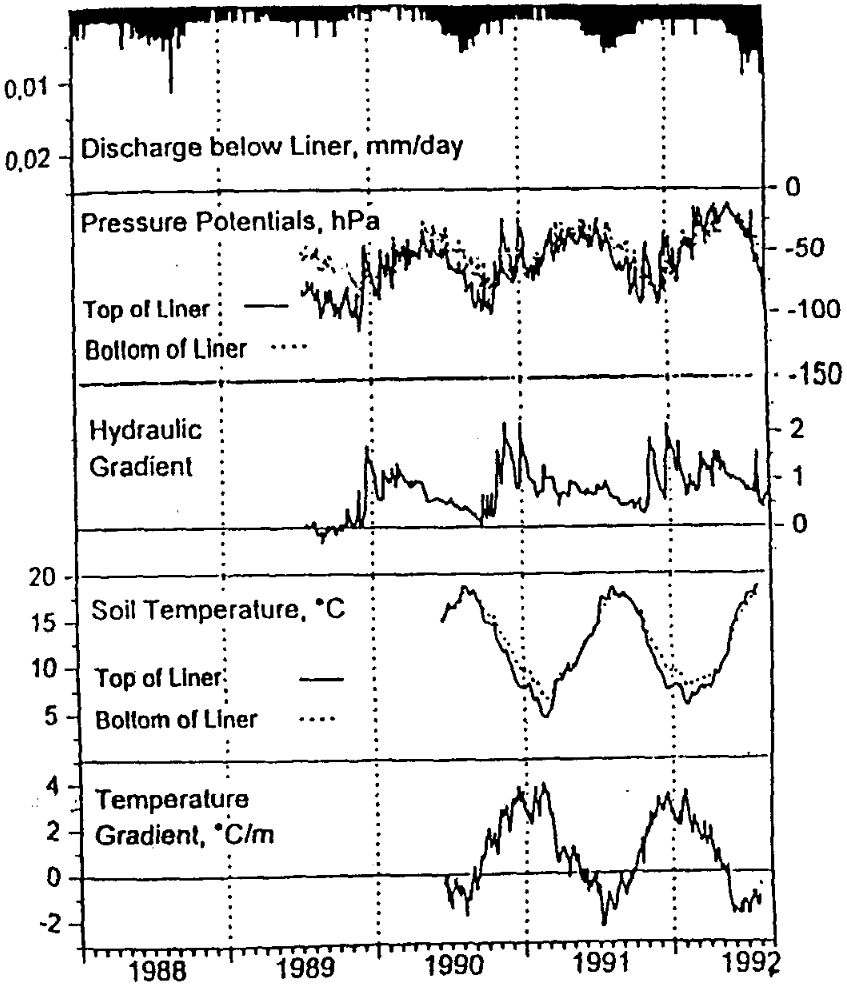

Figure 5. Composite liner—discharges, pressure potentials, hydraulic gradients, and soil temperature.

content, 12.1% dry weight. Proctor density was 2.039 g/cm^3, and optimum water content was 9.6%. The till was compacted to >95% of the Proctor density on the wet side of optimum with a smooth vibratory roller. Total pore volume of the liner is 27.0%; the degree of saturation, 87%. The geometric mean of the saturated hydraulic conductivity, measured in the laboratory during construction, was 2.4 x 10^{-10} m/sec. Due to its graded particle size distribution, its low clay content, and the dominance of relatively inactive clay minerals, the potential for shrinkage of the till is rather low compared to that of other "clay liners."

Figure 2 shows the discharges in the drainage layer above the liner and the liner leakage (the scale of the Y-axes of both discharges differs by a factor of 10). The drainage discharge above the liner is high during winter and spring, whereas little occurs during summer. Liner leakage was very low during the first 20 mo. In August, 1989, however, it rose sharply within a few days after a rather small discharge event above the liner following heavy rainfall. After that, both discharges corresponded. This flow pattern and the results of a tracer experiment prove the existence of continuous preferential flowpaths within the liner that allow rapid percolation. In fall, 1992, the liner leakage again increased and reached maximum values.

Tensiometers measure the pressure potential of the soil water. The pressure potential is dominated by the matric potential, although short-term variations of the tensiometer data in the liners are caused by gas pressure potentials due to delayed transmission of atmospheric pressure changes in the liners (see Melchior, 1993). The tensiometer data, however, clearly show the seasonal variation of matric potentials and therefore can be interpreted with respect to the degree of desiccation of the liners. Pressure potentials and the hydraulic gradient in the compacted soil liner are shown in the lower part of Figure 3. The liner was nearly saturated during winter and spring (potentials close to 0 hPa). Desiccation occurs during the summer, beginning at the top of the liner, until rainfall produces drainage discharges in the fall and remoistens the liner (data for the end of 1992 are not included in this figure).

The hydraulic gradients were positive most of the year and indicated downward water movement. During the summer, however, steep negative gradients were present; consequently, the water rose via capillary movement. The decrease of matric potential caused a moisture loss of only about 2.3% by volume and was, at least until 1992, low compared to the desiccation that usually occurs in topsoils. Relatively low moisture losses, however, already cause rather high capillary forces and, consequently, cause the risk of shrinkage of the compacted, low-porosity liners. The summer of 1992 was extremely dry compared to the long-term average water balance in Hamburg. Pressure potentials decreased drastically and, consequently, resulted in further shrinkage and additional formation of preferential flowpaths through the liner. Excavations in spring, 1993, revealed the existence of barely visible, very small fissures between soil aggregates (around 5 cm in diameter). The fissures were visible only because there was shiny free water on the surface of the aggregates. Hypotheses other than shrinkage to explain the formation of the macropores can either be excluded (freezing, penetration of roots, or burrowing by animals), or are not supported by the available data (subsidence). Plant roots have reached the upper parts of the liners in 1992, 3 yr after preferential flow began. From 1992 on, however, plant roots contributed directly to the desiccation and formation of soil structure and represent the dominant, long-term threat to the liners.

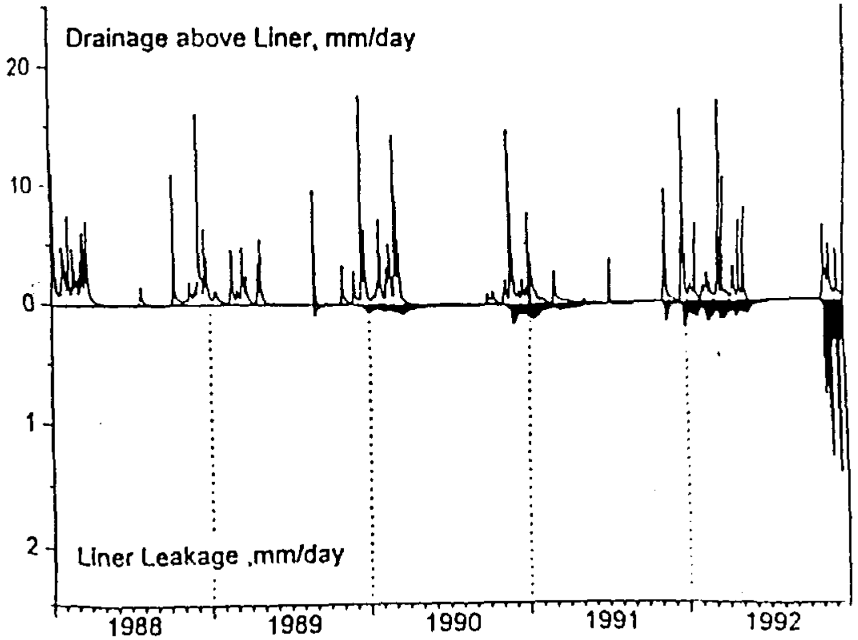

Figure 2. Compacted soil liner - discharges above and below liner

MULTILAYERED LANDFILL COVERS: FIELD DATA ON THE WATER BALANCE AND LINER PERFORMANCE

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Key words: *Landfill cover, water balance, liner performance, desiccation, field lysimeter*

ABSTRACT

The water balance and long-term performance of different covers have been monitored on the Georgswerder landfill (Hamburg, Germany) since 1988. Evapotranspiration and drainage above the liners are the major components of the water balance. The liners tested performed very differently. The compacted soil liners have lost their efficiency due to desiccation and shrinkage. The flexible membrane liners (used in combination with compacted soil liners) and an extended capillary barrier performed very well. A slight periodical desiccation due to thermally induced water transport was observed within the soil liners below the flexible membranes. Finally, we will discuss the suitability of compacted soil liners in landfill covers and the use of other, proposed systems with an intrinsic ability for control.

INTRODUCTION

Cover systems are an important component of new landfills and are widely used to safeguard old contaminated sites. They serve to avoid the transfer of contaminants into the biosphere and to prevent precipitation from infiltrating waste, thus limiting the risk of groundwater and surface-water contamination. Vegetation and topsoil temporarily store the atmospheric water input and, even under humid climatic conditions, evapotranspirate a large part of it. The rest, however, percolates downward periodically and therefore has to be drained laterally above a liner. Different types of liners are used, and they are often combined: compacted cohesive soil liners, flexible membrane liners (high-density polyethylene, HDPE), and capillary barriers, as well as other materials such as asphalt, geosynthetic clay liners, or soil mixed with differen[illegible]ditives. Despite the number of covers that have been constructed, little is known about their long-term performance in the

Fig. 7. Water content of the composite soil cover at Waite Amulet, Quebec.

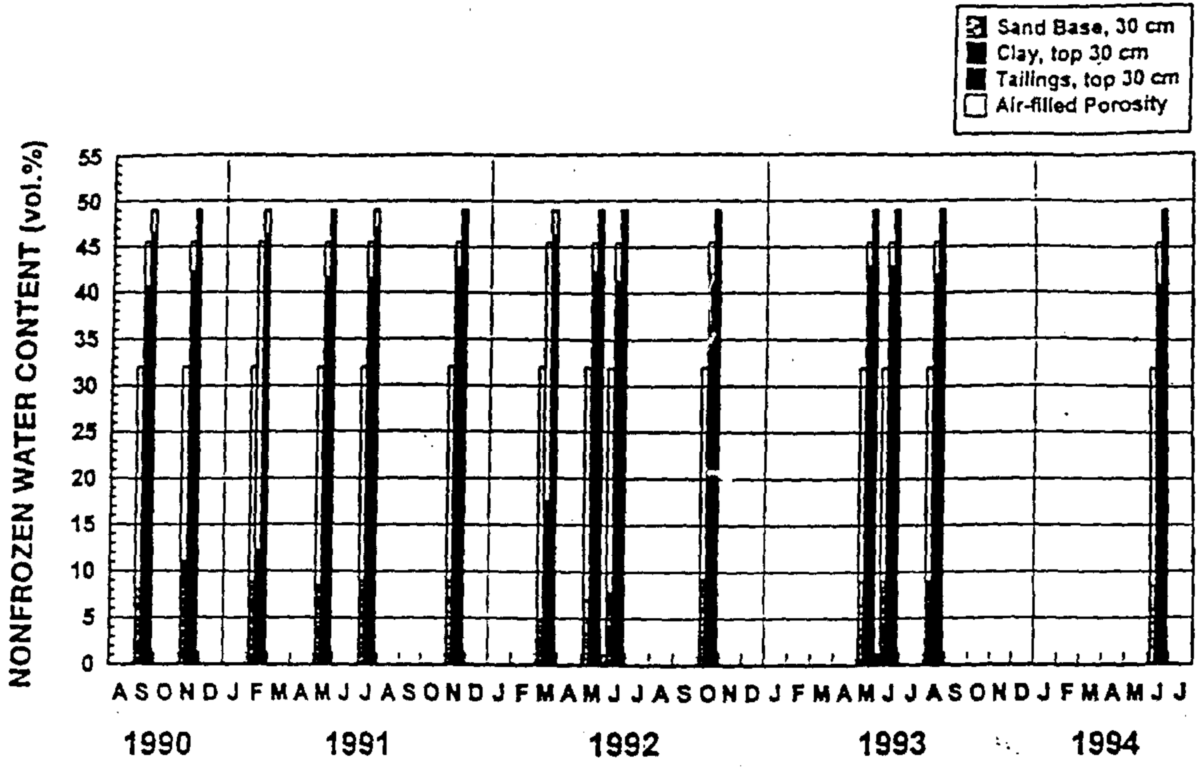
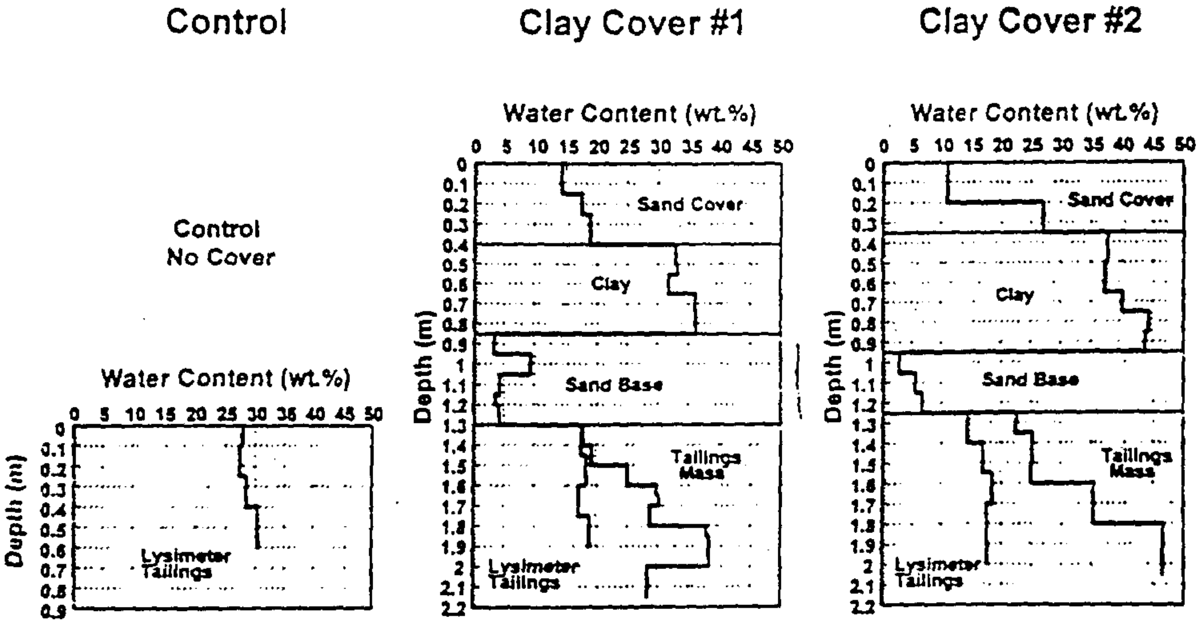


Fig. 8. Gravimetric water content measurements in June 1993.



tailings, near Rouyn-Noranda, Quebec. The model predictions were corroborated by field measurements of percolation, evaporation, and soil water content. The Hydrologic Evaluation of Landfill Performance (HELP) model was used to evaluate the effectiveness of the cover at four meteorological stations surrounding the site, within a 400–500 km radius. The HELP modelling showed that approximately 56% of average annual precipitation evaporates and 11% runs off. The amount available for subsurface flow is therefore 33% of precipitation. Using 33% of the precipitation Amos, Quebec, as a surface boundary condition i saturated–unsaturated flow modelling, it was determin that 34.4 mm of water would percolate through the cov HELP modelling determined that 38 mm would percola through the cover. The modelling exercises predict th 4% of precipitation percolates through the cover. Fie lysimeter measurements indicate that 4% of precipitati percolates through the cover. Both modelling methods al

Fig. 5. Pressure head versus hydraulic conductivity functions used in SEEP/W modelling.

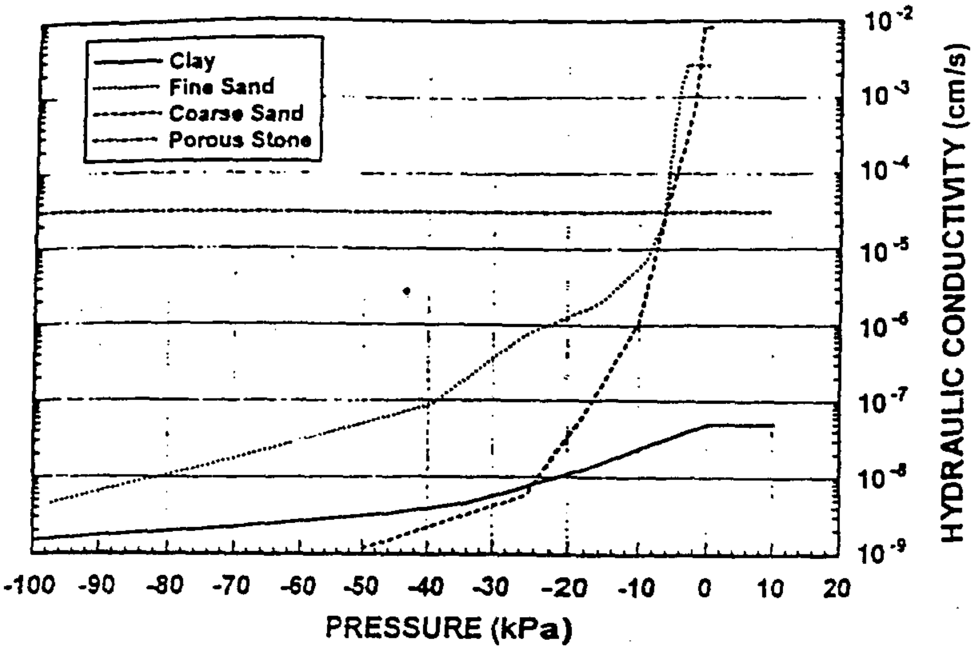


Table 2. Observed percolation through the experimental clay cover at Waite Amulet.

Period	Oct. 26 to Nov. 20, 1992 (Fall)	Nov. 20 to May 21, 1993[a] (Winter to early spring)	May 21 to June 11, 1993[b] (Spring)	June 11 to Aug. 19, 1993 (Summer)	Aug. 19 to Sept. 22, 1993 (Late summer to fall)	Oct. 26, 1992 to Sept. 22, 1993 (Annual)
Precipitation (mm)	75	440	82	257	105	958
Lysimeter discharge (L)	10	0	30	20	22	82
Lysimeter discharge (mm)	5	0	14	9	10	37
Lysimeter discharge (% of precip.)	6	0	17	4	10	

[a] Precipitation measured at Duparquet, Quebec.

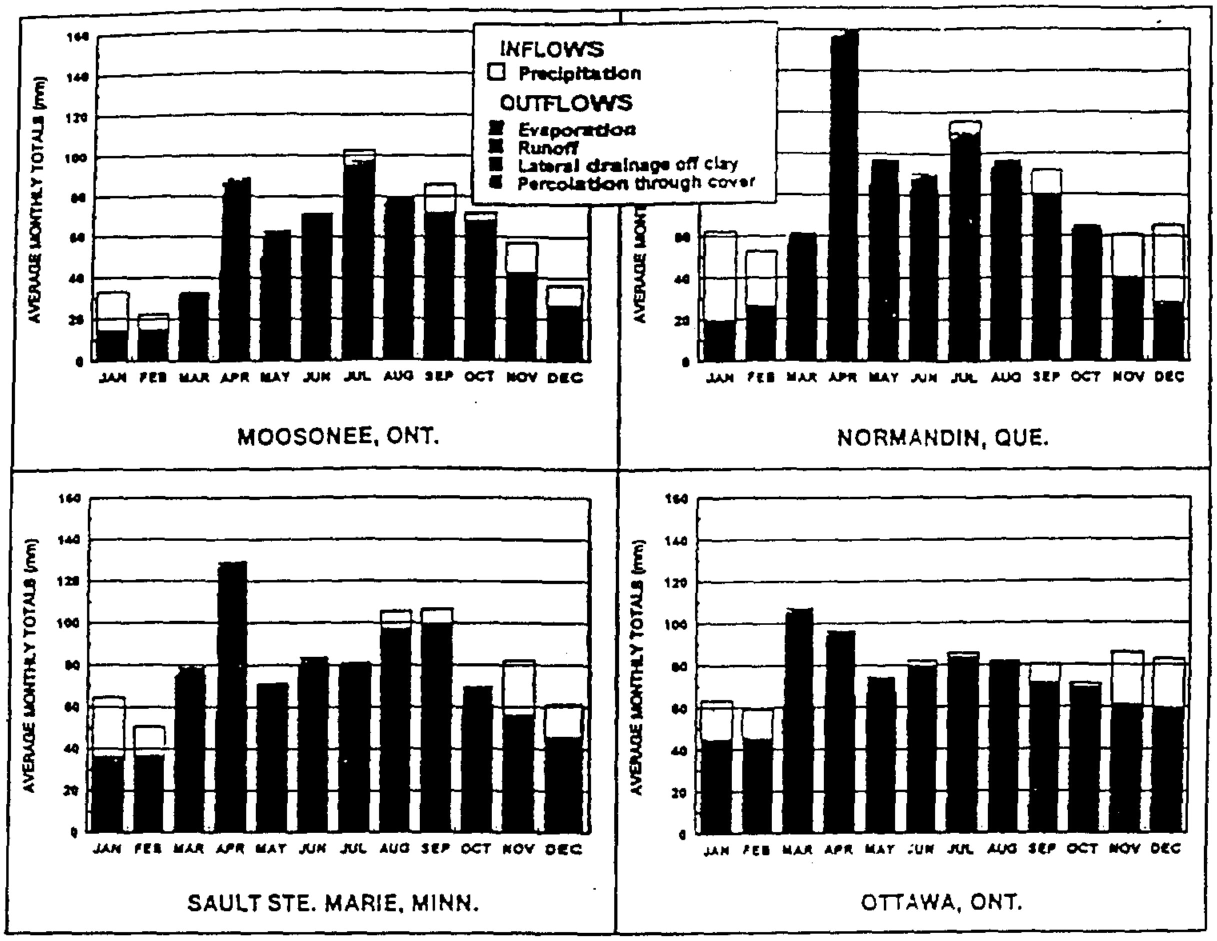
[b] The spring thaw appeared to percolate to the lysimeter between site visits on May 21 and June 11, thus showing a time lag.

systems consisting of soils with contrasting grain-size distributions, such as a composite soil cover, a high K_s implies horizontal flow and a low K_s, a vertical flow.

The water that enters the clay flows vertically, as indicated by the hydraulic head contours: flow is perpendicular to the head contours. The flow continues vertically across the sand base, suggesting a low unsaturated hydraulic conductivity, *K*. The head contours also concentrate across the sand base, illustrating the larger gradient needed to push the flow through the sand. Since the flux is constant and the gradient across the sand base is greater than that across the clay, the *K of the sand must be less than the* K_s of the clay, in accordance with Darcy's law. Thus, the sand base, being unsaturated, has a lower hydraulic conductivity than the clay, which is saturated. The flow modelling therefore confirms the sand base as a capillary barrier that restricts drainage from the clay. This result is consistent with the HELP modelling. Flow modelling results predicted vertical flow through the cover to be 34.3 mm of water, which is also consistent with the HELP modellin (Fig. 1).

The water table indicates where the pressure head equals zero ($\psi = 0$); this is also called the free water surface When ψ is less than zero, water is under tension (or suc tion), and when ψ is greater than zero, water is under pres sure. Unsaturated soils contain water under tension. The water table occurs in the tailings at 1 m below the cove and in the clay, as shown by the modelling results in Fig. The fact that the clay has a perched water table indicates i is saturated, which is consistent with the HELP model ling. The extent of saturation or the size of the perche water table envelope is not actual, its presence is simply a indication of saturation. The sand layer below the clay i unsaturated.

Fig. 2. HELP modelling results, average monthly totals.



balance components with varying levels of K_s (Fig. 3). The hydraulic gradient (i) across the clay was calculated by dividing flow through the clay by K_s. Percolation increased with K_s values greater than 1×10^{-7} cm/s, while runoff, lateral drainage, and hydraulic gradient decreased. Percolation was most sensitive at K_s values between 2×10^{-7} and 2×10^{-6} cm/s, and i at values greater than 4×10^{-7} cm/s. When K_s is less than 7×10^{-7} cm/s, i is greater than 1, which indicates that free water is available at the surface of the clay. The percolation for this value of K_s is 220 mm/a or 25% of mean annual precipitation. This would be the maximum amount of percolation to expect while still retaining free water conditions at the surface of the clay, and therefore a high degree of saturation of the clay. Monthly results from this run confirm these conditions are sustained from April through December, with no loss in the degree of saturation of the clay at the end of the 20 year simulation. From January through March, the cover is frozen: precipitation accumulates as a snow pack and there is no gain or loss of water and hence no change in the degree of saturation.

Flow modelling

To enhance the HELP modelling, the flow model SEEP/W (Geo-slope International 1992) was used to simulate flow through the composite soil cover at Waite Amulet. The test plot was modelled as a two-dimensional system and under steady-state conditions. SEEP/W is formulated to analyze both saturated and unsaturated flow. Pressure head versus water content functions (Fig. 4), used in the flow modelling, were adapted from pressure plate and column studies conducted by McGill University and Noranda Technology Centre. Pressure head versus hydraulic conductivity functions (Fig. 5) were developed with a routine in SEEP/W that utilized the drainage curves and other soil properties. The top boundary condition was specified as a constant flow of water, equivalent to 303.6 mm/a, which was infiltration deduced from the HELP modelling. The sides of the covered tailings domain were specified as a constant head boundary set to piezometer head measurements. The base of the tailings, which generally sits on clay, was defined as impermeable. All other soil properties were similar to those used in the HELP modelling.

Modelling the test plot as a steady-state system simulates the flow conditions as if precipitation and evaporation were constant throughout the year, which yields equilibrium conditions of flow with steady infiltration. Realistically, precipitation would fluctuate throughout the year; runoff and infiltration would therefore also fluctuate. Evaporation is greatest during the summer and least during the winter. The cover would also freeze during winter and limit percolation. Results of the flow modelling therefore represent the average flow conditions. It is similar to a system with

Table 1. HELP model input data.

Layer:	Sand cover	Clay	Sand base
Layer type	Lateral drainage	Barrier	Vertical percolation
Layer thickness (cm)	30	60	30
Porosity[a]	0.33	0.445	0.39
Field capacity[a]	0.08	0.43	0.05
Wilting point	0.03	0.35	0.025
Initial water content[a]	0.08	0.44	0.05
Saturated hydraulic conductivity (cm/s)[a]	2.6×10^{-3}	1.0×10^{-7}	8.4×10^{-3}
Slope (%)	0		
Maximum drainage length (m)	10		
Cover area (m^2)	400		
SCS runoff curve number	81		
Evaporative zone depth (cm)	20		
Maximum leaf area index	0; bare ground		
Initial snow water content (mm)	50.8 (2 in.)		
Growing season	June–September; not applicable to bare ground		

[a]Laboratory measured soil parameters.

The phenomenon was illustrated in a combined experimental and modelling study by Yanful and Aubé (1993).

Two experimental soil covers, incorporating the capillary-barrier concept, were constructed on acid-generating tailings at the Waite Amulet site, near Rouyn-Noranda, Quebec. The design, construction, and instrumentation details are documented in two papers by Yanful and St-Arnaud (1991) and Yanful (1993) and are only briefly described here. The test plots were 20 by 20 m in plan and consisted of a 60 cm compacted clay layer placed between a 30 cm sand base and a 30 cm sand cover. A 10 cm gravel crust blanketed the sand cover to control erosion. A collection basin lysimeter was placed below each cover. Lysimeters are commonly used to assess evapotranspiration in water-balance studies, but in this study they were used to collect water percolating through the cover. They consisted of semicylindrical, acid-resistant, high-density polypropylene laid horizontally along the axis of the cylinder. Each lysimeter had an exposed, receiving surface area of 2.2 m^2 and a volume of ~2 m^3. The water content of each layer of the covers was also measured.

Percolation through the cover was predicted using two computer models. This paper compares predicted amounts with those measured in the lysimeter. The predicted level of saturation is also compared with field measurements. Overall, the capillary-barrier concept is illustrated and clarified through hydrologic flow modelling.

Hydrologic evaluation and prediction

The Hydrological Evaluation of Landfill Performance (HELP) model is a deterministic water balance model, developed by the United States Environmental Protection Agency (EPA), which uses climatic, soil, and design data to determine the water budget of a landfill (Schroeder et al. 1984). The HELP model for windows (HMfW) utilizes the EPA computer code and incorporates meteorological data from Environment Canada (Grace Dearborn Inc. 1993). Since the soil covers at Waite Amulet are similar in design to landfill covers, HMfW was used to evaluate the magnitude of the water balance components at the field site.

The amount of annual infiltration predicted with HMfW was used as the soil surface boundary condition in SEEP/W, a finite-element flow model used to solve the two-dimensional equation of flow for steady-state saturated and unsaturated flow at the site.

HELP model

The HELP model simulates 4 hydrologic processes on a daily account: (*i*) runoff, and hence infiltration, is computed using the United States Soil Conservation Service (SCS) Curve Number method; (*ii*) percolation (i.e., saturated and unsaturated vertical flow) is modelled using Darcy's law; (*iii*) lateral drainage is computed using the Boussinesq equation; and (*iv*) evaporation is estimated with a modified Penman method. Other components of the water budget are deduced from these results.

Cover design specifications consist of the thickness and soil type of each layer. There are four types of layers that are defined by the HELP model: (*i*) a vertical percolation layer that allows only vertical flow; (*ii*) a lateral drainage layer that allows vertical flow but also horizontal flow through drainage pipes; (*iii*) a barrier soil layer that restricts vertical flow; and (*iv*) a waste layer (not used in this soil cover application).

Table 1 lists the input data used to apply HMfW to the composite soil covers at Waite Amulet. Laboratory measured soil parameters were used where possible. The SCS runoff curve number was chosen using a relationship to the minimum infiltration rate and vegetative cover (Schroeder et al. 1984). The default SCS curve number for fine sand and bare ground was used. In the present study, the impact of vegetation was negligible and bare ground values were used when applicable.

slope and on the leeward side of the cover. In addition, the cone shape minimizes ponding of water on the impermeable layer, thereby reducing percolation to the till. Water would, instead, tend to flow through the granular cover, down slope. These hydrologic conditions are more enhanced on top of the pile and could result in a low replenishment of water to the cover, thereby providing a worst-case scenario for this study.

Summary and conclusions

A composite soil cover was constructed on an acid-generating waste-rock pile located at the Heath Steele mine site near Newcastle, New Brunswick. The cover was constructed by compacting a glacial till in three lifts of 20 cm each on a sand base prepared on the levelled surface of the waste-rock pile. The compaction energy used yielded a minimum field dry density of at least 95% of the maximum Modified Proctor value. Moulding water contents were about 3% higher than the optimum value. A 30 cm thick gravelly sand layer was placed on the till followed by a final 10 cm thick erosion-protection layer.

Instrumentation was installed to measure the following parameters:

(*i*) gaseous oxygen concentrations in both cover and pile,
(*ii*) moisture contents and suctions developed in the cover,
(*iii*) temperatures within the pile, and
(*iv*) quality and quantity of the runoff and percolated water reporting to the bottom of the pile (underdrain).

Based on the monitoring results obtained to date, the following can be concluded.

(1) The cover has reduced gaseous oxygen concentration in the pile from 20% to less than 3%.
(2) The volumetric water content of the compacted till layer has remained essentially the same at about 32% since cover installation. The till continued to remain nearly fully saturated.
(3) Infiltration through the cover observed during a 55-day wet period was about 2–2.5% of precipitation.
(4) Reduced temperatures observed in the pile since cover installation appear to be a result of seasonal fluctuations. Continued monitoring will be required to confirm these data.
(5) No significant change in the water quality of the seepage from the pile has been noted since cover installation .

These conclusions indicate that the placement of the cover has reduced the flux of oxygen and water to the waste rock, which suggests a reduction in oxidation and acid production in the pile. Long-term monitoring of quality of the seepage from the pile will be required to confirm the reduction in acid production because of the presently stored acidity and low percolation of water through the cover.

Acknowledgements

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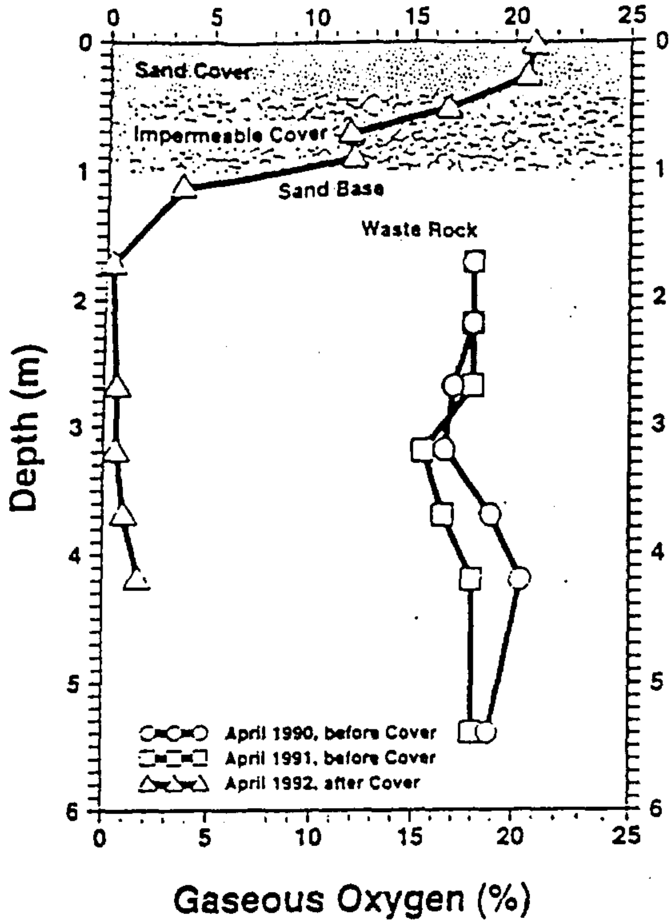

Fig. 12. Gaseous oxygen concentrations in pile 7/12 before and after cover installation.

TABLE 3. Comparison of the quality of seepage from the pile before and after construction of the cover

Date	pH	Acidity (mg/L $CaCO_3$)	Total Fe (mg/L)	SO_4^{2-} (mg/L)
		Before construction of the cover		
July 1989	2.4	44 000	5 100	43 440
Sept. 1989	2.8	30 500	2 800	28 000
May 1990	2.4	16 400	5 510	12 700
Sept. 1990	2.2	73 250	7 920	32 970
Oct. 1990	2.1	64 400	3 700	—
		After construction of the cover		
Oct. 30 1991	2.3	54 450	19 590	71 042
June 29, 1992	2.4	35 000	10 500	5 140
Aug. 17, 1992	—	14 400	3 720	14 800
Sept. 29, 1992	2.9	15 800	5 250	15 400

NOTE: Construction of the cover was completed in October 1991.

compaction, a small-diameter (25 mm) hole was augered, the sensor installed in a soil slurry, and the hole backfilled and sealed to the surface with bentonite.

Moisture content

The moisture content of each layer of the soil cover was measured by time-domain reflectometry (TDR). TDR is a radar technique in which a fast rise time voltage pulse is propagated through the soil and its reflection measured. The pulse is guided through the soil by stainless-steel rods of known dimensions. The measurement of travel time (Δt) yields an estimate of "apparent" dielectric constant (K_a) of the soil. The volumetric soil-moisture content (θ_v) is then calculated using a relation developed by Topp et al. (1980), or other soil-specific relations. A good review of the method can be found in Topp and Davis (1985).

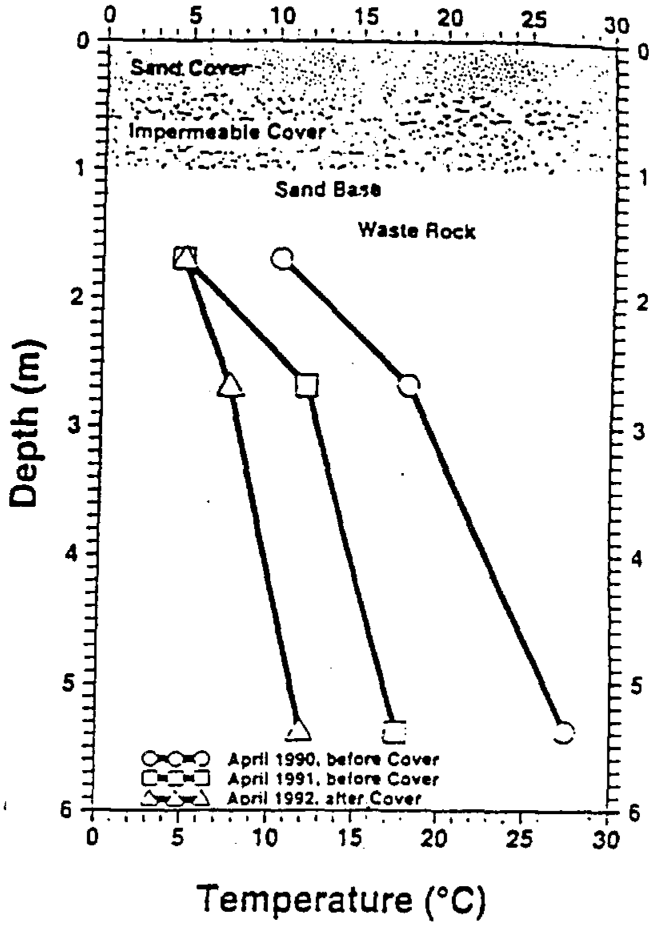

Fig. 13. Temperature profiles in pile 7/12 before and after cover installation.

A three-rod TDR probe system (Fig. 11) was adapted from Zegelin and White (1989). The rods were 30 cm long in the sand layers and 20 cm long in the till. The probes were placed in each layer horizontally as the cover was being constructed. Probes were installed in the top and bottom lifts of the till layer. The application of the voltage pulse and measurement of Δt were performed with a Tektronix 1502B TDR metallic cable tester. The unit was attached to a data logger to automate measurements.

Results to date

The effectiveness of the cover in reducing sulphide oxidation and acid generation can be assessed with the data collected to date:

(i) gaseous oxygen concentrations in both cover and pile,
(ii) moisture contents and suctions developed in the cover,
(iii) temperatures within the pile, and
(iv) quality and quantity of the runoff and percolated water reporting to the bottom of the pile (underdrain).

Gaseous oxygen concentrations measured before and after the placement of the cover (Fig. 12) clearly indicate the presence of the cover reduces oxygen penetration into the

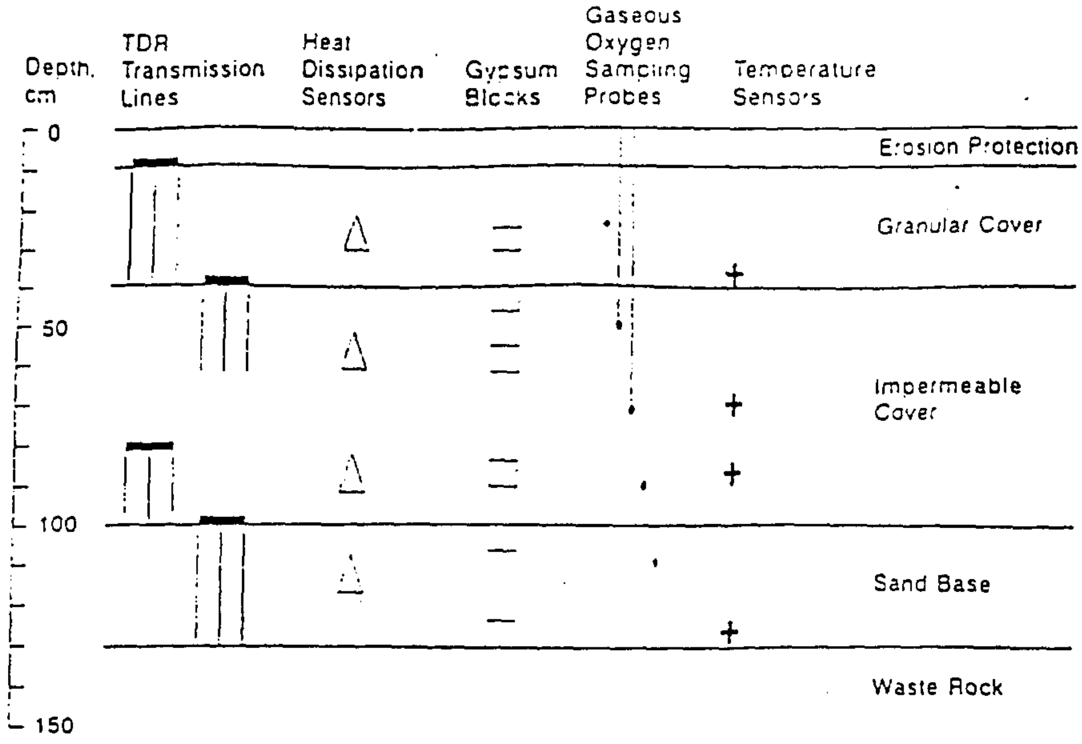

FIG. 9. Schematic representation of a vertical profile at an instrumented station.

FIG. 10. Backfilling of northeast lysimeters following installation.

chambers allow flow and water quality to be monitored individually. The cover of the outfall structure was insulated with 50-mm styrofoam, and all internal exposed surfaces were covered with fiberglass epoxy. Overflow from the outfall structure is directed to 100-mm drainage pipes sloping away from the site to a settling pond located nearby.

Gaseous oxygen

The gaseous oxygen concentration within the cover was determined with a Teledyne portable oxygen meter. A gas sample was extracted from a 6.3 mm diameter stainless steel tube permanently installed at the depth of interest. Five sampling tubes extending vertically to the centre of each

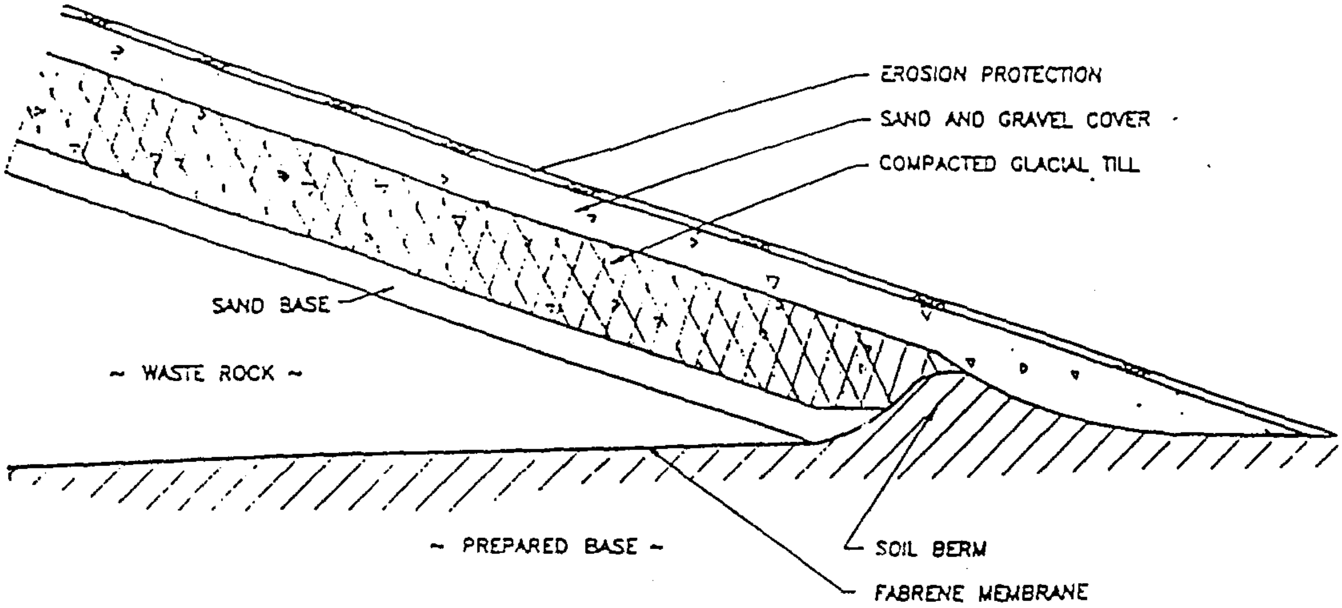

FIG. 6. A cross section of completed composite cover.

FIG. 7. Waste rock pile 7/12 before cover installation.

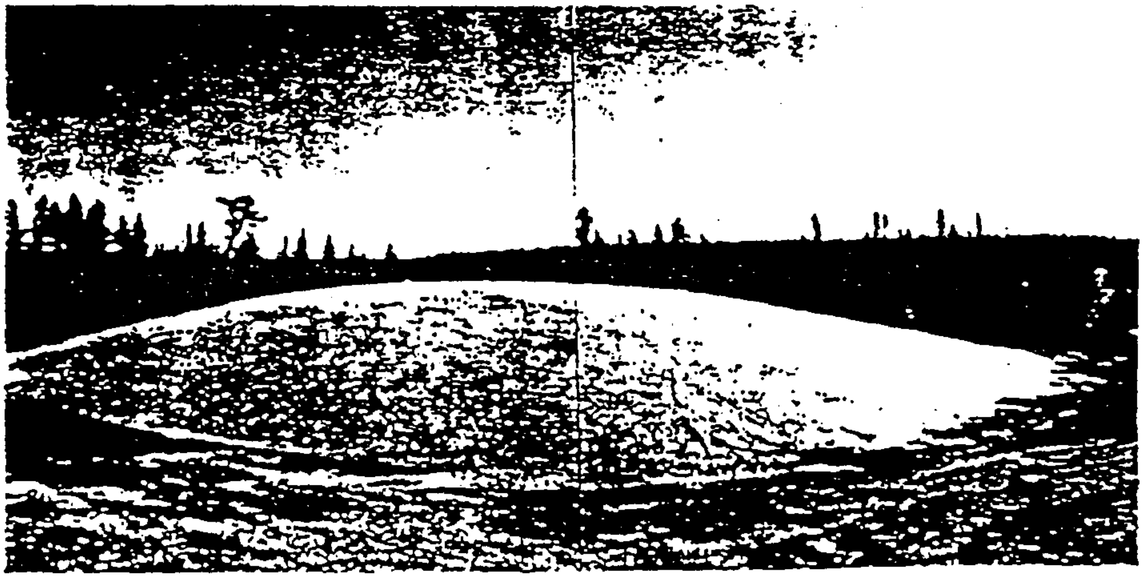

FIG. 8. Waste rock pile 7/12 after cover installation.

Erosion protection

A final 100-mm layer consisting of a well-graded gravel was added to the covered pile to provide erosion protection. This material was compacted with several passes of the vibratory compactor. A cross section of the completed composite cover is shown in Fig. 6. Photographs of the

FIG. 3. Placement and compaction of impermeable cover (glacial till).

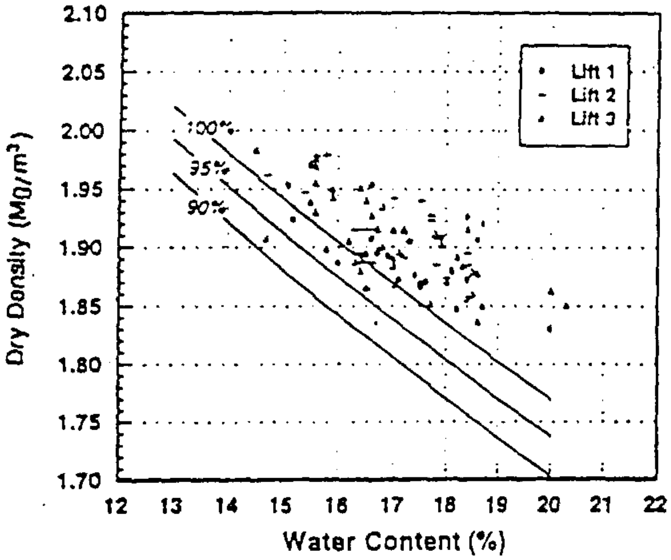

FIG. 4. In situ density vs. water content for compacted till.

each lift to ensure that the entire area (50 × 50 m in plan) was well covered. The next lift was placed only when the results of the density tests indicated that the till was being placed within an acceptable range of densities and water contents (−2 to −4% wet of the optimum water content). A total of 94 density tests were conducted. Figure 4 presents the dry densities and water contents obtained during the placement of each lift. The data indicate at least 95% of water saturation was achieved after compaction of each lift. The placement water content was, however, too high at some locations where an excessive number of passes of the smooth-wheeled, vibratory compactor may have been used to achieve the specified densities. The implication of this overcompaction (Holtz and Kovacs 1981) is a reduction in shear strength. For this cover where the overburden stress due to the granular cover is small (less than 10 kPa), stability may not have been unduly compromised by the overcompaction. The results of the tests are further illustrated in Fig. 5 for the first lift. The degree of compaction achieved for the three lifts ranged from 93 to 99%. Moulding water contents were from 15 to 19.5%, giving an average of about 17.3%, which was 3.5% above optimum.

The till was placed on the entire pile during September 4–14, 1991. Placement was completed on the west, south, and east side slopes during September 3–10, 1991 when the weather was generally sunny with moderate temperatures. On the top part of the pile, however, only the first lift was completed during this period. A major rainstorm on September 10, 1991 resulted in wetting of the first lift. The wet till was subsequently excavated, allowed to dry, and recompacted prior to the placement of the second lift on September 14. Placement of the cover on the north side slope was completed last. Precautions were taken during placement to ensure that no damage was done to existing piezometer installations located in the top and north side of the pile.

Following the installation of the final lift, field hydraulic conductivity tests were performed in the till using a single ring infiltrometer similar to the type described by Fernuik and Haug (1990). Hydraulic conductivity values, obtained at two locations on the top of the pile, were of the order of 1.0×10^{-7} and 1.0×10^{-8} cm/s.

Granular cover

A granular cover consisting of clean sand and gravel was placed over the entire pile. Grain-size analysis indicated the granular cover to consist of 40% gravel, 58% sand, and 2% silt- and clay-size particles. Modified Proctor compaction

TABLE 1. Construction specifications for composite soil cover

Surface preparation

Grade identified high areas on slide slopes (3H:1V), minimizing disturbance to pile
Excavate two 3.5 × 2 × 1.2 m holes at identified monitoring stations at the top of the pile for lysimeters: provide sand cushion at bottom of excavation and slope at 2% to promote drainage
Level top of pile filling voids and depressions with excavated waste rock or non-acid-generating crushed rock (−37.5 mm) or approved equivalent
Provide a tight seal between compacted till layer and pile

Sand base

Compact with several passes of a medium-size vibratory roller to 92% of maximum Modified Proctor density (ASTM 1987c)
Compact in two lifts to a finished total thickness of 30 cm
Ensure smooth surface of sand base to allow drainage
Ensure compacted surface is flat, with surface irregularity within ±25 mm of average grade
Finish final slopes at 3H:1V

Impermeable cover

Compact with medium-weight vibratory compactor or sheepsfoot roller (as approved by engineer) to achieve design specifications (Yanful et al. 1993)
Conduct preplacement test on a till pad using proposed equipment; pad to be compacted in a minimum of two layers and to measure at least 5 × 10 m in plan
Engineer to determine minimum number of passes of compactor (from test on pad) required for design densities
Compact till on sand base to at least 95% Modified Proctor density in three lifts (20 cm per lift) to a finished thickness of 60 cm
Apply water as necessary during compaction to maintain specified water content (−2 to +4% of optimum); if cover is excessively dried out, remove from site and replace
Engineer to perform field density tests on each lift before approving placement of next lift
In areas not accessible to rolling equipment, compact to specified density with approved mechanical tamper
Smooth top surface of cover to promote drainage

Granular cover

Place in maximum 15-cm lifts and compact to 92% of Modified Proctor to a finished thickness of 30 cm
Ensure compacted surface is flat, with irregularities within ±50 cm of average grade
Complete final slope at 3H:1V

Erosion protection

Particle size to be maximum of 75 mm and 15% by weight finer than 4.75 mm
Place uniformly over entire pile surface of granular cover to a minimum thickness of 10 cm

The design of a composite soil cover on a 0.25-ha experimental waste-rock pile located at Heath Steele mines near Newcastle, New Brunswick, is presented in Yanful et al. (1993). The design of the cover called for a three-layer system consisting of a 60-cm compacted till (impermeable cover) sandwiched between a 30 cm thick well-graded sand (sand base) and a 30 cm thick coarse-grained soil layer (granular cover).

This paper deals with the construction and instrumentation of the cover. A brief description of the geotechnical properties of the selected soils is presented. Monitoring data collected to date are also discussed.

Construction of cover

The design requirements for the cover presented by Yanful et al. (1993) and construction specifications outlined in Table 1 were developed into a request for a proposal that was submitted for costing. A contract was subsequently awarded for the construction of the cover in accordance with the specifications outlined in Table 1.

Surface preparation

The initial task in the placement of the cover was the preparation of the side slopes and the top of the pile. A Caterpillar 215 hydraulic excavator was used to level the top of the pile and remove high points on the side slopes. Voids and depressions were filled with excavated waste rock and non-acid-generating crushed rock. A total of 50 t of crushed rock was used for surface preparation. Sand and gravel covering the edges of the impermeable membrane underlying the pile at the perimeter were excavated manually to expose the membrane. Additional membrane was joined to the existing one at the edges of the pile and then extended out to provide a lap that ensured a tight seal between the till layer and the waste rock.

Sand base

The prepared surface of the pile was covered with a 30 cm thick layer of medium to coarse sand. In areas near the base of the pile, the thickness of the sand had to exceed 30 cm to achieve the required grades. Grain-size data indicated the sand consisted of 4% gravel particles, 90% sand, and 6% silt- and clay-size particles. The sand was compacted with a minimum of four passes of a 5-t vibratory compactor to achieve the required densities. The final surface of the sand was sloped at a minimum gradient of 2%.

Impermeable cover

Source and properties of glacial till

A borrow source for the appropriate glacial till was located approximately 2.5 km east of pile 7/12. Preconstruction grain-size analysis (ASTM 1987*a*, 1987*b*) indicated the till

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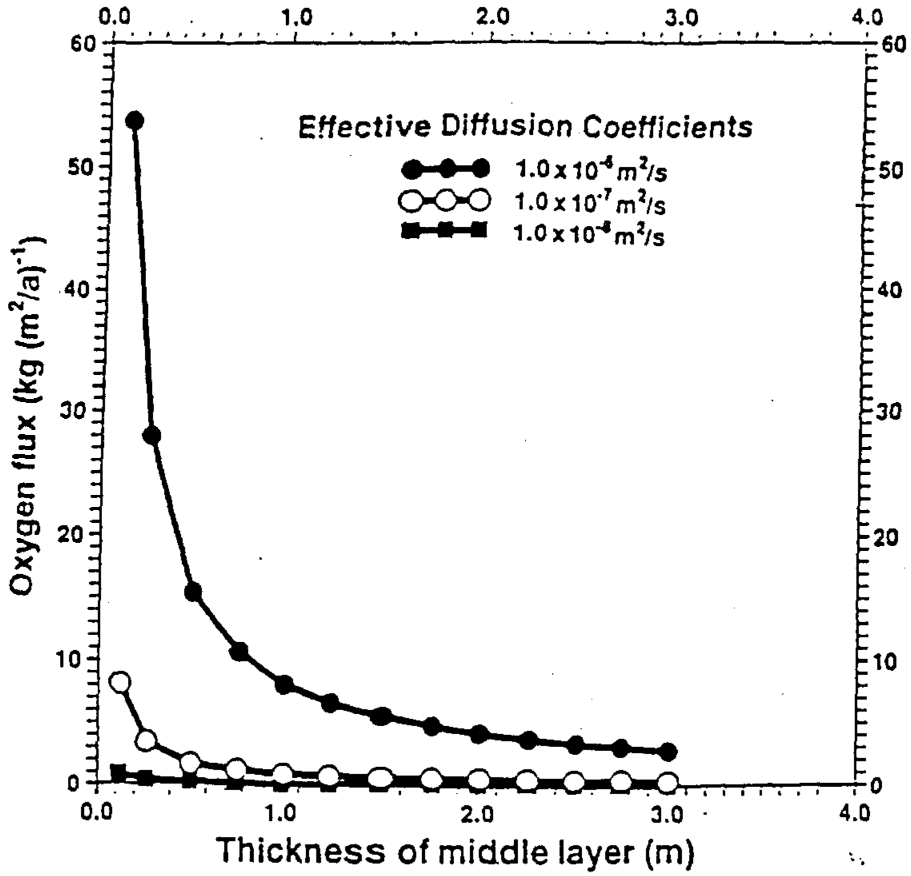

FIG. 6. Predicted oxygen flux vs. thickness of compacted till layer as a function of oxygen diffusion coefficient.

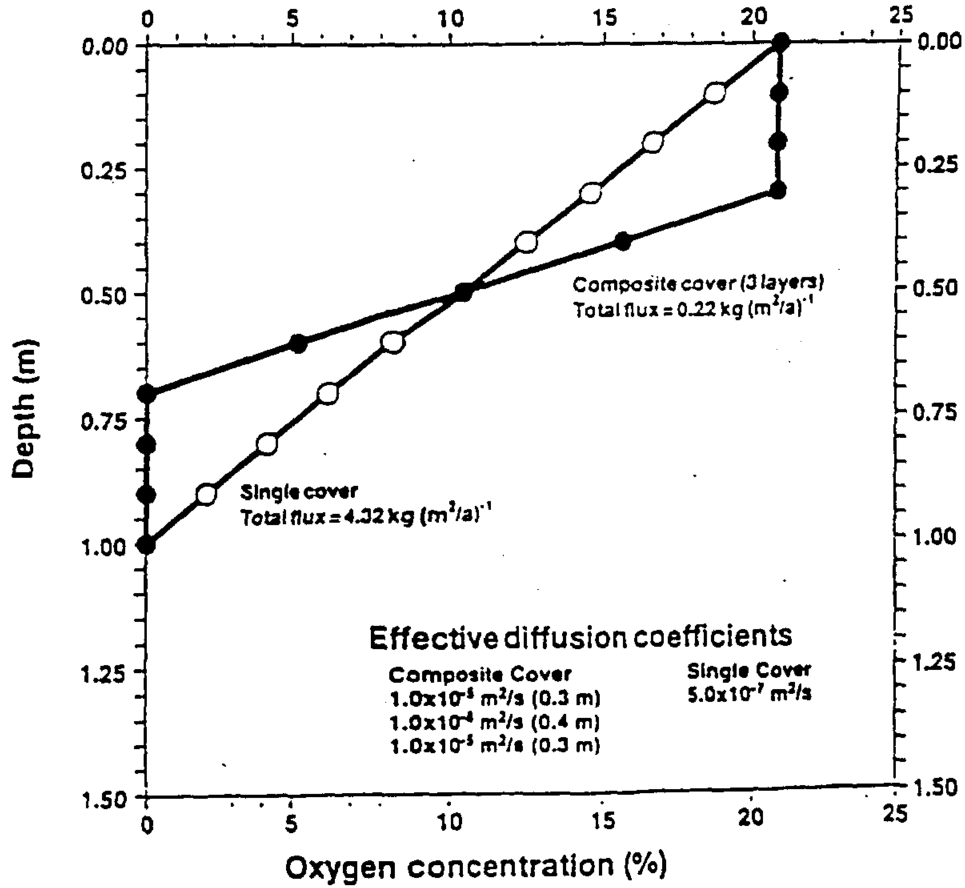

FIG. 7. Predicted depth of oxygen penetration in a composite soil cover compared with the penetration in a single cover.

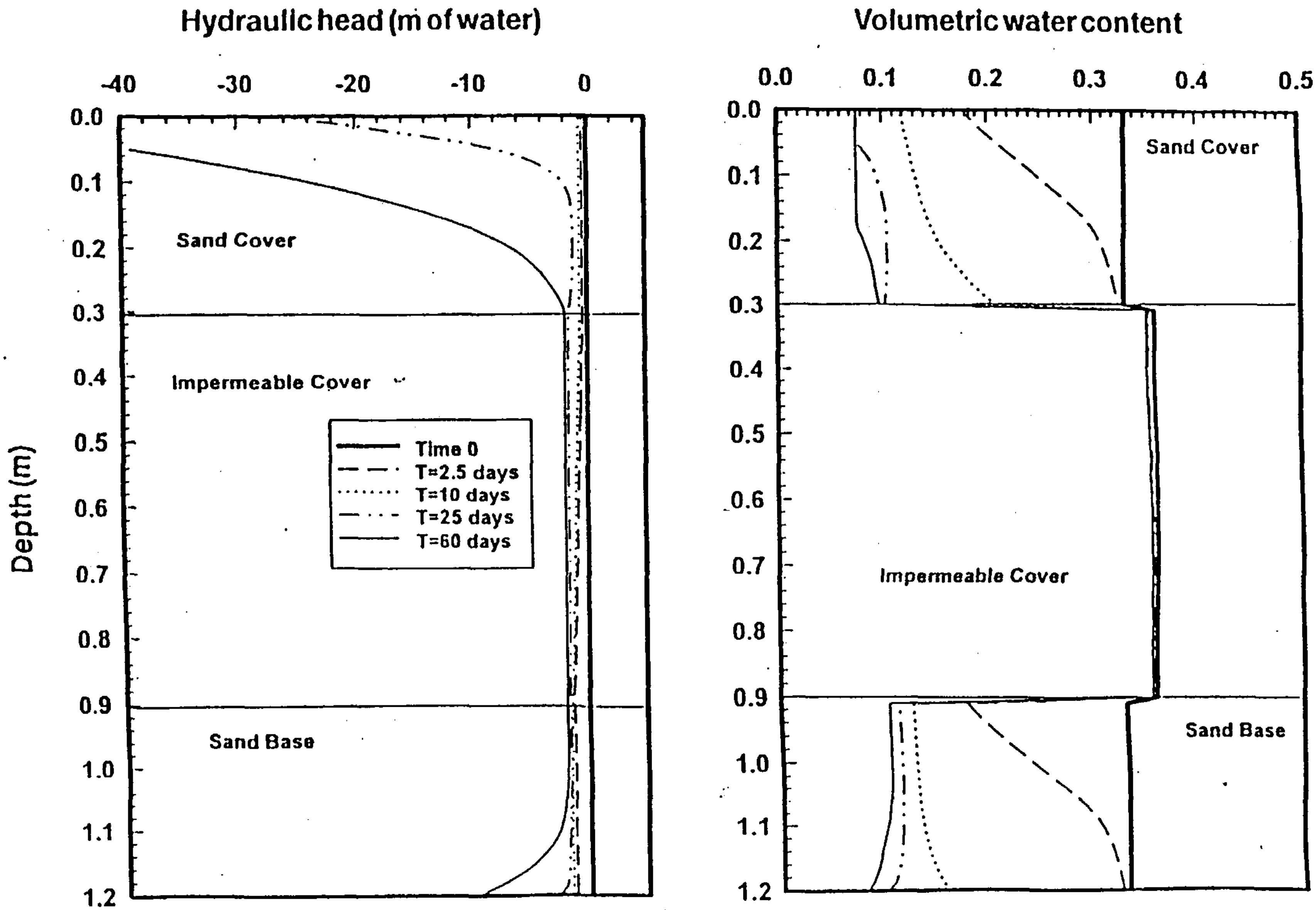

FIG. 4. Modelled hydraulic heads and water contents in composite soil cover.

TABLE 2. Summary of water-quality data for pile 7/12 from the period July 1989 – October 1990

	Surface runoff	Underdrains
pH	2.0–3.0	2.1–2.8
Acidity (as $CaCO_3$) (mg/L)	22 000 – 67 850	15 800 – 73 250
Sulphate (mg/L)	22 970 – 70 500	12 700 – 43 440
Dissolved iron (mg/L)	3600 – 18 800	3510 – 13 767

Waste-rock pile 7/12

Pile 7/12 was one of the four acid-generating waste rock piles at Heath Steele mine selected for monitoring and evaluation of remedial measures. It is located approximately 1 km from the Heath Steele mill complex off the main haul road (Fig. 1). The pile was moved to its present location and reconstructed in June 1989 as part of an ongoing test program to evaluate soil covers. It was placed on a prepared sand base, underlain by an impermeable membrane, by truck end dumping from the perimeter and pushing into the middle section with a loader. Placement on the impermeable membrane would permit the collection of leachate at the base of the pile before and after placement of the soil cover. Reconstruction included recontouring the pile to a maximum slope of approximately 3:1 (*H*:*V*). It was also isolated from the influence of any neighbouring topographical features. The reconstruction resulted in a more uniform pile configuration that was likely to minimize any shape-induced effects on the monitoring results and also facilitate the placement of monitoring instrumentation. A perimeter ditch was also constructed to allow for separate collection of surface runoff. The pile configuration prior to installation of the cover is presented in Fig. 2.

The relocated pile contains approximately 14 000 t of pyritic waste rock with maximum depth of 5 m. The predominant constituent sulphide mineral is pyrite (FeS_2), and total sulphur content averages about 5%. The physicochemical characteristics of the pile are presented in Table 1. The pile was instrumented with seven sets of thermocouples and six sets of pore-gas samplers. It is the only pile at the mine for which a water and contaminant balance can be determined and was therefore selected for cover placement and monitoring.

Although pile 7/12 has a maximum height of only 5 m, pre-cover temperature and gaseous oxygen data indicated behaviour similar to large waste rock dumps (of average height of 20 m) at the Rum Jungle site in Australia (Harries and Ritchie 1981, 1985). For instance, oxygen concentrations within the pile were found to be high enough (up to 19%) to allow oxidation to occur. Elevated temperatures tended to occur at locations where low oxygen concentrations were observed, confirming the exothermic nature of the oxidation process. In addition, thermal convection was found to be an important mechanism for oxygen transport into the pile through the base.

Waste-rock oxidation and cover requirements

Pile 7/12, like the other acid-generating waste-rock piles at Heath Steele mine, has already started oxidizing and presumably contains a large volume of stored acidity. Water quality of underdrain flows reported for the period April–October 1990 showed pH values in the range of 2.1–2.5, sulphate levels of 17 000 – 33 000 mg/L, and dissolved-iron levels of 3000 – 17 000 mg/L. Acidity, which is a measure of the total concentration of dissolved species capable of consuming alkaline materials, ranged from 16 000 to 73 000 mg/L. Surface runoff was also characterized by low pH and high acidity, sulphate, and iron (Table 2). These chemical characteristics are definitely indicative of acidic conditions. The mineralogical data (Table 1) also indicate that there is a substantial amount of unoxidized sulphide minerals left in the pile. Therefore, the two key aspects of an effective cover system are the control or mitigation of water infiltration and oxygen ingress into the pile. High infiltration rates would flush out large volumes of stored acid, resulting in high treatment costs. Residual iron sulphide minerals left in the pile will oxidize if the pile is exposed to air and moisture. Placement of an effective soil cover will decrease both infiltration and oxygen flux into the pile. Although the cover could decrease further oxidation to an insignificant level, release of stored acidity would continue, probably at a reduced rate, for a few years.

For the cover to be effective, it should have a low hydraulic conductivity and a high degree of water saturation. The high saturation results in a low oxygen diffusion coefficient which, in turn, leads to a low oxygen flux, since the flux *F* is proportional to the effective diffusion coefficient D_e according to Fick's first law:

$$[2] \quad F = -D_e \frac{\delta C}{\delta z}$$

where *C* is the gaseous oxygen concentration in the pores, and *z* is the distance in the direction of diffusion.

The cover will remain effective as long as it retains the properties of low hydraulic conductivity and high saturation. In adverse climatic conditions such as drying, freezing and thawing, these requirements may not be met in a single-layer cover. Moisture losses by evaporation and drainage will lead to desaturation and, possibly, cracking. Covers constructed from soils with high plasticities may develop shrinkage cracks upon freezing (Chamberlain and Gow 1979). The integrity of such covers could also be adversely affected by differential settlement of the underlying waste rock. Differential settlement may not be a major problem in pile 7/12 because of its small size. However, other aspects of the performance evaluation of the cover (such as the effects of freezing and thawing and reductions in temperature following cover placement) would still be applicable to other waste-rock piles. Vick (1983) noted that mill tailings, because of their low cohesion, could tolerate up to 1 m of settlement without fracturing. This would seem to suggest that covers constructed from soils with low cohesion such as silts would undergo less cracking as a result of differential settlement in the underlying waste.

In mill tailings where the grain-size distribution is finer than in waste rock, the water table can occur close to the

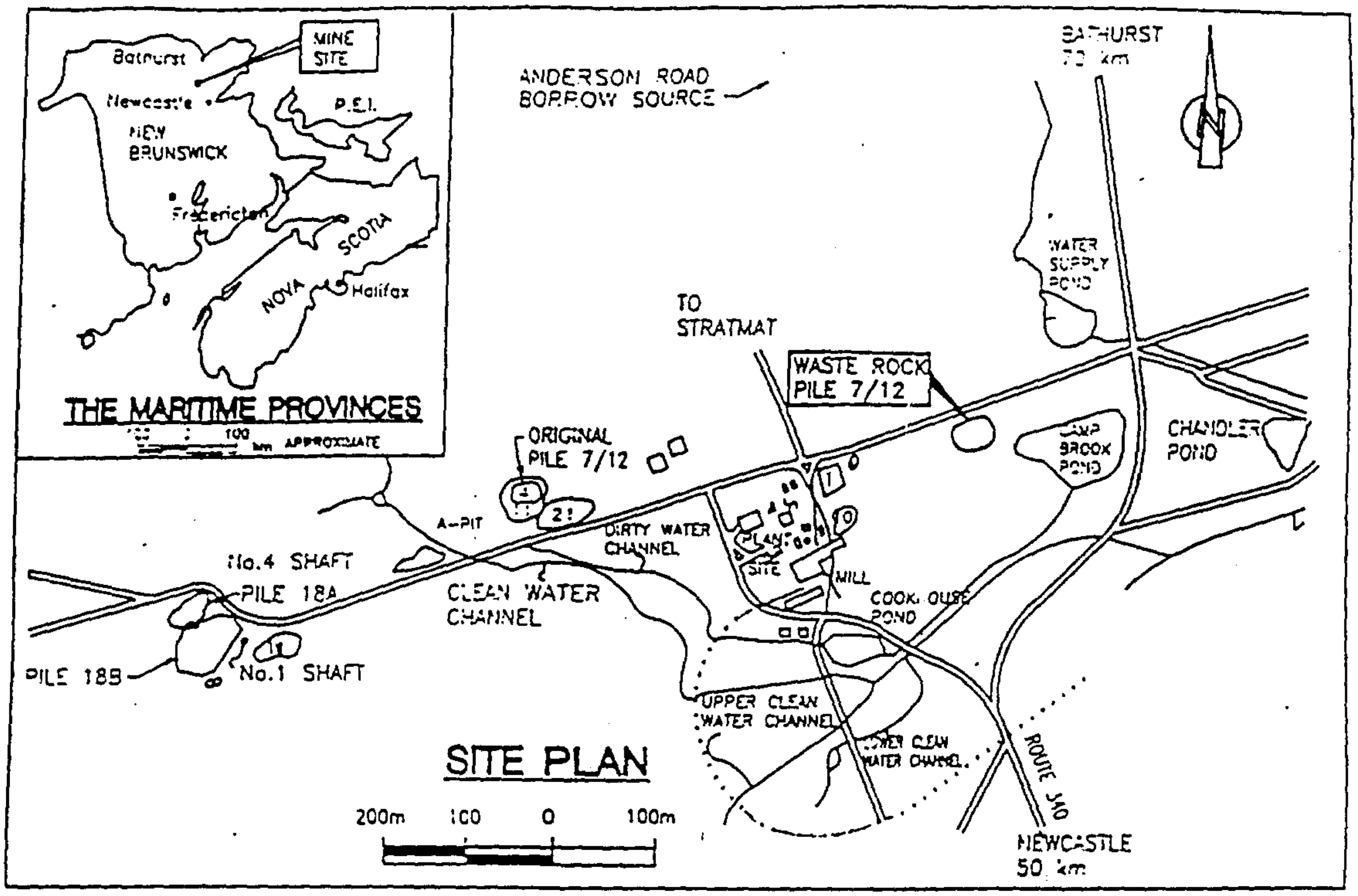

FIG. 1. Location of Heath Steele mine site and waste rock pile 7/12.

$$2FeS_2(s) + 7O_2(g) + 2H_2O(l) \rightarrow 2Fe^{2+}(aq) + 4SO_4^{2-}(aq) + 4H^+(aq) \quad [1]$$

The ferrous iron (Fe^{2+}) may in turn oxidize to ferric iron (Fe^{3+}) under bacterial mediation at low pH (1.5–3.5) conditions. The ferric iron released into solution can oxidize other heavy-metal sulphides present, such as galena (PbS), sphalerite (ZnS), and chalcopyrite ($CuFeS_2$). The final acidic solution seeping from the rock may therefore also contain high concentrations of heavy metals. This solution is generally referred to as acid rock drainage (ARD) and is considered the single largest environmental problem facing the mining industry (Filion and Ferguson 1989).

Generally, the waste rock is left underground after mining, or in the case of open pits it is piled on the ground surface and any acidic seepage produced is collected and treated by lime neutralization. At cessation of mining operations, the pile may be decommissioned either by covering or by continuing the collection and treatment of the seepage. In recent years, waste-rock decommissioning practices have also involved moving the rock back into the pit and flooding. Flooding requires successfully maintaining a certain depth of water above the acid-generating rock in the pit. This may be difficult if the bedrock in the pit area is fractured or if excessive drought conditions occur. Sometimes the residual iron sulphide minerals in the exposed pit walls oxidize, requiring further treatment of the pit water. Most cases of waste rock covering involve the use of engineered soil covers. The principal function of these covers is to minimize the transport of oxygen and water into the rock.

In 1989 a program was initiated by Brunswick Mining and Smelting Corporation Limited to develop and test strategies for long-term management of several acid generating waste rock piles located at the Heath Steele mine site. The program was conducted in four phases under the auspices of Mine Environment Neutral Drainage (MEND), Canada's national task force for ARD research (Filion and Ferguson 1989; Wheeland and Feasby 1991). The four phases comprised the selection of a few rock piles for field trials, definition of physicochemical characteristics of the selected piles; identification and evaluation of suitable candidate soils for a cover; and the design, installation, and monitoring of the cover on a selected pile.

This paper deals with the design of the composite soil cover installed on the selected waste rock pile, pile 7/12. Modelling results used in the design are discussed along with the geotechnical specifications for the cover materials. The physicochemical characteristics of the waste rock pile, prior to cover installation, and the history of mining and milling operations at the Heath Steele mine are briefly discussed. The construction, instrumentation, and monitoring of the cover are described in Yanful et al. (1993).

Site location and history

The Heath Steele mine site is located approximately 50 km northwest of Newcastle, New Brunswick, and about 60 km

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Pasco, Washington, U.S.A.

PART 1

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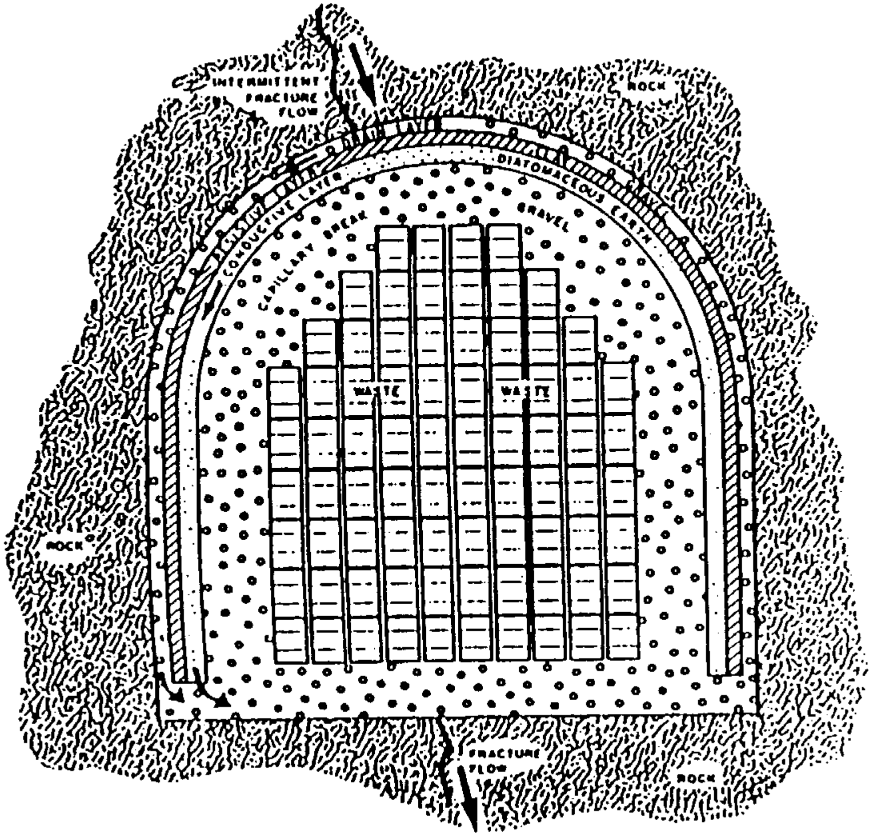

Figure 27. Artist's concept of resistive and conductive layer barriers to protect high-level waste from water flowing through rock fracture. Resistive (clay) layer diverts almost all fracture flow water. Conductive layer (very fine sand or diatomaceous earth) scavenges small quantities of water that pass through clay layer. Conductive layer transports scavenged water, under tension, around waste.

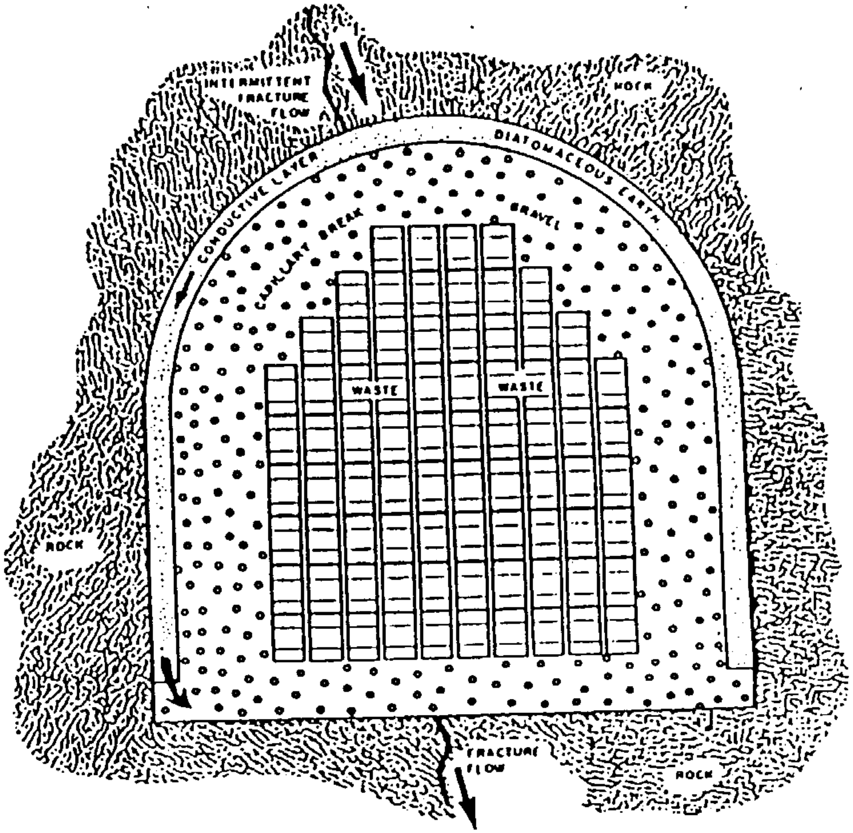

Figure 28. Simplified case of Figure 27. If fracture flow is slow (i.e., dropwise), conductive layer transports all water around waste; clay layer is then not needed.

ACKNOWLEDGMENTS

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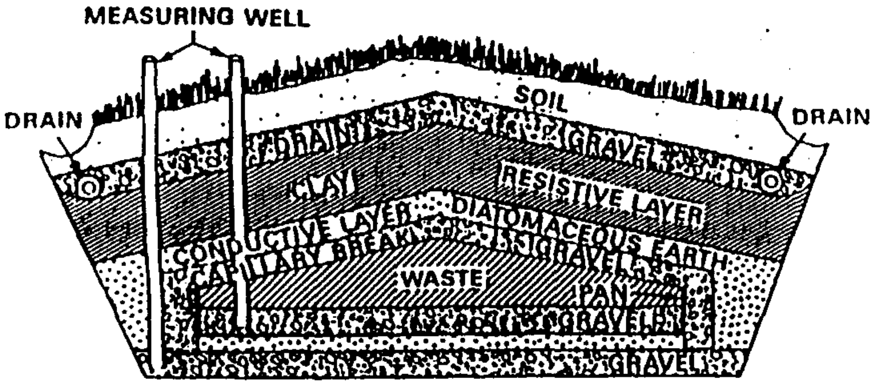


Figure 24. Combination resistive-layer barrier over a conductive layer barrier. Clay-barrier (resistive layer barrier) needs only to protect to approximately 10^{-4} cm/sec. Conductive-layer barrier of diatomaceous earth readily transports percolating water around waste.

making sand more attractive to some installers. Therefore, we have been conducting further studies with various sands. Results of studies of the unsaturated flow characteristics of four different sands are given in Figure 25. All these sands exhibit unsaturated flow rates that are about twice that of the diatomaceous earth at any given negative matric potential. The particle size distribution of the four sands is given in Table 3. The mortar sand, for example, had the narrowest particle size range, and the foundry sand had the widest particle size distributions, although the particle size distribution did not have an important effect on the flow rates reported in Figure 25. The Nevada dune sand and the Kelso dune sands are from large eolian deposits in the Nevada and California deserts, respectively. The Kelso deposit has been mined commercially. This work is ongoing; the hydraulic properties will be studied over a larger range of matric potentials; further deposits will be located and investigated; and these investigations will be described in a future report.

APPLICATION

The three procedures described in the Introduction may be used singularly or in combination to protect disposal units from percolating water. The principles apply equally to above-ground or below-ground disposal. For example, a combination of covers (1) and (2) described in the Introduction, could be ideal for a stabilized, shallow, land-burial facility, whether it is above or below ground: e.g., the subsurface disposal could be in below-ground vaults, and the above-ground disposal units could be earth-mounded concrete bunkers. A combination of a resistive layer over a conductive layer in a concrete bunker or above-ground application is shown in Figure 26. The resistive (clay) layer is the primary barrier. The small amount of water passing through the clay layer will be diverted around the concrete bunker by the conductive layer. This cover over the concrete bunker can, in theory, be 100% effective.

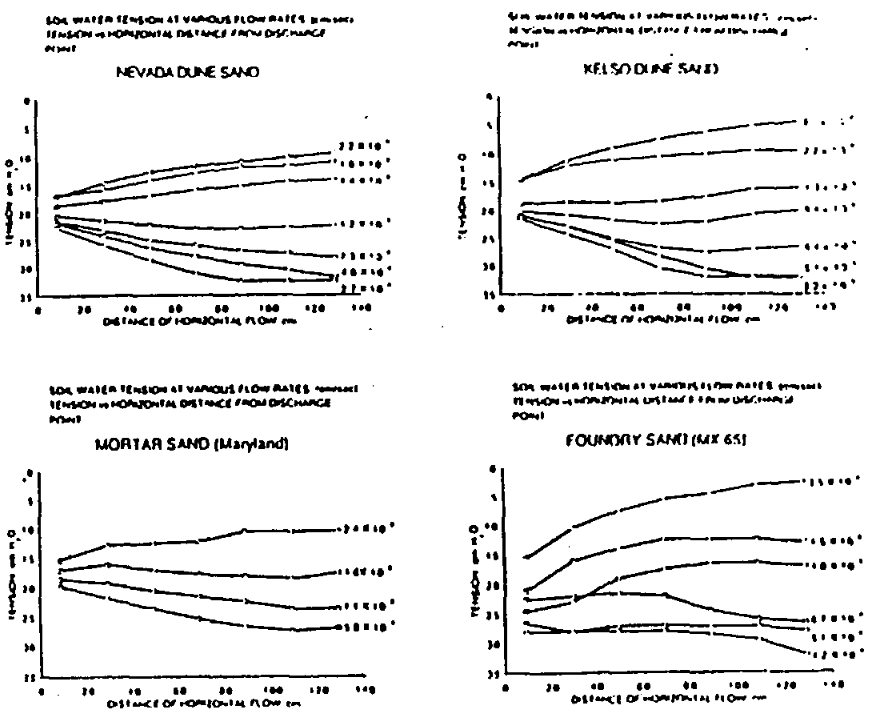


Figure 25. Unsaturated flow characteristics of four sands. Soil water tension at various flow rates, measured in miniature soil beam shown in Figure 20. Tension vs. horizontal distance from discharge point. Results suggest that, at about 10^{-7} cm/sec or less, water would remain under tension at any beam length. Slope of beam is 1:5.

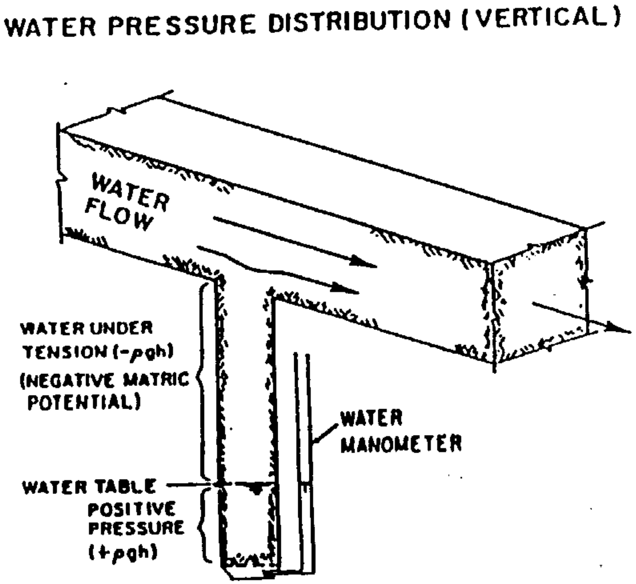


Figure 19. Schematic of laboratory apparatus for measurement of water tension, using different materials and varying flow rates.

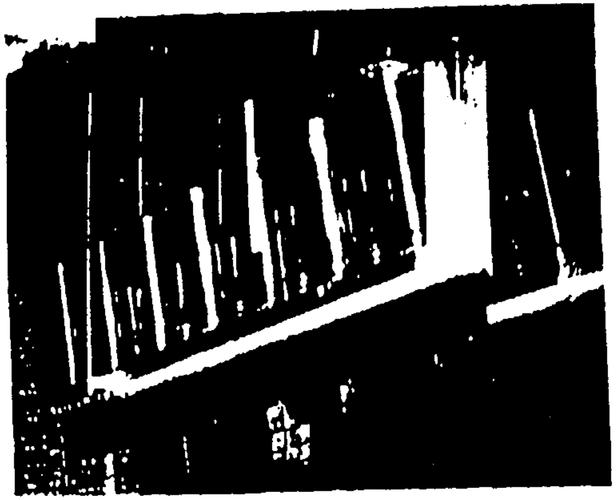


Figure 20. Miniature soil beam used for evaluation of materials for possible use in conductive-layer barrier application. Soil beam has total length of 4.5 ft. Lead bricks were placed on top of test material to simulate overburden.

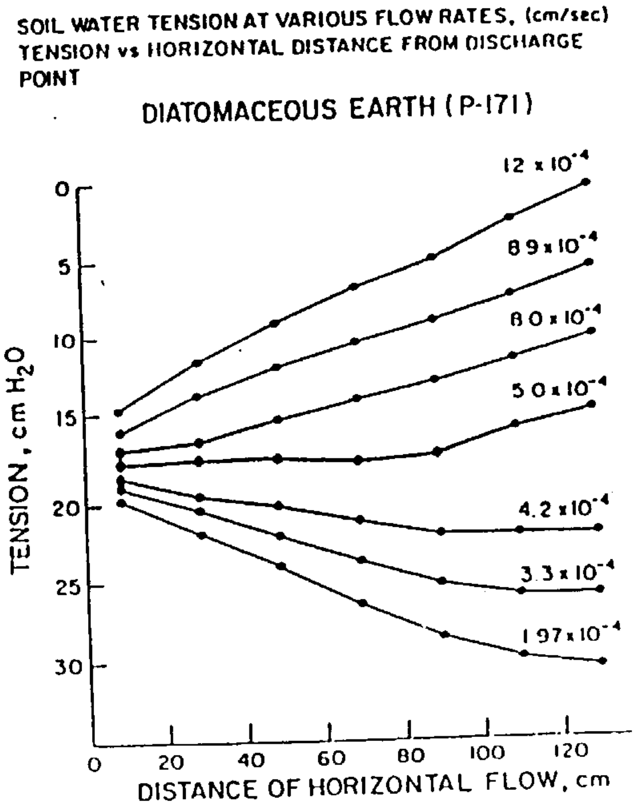


Figure 21. Soil water tension at various flow rates, measured in miniature soil beam shown in Figure 20. Tension vs. horizontal distance from discharge point. Results suggest that, at 4.2×10^{-4} cm/sec or less, water would remain under tension at any beam length. Slope of beam is 1:5.

The results of this experiment in the 4.5-ft-long beam suggest that, as long as the flow rate is no greater than 4.2×10^{-4} cm/sec, the soil water will remain under tension regardless of the soil beam length. These results show that with the use of diatomaceous earth for the conductive layer and following the easily achievable standard set above for the resistive layer, it should be possible to construct a barrier that would allow no water leakage to a waste-disposal unit. However, before final selection of the diatomaceous earth as the conductive layer material, we believed it to be prudent to conduct tests in a large-scale soil beam.

run-off from the rock-covered plot as from the grass-covered plot. Although the data show no deep percolation through the clay layers to date in either lysimeter, there is little indication as to how much safety margin has been offered. Nor is it known how consistently such near-perfect clay barriers would be installed in a routine operation. That remains a problem for future consideration.

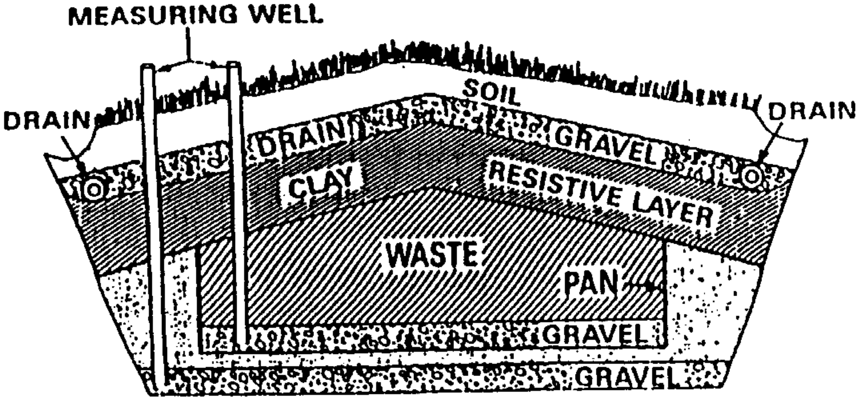


Figure 14. Resistive-layer barrier with grass cover. Similar to UMTRA cover but has vegetation in place of riprap. See Figure 13.

Another concern is the possible drying out of clay barriers. If this were to happen, the clay layer would not be as efficient a barrier for preventing radon escape as planned in the UMTRA application. In addition, drying out of the clay layer could lead to cracking, leading to subsequent leakage prior to resealing by wetting. Figure 15 gives the volumetric moisture content of clay in the rock-covered (lysimeter 4) and the grass-covered (lysimeter 6) plots. In no case did the clay layer dry out significantly. On the contrary, in the UMTRA or rock-covered plot, which was devoid of vegetation, there was a slight increase in moisture content with time, suggesting that some leakage of water through the clay layer may occur in the future. Lysimeter 6 has a clay layer and a grass cover. In this case, no increase in moisture content has been observed. On the contrary, to date the moisture content of the clay layer seems to be in a rather steady state, [illegible]n over the 5-yr period of measurement.

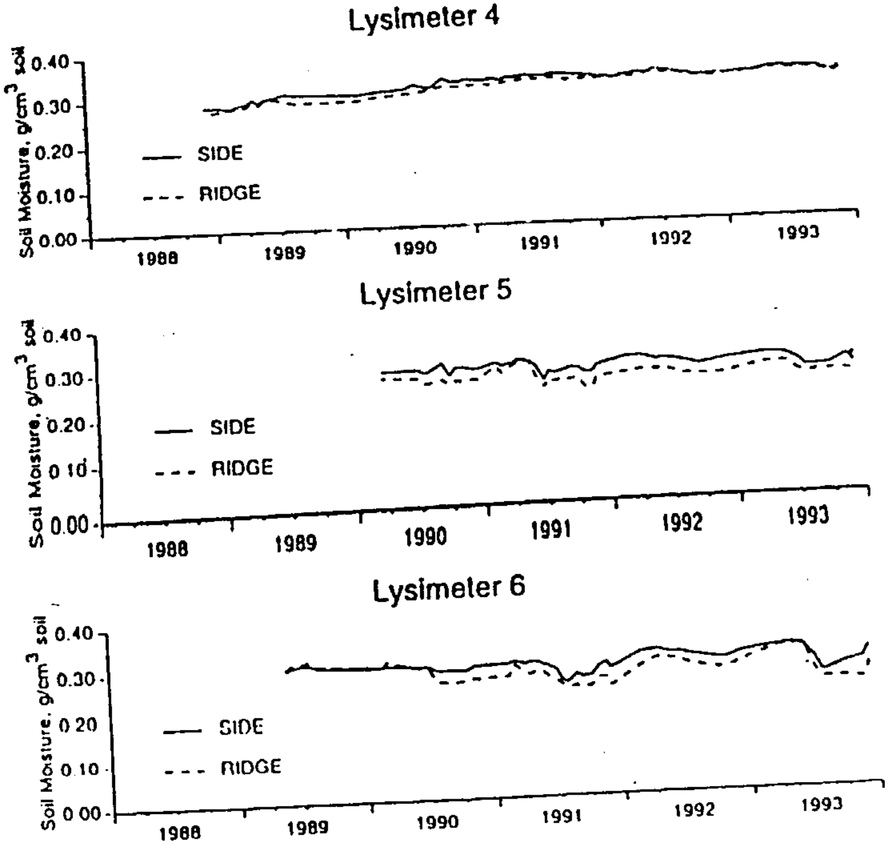


Figure 15. Moisture content of clay layers with time. Lysimeter 4 cover system is clay layer covered with gravel and riprap. No vegetation is present, and clay shows very slight increase of water content with time. Lysimeter 5 has capillary (conductive-scavenging) layer underneath clay layer; plot is planted with grass. During 4-yr life of plot, largest variations in moisture content were during summer. Lysimeter 6 has clay layer with grass cover. As in lysimeter 5, largest moisture excursions were in summer

Conductive Layer Barrier

If we consider the case of water flowing downhill in an unsaturated porous medium, we have the case shown in Figure 16. The "holes" shown in the diagram could be a rock layer, affording a capillary break or capillary discontinuity (Figure 17). Under appropriate conditions, water ever[illegible]here in these cross-sections will be under tension, and there will be no leakage. This might then serve as an excellent means

Table 2. Calibration of neutron probe used in lysimeters 1, 2, 4, 5, and 6. Calibration was carried out in a weighing lysimeter using soil of field lysimeters.

		Moisture Content	
		Volumetric	Oven-Dry Weight Basis
Date of Measurement	Std Count	$\frac{cm^3\,H_2O}{cm^3\,Soil}\left(\frac{V}{V}\right)$	% Measurement (Pw)
9-11-87	0.191	0.0109	0.65
10-14-87	1.78	0.258	15.6
10-23-87	1.72	0.246	15.0
2-02-88	1.62	0.223	13.6
5-27-88	1.52	0.203	12.4
10-05-88	1.44	0.183	11.2
11-30-88	1.38.	0.170	10.4
1-11-89	1.29	0.159	9.7
3-02-89	1.23	0.147	9.0
4-26-89	1.13	0.132	8.0
6-14-89	1.04	0.115	7.0
8-04-89	0.93	0.097	5.9
10-11-89	0.84	0.084	5.1
1-03-90	0.76	0.072	4.4
7-09-90	0.73	0.065.	4.0
12-07-90	0.62	0.052	3.1
5-22-91	0.56	0.043	2.6
11-14-91	0.52	0.040	2.4
4-28-92	0.50	0.036	2.2
9-10-92	0.46	0.033	2.0
1-18-93	0.44	0.030	1.8
6-13-93	0.41	0.025	1.5
9-17-93	0.37	0.021	1.3
1-7-94	0.35	0.020	1.2

Volume of soil in weighting lysimeter = 382 L; oven-dried weight of soil in weighting lysimeter = 628 kg; bulk density of soil = 1.65 g/cm³; 15 atmosphere moister (Pw) = 3.1%; 1/3 atmosphere moisture (Pw) = 7.1%; 15 atmosphere moisture (V/V) = 0.051 g/cm³; 1/3 atmosphere moisture (V/V) = 0.117 g/cm³; Air-dried moisture % (Pw) = 0.65%.

tion, are given in Figure 10. It is evident that use of the factory calibration on sand would result in a very large error in soil moisture determination.

Results of some neutron-probe measurements are shown in Figure 11 for bioengineered lysimeters 1 and 2. The data are plotted as volumetric moisture content, as a function of soil depth, on specific dates. Only

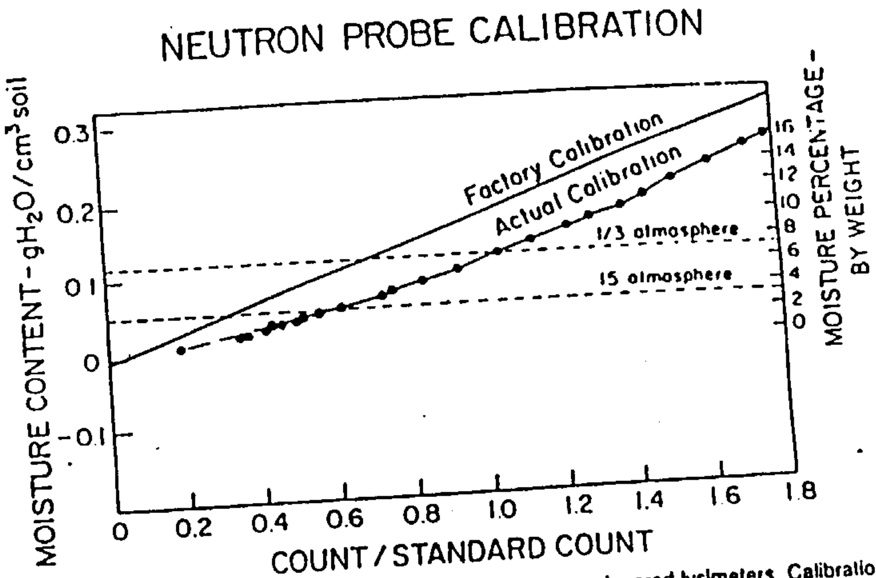


Figure 10. Calibration of neutron probe using soil of bioengineered lysimeters. Calibration carried out in weighing lysimeter over a 6-yr period. Factory calibration was supplied by manufacturer of neutron probe and made against sand rather than soil.

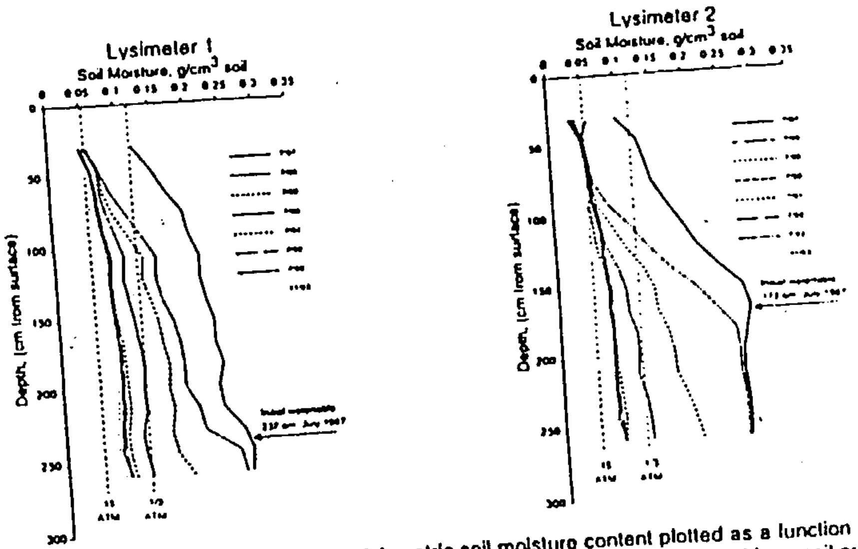


Figure 11. Bioengineered covers. Volumetric soil moisture content plotted as a function of soil depth at seven different dates. By July, 1989, water table was eliminated from soil profiles. As of November, 1993, all soil profiles, although relatively dry, still showed slightly increasing moisture content with depth.

two bioengineered lysimeters (i.e., a slope of 1:5). Performance data for the reference lysimeters are given in Figure 7.

The water level in the two reference plots or trenches (lysimeters 3 and 4) rose until it was near the surface. At that time, water was pumped

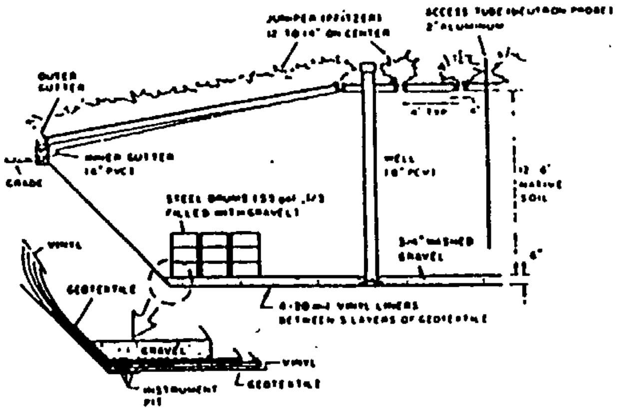


Figure 6. Side view of bioengineered lysimeter. Surface run-off is collected from both engineered surface and soil surface. Soil moisture content measured with neutron probe. Water table measured in well.

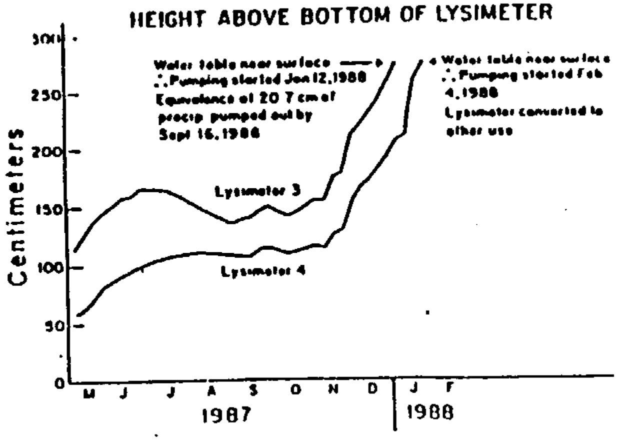


Figure 7. Water table vs. time in reference lysimeters. Crowned surface is planted with fescue grass. Water table increased with time until pum[illegible] was necessary to keep trench from running over. Surface run-off was 11% of precipitation...

from the lysimeters to keep them from running over. The graphs of the water tables (i.e., water levels) in the bioengineered plots (lysimeters 1 and 2) show an entirely different story, as evidenced in Figure 8. In both cases, the elevation of the water table was lowered. It appears that the bioengineering approach could prevent water infiltration to a disposal unit. It also could be used for a remedial action in dewatering existing problem sites such as Maxey Flats.

On February 4, 1988, lysimeter 4 was pumped out to prevent overflow. It was then discontinued as a reference lysimeter and converted to a rock-surfaced, resistive-layer barrier plot. Lysimeters 1 and 2 (bioengineered) and lysimeter 3 have been continued. A summary of run-off, evapotranspiration, and pumping from those three lysimeters is given in Figure 9.

Figure 9 shows that there was very little run-off from the grass-covered plot. Most of the precipitation was disposed of, by evapotranspiration by the fescue crop, but this was not adequate to prevent the rise of th water table. Table 1 gives the run-off, evapotranspiration, and dee percolation in the bioengineered plots during the past 6 yr. There wa no deep percolation during this period. The evapotranspiration ha been rising annually, probably as a result of the greater vegetativ canopy intercepting a greater percentage of the precipitation. In 198 1989, 1990, 1991, and 1992 the runoff percentages were 80, 74, 70, 6

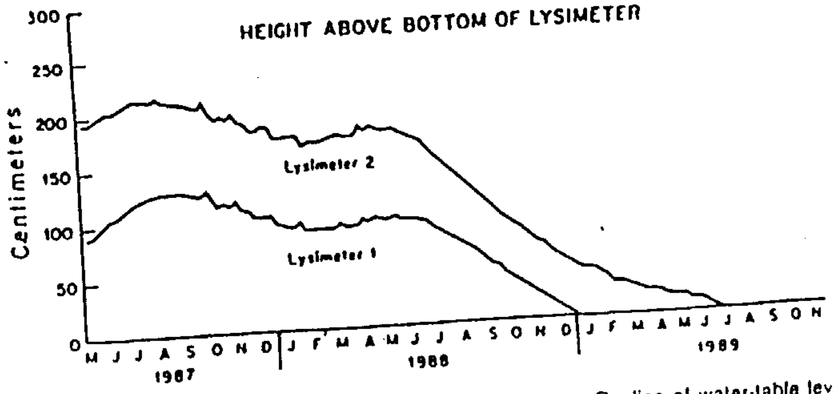


Figure 8. Water table vs. time in bioengineered lysimeters. Decline of water-table lev with time shows bioengineered covers effectively prevented water percolation. Eliminat water table shows that this procedure could be used for remedial action ("drying out" [illegible]ater table shows that this procedure could be used for remedial action [illegible]ding water logged burial sites. Compare with Figure 7

This system consists of a porous medium underlaid by a capillary break (rock layer). Infiltration barriers such as a conductive layer barrier or a clay layer barrier (or a combination thereof) must fail if subjected to substantial shearing caused by waste subsidence. Reestablishment of a layered system after subsidence failure is a difficult undertaking and is exacerbated by the increasing complexity of the layered system. The failure potential of in-ground layered systems during the subsidence period argues for development of an easily repairable surface barrier for use during that period. To that end, a procedure called "bioengineering management" was developed (Schulz et al., 1987). The bioengineering management technique utilizes a combination of engineered enhanced run-off and moisture-stressed vegetation growing in an overdraft condition to control deep water percolation through disposal unit covers. An artist's conceptual drawing is shown in Figure 3.

FIELD EXPERIMENTS

In this section we will discuss experiments being conducted in large-scale lysimeters at a humid region site in Beltsville, Maryland (see Figure 4).

In bioengineering management the necessary run-off is provided by features installed at or above the soil surface rather than within the profile. The procedure, described by Schulz et al. (1987), was designated bioengineering management. Its principal advantage is that subsidence can easily be managed by relatively simple, inexpensive maintenance of the above-ground features rather than by difficult reconstruction of below-ground layers. It should be noted that, after a length of time sufficient so that the organics have decayed and the waste containers have completely failed, subsidence will cease, and a layered system could then be installed which could last over geologic time periods.

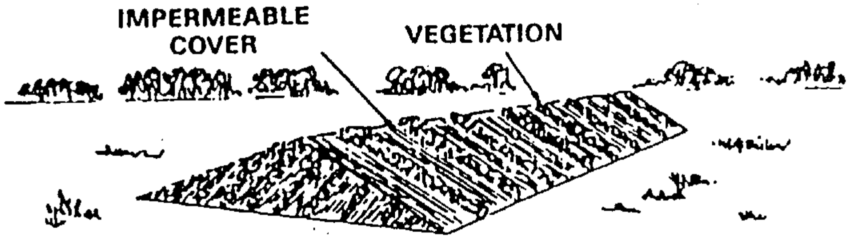
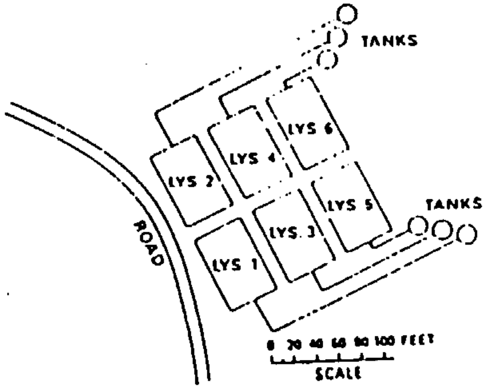


Figure 3. Bioengineering management.



Lysimeter		Date Completed
1	Bioengineering management	5/87
2	Bioengineering management	5/87
3	Vegetated crowned soil cover	5/87
4	Rip-Rap over resistive layer barrier	10/86
5	Resistive layer barrier over conductive layer barrier	1/90
6	Vegetation over resistive layer barrier	4/89

Design type and completion dates of experimental lysimeters located at Beltsville, MD.

Figure 4. Plan view showing placement of experimental lysimeters at Beltsville, Maryl

In essence, the bioengineering management technique utilizes a c
bination of engineered, enhanced run-off and stressed vegetation i
overdraft condition to control deep water percolation through disp
unit covers. To describe it further: if a waste burial site is selecte
that incoming subsurface flow is negligible, then precipitation is
sole source of input water. In a simplified model, that water has t
possible fates: (1) evapotranspiration, (2) run-off, and (3) deep per
tion. Evapotranspiration has a definite limit, governed by energy i
Ideally, deep percolation should be zero, leaving only the run-off
ponent available for unlimited manipulation. Positive control of ru
becomes difficult with the use of compacted porous media trench
as the sole barrier to water infiltration. The compacted material

CONTROL OF WATER INFILTRATION INTO NEAR-SURFACE, LOW-LEVEL WASTE-DISPOSAL UNITS IN HUMID REGIONS

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Key words: Waste disposal, water infiltration

ABSTRACT

This study's objective is to assess means for controlling water infiltration thro
waste-disposal unit covers in humid regions. Experimental work is being
formed in large-scale lysimeters (75 ft × 45 ft × 10 ft) at Beltsville, Maryl
Results of the assessment are applicable to disposal of low-level radioac
waste (LLW), uranium mill tailings, hazardous waste, and sanitary landfills.

Three kinds of waste-disposal unit covers or barriers to water infiltration are b
investigated: (1) *resistive layer barrier,* (2) conductive layer barrier, and (3)
engineering management. The resistive layer barrier consists of compa
earthen material (e.g., clay). The conductive layer barrier consists of a conduc
layer in conjunction with a capillary break. As long as unsaturated flow condit
are maintained, the conductive layer will wick water around the capillary br
Below-grade layered covers such as (1) and (2) will fail if there is appreciable s
sidence of the cover, and remedial action for this kind of failure will be difficu
surface cover, called bioengineering management, is meant to overcome
problem. The bioengineering management surface barrier is easily repairab
damaged by subsidence; therefore, it could be the system of choice under ac
subsidence conditions. The *bioengineering management procedure* also
been shown to be effective in dewatering saturated trenches and could be u
for remedial action efforts. After cessation of subsidence, that procedure coul
replaced by a resistive layer barrier or, perhaps even better, by a resistive la
barrier/conductive layer barrier system. The latter system would then
long-term effective protection against water entry into waste without institutio
care.

As mentioned in the preceding paragraph, a bioengineering management c
might well be the cover of choice during the active subsidence phase
waste-disposal unit. Some maintenance is required during that period. Final
ure, using geological materials, could follow cessation of subsidence. No fu
significant maintenance would then be required. If the geological material us

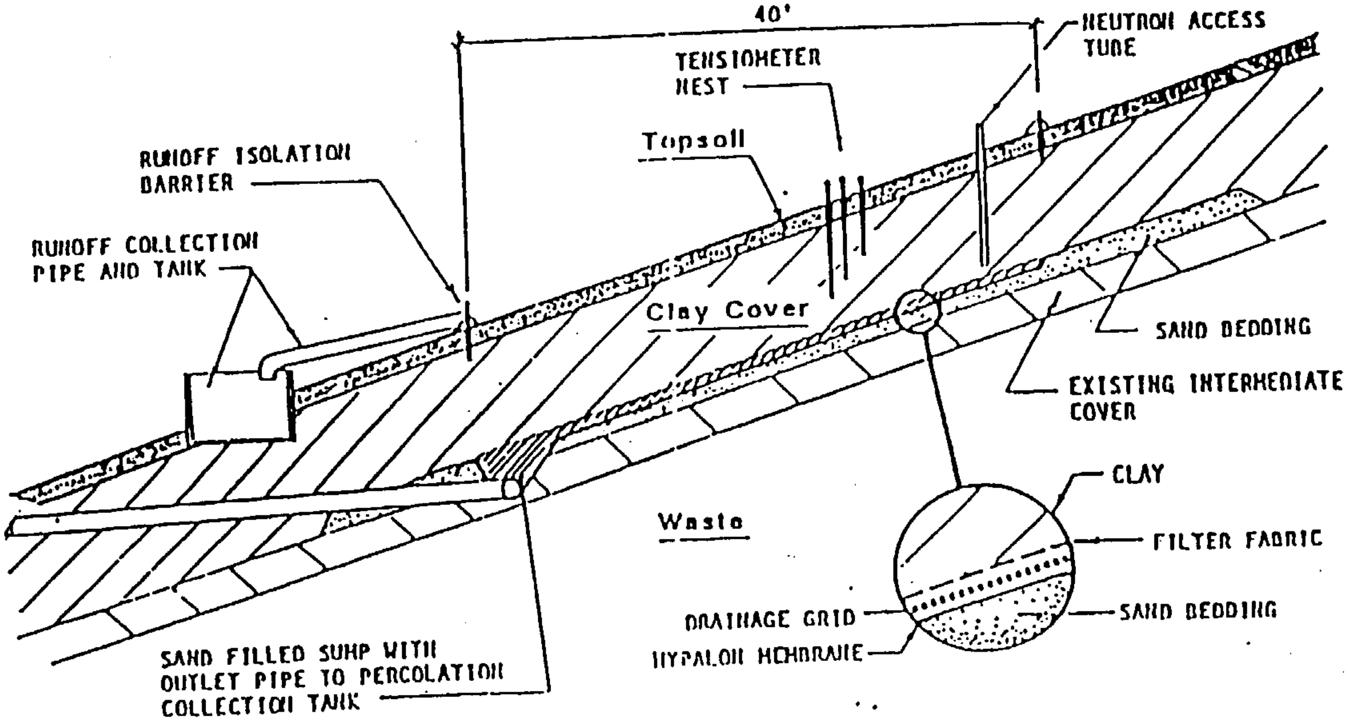

FIGURE 3: SCHEMATIC SECTION OF TYPICAL TEST PLOT

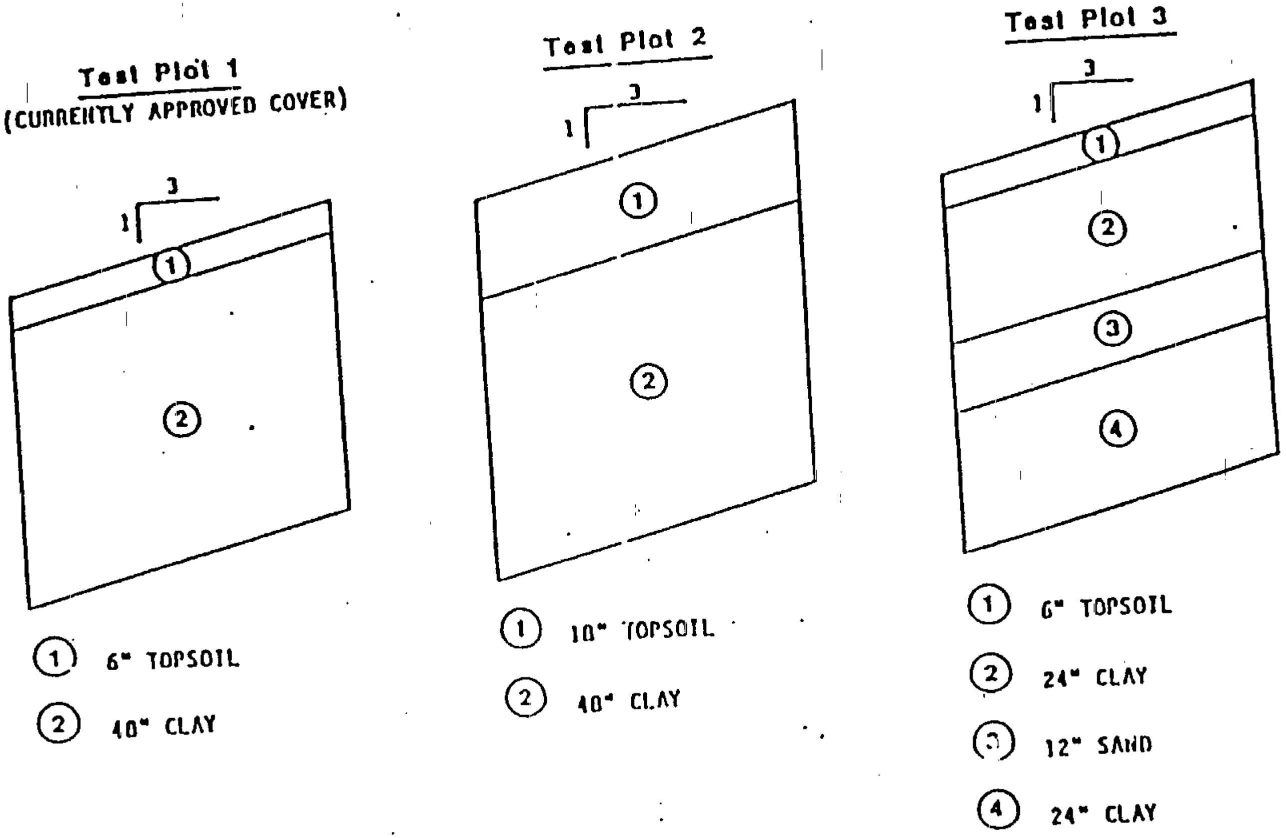

FIGURE 1: COVER DESIGNS INSTALLED AT OMEGA HILLS TEST PLOT SITE

TABLE 1 - PAGE 3 OF 4

SEPTEMBER 1988 THROUGH AUGUST 1989
RECORDED MONTHLY PRECIPITATION, RUNOFF, PERCOLATION AND COMPUTED MONTHLY WATER BALANCE

	PRECIPITATION		TEST PLOT 1				TEST PLOT 2				TEST PLOT 3				
MONTH	LONG TERM[1]	ON-SITE[2]	RUNOFF	PERC	STORAGE	CALC ET	RUNOFF	PERC	STORAGE	CALC ET	RUNOFF	PERC	SAND	STORAGE	CALC ET
SEP	2.88	4.81**	0.13	0.79	2.54	1.35	0.26	0.02	2.24	2.28	0.11	0.06	0.71	2.706	1.23
OCT	2.25	1.95	0.05	0.03	-0.22	2.09	0.03	0.02	-0.33	2.23	0.00	0.04	0.01	-0.53	2.43
NOV	1.98	3.70	0.18	0.50	0.70	2.30	0.15	0.59	2.19	1.51	0.00	0.23	0.96	--	--
DEC	2.03	1.22	0.13	0.16	0.11	0.82	0.03	0.24	0.20	0.75	0.06	0.14	0.70	--	--
JAN	1.64	0.57	0.00	0.08	0.05	0.44	0.00	0.26	0.07	0.24	0.0[illegible]	0.08	0.52	--	--
FEB	1.33	0.30	0.00	0.04	0.11	0.15	0.00	0.25	0.13	-0.08	0.01	0.03	0.25	--	--
MAR	2.58	1.22	0.25	0.19	0.05	0.73	0.70	0.27	0.13	0.12	2.03	0.10	0.90	--	--
APR	3.37	0.89	0.08	0.05	-0.38	1.14	0.07	0.09	-0.59	1.32	0.01	0.11	0.17	--	--
MAY	2.66	3.41	0.14	0.07	-0.27	3.47	0.14	0.10	-0.66	3.83	0.08	0.12	0.32	--	--
JUN	3.59	3.05**	0.23	0.13	-0.05	2.74	0.18	0.31	-0.59	3.15	0.07	0.23	0.30	--	--
JUL	3.54	5.08**	0.26	0.08	-0.27	5.01	0.20	0.08	-0.33	5.13	0.06	0.22	0.15	--	--
AUG	3.09	6.17**	0.23	0.07	0.49	5.38	0.20	0.12	1.39	4.46	0.08	0.24	0.22	--	--
TOTAL	30.94	32.40	1.68	2.19	2.86	25.62	1.96	2.35	3.85	24.94	2.60	1.60	5.21	--	--

Notes: All units in dimension of inches of water depth.

Precipitation Data: (1) Long Term Normal Recorded at Milwaukee Mitchell Field NOAA Station based on the 1951-1980 record period.
(2) Measured On-Site at Omega Hills Test Plots

CALC ET - Calculated Evapotranspiration

STORAGE - Change in moisture content from Neutron Probe data, expressed in inches.

NA Data collected, but not yet reduced

* Estimated for period Sep 4-24, 1986 and for later periods of tank overflow.

** On-site record augmented using Germantown NOAA Station Data for periods of site raingage failure.

-- Soil moisture storage data collection for Test Plot 3 discontinued in November 1988.

TABLE 1 - PAGE 1 OF 4

SEPTEMBER 1986 THROUGH AUGUST 1987
RECORDED MONTHLY PRECIPITATION, RUNOFF, PERCOLATION AND COMPUTED MONTHLY WATER BALANCE

(inches)

	PRECIPITATION		TEST PLOT 1				TEST PLOT 2				TEST PLOT 3				
MONTH	LONG TERM[1]	ON-SITE[2]	RUNOFF	PERC	STORAGE	CALC ET	RUNOFF	PERC	STORAGE	CALC ET	RUNOFF	PERC	SAND	STORAGE	CALC ET
SEP	2.88	9.78	4.40*	0.00	1.30	4.08	2.80*	0.00	1.72	5.26	2.80*	0.20	4.90*	2.18	-0.30
OCT	2.25	1.63	0.40*	0.00	0.00	1.23	0.18	0.00	0.13	1.32	0.32	0.18	0.80*	-0.07	0.40
NOV	1.98	0.86	0.00	0.00	0.00	0.86	0.00	0.00	0.00	0.86	0.00	0.00	0.04*	-0.20	1.02
DEC	2.03	0.86	0.00	0.00	-0.59	1.45	0.00	0.00	-0.13	0.99	0.00	0.00	0.40*	-0.53	0.99
JAN	1.64	0.65	0.00	0.00	0.16	0.49	0.00	0.00	-0.20	0.85	0.00	0.00	0.50*	0.53	-0.38
FEB	1.33	0.89	0.31	0.02	0.27	0.29	0.08	0.00	0.20	0.61	0.26	0.01	0.04*	0.26	0.32
MAR	2.58	1.81	0.00	0.00	-0.16	1.97	0.00	0.00	0.00	1.81	0.08	0.06	2.15*	-0.20	-0.28
APR	3.37	4.31	1.60	0.0	-0.70	3.37	0.82	0.06	-0.99	4.42	0.06	0.34	1.39	-1.12	3.64
MAY	2.66	1.32	0.00	0.00	-0.43	1.75	0.00	0.05	-0.59	1.86	0.00	0.19	0.53*	-0.66	1.26
JUN	3.59	1.48	0.10	0.00	-1.51	2.89	0.10	0.03	-2.11	3.46	0.07	0.13	0.14	-1.45	2.59
JUL	3.54	7.28	0.19	0.01	0.70	6.38	0.20	0.05	0.66	6.37	0.09	0.27	2.34	0.92	3.66
AUG	3.09	4.41**	0.11	0.03	0.97	3.30	0.13	0.08	1.32	2.88	0.12	0.21	0.16	0.99	2.93
TOTAL	30.94	35.28	7.11	0.06	0.01	28.06	4.31	0.27	0.01	30.69	3.80	1.59	13.39	0.65	15.85

Notes: All units in dimension of inches of water depth.

Precipitation Data: (1) Long Term Normal Recorded at Milwaukee Mitchell field NOAA Station based on the 1951-1980 record period.
(2) Measured On-Site at Omega Hills Test Plots

CALC ET - Calculated Evapotranspiration
STORAGE - Change in moisture content from Neutron Probe data, expressed in inches.
NA Data collected, but not yet reduced
* Estimated for period Sep 4-24, 1986 and for later periods of tank overflow.
** On-site record augmented using Germantown NOAA Station Data for periods of site raingage failure.
-- Soil moisture storage data collection for Test Plot 3 discontinued in November 1988.

Total Precip = 104.23"

Test Plot 3. Root densities have been consistently higher in the 18 inch topsoil (Test Plot 2) and have progressively become more dense and more deeply penetrating into the clay soils. The density data was not noticeably different for primary vs. alternative vegetation mixes.

CONCLUSIONS

A great deal of data on final cover performance has been obtained from the Omega Hills Test Plot Study, of a type which is not generally available. The principal long-term value of the project may be the development of this large body of record information, which could be utilized for development of improved analysis techniques or alternative cover design development. Regarding the specific objectives of this project, the following conclusions can be drawn at this time:

1. The timing and response of percolation data suggests, and the test pit investigations have tended to confirm, that the development and propagation of cracks in the cover soils dominates the factors controlling percolation performance. The apparent impact of dessication cracks developed during 1988 indicates that drought conditions may be much more damaging to cover performance than a continuous supply of moisture.

2. The re-wetting of the clay soil profiles in 1989 and 1990 has substantially reduced the appearance of cracking in the clay soils, but has not reduced percolation rates to pre-drought conditions. Longer term data needs to be collected to evaluate this issue.

3. Analysis procedures which are based on assumptions of either saturated or unsaturated porous media flow may not be applicable to many practical landfill cover situations without careful evaluation.

4. The multi-layered cover design did not result in lower percolation rates due to retention of soil moisture in the upper clay layer. To the contrary, the upper clay became thoroughly cracked, allowing rapid infiltration of moisture to the intermediate sand layer.

5. The thicker topsoil utilized in Test Plot 2 has not noticeably reduced cover percolation. The effects of increased moisture retention in the thicker topsoil during the dormant season may outweigh the possible effect of increased evapotranspiration.

6. Although the alternative vegetation species mix appears to produce a more vigorous vegetation cover, comparison of the two sets of vegetation regarding cover percolation performance is not possible.

The above conclusions are based on data drawn from a particular set of soils, construction and climatic conditions, over a specific observation period. Extreme caution should be taken in attempting to generalize these conclusions to other sites or conditions.

PROJECT STATUS

Data collection for the instrumented test plots and the alternative vegetation areas is continuing, and is expected to be conducted for the next several years.

B. Runoff

Runoff production during the first year of data collection was substantial from each test plot, with Test Plot 1 producing over 7 in. of runoff. However, these runoff depths are dominated by response to the very heavy rains of September, 1987, and are also probably due to the immature growth of the cover vegetation. It is interesting to note that runoff from Test Plot 3 was even higher than that for Test Plot 1, if the moisture flow from the intermediate sand layer is included.

Runoff production decline substantially in the second and third years of data collection. The obvious reason for low runoff in 1987-1988 is the drought. However, the intermediate sand layer continued to produce moisture in response to the small rainfall events which occurred in the summer of 1988, indicating very rapid percolation through the cracked soils of the upper clay layer. During the 1988-1989 period, runoff from Test Plots 1 and 2 was similar, while runoff from Test Plot 3 was the largest. This surprising result may be due to the continued poorer condition of the vegetation on Test Plot 3, although this trend was not continued in the first eight months of 1989-1990 data collection. The collected data does not indicate that the greater topsoil thickness (and hence possibly larger rapid infiltration capacity) of Test Plot 2 serves to reduce runoff.

C. Evapotranspiration

The calculated evapotranspiration (ET) term of the water budget accounts for a significant fraction of total precipitation for each of the test plots. Approximately 90% of the total two year precipitation was calculated as lost to ET in Test Plot 1 and 94% in the thicker topsoil, Test Plot 2. Lower ET rates were calculated for Test Plot 3 (approximately 57% of the total two-year precipitation in 1987 and 1988). This was attributed to the substantial moisture flow through cracks in the upper clay layer and interception by the intermediate sand layer, thus reducing moisture availability for evaporation or transpiration. Evapotranspiration percentages are higher for later periods of the study, when vegetation was better established and without the influence of the record rainfall rates occurring in September 1986.

Based on 1988-1990 data, the 18-inch thick topsoil of Test Plot 2 is not providing any substantial increase in evapotranspiration, and the originally anticipated increase in ET moisture retention capacity (and hence ET) of the upper clay in Test Plot 3 has not occurred. Moisture monitoring for Test Plot 3 was discontinued in 1988, and calculation of ET values for the fourth year of data collection awaits reduction of neutron probe soil moisture data.

D. Soil Moisture Content Variations

Monthly soil moisture storage changes were interpreted from CPN neutron probe data collected at 6 inch to 12 inch intervals at seven locations in each test plot. Little horizontal variation of soil moisture content within each test plot was noted. However significant variations in moisture content occurred with depth. In general, drying influences were seen through the upper three feet of each cover during summer months, particularly during the drought period in 1988. Below depths of 3 feet in Test Plots 1 and 2 moisture contents remained fairly static.

The observed hydrologic responses of Test Plot 3, where substantial moisture was transmitted through the upper clay layer, correlated with moisture content data in that cover soil profiles and to aid in the interpretation of the hydrologic budget data.

The 4 ft by 10 ft test pits were excavated to 6 ft deep via a track mounted backhoe. Samples were taken at approximately one foot increments or when material characteristics changed and soil moisture contents (dry weight basis) were determined. Shrinkage limits were determined on the upper and lower clay for Test Plots 1, 2 and 3 following ASTM D427 procedures. Key results of the test pit investigation are listed below.

- The upper 8 to 10 inches of clay in all three test plots appeared weathered and exhibited a medium to coarse sized blocky structure.
- Occasional larger cracks, 1/4 to 1/2 inch wide, extended 35 to 40 inches into the clay, beyond the topsoil/clay interface, in Test Plots 1 and 2 and through the entire upper clay in Test Plot 3. A noticeable curvature of cracks downslope was observed, particularly in Test Plots 1 and 2.
- A continuous root mass penetrated 8 to 10 inches into the clay below the topsoil/clay interface. Further root penetration occurred along crack planes approximately 30 inches below the topsoil/clay interface.
- The clay texture at the base of each test plot exhibited higher moisture contents and no evidence of cracking.
- No distinguishable separations between lifts associated with placement of the clay were observed in any of the profiles.
- Shrinkage limits ranged from 10 to 12% moisture content on a dry weight basis (approximately 20 to 24% on a volume basis). The shrinkage limit is the moisture content at which the soil volume will not change upon further drying. Moisture content data taken via the neutron probe during the dry period in June-July 1988 indicated levels close to the shrinkage limit in the upper clay of all three test plots suggesting that more substantial cracking than observed (due to dessication and shrinkage) would be unlikely.
- Soil profile characteristics in the vegetation assessment areas were similar to Test Plot 1 and 2 profiles with roots observable at cleavage faces between cracks.

A second test pit in Test Plot 1 was excavated in May, 1990, to evaluate changes in the profile due to recovery from the drought of 1988, and to evaluate additional vegetative root penetration. This test pit was excavated in the buffer strip area adjacent to Test Plot 1, approximately 10 ft upslope from the 1988 test pit. The pit exposed the full depth of the profile, down to the underlying intermediate cover on which the test plots were constructed. Samples were collected for moisture content and density at approximately 1 ft increments in the cover clay, and Shelby tube samples were obtained from near the base of the cover for permeability testing. Observations made in this second test pit in the Test Plot 1 cover are summarized below:

- No major cracks were observed in the clay soils, in sharp contrast to the pronounced cracking of the upper portion of the clay which was so obvious in 1988.

system, as well as the soil moisture monitoring instrumentation. Figure 4 depicts the overall layout of the instrumented test plots and vegetation assessment area, all located on the western outboard slope of the Omega Hills landfill.

Construction of the basal percolation collection systems and placement of the clay cover soils was conducted in September through November of 1985. Topsoil placement and instrumentation of the test plots was completed by July of 1986, and data collection began in August.

DATA COLLECTION

Precipitation, runoff, percolation, air and soil temperature, and soil moisture tensiometer data is collected using a data logging system, which allowed remote access to data via telephone modem. Precipitation data is collected using a heated tipping bucket rain gage. Runoff and percolation data is collected for each test plot using pressure transducers installed in collection tanks (refer to Figure 2). The transducers indicate water level within the tank, with the ratio of tank area to plot area used to obtain runoff and percolation depths. Test Plot 3 utilizes a collection tank for collecting flow from the intermediate sand layer, as well as for percolation and surface runoff (See Figure 4). Air temperature and relative humidity data is collected using sensors monitored by the data logger. Cover soil temperature is also monitored using the data logger, with sensors buried at depths of 1, 3 and 5 ft below the surface of the 3H:1V sideslopes of the landfill. Two nests of soil moisture tensiometers are installed in each instrumented test plot, with from 5 to 7 tensiometers (with tips at different levels) in each nest. Each of the tensiometers was equipped with a pressure transducer wired to a multiplex input to the data logger. Data logger collection frequency was hourly from August, 1986 through September 1989, when it was altered to four-hourly.

Soil moisture data was also collected using a neutron probe. Seven galvanized steel access tubes were driven into each test plot, and the probe was field-calibrated using laboratory soil moisture data from field samples.

Vegetation density and root penetration data was collected approximately twice-yearly, for both the alternative seed mix assessment areas, as well as for non-instrumented sections of Test Plots 1, 2 and 3.

Data collection has been continuous since mid-August 1986, and the collected data is believed to present an accurate description of overall test section performance. However, some problems have been encountered in the data collection program, summarized below:

- The heated tipping bucket rain gage occasionally malfunctioned, requiring the use of daily precipitation data form the NOAA observation station at Germantown, Wisconsin (3.2 mi NW of the landfill) to fill in the gaps.
- The tensiometer pressure transducers experienced a high rate of failure, and monitoring was discontinued in September 1988. Soil moisture monitoring with the neutron probe has continued.
- Evaluation of vegetation density and root penetration, and comparison of the primary and alternative seed mixes was very difficult, due to the immaturity of the vegetation stand, disturbance caused by instrumentation maintenance and mowing, and the effects of the drought of 1988.

THE OMEGA HILLS FINAL COVER TEST PLOT STUDY: FOURTH YEAR DATA SUMMARY

by

ROBERT J. MONTGOMERY and LAURIE J. PARSONS

ABSTRACT

Instrumented test plots have been installed at the Omega Hills Landfill, located near Milwaukee, Wisconsin, to collect data on the hydrologic performance of three final cover designs. Each of the test plot designs employs natural soils installed on 3H:1V landfill sideslopes. Two designs incorporate different thicknesses of local silty loam topsoils over thick sections of compacted clay soils. The third design is a multi-layered cover, intended to take advantage of the so-called "wick effect" by placing a sand layer between two compacted clay layers, with topsoil above. In addition, two cover vegetation species mixes are being evaluated in separate test areas. Data collection began in August of 1986, and included a significant period of drought in 1988, as well as periods of heavy precipitation. After nearly four years of data collection, several observations appear to be significant. The propagation of cracks within the clay soils appears to be all-important to the performance of the cover designs evaluated. The upper clay layer of the multi-layered design has developed substantial cracking which has apparently allowed transmission of large amounts of infiltrated moisture to the intermediate sand layer. However, percolation from the base of the multi-layered cover has remained relatively low, apparently due to the continued moist and homogeneous conditions in the clay layer below the intermediate sand. The two all-clay test sections initially showed very little percolation. However, percolation has increased substantially through time, again apparently related to the development and propagation of cracks through the clay soils. A summary of the collected data is presented, as well as observations and interpretations based on field observations and test pits.

BACKGROUND

The Omega Hills Landfill, operated by Waste Management of Wisconsin, Inc., is located approximately 20 miles northwest of the center of Milwaukee, Wisconsin. The 83-acre site has been active since the 1970's, and has recently completed filling of its approximately 14 million cu yd licensed capacity. Waste Management of Wisconsin has conducted a very substantial program of environmental measures to control offsite leachate migration, provide gas control and energy conversion and to extract and treat leachate from within the site. This program won recognition in the American Society of Civil Engineers 1986 Outstanding Civil Engineering Achievement Awards.

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SURFACE BARRIERS: PROBLEMS, SOLUTIONS, AND FUTURE NEEDS

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Key words: *Cover, cap, barrier, clay, permeability, infiltration*

ABSTRACT

The problem of designing a surface barrier for a remediation project can be an enormously challenging task. There is a widely held misconception that surface barrier technology is well developed and works as expected. In fact, the technology is largely unproved and experimental, particularly in terms of long-term performance.

The most difficult problem with surface barriers is to provide a long-term barrier to infiltration of water. The materials that have traditionally been considered for the hydraulic barrier within surface barrier systems are low-permeability compacted soil, geomembranes, and the geosynthetic clay liner (GCL). Data are presented to suggest that low-permeability compacted soil is often a poor choice of materials. Unless the compacted soil liner is buried under a very thick layer of protective soil or covered by a geomembrane, the low-permeability, clay-rich, compacted soil is likely to desiccate and lose its low hydraulic conductivity. Differential settlement of a compacted soil liner from uneven compression of underlying waste or other causes is almost certain to produce cracks within the soil liner. Geomembranes do not suffer as much from these problems, but their design life is, at best, a few centuries. The GCL, which contains a thin layer of bentonite, is much better able to resist damage from freezing/thawing, desiccation, and differential settlement than compacted soil liners. The technology of the GCL, which is particularly well suited for arid sites, is reviewed in some detail in this paper because of its technical attributes in surface-barrier applications.

Published case histories of the performance of surface barriers are summarized. There are many more published examples of failures than successes. It is likely that many, perhaps most, surface barriers are failing to achieve fully their long-term design objectives.

There is a great need to understand more about surface barriers. The primary challenges are: (1) developing surface barriers that can withstand large differential settlement; (2) using materials that can withstand seasonal changes in water content without cracking; (3) developing hydraulic barriers that will be essentially impermeable for hundreds of years or longer; and (4) verifying in the field that surface barriers can and are working as well as anticipated.

to control the lateral flow of water from the toe of the barrier (where water accumulates) to the waste zone. If the barrier overhang is great enough, the amount of water (if any) that gains access to the waste zone via lateral flow would be sufficiently minimized to reduce the potential for contaminant leaching and subsequent transport.

The asphalt or grout curtains consist of a vertical ring or band of low-permeability materials that completely encircles a waste site. The curtain would be constructed so that runoff water from the barrier would be diverted onto the side of the curtain opposite the waste zone.

The barrier toe could be designed to intercept and retain runoff water from the barrier until it can be passively recycled back to the atmosphere via evapotranspiration. One concept being evaluated is the construction of a retention-pond type of structure. This feature is constructed by extending the subsurface asphalt layer in the barrier into a shallow trench dug along the periphery of the toe of the barrier. The asphalt layer serves as a liner in the trench. Gravel and silt loam fine soil are backfilled over the asphalt liner. The silt loam fine soils are vegetated to take advantage of the transpiration capabilities of plants. Runoff water from the barrier is allowed to flow into the soils in the retention pond system. Based on lysimeter studies at the Field Lysimeter Test Facility (FLTF), the fine soils will probably store moisture during the fall and winter months. This stored water will subsequently be removed from the soils by evapotranspirational processes during the warmer spring and summer months, reducing the amount of water available for recharge.

STATUS OF THE BARRIER DEVELOPMENT EFFORT

The BDP, as it is currently structured, has been in existence since 1986. During this time, the emphasis of the program's efforts has been on the development and testing of various barrier components that are based on preliminary barrier conceptual designs. Mostly, these development and testing efforts have been performed either in the laboratory or on relatively small-scale field plots. Although not completely resolved, issues pertaining to protective barrier performance with respect to water infiltration, biointrusion, erosion and deposition, physical stability, and climate change are being addressed. Natural analog studies of various barrier components also have been conducted, and computer simulation models have been used to predict the performance of preliminary barrier conceptual designs.

The data and insights gained from conducting barrier development tasks have enabled the BDP to progress to the point where the design, construction, and testing of a full-scale prototype is vital to continued barrier development. Although the results of development and testing efforts conducted heretofore are not final and additional work needs to be performed, enough information and data exist to allow the design, construction, and testing of a prototype barrier. A full-scale prototype of a permanent isolation surface barrier is enabling engineers and scientists to gain insights and experience with issues regarding barrier design, construction, and performance that have not been possible with the individual tests and experiments conducted to date in the program.

The design of the prototype barrier was completed in 1993. Following the completion of the design effort, a bid package was prepared and a construction contract let. The contractor began construction activities in late 1993 and completed construction of the prototype barrier near the end of summer, 1994.

Once constructed, the prototype barrier will be tested and monitored for a minimum of 3 yr to evaluate its performance within the range of conditions representative of those expected to be experienced during the design life of a permanent isolation surface barrier (Gee et al., 1993). Many tests and experiments are planned to assess the performance of the prototype barrier vis-à-vis water infiltration, biointrusion, erosion, and physical stability. Because only a finite amount of time exists to test a prototype barrier that is intended to function for a minimum of 1000 yr, the testing program has been designed to "stress" the prototype so that barrier performance can be determined within a reasonable time frame.

The 3-yr testing period is considered the minimum amount of time necessary. Approximately 1 yr is expected to be required for the prototype barrier to stabilize following construction. During this first year after construction, the soils in the prototype barrier probably will experience minor amounts of uniform settlement. Moisture content in the soils also will equilibrate from construction levels to natural field conditions. Even though the prototype's surface will be revegetated, the vegetation will need some time to become established. Efforts will be made to expedite the establishment of vegetation on the prototype's surface by

Field Tests and Experiments

Field tests and experiments enable scientists and engineers to test various barrier components using actual barrier construction materials. These tests are designed to be conducted under ambient climatic conditions as well as under conditions simulating a change in climate over the next 1000+ yr. In this manner, components of the surface barrier can be tested under the range of conditions that are expected to be encountered during the barrier's design life. The results of the field tests and experiments are used to develop final barrier designs.

Computer Simulation Models

Computer simulation models are being developed for use in assessing the performance of permanent isolation surface barriers over their intended design life. The collection of field and laboratory data is necessary to generate the information required to validate the computer models. Many of the field and laboratory tests and experiments mentioned previously are designed to quantitatively evaluate the performance of protective barriers. The field and laboratory data will be compared with the predictions of the computer simulation models. Modifications and refinements of the models will be made, as needed, so that the natural processes taking place in the barrier are accurately simulated. Once validated, the computer models become particularly effective tools for predicting barrier performance (1) during periods of time much longer than can be tested in the field and (2) under environmental conditions representative of anticipated future climates.

While the models are being developed, they are used to perform sensitivity analyses to gain insights into the design, testing, and performance of various barrier systems and components.

Natural Analog Study Tasks

Insights into permanent isolation surface barrier performance can be obtained by studying analogous natural or man-made objects. For example, many of the borrow pits at the Hanford Site have relatively fine soils overlying coarser-textured materials. This layering sequence, which closely resembles the permanent isolation surface barrier, was primarily caused by the deposition of waterborne materials during catastrophic floods that occurred about 13,000 yr [illegible]. Because these materials have remained relatively unchanged through such long periods, the materials can serve as functional models for the performance of and changes expected to occur to permanent isolation surface barriers during extended periods of time.

Similarly, mounds constructed to protect tombs or for temple platforms are known to have existed for hundreds to thousands of years. Many of these ancient mounds have survived extremely well and are still intact. The BDP has studied these anciently engineered mounds to gain insights that will enable current design efforts to produce a similarly durable and functional structure. This study and that of other analogs is particularly effective for predicting barrier performance with regard to physical stability and maintenance requirements.

Studies of other barrier analogs have been conducted, planned, or considered to provide insights into how the barrier can best be designed to accomplish the design objectives. For example, studies of asphalt durability are being performed on asphalt specimens from museum collections that range in age from 150 to 5000 yr. Desert pavements and other naturally occurring rock-armored surfaces have been studied to develop erosion-resistant surfaces and to determine the effects of these armored surfaces on water balance. The ability of plants to re-establish themselves following perturbations such as range fires can be predicted from studies of plant community dynamics on the soils that will be used for barrier construction. The potential for biointrusion of various layers of surface barriers can be assessed by observing the burrowing activities of animals and the rooting behavior of plants living in analogous layered soils. Furthermore, the potential effects on barrier performance caused by future shifts in climate can be deduced by comparing the parameters of interest at locations that exhibit the predicted climatic variability.

Input to the Final Design of the Barrier

The information and experience gained from conducting field tests and experiments, performing computer simulations, and studying natural analogs will be used as input for the final design of permanent isolation surface barriers. These activities are also necessary to assess the barrier's ability to meet design objectives.

INTRODUCTION

Engineered barriers are being developed to isolate wastes disposed of near the earth's surface at the U.S. Department of Energy's (DOE) Hanford Site near Richland, Washington. Much of the waste that would be disposed of by in-place stabilization is currently located in relatively shallow subsurface structures, such as solid-waste burial grounds, tanks, vaults, and cribs. Unless protected in some way, the wastes could be transported to the accessible environment via the following pathways: plant, animal, and human intrusion; water infiltration; erosion; and the exhalation of noxious gases.

Permanent isolation surface barriers have been proposed to protect wastes disposed of "in place" from the transport pathways identified previously (Figure 1). The protective barrier consists of a variety of different materials (e.g., fine soil, sand, gravel, riprap, asphalt, etc.) placed in layers to form an above-grade mound directly over the waste zone. Surface markers are being considered for placement around the periphery of the waste sites to inform future generations of the nature and hazards of the buried wastes. In addition, throughout the protective barrier, subsurface markers could be placed to warn any inadvertent human intruders of the dangers of the buried wastes (Figure 2).

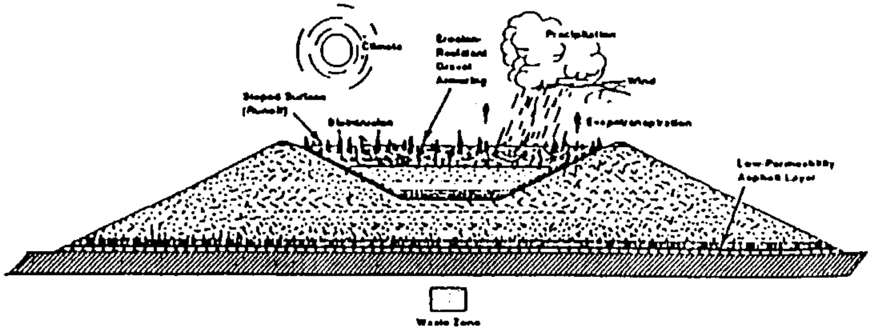

Figure 1. Functional performance of barriers.

The isolation barriers use engineered layers of natural materials to create an integrated structure with redundant protective features. Natural construction materials (e.g., fine soil, sand, gravel, riprap, asphalt) have been selected to optimize barrier performance and longevity.

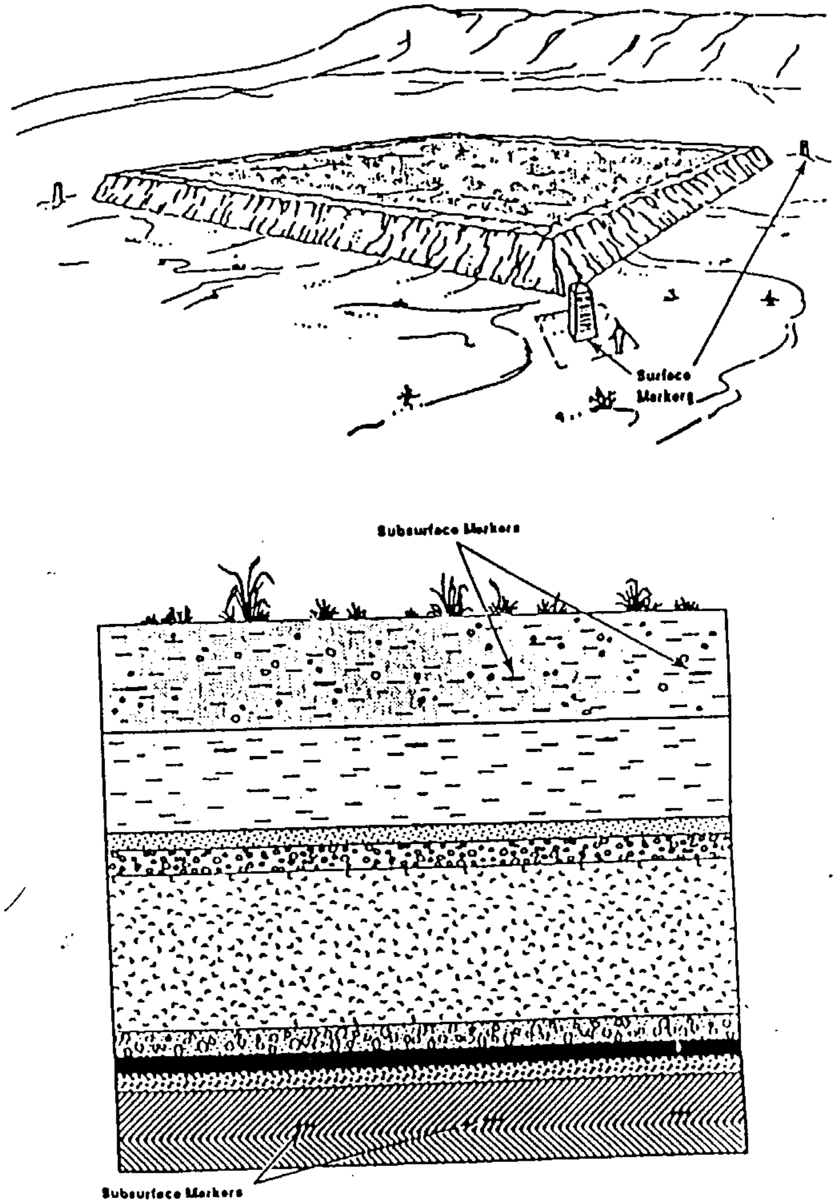

Figure 2. The placement of surface and subsurface markers.

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TABLE C.1. (contd)

		EVENING 07/01/92		MORNING 07/02/92	
SAMPLE	DEPTH(cm)	%H2O(g/g)	SUCTION(Mpa)	%H2O(g/g)	SUCTION(Mpa)
D08-2	0.5	0.56	145.4	1.88	56.1
Dry, bare	1	1.78	96.1	2.44	18.6
	5	4.86	1.8	5.53	1.8
	10	7.53	1.5	8.74	1.2
	15	8.59	1.3	8.73	0.8
	20	7.98	1.4	8.98	1.2
D04-1	0.5	1.21	122.6	1.80	66.2
Dry, veg	1	1.76	87.3	2.12	42.4
	5	4.92	2.2	4.19	3.2
	10	4.96	2.2	4.53	3.9
	15	4.61	1.9	4.07	3.6
	20	5.67	1.9	4.16	3.6

TABLE C.1. (contd)

MORNING 10/18/91

SAMPLE	DEPTH(cm)	%H2O(g/g)	SUCTION(Mpa)
D08-2	0.5	1.35	132.3
Dry (Ambient)	1	1.48	97.7
bare	5	1.99	50.7
W02-2	0.5	1.26	205.9
Dry (Ambient)	1	1.48	133.7
bare	5	2.70	28.6
W03-3	0.5	1.93	67.0
Wet (Irrigated)	1	4.43	3.4
Vegetated	5	8.61	0.7
D14-3	0.5	2.42	20.1
Wet (Irrigated)	1	6.19	1.4
Vegetated	5	7.98	1.0
D10-4	0.5	2.82	8.1
Wet (Irrigated)	1	7.66	1.1
Vegetated	5	9.47	0.7
D04-1	0.5	1.42	119.6
Dry (Ambient)	1	1.41	116.1
Vegetated	5	1.49	114.5
D04-1	0.5	2.06	92.8
Dry (Ambient)	1	2.58	48.1
Vegetated	5	3.53	17.2

APPENDIX C

SURFACE WATER CONTENT AND SUCTIONS AT SELECTED TIMES ON SELECTED LYSIMETERS

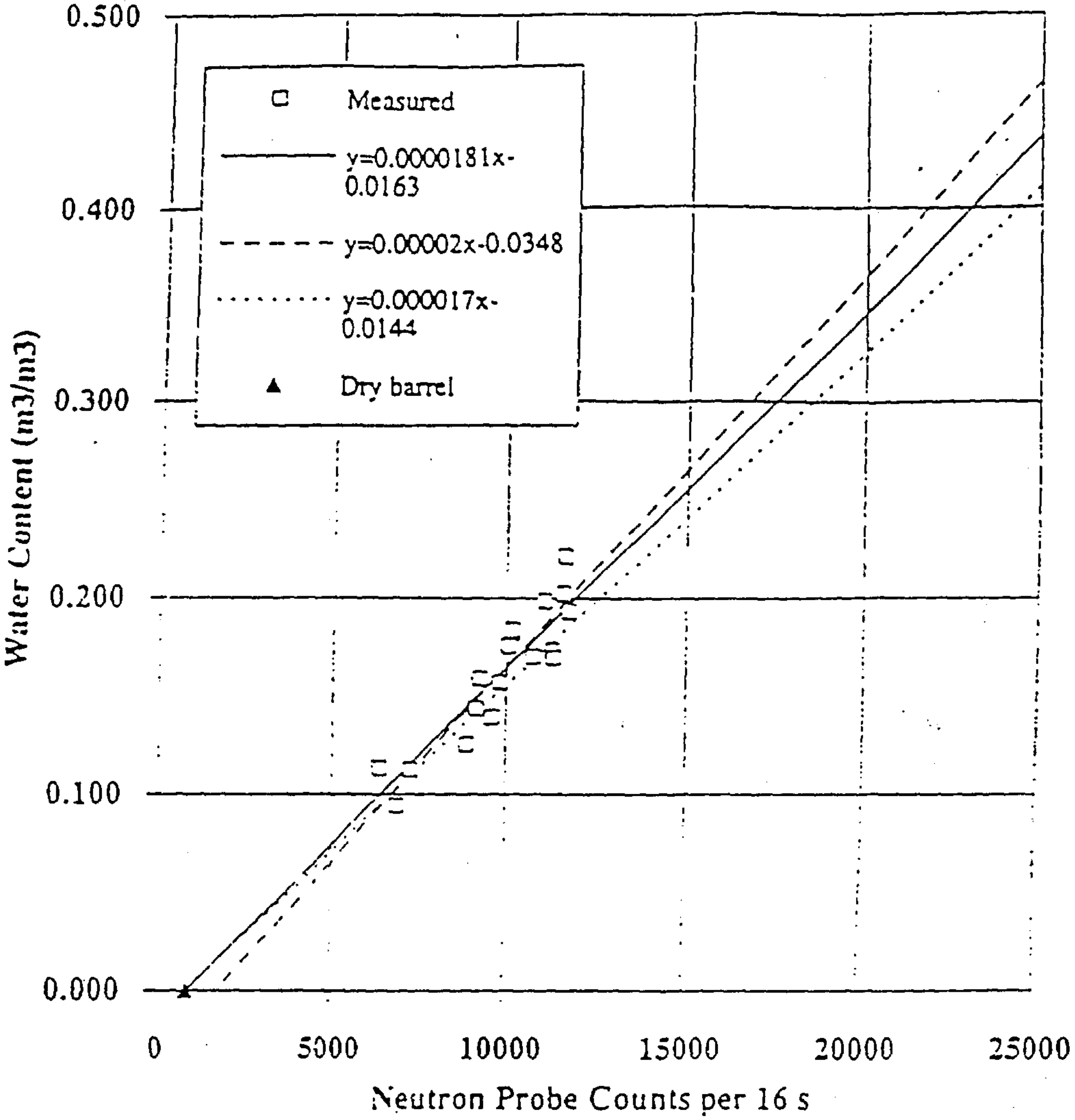


FIGURE B.3. Neutron Probe Calibration Equations

TABLE I
Interflow and Seepage Estimates for the Protective Barrier Landfill Cover Demonstration at Los Alamos, NM (November 1991 through January 1993)

Total Precip ~~During~~ Bet~ Nov 91 – Jan 9[illegible] = 53 c[illegible]

Landfill Cover Design	Interflow (Seepage) (cm) for Dominant Downhill Slopes of 5%	10%	15%	25%
Conventional	3.2 (3.4)	8.8 (0)	5.8 (4.0)	4.6 (0.41)
EPA	5.4 (0)	6.1 (0)	4.3 (0)	4.5 (0)
Loam Capillary Barrier	4.8 (0)	5.1 (0)	3.4 (0)	3.9 (0)
Clay Loam Capillary Barrier	0.78 (0)	3.2 (0)	0.12 (0)	0.36 (0)

← lot of seepage

TABLE II
Runoff Estimates for the Protective Barrier Landfill Cover Demonstration at Los Alamos, NM. (November 1991 through January 1993)

ET (cm)	Landfill Cover Design	Runoff (cm) for Dominant Downhill Slopes of 5%	10%	15%	25%	ΔS (cm)
[illegible]·9	Conventional	1.3	0.48	0.87	0.10	-19.0
39·7	EPA	0.27	0.50	0.72	0.74	-7.9
36·5	Loam Capillary Barrier	0.31	2.6	0.79	1.6	-11.0
3[illegible]·6	Clay Loam Capillary Barrier	0.88	2.1	1.7	3.3	-11.5

(Final: [illegible])

No Relative [illegible]

Figures

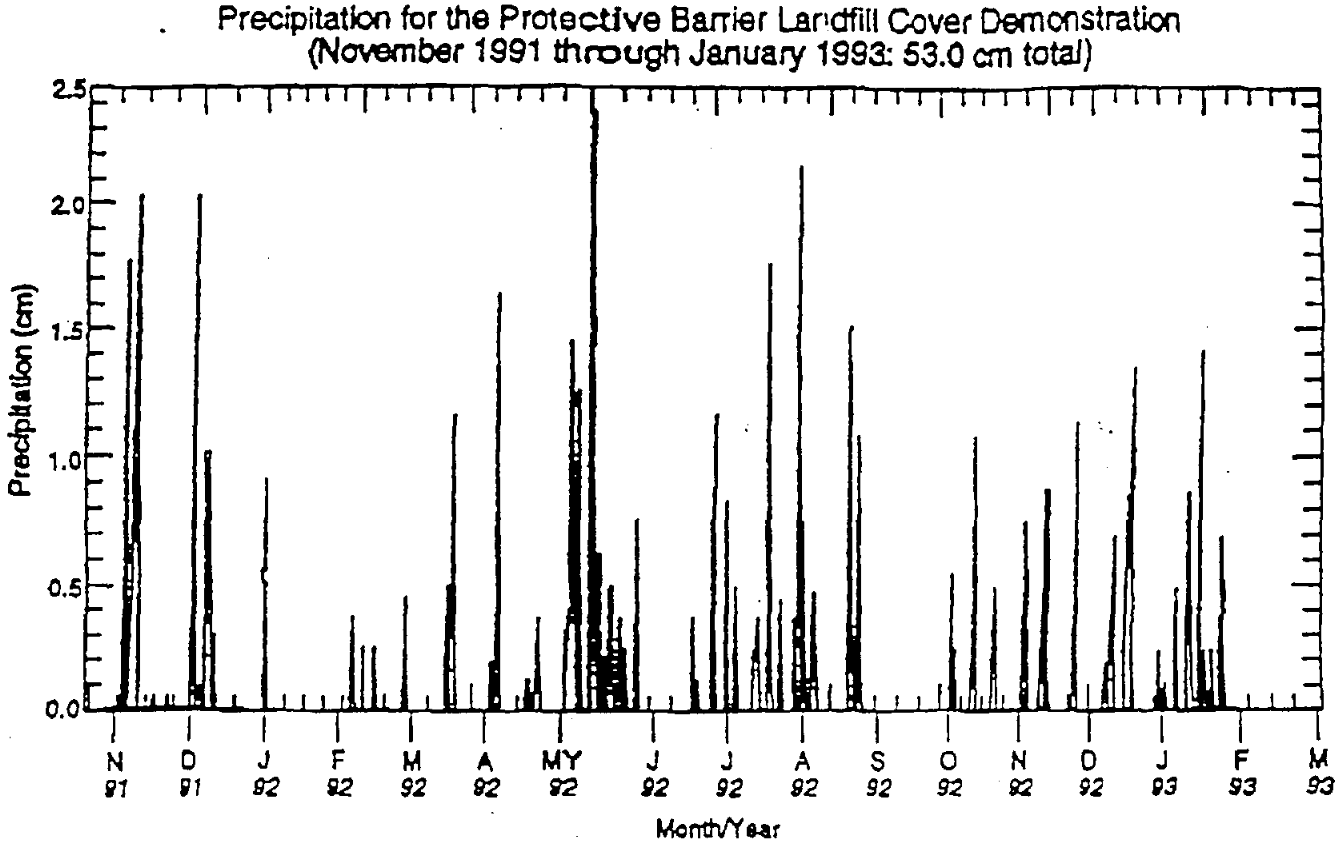


Fig. 1. Precipitation Data Collected at the Protective Barrier Landfill Cover Demonstration From November 1991 Through January 1993.

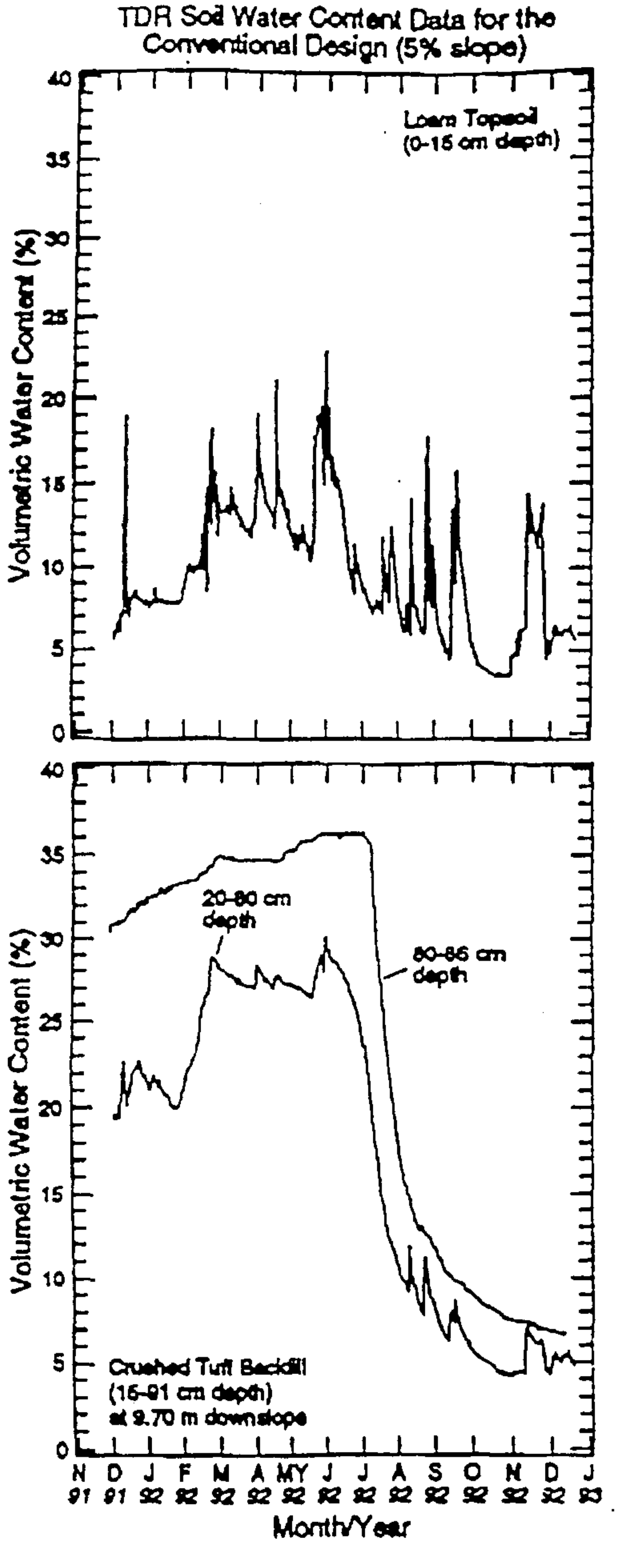
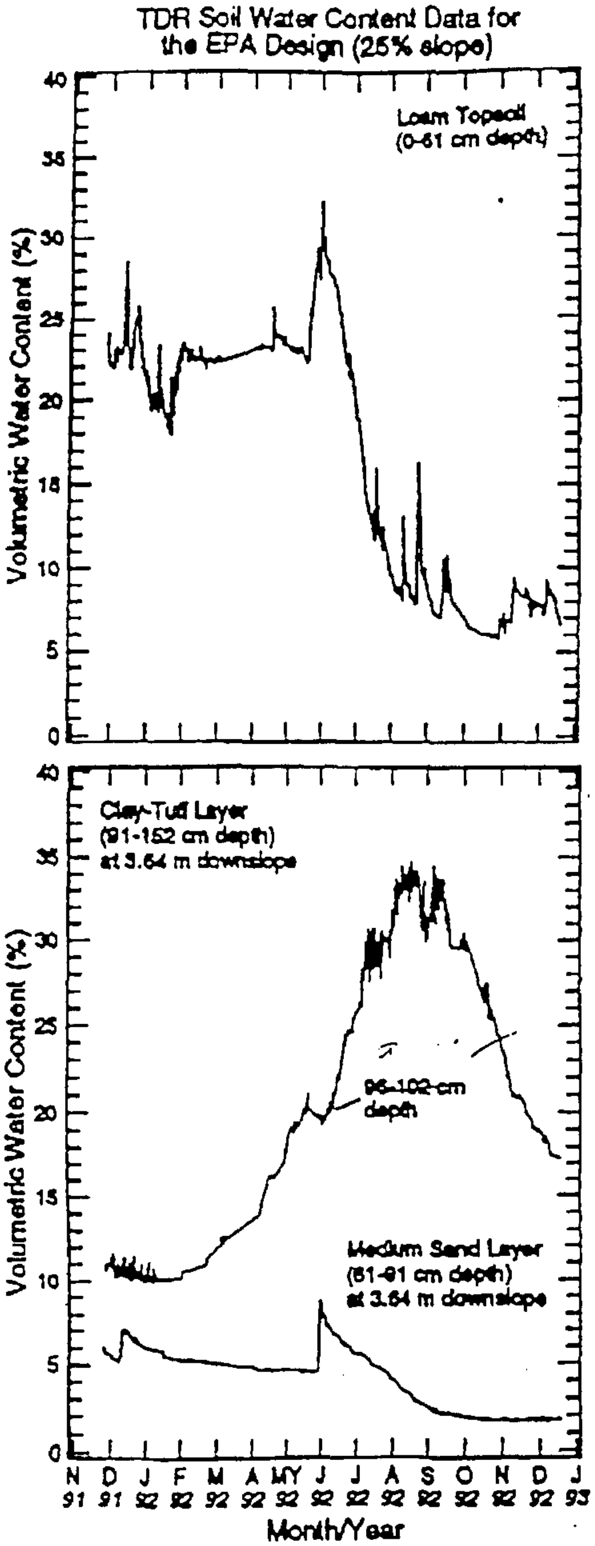


Fig. 3. TDR Soil Water Content Data Collected For the Conventional Landfill Cover Design With the 5% Dominant Downhill Slope At the Protective Barrier Landfill Cover Demonstration.



0.07 - 0.24

~~0.21 0.17~~

~~0.2~~

0.17 - 0.11

→ 0.01 - 0.06

Fig. 5. TDR Soil Water Content Data Collected For the EPA Landfill Cover Design With the 25% ~~Dominant Downhill~~ Slope At the Protective Barrier Landfill Cover Demonstration.

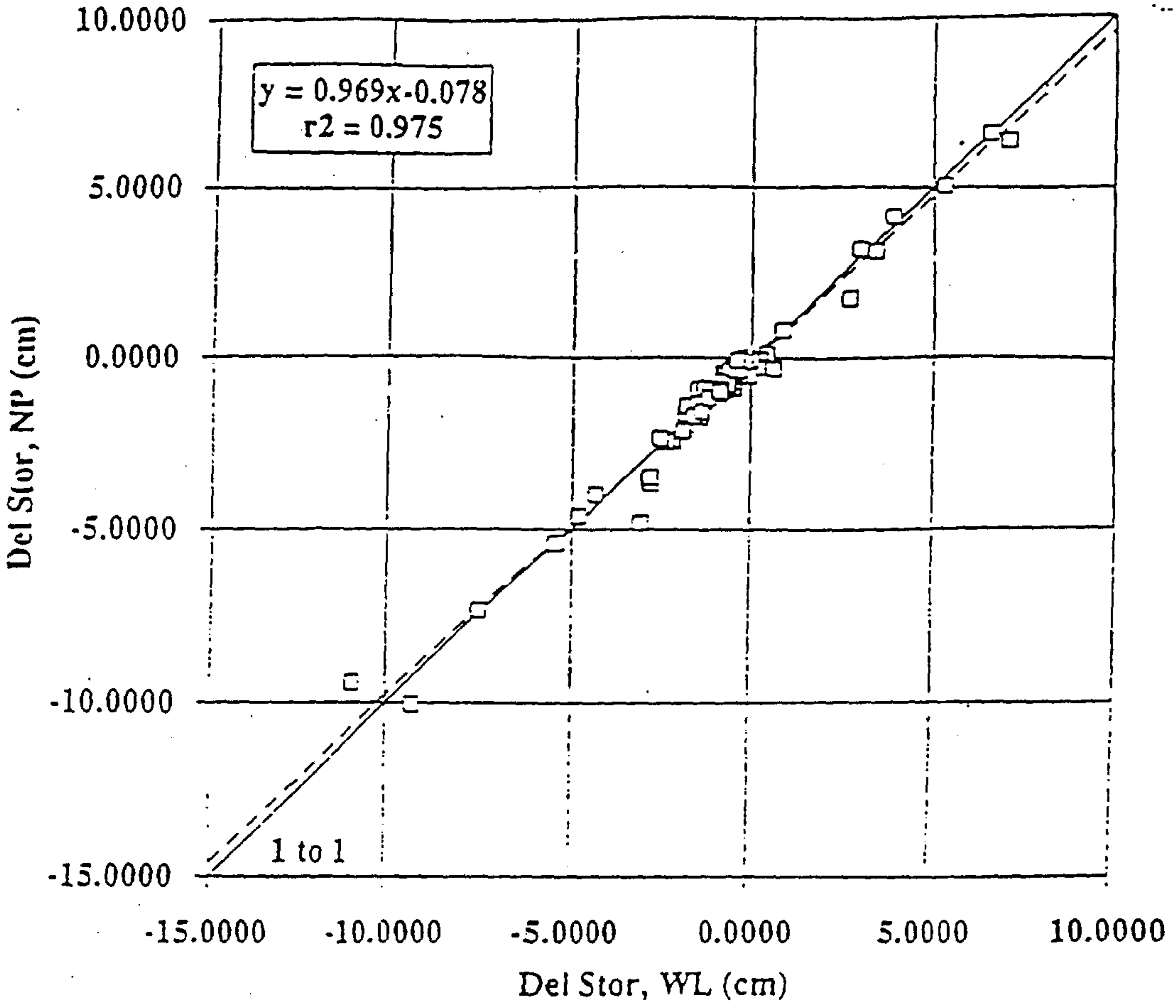


FIGURE B.1. Comparison of Storage Changes Determined with the Neutron Probe and Weighing Lysimeters where θ = water content (m^3/m^3)

a_0 = intercept

a_1 = slope

C = neutron counts during 16-s reading.

Water storage (S_{np}, cm) in each lysimeter was calculated using Simpson's method as described by Haverkamp et al. (1984):

$$S_{np} = [\theta_1 + (\theta_1 + 4\theta_2 + 2\theta_3 + 4\theta_4 + 2\theta_5 + 4\theta_6 + 2\theta_7 + 4\theta_8 + \theta_9)/3 + \theta_9]\Delta z \quad (2)$$

where Δz is 15 cm. Water storage changes in the sand and gravel layers underlying the silt loam were considered negligible based on their retention properties and the observation of water potentials consistently below -250 cm.

Probe readings were conducted on 47 dates between November 1987 and October 1989. For each date, S_{np} values were calculated and associated with the lysimeter weight at 0600 h. Discrepancies could exist between neutron probe and lysimeter storage values for the following reasons: measurement times, snow cover, irrigation and precipitation, and temperature. Probe measurements occurred during the day rather than at 0600 h. A snow cover is detectable with a weighing lysimeter but not with the probe. Recent irrigation or precipitation that had not infiltrated beyond the top several centimeters would be detected by the weighing lysimeter but would not be adequately detected by the probe. Temperatures below freezing could have affected the equipment. To minimize the possible effects of these factors, the number of dates was reduced by eliminating those dates that did not satisfy the following screening criteria:

- lysimeter weight change between 0600 and 1800 h (the interval during which probe measurements occurred) must be <0.25 cm
- snow must be absent
- average daily air temperature must be >0°C
- irrigation or precipitation must not occur on the measurement date or its preceding date

APPENDIX B

NEUTRON PROBE CALIBRATION

TABLE A.1. Target Amounts of Water for Irrigated FLTF Treatments

Date	Target 2X Treatment (mm)	Date	Target 3X Treatment (mm)
07-Nov-87	7.8	07-Nov-90	12.0
14-Nov-87	19.2	14-Nov-90	29.2
21-Nov-87	31.2	21-Nov-90	47.2
28-Nov-87	42.8	28-Nov-90	64.5
05-Dec-87	53.9	05-Dec-90	81.2
12-Dec-87	64.7	12-Dec-90	97.3
19-Dec-87	75.0	19-Dec-90	112.8
26-Dec-87	85.0	26-Dec-90	127.7
02-Jan-88	94.5	02-Jan-91	142.0
09-Jan-88	103.7	09-Jan-91	155.8
16-Jan-88	112.5	16-Jan-91	169.0
23-Jan-88	121.0	23-Jan-91	181.8
30-Jan-88	129.2	30-Jan-91	194.0
06-Feb-88	137.0	06-Feb-91	205.8
13-Feb-88	144.6	13-Feb-91	217.1
20-Feb-88	151.8	20-Feb-91	227.9
27-Feb-88	158.7	27-Feb-91	238.3
06-Mar-88	165.3	06-Mar-91	248.4
13-Mar-88	172.7	13-Mar-91	258.0
20-Mar-88	178.8	20-Mar-91	267.2
27-Mar-88	184.7	27-Mar-91	276.1
03-Apr-88	190.4	03-Apr-91	284.7
10-Apr-88	195.8	10-Apr-91	292.9
17-Apr-88	201.1	17-Apr-91	300.9
24-Apr-88	205.1	24-Apr-91	308.5
01-May-88	210.3	01-May-91	315.9
08-May-88	215.1	08-May-91	323.0
15-May-88	219.6	15-May-91	329.9
22-May-88	224.1	22-May-91	335.6
29-May-88	228.4	29-May-91	343.0
05-Jun-88	233.2	05-Jun-91	349.3
12-Jun-88	237.2	12-Jun-91	355.5
19-Jun-88	241.2	19-Jun-91	361.4
26-Jun-88	245.1	26-Jun-91	367.3
03-Jul-88	248.9	03-Jul-91	373.0
10-Jul-88	252.7	10-Jul-91	378.7
17-Jul-88	256.4	17-Jul-91	384.3
24-Jul-88	260.1	24-Jul-91	389.8
31-Jul-88	263.8	31-Jul-91	395.2
07-Aug-88	267.4	07-Aug-91	400.7
14-Aug-88	271.1	14-Aug-91	405.1
21-Aug-88	274.5	21-Aug-91	411.5
28-Aug-88	278.5	28-Aug-91	417.0
04-Sep-88	282.2	04-Sep-91	422.5
11-Sep-88	285.0	11-Sep-91	428.1
18-Sep-88	289.8	18-Sep-91	433.8
25-Sep-88	293.7	25-Sep-91	439.5
02-Oct-88	297.7	02-Oct-91	445.4
09-Oct-88	301.8	09-Oct-91	451.4
16-Oct-88	305.0	16-Oct-91	457.5
23-Oct-88	310.4	23-Oct-91	463.9
31-Oct-88	320.0	31-Oct-91	480.0

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6.0 RECOMMENDATIONS

The past year provided valuable information on the operation of a capillary barrier system at an arid site under extreme precipitation (snowfall) conditions. Continued operation, with imposed supplemental winter snowfall, would test the performance of capillary barrier systems under repeated extreme events. For this reason, we recommend that the FLTF be maintained and tested for a minimum of three additional years.

We also recommend adding six additional treatments to the FLTF. These treatments will consist of pairs of lysimeters filled with 1) basalt rock (prototype barrier side-slope), 2) clean-fill gravel (another prototype barrier side-slope), and 3) vegetated silt loams (prototype barrier cover). Because of cost constraints, we recommend that these treatments be conducted in existing lysimeter containers. We recommend excavating and refilling lysimeters D02-5 and D09-7 (see Figure 2.4) with basalt rock, lysimeters D04-1 and D11-7 with clean-fill soil, and lysimeters D07-1 and D14-3 with vegetated silt loam, 2-m-thick (with 15 wt% pea-gravel admixed into the top 1 m). One of each pair of lysimeters will receive ambient precipitation; the other lysimeter of each pair will receive 3X precipitation.

We recommend that the FLTF, including these new treatments, be monitored for at least 3 more years. Water balance data from the new treatments will be compared with water balance observations in the other eleven FLTF treatments and at the prototype barrier. Comparisons between prototype and FLTF water balance will allow us to evaluate scale-effects (i.e., lysimeter to field scale) and the merit of using lysimeter data to extrapolate in time and space to full-scale barrier situations. If such efforts prove successful, much time and money can be saved by utilizing past lysimeter records to forecast large-scale water balances of waste covers for Hanford, under present and expected future climatic conditions.

5.0 CONCLUSIONS

The FLTF continues to provide important water balance data needed in the design of surface barriers (covers) for the Hanford Site. During FY 1993, a record snowfall occurred, resulting in "above-normal" water storage in all lysimeters. Water storage in bare, irrigated, lysimeters (with 1.5-m-deep silt loam soils) exceeded the 500-mm water storage limit and drainage occurred. No drainage occurred in any other capillary barrier treatment. These data demonstrate the limits of capillary barriers when soil water storage capacities are exceeded. Soil water storage responded to climatic variation and to presence and absence of vegetation. Storage differed dramatically between treatments, being the least under vegetated treatments and greatest under bare, irrigated conditions.

The irrigated, bare soil treatment is an extreme case. Bare surfaces presently exist at the Hanford Site, only at sites with coarse (gravel-covered) surfaces that have received soil sterilants or herbicides. Bare surface conditions, which result from fire or drought, are typically transient conditions, lasting less than one year at the Hanford Site. Since the irrigated bare soil treatment has been maintained for nearly 6 years, water storage in the bare soil lysimeters was abnormally high. High initial water storage, coupled with elevated precipitation, caused the lysimeters to drain.

Under irrigation, where vegetation was present, summer and fall water storage was reduced to values similar to that occurring in vegetated treatments without irrigation. The low water storage in the vegetated treatments allowed the extreme winter snowmelt events in 1993 to be stored without exceeding the storage limit (500 mm) and by July all winter precipitation (including irrigation) was removed via evapotranspiration.

These data support the concept that vegetation can efficiently remove excess water from a surface barrier at the Hanford Site. Should fire or drought remove vegetation on silt loam soils at Hanford, new vegetative growth will most likely be initiated rapidly because of the abundance of seed sources (Rickard and Vaughan 1988).

TABLE 4.1. Linear Regression Parameter Values for the Leaf Area and Biomass Models Described in Equations 1-3

Parameters	*P. sandbergii* Leaf Area (cm^2)	*P. spicata* Leaf Area (cm^2)	*A. tridentata* Total Aboveground Biomass (g)
b_0	438	514.7	196
b_1	-50.4	12.46	0.00102
b_2	-78.4	-18.72	
b_3	155.5	-21.73	
b_4	-494	0.01121	
b_5	1.1958		
b_6	6.325		
b_7	-2.016		
b_8	23.99		

TABLE 4.2. Estimated Total Plant Biomass (g) and Biomass Index (g/m^2) on Each Lysimeter in 1989 and 1992

Surface Area (m^2)	Lysimeter	Treatment	Biomass			
			Total (g)	Index (g/m^2)	Total (g)	Index (g/m^2)
2.99	D04-1	Ambient, 1.5 m	3442	1150	3455	1160
2.99	D07-1		3417	1140	3291	1100
2.34	W01-1		3203	1620	3337	1430
2.99	D13-3	Irrigated, 1.5 m	5318	1780	10491	3510
2.99	D14-3		6381	2130	9582	3200
2.34	W03-3		3844	1640	7131	3050
2.99	D02-5	Ambient, 1.5 m,	2623	750	1357	450
2.99	D05-5	Gravel Admix	3343	1110	4164	1390
2.99	D03-6	Ambient, 1.0 m	3325	1110	4015	1340
2.99	D06-6		3045	1020	3481	1160

located off the lysimeters for harvest. The same dimensional measures were taken on these individuals before harvest. All shoot material was clipped and placed in a plastic bag for later analysis. Single-sided leaf area was measured with a LI-COR 3100 leaf area meter. Shoot material was then dried in a convection oven at 55°C for at least 48 hours for biomass values. A linear regression model was developed to predict shoot leaf area from morphometric measures (cm) as follows:

$$Y = b_0 + b_1 w + b_2 pw + b_3 fht + b_4 lht + b_5 w^2 + b_5 pw^2 + b_7 fht^2 + b_8 lht^2, \quad (1)$$

where Y is predicted leaf area (cm^2), w is the greatest projected basal diameter (cm), pw is the perpendicular width to w, fht is the floral height, lht is leaf height, and b_i are linear regression parameters.

Agropyron sibericum and Oryzopsis hymenoides are uncommon species which precluded the development of a similar model. Both species are related to Pseudoroegneria spicata; therefore, their leaf areas were estimated using a P. spicata model. All measures except leaf height were taken on 15 individuals spanning all sizes above seedlings. Sample processing was as described for P. sandbergii. The model is as follows:

$$Y = b_0 + b_1 w + b_2\, pw + b_3\, fht + b_4\, w*pw*fht. \quad (2)$$

Shoot biomass was estimated from predicted leaf area by making use of the biomass to leaf area ratios of 0.0215 for P. sandbergii, and 0.0285 for P. spicata. Biomass for A. tridentata was estimated using the model of Uresk et al. (1977) which is as follows:

$$Z = b_0 + b_1 w*pw*lht. \quad (3)$$

where Z is total (leaves, stems, wood) shoot oven dried biomass (g). Shoot biomass for B. tectorum was obtained by harvesting and drying all shoots within a 100-cm^2 area and assuming that the stand density on the lysimeters was constant and equal to the average of the five harvested values. The

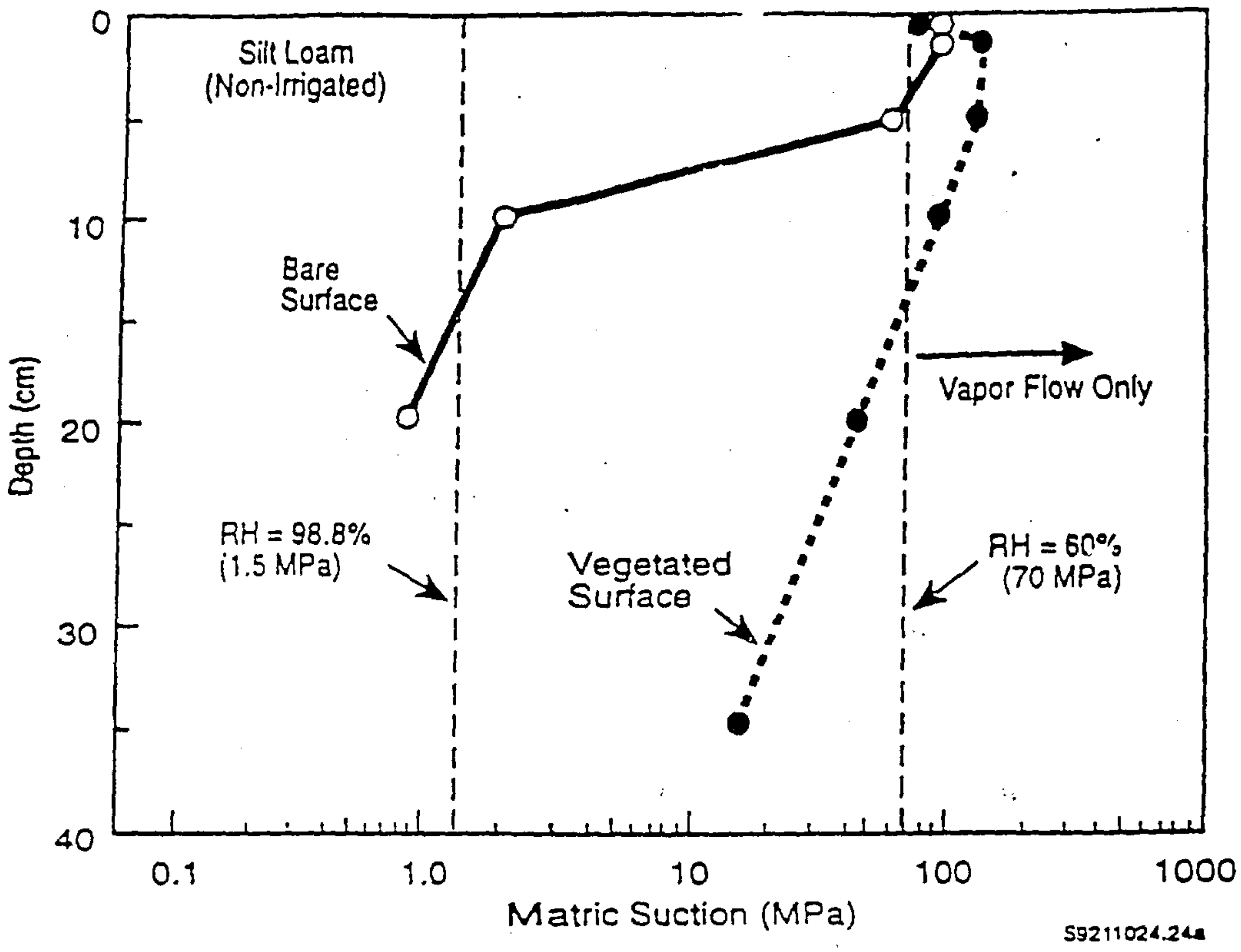

FIGURE 3.7. Water Potentials (Suction Profiles) for Bare and Vegetated, Ambient Surfaces of Capillary Barrier Lysimeters, October 1991

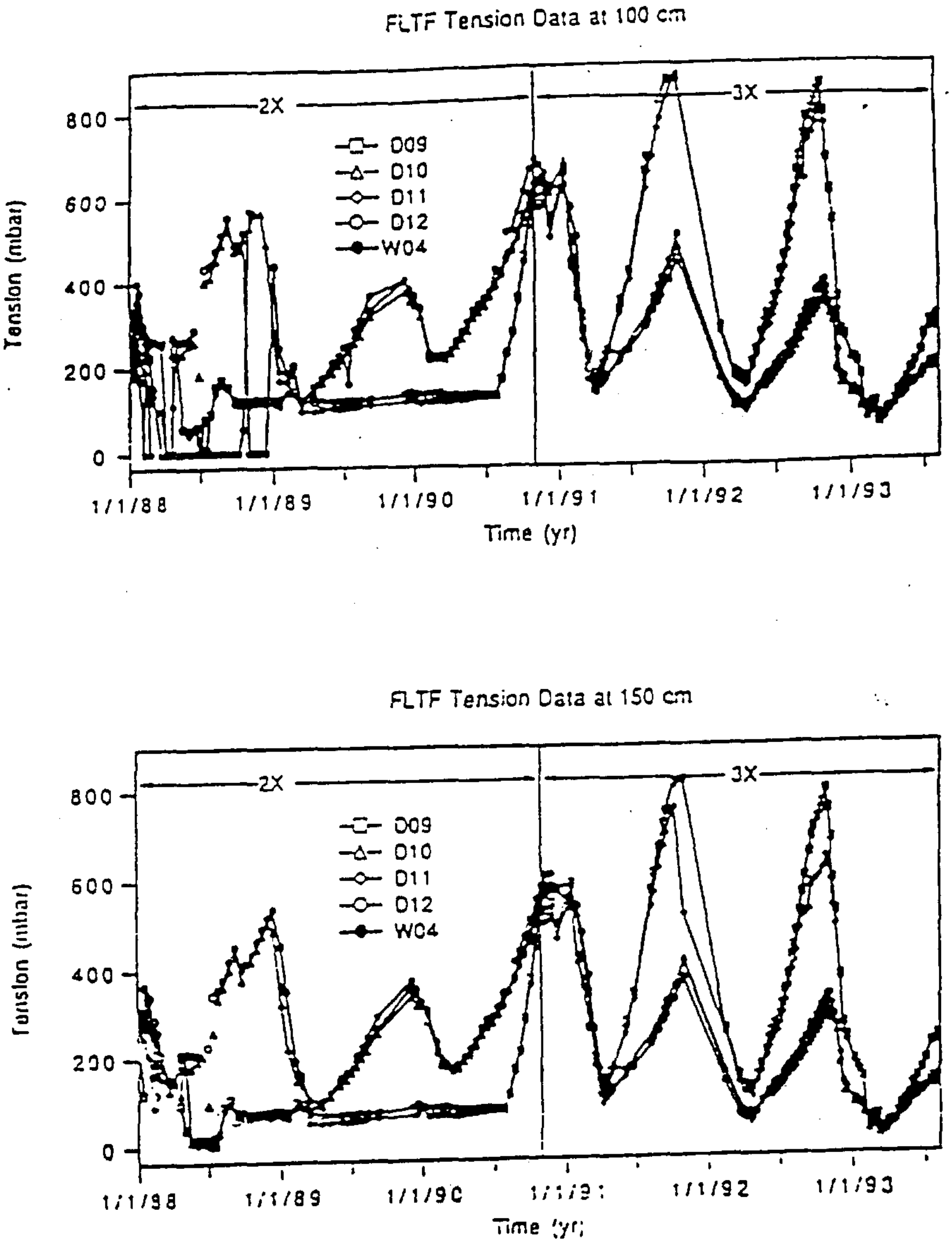

FIGURE 3.6. Tensiometer Data (Tensions) at Two Depths (100 cm and 150 cm) as a Function of Time for Bare, Irrigated Lysimeters

over the course of several months a proliferation of roots was observed in the 1.5 m-deep silt loam soil layer. Over the next 3 years, roots were observed to permeate the silt loam but no roots penetrated more than 1 cm into the sand. In late 1991, in spite of an increase in irrigation to a 3X treatment, the sagebrush plant died.

By early February 1993, the entire profile of the irrigated, clear-tube lysimeter (C06-3), was noticeable wet, including the underlying rock materials. However, no drainage water was collected from this lysimeter. In March 1993, a small sagebrush was transplanted on lysimeter C06-3 and by late May sagebrush roots had penetrated more that 1.5 m through the silt loam and sand and had moved into the wetted gravel below the sand. By late July 1993, a few sagebrush roots had moved downward into the rock to a depth of about 2 m. As late as September 1993, there appeared to be no further root penetration and the sand and gravel appeared dry. Continued monitoring of root growth over the next several years is planned for this lysimeter.

These observations suggest two things. First, that wetted gravel and basalt rock fail to create a plant root barrier. Sagebrush roots apparently are not physically restricted in any way by coarse sands, gravels, or rocks. Second, these coarse subsoils have limited storage capacity. As soon as water is extracted from the coarse material-surfaces the roots are limited in their capacity to survive, and if water is not supplied the probability is high that they will die. It is expected that over the next year there will be no further root penetration into the subsoil, since evapotranspiration from the sagebrush should be sufficiently high to remove excess water from the silt loam soil, thus preventing any further drainage into the sand, etc. As long as deep-rooted vegetation persists on this lysimeter, drainage should be prevented.

3.3.2 Species Composition

Sagebrush vegetation was not maintained on the clear-tube, ambient, capillary barrier lysimeter (C03-1). The sagebrush died in 1989 within a year of transplanting. Over the past 4 years, the ambient capillary barrier has not been visibly wetted. Bromus tectorum L. (cheatgrass) has invaded the lysimeter, and in 1993, cheatgrass occupied most of the lysimeter surface. By

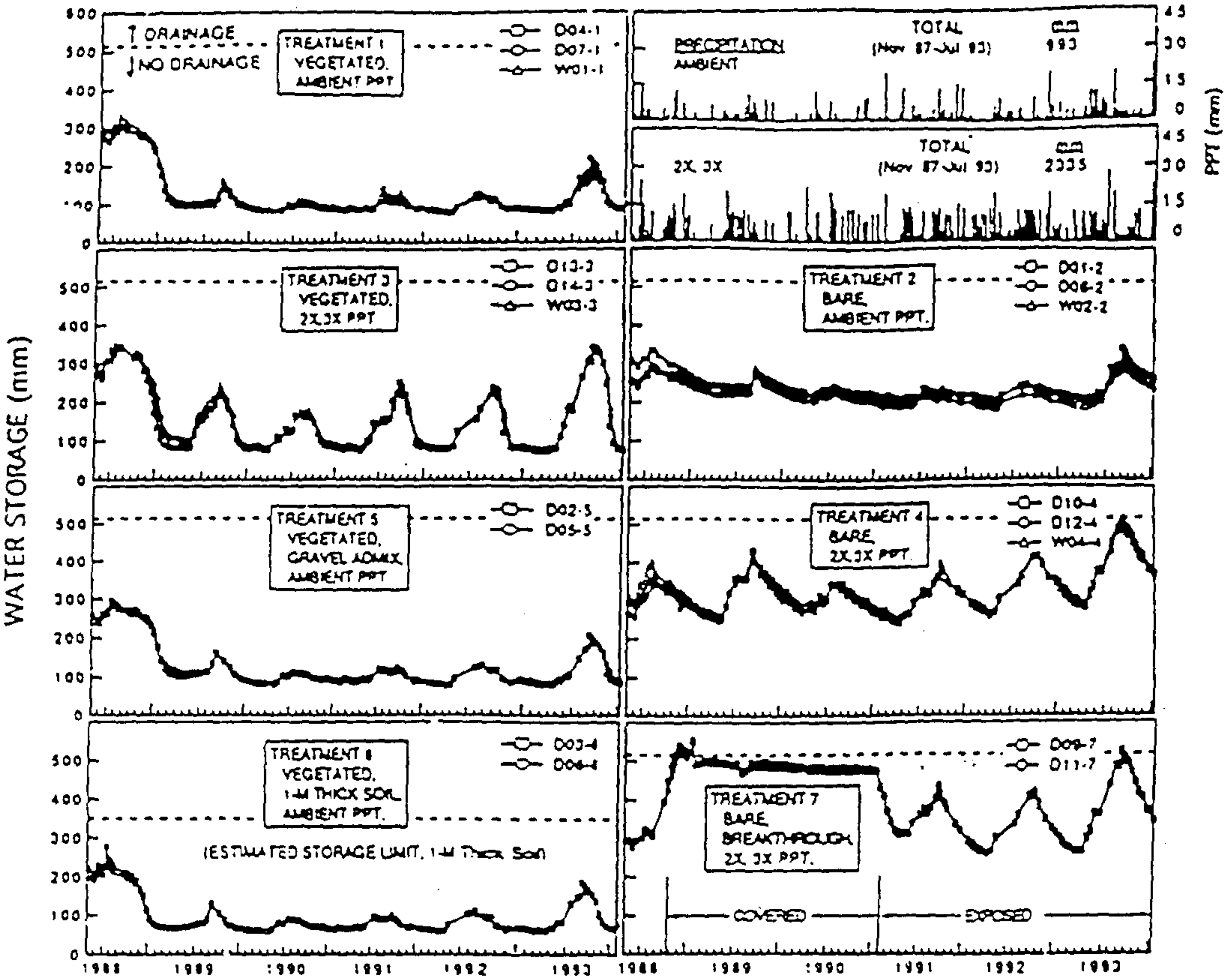

FIGURE 3.5. Water Storage for Lysimeter Treatments 1 to 7

conditions. After the first winter, storage in all vegetated treatments averaged less than 200 mm, which is less than half the 500 mm needed to cause drainage. Thus, it is reasonable to conclude that vegetated capillary barriers similar to the lysimeter design will perform extremely well.

3.2.2 Bare Lysimeters

The bare treatments maintained a relatively high storage throughout the course of the 6-year study. During the first 5 years, virtually all applied water (for both ambient and irrigated lysimeters) was removed through evaporation. Six of the lysimeters exhibited some response to summer thermal

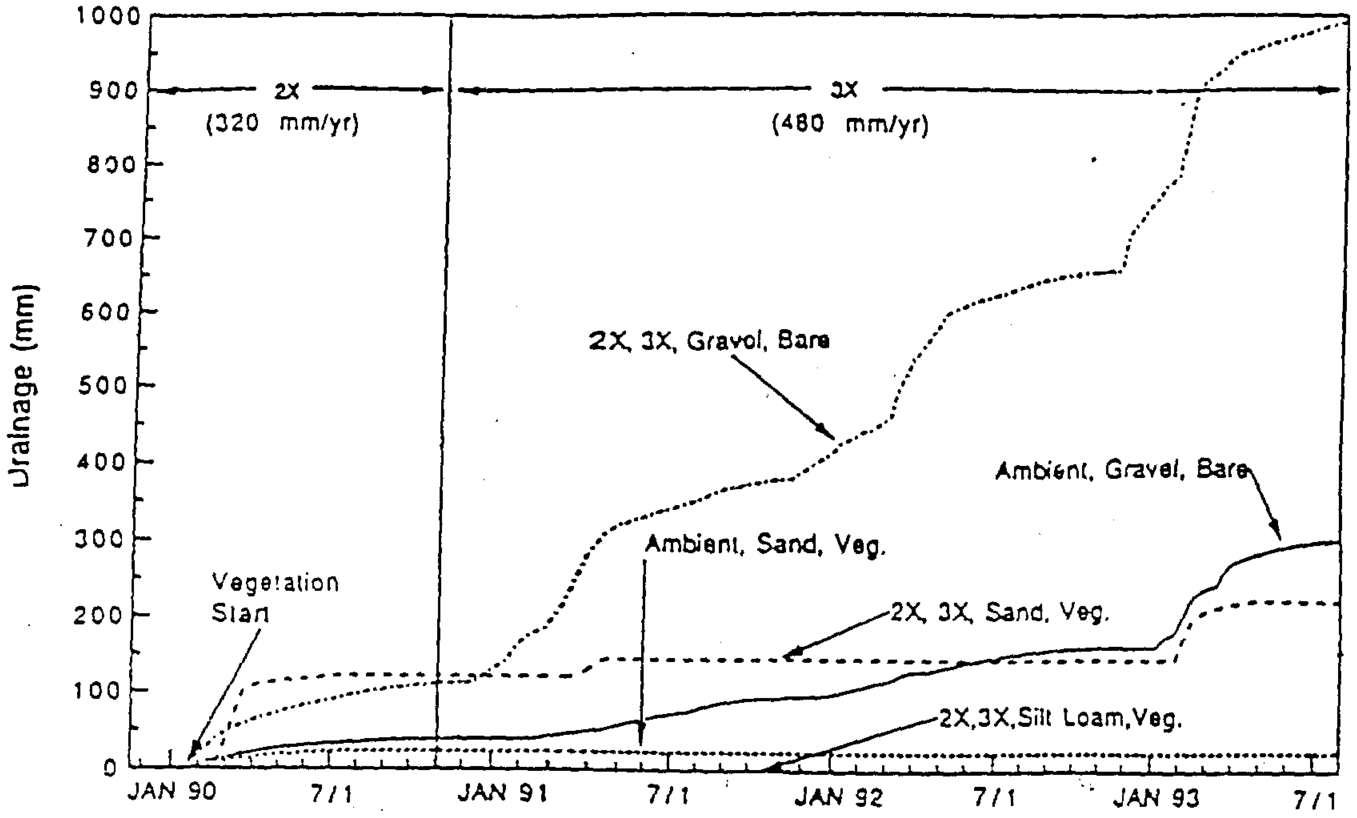

FIGURE 3.3. Drainage Data for Clear-Tube Lysimeters

water storage in all drainage lysimeters (treatments 1 through 7). Drainage lysimeter data are shown in Figure 3.5.

3.2.1 Vegetated Lysimeters

Vegetation, coupled with surface evaporation (via evapotranspiration), is able to remove at least 480 mm/yr. The data in Figure 3.5 clearly indicate that vegetated, capillary-barrier lysimeters (treatments 1, 3, 5, and 6) all maintain water storage levels well below their estimated drainage limits. The water storage in all vegetated lysimeters was reduced from between 200 and 300 mm of water to a lower limit of storage (less than 100 mm) for all treatments. The water storage is reduced to a unique lower limit of storage for each treatment by summer of each year. Such an observation coupled with the observation of no drainage from the vegetated treatments (after a record snowfall, and above-normal annual precipitation) provides verification of the performance of capillary barriers for the Hanford Site, even under extreme

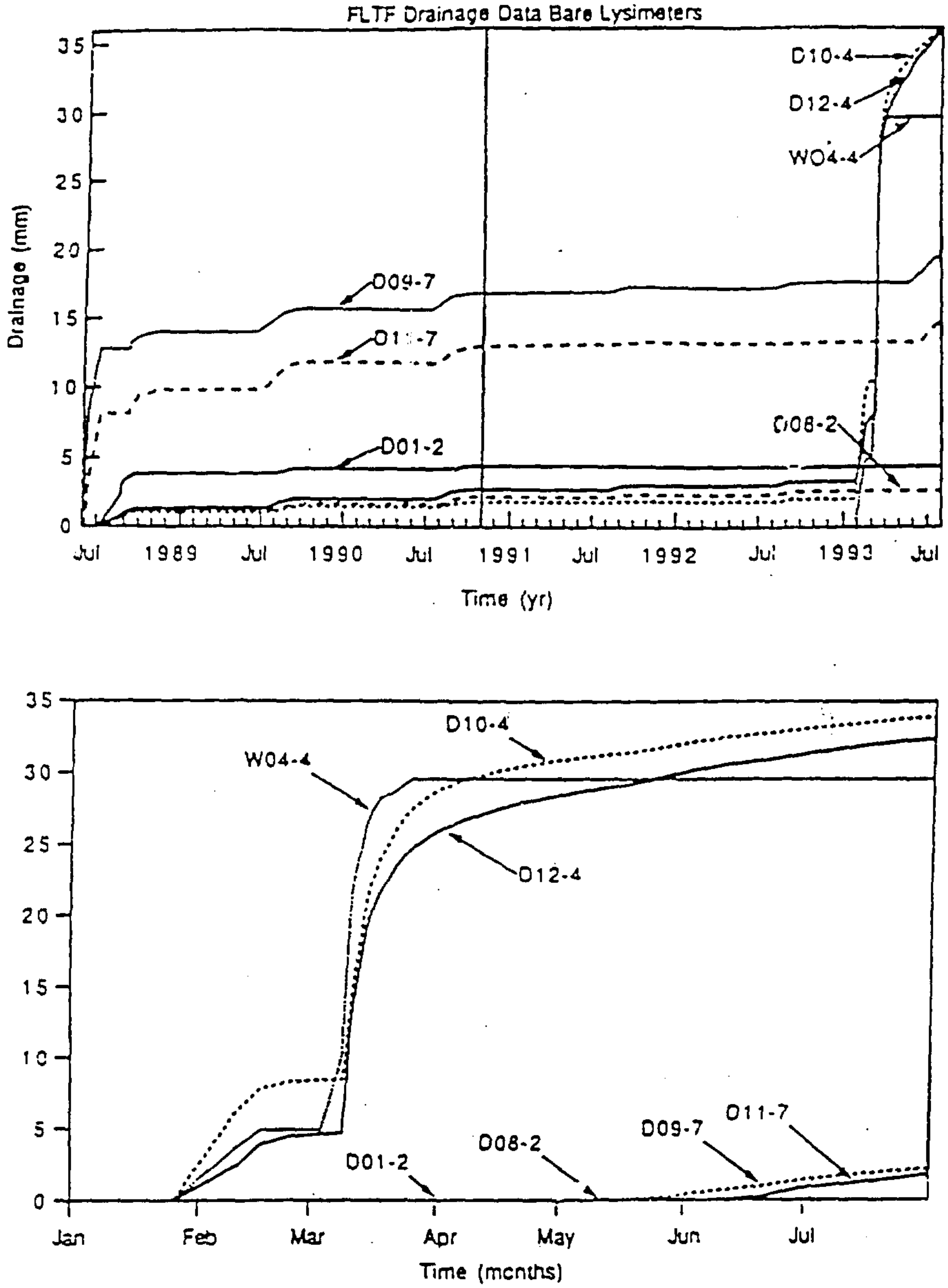

FIGURE 3.1. Cumulative Drainage Data for (a) 1988 to 1993 and (b) 1993, for Bare Lysimeters as Specified by Treatment Numbers (see Figure 2.4 for treatment description)

TABLE 3.1. (contd)

Lysimeter	Water Year[a]	Precipitation and Irrigation	Storage Change	ET	Drainage
		mm			
D11-7 (Breakthrough, Bare)	1991	479	-45	524	0
	1992	487	29	458	0
	1993	406	33	371	2

(a) Water Year - November 1 of previous year through October 31 of year specified.
(b) 1993 Water Year - exception = November 1 1992, through July 31, 1993.
(c) Numbers in parenthesis represent summer condensate water.

TABLE 3.1. (contd)

Lysimeter	Water Year[a]	Precipitation and Irrigation	Storage Change	ET	Drainage
		mm			
D10-4 (2X Precip., Bare)	1988	294	-33	325	(2)
	1989	367	30	337	0
	1990	304	-32	336	0
	1991	479	12	467	0
	1992	487	45	442	0
	1993	406	34	338	34
D12-4 (2X Precip., Bare)	1988	294	-21	313	(2)
	1989	367	34	332	(1)
	1990	304	-25	328	(1)
	1991	479	17	462	0
	1992	487	39	448	0
	1993	406	34	340	32
D02-5 (Ambient, Vegetated, Admix)	1988	127	-138	263	(2)
	1989	173	-27	199	0
	1990	144	16	128	0
	1991	144	-15	159	0
	1992	174	9	165	0
	1993	235	5	230	0
D05-5 (Ambient, Vegetated, Admix)	1988	127	-123	244	(6)
	1989	173	-11	184	0
	1990	144	14	130	0
	1991	144	-12	156	0
	1992	174	9	165	0
	1993	235	4	231	0
D03-6 (Ambient, Vegetated)	1988	127	-157	277	(7)
	1989	173	-7	180	0
	1990	144	12	132	0
	1991	144	-10	154	0
	1992	174	7	167	0
	1993	235	8	227	0
D06-6 (Ambient, Vegetated)	1988	127	-133	259	(1)[c]
	1989	173	-6	179	0
	1990	144	8	136	0
	1991	144	-9	153	0
	1992	174	7	167	0
	1993[b]	235	7	228	0
D09-7 (Breakthrough, Bare)	1991	479	-45	524	0
	1992	487	31	456	0
	1993	406	29	375	2

3.0 RESULTS OF LYSIMETER WATER BALANCE STUDIES

A summary of lysimeter water balance data for nearly 6 years (November 1987 - July 1993) is provided in the following subsections. Data from drainage, weighing and clear-tube lysimeters are grouped and analyzed according to treatment.

3.1 DRAINAGE RESULTS

Drainage data from all lysimeters are presented in Table 3.1 and shown in Figures 3.1 to 3.3. Table 3.1 lists the cumulative drainage values for each treatment. Excluded from Table 3.1 are 1988 tests, where excess water was applied to check for leaks and to saturate two lysimeters (D09-7 and D11-7) (Campbell and Gee 1990). All drainage values are rounded to the nearest mm of water. Drainage from all lysimeters is scaled to a unit cross-sectional area (i.e., water volume/area = length, expressed in mm, to conform to conventional S.I. units used for precipitation, recharge, etc.).

The data clearly indicate that all capillary-barrier (silt loam soil) treatments, except those with bare soil, exposed to the highest (3X) precipitation treatment, have had no drainage after nearly 6 years of testing. All other treatments (e.g., sandy soils) exhibited drainage. Drainage is least for vegetated sand under ambient precipitation and greatest for gravel-covered sand under elevated (3X) precipitation. The bare, irrigated (2X) treatment showed no drainage (3-year test). When the irrigation (elevated precipitation) treatment was modified (increased to 3X) the silt loam again showed no drainage for the first 2 years. Evaporation was sufficiently high that all of the applied water was removed from all silt loam soils (except for treatment 7, where excess water was applied and evaporation was purposely prevented).

During the past year (1992-1993) the record snowfall caused precipitation to exceed the 3X target (see Figure 2.6). Because water storage was initially high in irrigated, bare lysimeters, the excess winter precipitation

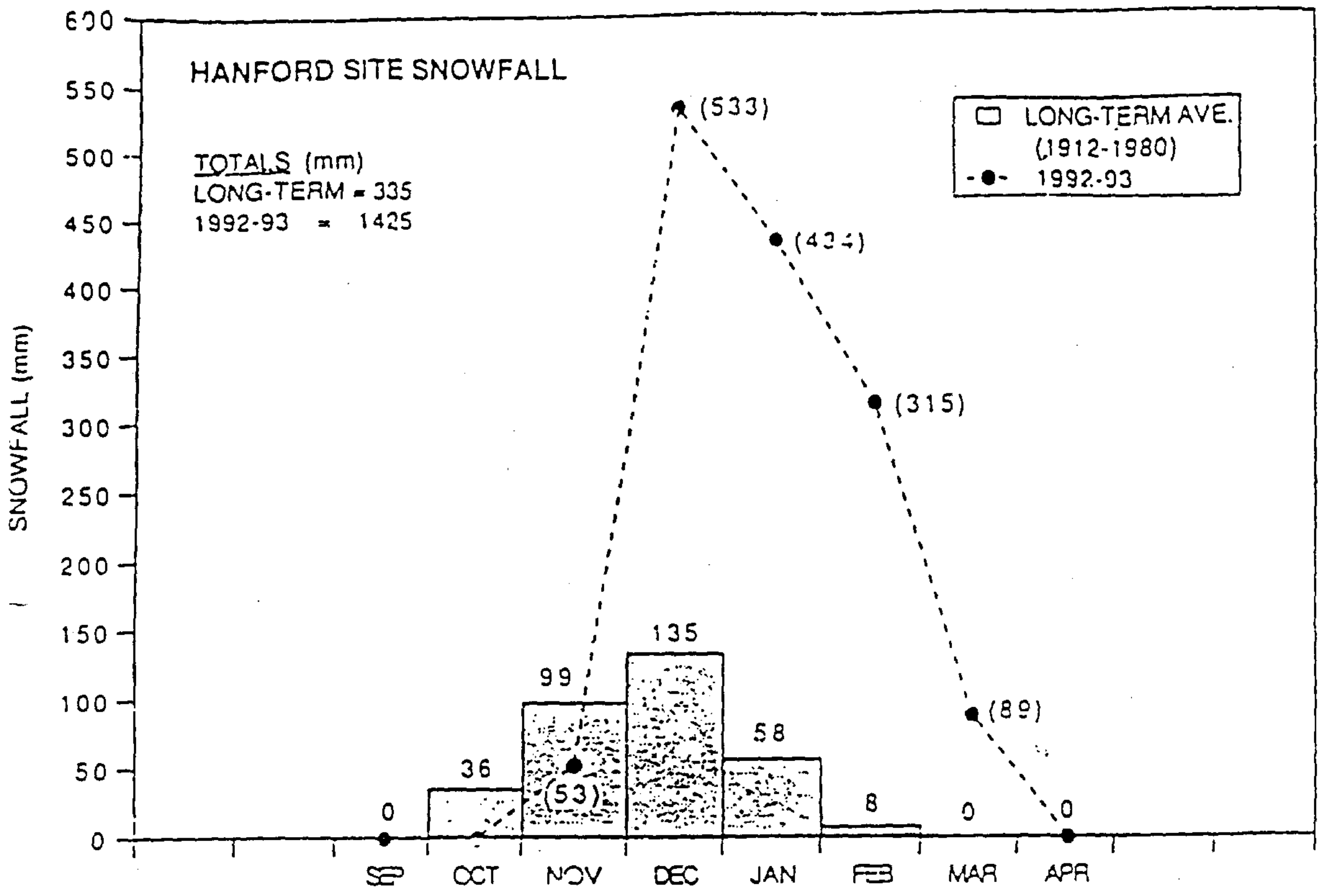

FIGURE 2.6. Hanford Site Monthly Snowfall Record. Bar graph represents averages (1912-1980), data points represent 1992-1993 winter values.

to minimize further debris accumulation. The weighing lysimeter calibration for WL01 was adjusted to account for the new scale. Because of the scale replacement, all data were checked for proper calibration both in early spring and fall of 1992. By fall of 1992, all scales were working correctly. Weight change data from the weighing lysimeters as well as precipitation, irrigation, temperature, and other key data are plotted and reviewed weekly. Appendix A (Figure A.1) provides an example of these weekly plots.

TABLE 2.1. Field Lysimeter Test Facility Treatments

	Precipitation			Surface				Soil	Thickness			
Treatment	A[a]	2A[b]	B[c]	Bare	Veg	Admix	Gravel	Texture	1.0 m	1.5 m	3.0 m	Lysimeter #
1	X				X			Si L		X		W01-1, D04-1, D07-1, C03-1
2	X			X				Si L		X		W02-2, D01-2, D08-2
3		X			X			Si L		X		W03-3, D13-3, D14-3, C06-3
4		X		X				Si L		X		W04-4, D10-4, D12-4
5	X				X	X		Si L		X		D02-5, D05-5
6	X				X			Si L	X			D03-6, D06-6
7			X	X				Si L		X		D09-7, D11-7
8	X						X	S			X	C01-8
9	X				X			S			X	C02-9
10		X					X	S			X	C04-10
11		X			X			S			X	C05-11

[a] Ambient precipitation
[b] 2X, 3X annual average
[c] Breakthrough +2X, 3X annual average

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2.6.1 Drainage Errors

We checked all outflow lines for evaporation losses. Evaporation losses were found to be 5 g in 480 days. This is equivalent to an error in drainage of <0.0025 mm/yr, thus was considered to be insignificant. There was an inadvertent error observed on one of the clear-tube tests. The closed tube on C04-10 (gravel-covered sand, 3X precipitation) was found in early summer (July 14-23) of 1993 to be open for a week, and drainage water was lost during that period of time. As there was measured drainage before and after that time period, the lost data was synthesized by averaging the before and after data and incrementally adding this amount to the drainage data set. All other records represent actual recorded drainage values.

2.6.2 Water Storage Analysis

Neutron probe data were collected manually (recorded in laboratory record books) and electronically. The electronic data were read by computer, stored in FLTF data files, then processed in terms of water content and water storage. Details of the process used to transform neutron probe data from raw contents to water content and water storage are given in Appendix B.

water storage data are also used to analyze performance of lysimeter treatments with no drainage.

2.6 EXPERIMENTAL DESIGN AND METHODS OF ANALYSIS

Eleven distinct treatments are currently being tested at the FLTF. Figure 2.4 and Table 2.1 identify these treatments. The various soil, plant and precipitation combination in these treatments represent a range of surface conditions that presently exist at the Hanford Site, plus conditions that reflect elevated precipitation. The elevated precipitation treatment was considered important for projecting barrier performance under potential future climate change.

During the past 6 years, annual precipitation has ranged from 127 mm (in 1987) to >240 mm (in 1993) and average 169 mm/yr. [The long-term (1912-1980) average for the Hanford Site is 160 mm/yr]. Figure 2.5 shows monthly values of the past 6-year average as well as long-term (1912-1980) average reported.

On average, 38% of winter precipitation is snow, and annual snowfall averages 335 mm (13.2 in.). This past winter, 1992-1993, there was a record snowfall of 1425 mm (56.1 in.) which was more than four times the long-term average. Figure 2.6 shows the actual snowfall for 1992-1993 and the long-term average (1912-1980).

Irrigation was used to supplement natural precipitation on some of the lysimeters (see Figure 2.4). Irrigation was applied to lysimeters on the west side, except D08-2. Lysimeters D09-7 and D11-7 (see Figure 2.4) were covered and sealed with plastic from August 1988 through July 1990, when covers and plastic seal were removed. Each irrigated lysimeter had a small, manual plastic precipitation gage next to it. Irrigation was scheduled to remove deficits at the beginning and middle of each month. During the first 3 years (November 1987 - October 1990), the irrigation treatment was designed to create a 2X (twice the annual average) precipitation condition. For the past 3 years (November 1990 to present), irrigation was increased to create a 3X (three times the annual average) precipitation condition. Irrigation was applied at intervals that were dictated in part by weather, equipment, and technician availability. A target amount of supplemental irrigation was

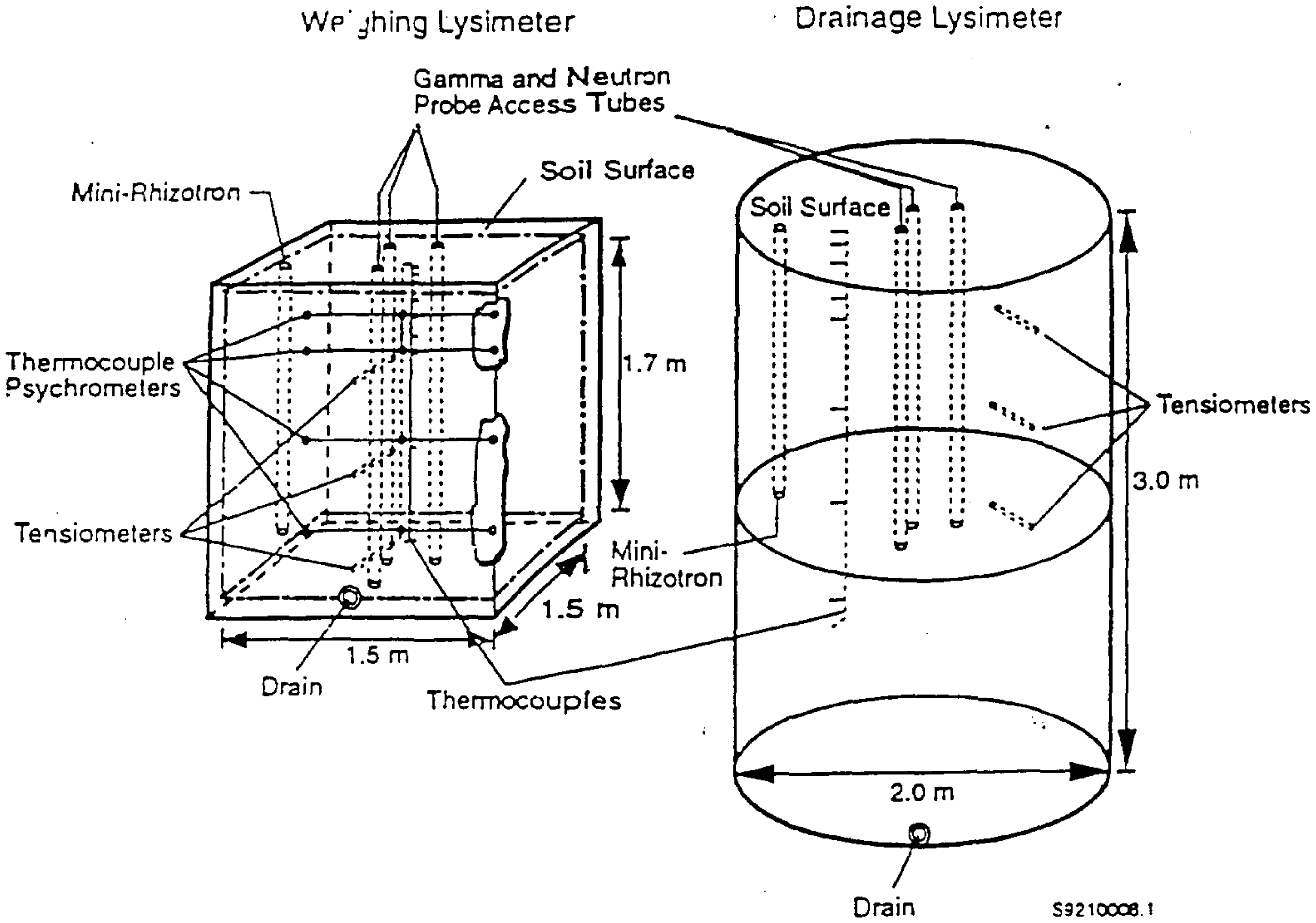
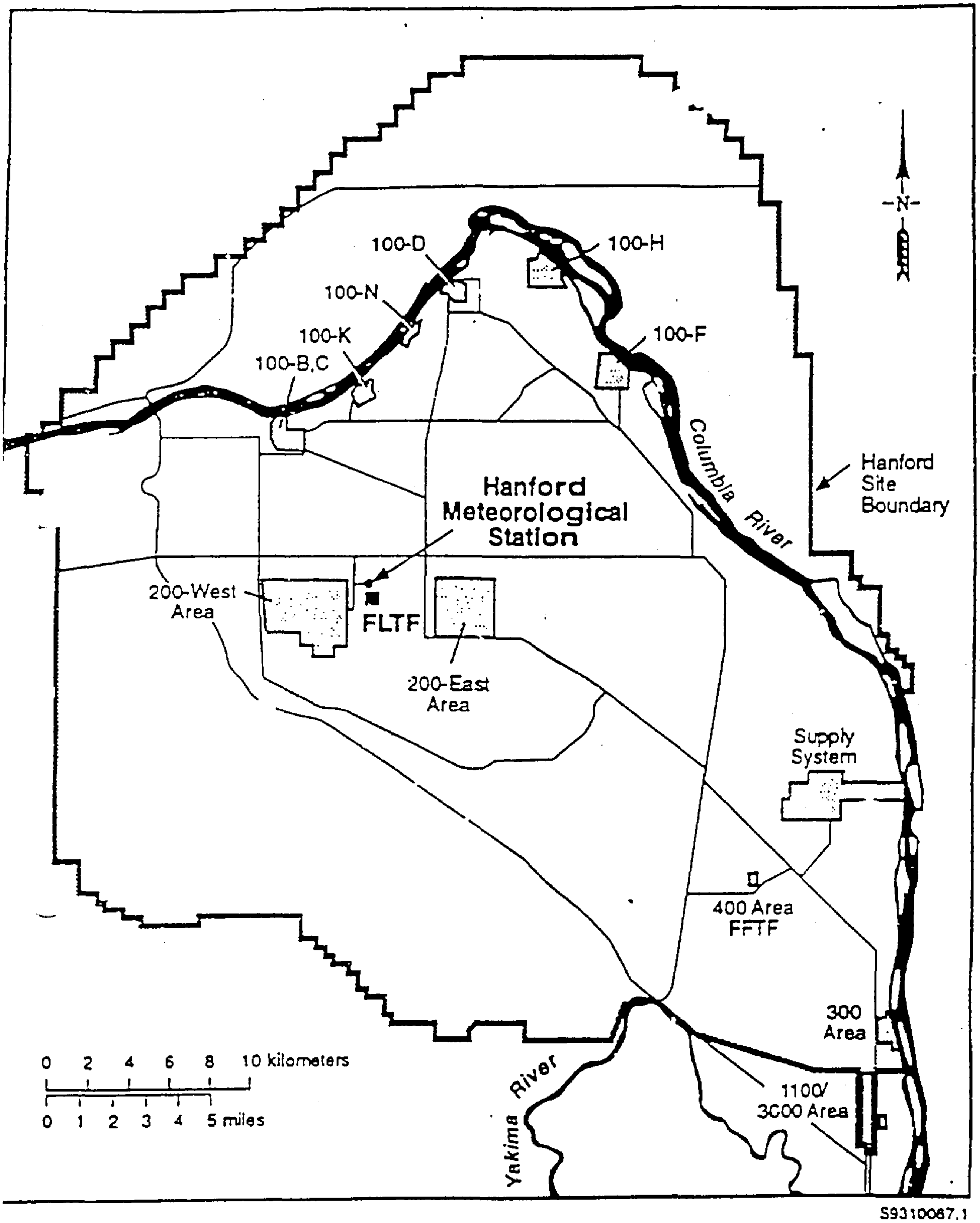


FIGURE 2.3. Instrument Locations in Weighing and Drainage of Lysimeters

Two clear-tube lysimeters (designated as C03-1 and C06-3) were installed and filled in November 1988 with basalt riprap, capped by a filterbed in the lower half, and 1.5 m of Warden silt loam soil (Xerollic Camborthid) from McGee Ranch in the top half (identical to 12 of the drainage lysimeters). A small (above-ground height, approximately 0.15 m) *Artemisia tridentata* (sagebrush) was transplanted into each of these lysimeters. Four additional lysimeters were installed in October 1989, each filled with pit-run gravely sand in the bottom half (1.5 m) and with screened sand in the top 1.5 m. Two of these sand-filled lysimeters (designated as C02-9 and C05-11) were topped with 0.15 m of coarse gravel. The remaining two sand-filled lysimeters (designated as C02-9 and C05-11) were each transplanted with small sagebrush in late 1989.



IGURE 2.1. Location of the Field Lysimeter Test Facility on the Hanford Site

1.0 INTRODUCTION

Cover systems are used to isolate buried waste from the accessible environment at most, if not all, waste sites throughout the United States (Lutton et al. 1979; EPA 1986, 1987, 1991; Anderson et al. 1989). These covers range from very simple designs, consisting of nothing more than a thin mantle of soil placed over the waste, to complex designs, consisting of multiple layers of soils and geosynthetic materials. Control of water intrusion into the waste is a major feature of the more complex designs.

1.1 CAPILLARY BARRIERS

A proposed surface cover design for the Hanford Site includes a "capillary barrier" (Wing and Gee 1990). The "capillary barrier" is a cover system consisting of layers of fine soil overlying coarse soils. Textural contrast in soils provides a "capillary break," which limits drainage and stores water in the upper (fine) soil until the soil at the interface approaches saturation. The resulting increased water storage increases water availability for evaporation and plant transpiration (Miller 1973).

Capillary barrier systems have been proposed and tested under varied climate and site conditions throughout the world (Rancon 1980; Nyhan et al. 1986; Cartwright et al. 1987; Andersen and Clausen 1988; Healy 1989; Schulz et al. 1989; Melchior et al. 1993). While this concept has been known for many years (Alway and McDole 1917), practical use of the concept for infiltration control at waste sites is a relatively recent innovation (Rancon 1980).

In humid climates, a capillary barrier is less effective than in arid climates because soil is often wetted to near saturation, resulting in periodic drainage into the underlying coarse soil (Melchior et al. 1993). Booth and Price (1989), Healy (1989), and Andersen and Clausen (1988) have shown that significant portions (ranging from 20% to 50%) of the annual precipitation at humid sites can drain through a capillary barrier, which on sloping surfaces in wet climates acts more like an internal drain.

In contrast, Schulz et al. (1989) have demonstrated that a capillary barrier at a humid site (Beltsville, Maryland) when covered with adequate

FIGURES

CONTENTS

ACKNOWLEDGMENTS

We acknowledge the technical assistance of A. C. Phillips (for data archiving) and O. B. Abbey (for field equipment calibration and maintenance) during the past several years. Without their assistance, this work would not have been completed. We also acknowledge the efforts of L. L. Gorham, who assisted in typing and assembling this document. We also thank the Protective Barrier Development Team, especially N. R. Wing and J. W. Cammann, of Westinghouse Hanford Company who have provided continuing support for this field study, and J. D. Goodenough and R. K. Stewart, of the U.S. Department of Energy, who have supported both the field lysimeter studies and the overall barrier development effort. This work was funded by the U.S. Department of Energy Office of Environmental Restoration and Waste Management (Environmental Restoration Division) under Contract DE-AC06-76RLO 1830.

Detailed soil water measurements were made at near-surface on selected silt loam-covered (capillary barrier) lysimeters during FY 1992. Soil cores were taken to depths of 35 cm and analyzed for soil water content and matric suction. Soil water contents at the near surface varied according to both treatment and sampling time. Vegetated soils were driest, with highest matric suctions at depth. Matric suctions exceeding 10 Mpa (100 bars) were observed at depths of 35 cm. The data suggest that near-surface monitoring of soil water may be needed to complement the neutron probe estimates of soil water and water storage.

A vegetation survey was made on selected capillary-barrier lysimeters. The survey showed significant increases in vegetation in response to the applied water. Under elevated precipitation treatments there were increases in plant density and leaf area index. Total biomass was correlated with plant density and leaf area index.

The FLTF test results have been used to guide the design, development, and testing program of a large-scale (100 x 60 x 15 m) prototype barrier facility located over a waste disposal facility (200 BP-1) at the Hanford Site. The prototype barrier construction was begun in September of 1993 and is scheduled for completion in April of 1994. Water balance data for both soil and gravel surfaces are available from the FLTF and will continue to guide the water balance tests at the prototype barrier. These tests are expected to show that net water infiltration can be controlled effectively on silt loam soil cover surfaces but that large amounts of water will infiltrate gravel-covered side slopes. Quantification of the actual water infiltration and drainage through the sideslopes will be a key contribution from the prototype barrier testing.

Complementary work to prototype-barrier testing will be conducted at the FLTF. Six drainage-type lysimeters will be exhumed in early FY 1994 and replaced with materials representing the prototype barrier. Two of the lysimeters will be filled with silt-loam soil, amended with pea gravel in the top 1-m depth, to represent the prototype barrier surface, while two lysimeters will be filled with basalt rock-rip/rap to represent the extreme coarse side-slope conditions of the prototype test. An additional two

EXECUTIVE SUMMARY

The Field Lysimeter Test Facility (FLTF), a unique facility for monitoring water balance of surface isolation barriers at the Hanford Site, is completing its sixth year of operation. The facility, located adjacent to the 200 West Area, near the Hanford Meteorological Station (HMS), consists of 24 lysimeters filled with a variety of soil/sediment configurations. Twenty lysimeters were constructed as capillary barriers filled with either a 1-m- or 1.5-m-thick layer of fine soil (silt loam) overlying a coarse-textured subsoil (capillary break) and simulate surface isolation barriers with two different water storage capacities. Four lysimeters were filled with gravel-covered coarse sand and simulate surfaces that lack an isolation barrier. The soil configurations, combined with different vegetation and climate (precipitation) regimes, produce 11 distinct treatments which span the extremes in expected surface water balance for Hanford Site soils and cover systems. Precipitation treatments have ranged from ambient (non-irrigated) precipitation, averaging 169 mm/yr, to accelerated precipitation, which includes ambient plus irrigation, and currently averages 480 mm/yr.

The water storage capacity and drainage characteristics of the capillary-barrier (i.e., silt loam over coarse sand/gravel) lysimeters were determined. In early 1988, shortly after the initiation of lysimeter testing, two lysimeters were saturated with water and then allowed to drain. The water storage limit (i.e., amount of water held before drainage) for these lysimeters (with 1.5-m-thick silt loam layers) was determined to be slightly over 500 mm. Decreasing amounts of drainage from these two lysimeters and from three other bare-surfaced lysimeters were observed to occur only in the summers for several years (1988-1990). Small amounts of drainage (<0.4 mm/yr), attributable to thermal gradients, occurred in five of the bare surface (wettest) lysimeters during 1991 and 1992. No drainage was observed in any of the remaining 15 capillary-barrier lysimeters. and water storage in all lysimeters remained well below 500 mm until February 1993.

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FIELD LYSIMETER TEST FACILITY STATUS REPORT IV: FY 1993

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selected for remediating a particular waste site should be designed to adequately control contaminant transport to ensure protection of human health and the environment. Developing that design not only must incorporate good engineering principals but must also include sound ecological principals to account for the interactions between the physical, biological, and chemical factors influencing waste site integrity and contaminant transport.

The exclusion of ecological principals, in my opinion, is the greatest failing of current practices in designing capping technology. That omission prevents the designer from using (or maximizing) beneficial (an very inexpensive) processes (i.e. evapotranspiration) and from foreseeing failure modes (that are usualy very expensive to remedy) that would be obvious to an ecologist (e.g. plant root intrusion into a clay hydraulic barrier). In my view, the use of capping alternatives for closure of landfills, is not just an engineering problem, as is often stated, but rather involves complex physical, biological, and chemical processes requiring a multidisciplinary approach to develop designs that will work over the long haul and are cost-effective.

ACKNOWLEDGMENTS

We gratefully acknowledge the sources of funding to Los Alamos National Laboratory for the Hill AFB landfill capping demonstration including the US Air Force through the Engineering Services Center at Tyndall Air Force Base and the Department of Energy through the Mixed Waste Landfill Integrated Demonstration at Sandia National Laboratories. Ron and Karen McFarland and the employees of McFarland Excavating, J. L. Martinez, T. Schofield, G. Langhorst, J. W. Nyhan, S. Wohnlich, Lt. Col. John Obringer, Lt. Col. Doug Schelhaas, and Mark Ritchey, along with the authors, were key members of the team that constructed the demonstration, installed instrumentation, and monitored the plots through time. Captain Ed Heyse, Dr. Dan Stone, Paul Betts, Marcus Blood, and Dr. Bob James of Hill Air Forces Base Environmental Management Directorate and Base Engineering Personnel provided valuable help in obtaining the necessary approvals and clearances to install the demonstration and provided liaison with other Base departments for the study.

the topsoil and gravel interface. Two possible capillary barrier design options to further improve leachate control might be to increase the slope on the capillary barrier and/or to use a layer of material (i.e. sand) with a higher hydraulic conductivity, just above the capillary break, to promote faster lateral soil water flow rates. Many questions about the performance characteristics of capillary barriers advise caution in their use for remediating landfills. For example, little is known how to optimize barrier design to enhance lateral flow, the limits on slope length for diverting flow, the influence of type, seasonality, and amount of precipitation, and the effects of biological intrusion through the capillary break on barrier performance. Intuitively, It seems likely that capillary barriers will work best in arid and semiarid climates (< 50 cm annual precipitation) with relatively low amounts of snowfall as a source of the precipitation. However, definitive information to support their use in dry climates is not available. Of particular concern is the influence of plant roots, which will aggressively seek subsurface moisture in dry climates, on the performance of the capillary barrier.

The RCRA cap has been the most effective in preventing soil water movement completely through the cap. Breakthrough first occurred about 27 months into the study. Evaluation of the long term performance of the clay barrier in diverting soil water laterally or in preventing leachate production will require additional monitoring.

A potential concern about long term performance of the clay barrier stems from the natural establishment of deeper rooted plant species, such as shrubs, on the plot. These deeper rooted species will provide an important test of the barriers ability to withstand plant root intrusion and the potential desiccation of the clay during periods of moisture stress to the plants. Past experience (Hakonson, 1986) on the influence of plant roots on bentonite clay hydraulic barriers shows that transpiration losses of water stored in the clay, very quickly destroy the ability of the barrier to prevent downward flow of soil moisture.

The results presented in this report represent the performance characteristics of four cap design alternatives over a relatively short period of time. Further monitoring is needed to better define the relationship between the grass and shrub cover and the longer term performance of the capillary barrier. It is particularly important to continue the monitoring of the RCRA cap design to evaluate the leak characteristics of the clay barrier under current conditions and under those expected to occur as deeper rooted species invade the plot.

Current results should be useful to Environmental Restoration personnel in managing risks at the site by providing initializing data and rate constants for hydrologic models. These models are a necessary part of site characterization, assessment. and cleanup activities at Operable Units with landfills in that they can be used to define field sampling needs, calculate transport as a part of the risk assessment activities, and be used to help evaluate the consequences of various cleanup alternatives in reducing risks to acceptable levels.

Table 4: Water balance estimates on the Hill AFB Landfill Cover Demonstration Plots 01Jan90 - 20Sep93

	PLOT DESIGN			
	LA-1 (Grass)	LA-2 (Grass/Shrub)	RCRA	Control
Precipitation (cm) (P)	173	173	173	173
Soil Water Storage At Beginning CY90 (cm)	32	31	35	20
Net Change in Soil Water Storage CY90-Sept. 93 (ΔS)	-17 (-10%)	-15 (-9%)	11 (6%)	-11 (-6%)
Leachate (cm)† (L)	24 (14%)	30 (17%)	0.01 (0.006%)*	41 (24%)
Interflow (cm) (I)	20 (11%)	12 (7%)	43 (25%)	0 (0%)
Runoff (cm) (R)	1.4 (0.8%)	2.2 (1.3%)	5.5 (3.2%)	5.8 (3.4%)
Evapotranspiration (cm) (ET)	145 (84%)	144 (83%)	113 (65%)	137 (79%)
Sediment (g)	102	95	1534	2374

$$\frac{P}{\Delta t} = \frac{(\Delta S + L + I + R + ET)}{\Delta t}$$

† Does not include wall effect   * Breakthrough began March 20, 1992 (27 months elapsed time)

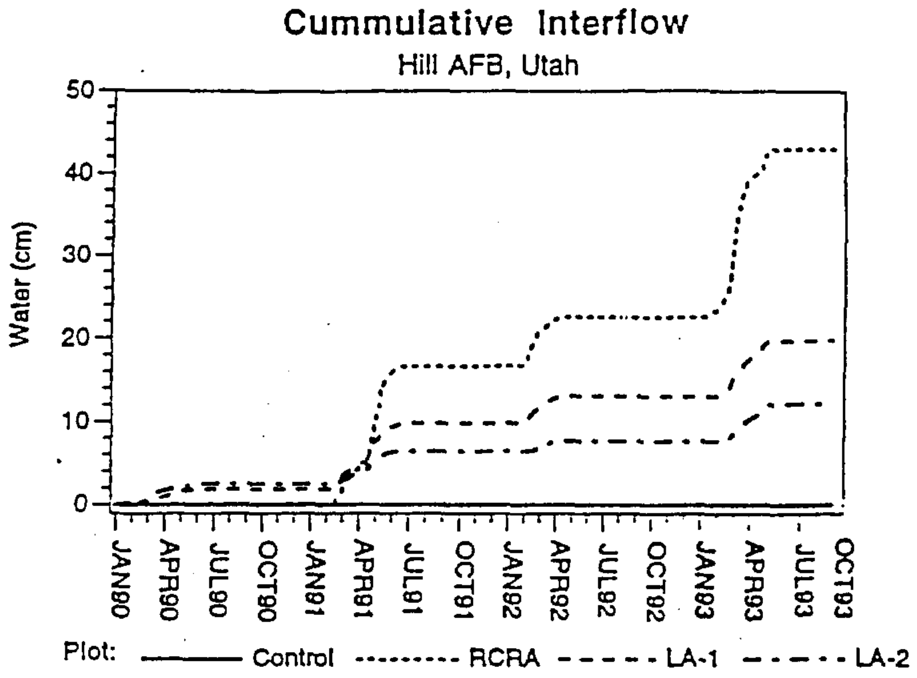


Figure 17. Cummulative barrier lateral flow as a function of time for all cap designs at Hill AFB.

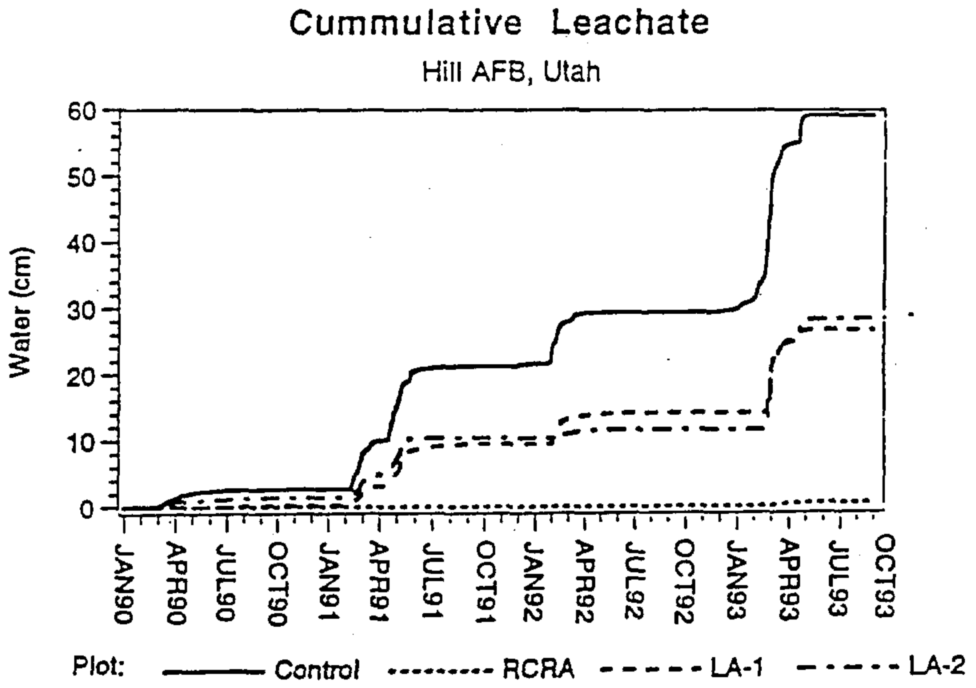


Figure 18. Cummulative leachate flow as a function of time for all cap designs at Hill AFB.

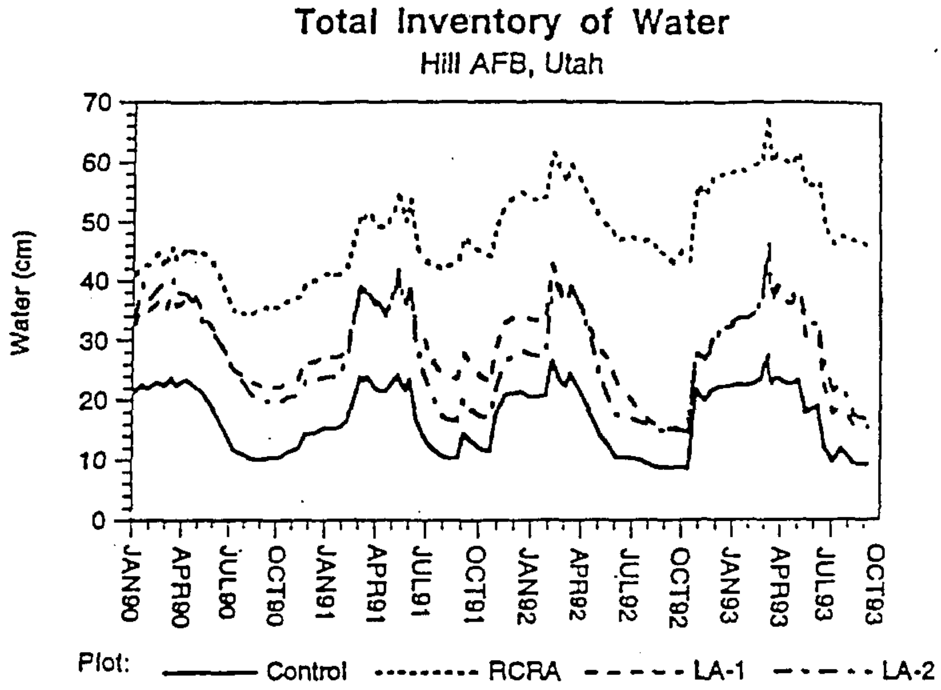


Figure 16. Total soil water inventory as a function of time for all cap designs at Hill AFB.

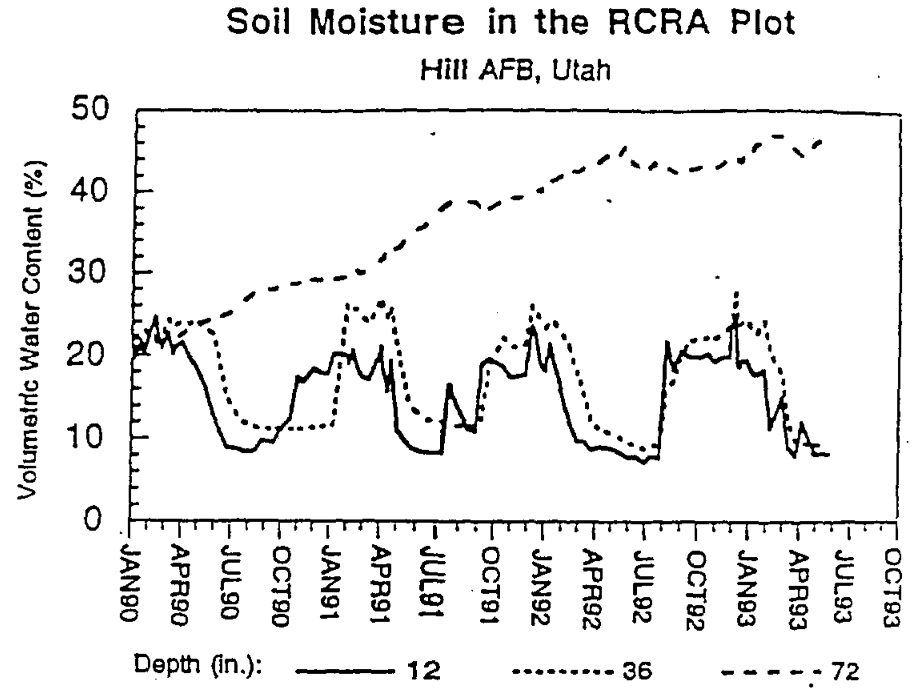


Figure 14. Volumetric water content as a function of time in the RCRA Plot soils at Hill AFB.

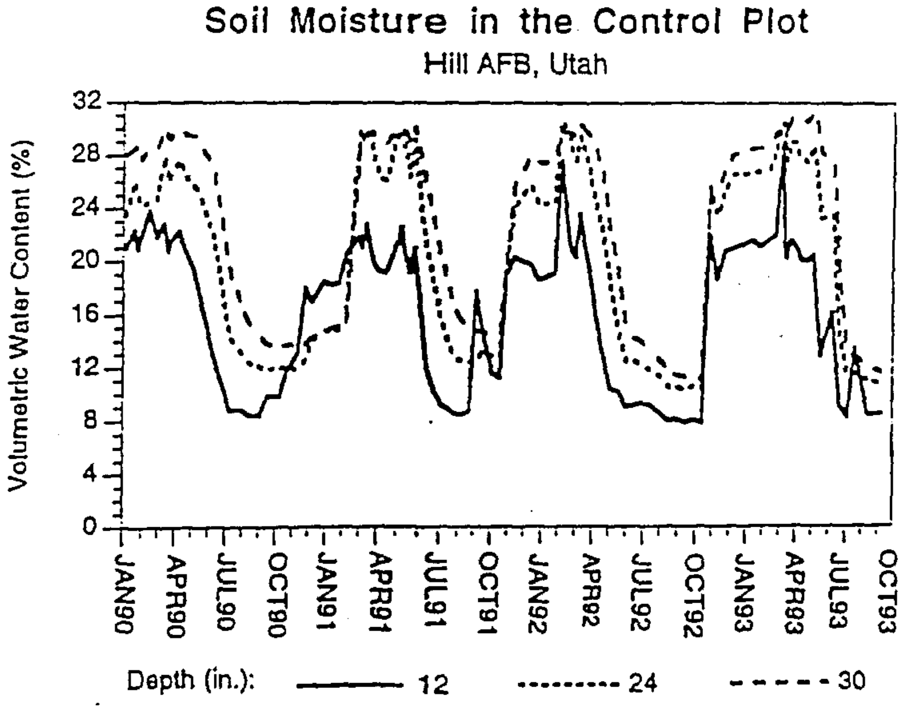


Figure 15. Volumetric water content as a function of time in the Control Plot soils at Hill AFB.

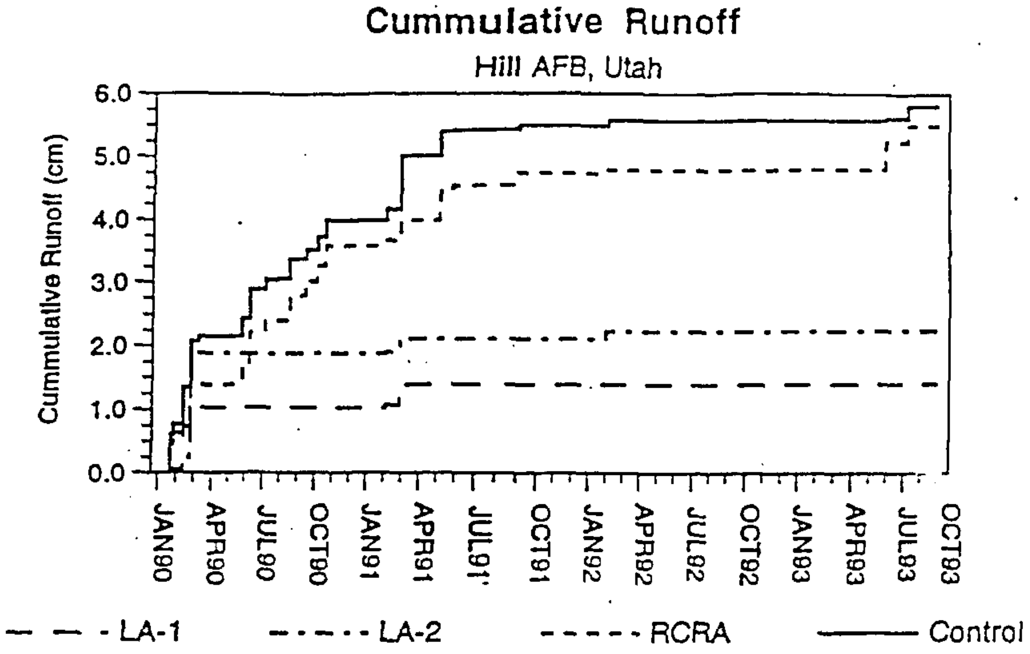


Figure 10. Cummulative runoff from the Landfill Capping Demonstration plots as a function of time for all cap designs at Hill AFB.

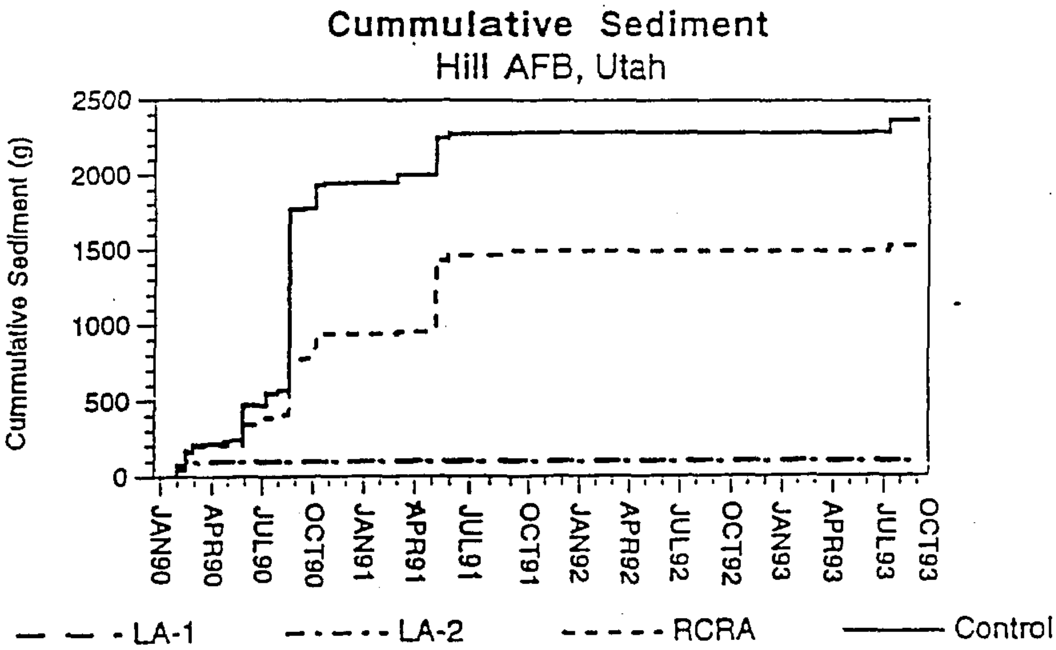


Figure 11. Cummulative sediment from the Landfill Capping Demonstration plots as a function of time for all cap designs at Hill AFB.

Table 3. Dry biomass estimates for vegetation types on the Hill AFB cover demonstration plots in June 1992 and September 1993.

	DRY BIOMASS (g/m^2)[1]							
	LA-1		LA-2		RCRA		CONTROL	
	92	*93*	*92*	*93*	*92*	*93*	*92*	*93*
GRASS	6.9	5.6	0.72	2.3	5.6	5.4	6.1	6.4
FORB	0.06	0.11	0.0	0.22	0.07	0.16	0.05	0.14
SHRUB	7.6	19	30	21	4.2	12	3.0	9.7
TOTAL	14	23	31	24	10	18	9	16

[1] DRY BIOMASS BASED ON THE FOLLOWING EQUATIONS DEVELOPED FROM DESTRUCTIVE SAMPLING OF 10 $0.5M^2$ PLOTS ADJACENT TO THE TEST CELLS:

GRAMS GRASS = 0.256 X % GRASS COVER, $R^2 = 0.913$, $P = 0.0000$
GRAMS FORB = 0.008 X % FORB COVER, $R^2 = 808$, $P = 0.0002$
GRAMS SHRUB = 0.691 X % SHRUB COVER, $R^2 = 0.673$, $P = 0.0020$
GRAMS LITTER = 0.378 X % LITTER COVER, $R^2 = 0.541$, $P = 0.0099$

Table 2. Some characteristics of the vegetation on the cover demonstration plots at Hill AFB during June 1992 and September 1993.

PLOT

	LA-1		LA-2		RCRA		CONTROL	
	92	*93*	*92*	*93*	*92*	*93*	*92*	*93*
TOTAL PLANT COVER (%)	51	63	58	67	38	58	35	56
FORB COVER (%)	7.8	14	0	27	8.5	20	6.5	17
GRASS COVER (%)	27	22	2.8	9	22	21	24	25
SHRUB COVER (%)	11	27	43	31	6.0	17	4.3	14
STANDING DEAD (%)	5.4	NM*	12	NM	1.1	NM	0.9	NM
GROUND COVER (%)	80	96	88	94	47	77	60	76
ROCK COVER (%)	36	30	17	10	1.0	1.0	0	0
LEAF AREA INDEX (CM^2/CM^2)	0.78	0.96	0.85	1.12	0.55	0.84	0.55	0.88

* Standing dead not measured separately from live vegetation

FIGURE 7. CAPILLARY BARRIER COVER DESIGN

(VERTICAL CROSS SECTION OF HILL AFB PLOT)

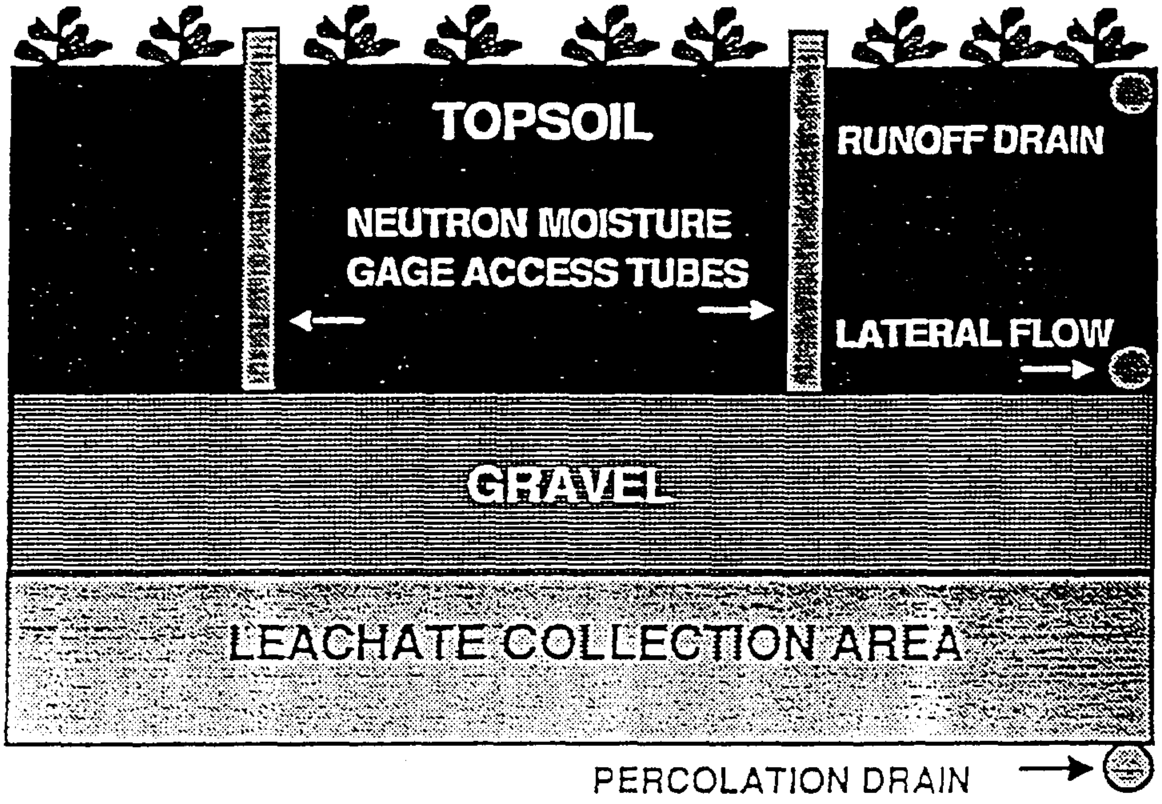


FIGURE 6. MODIFIED RCRA COVER DESIGN

(VERTICAL CROSS SECTION OF HILL AFB PLOT)

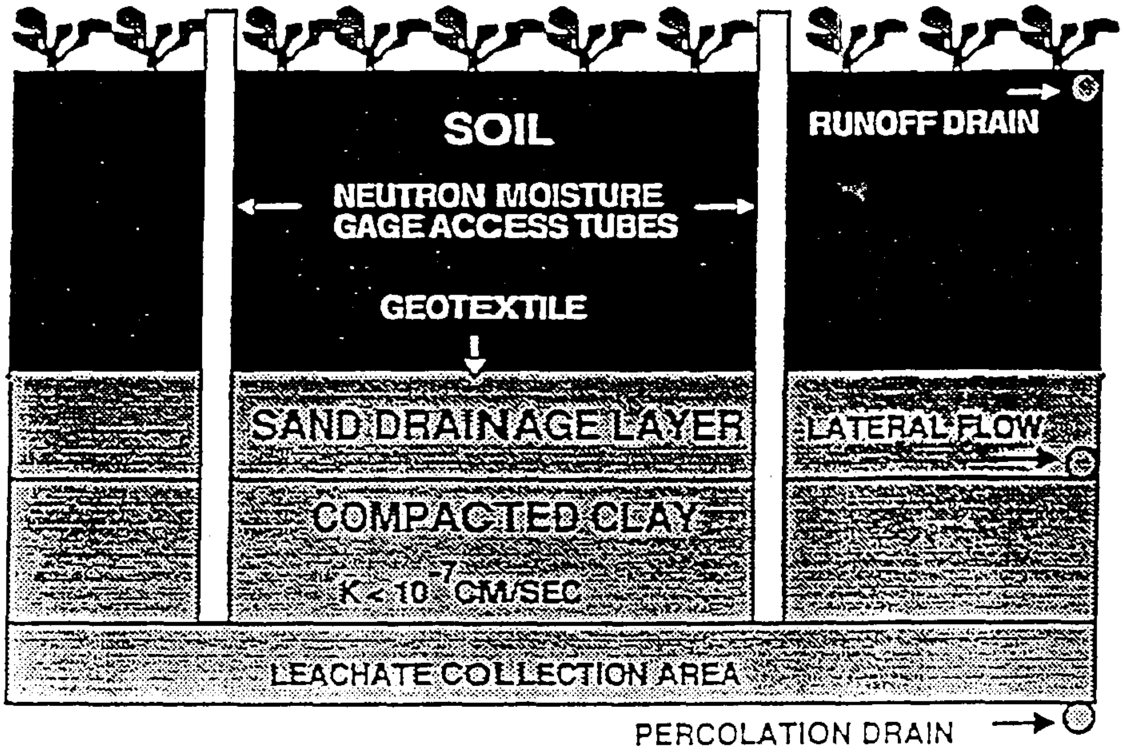
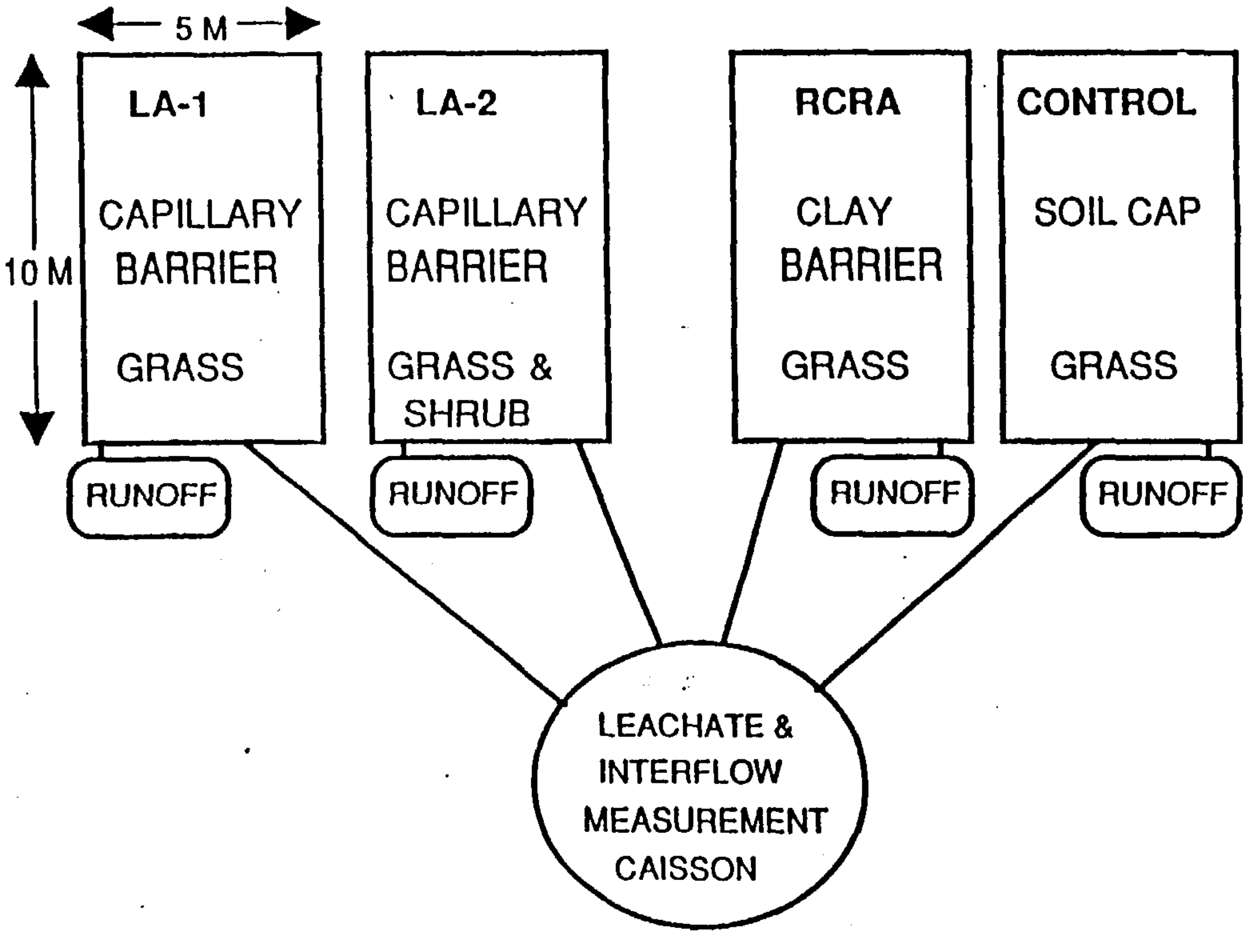


FIGURE 4. PLAN VIEW OF THE LANDFILL COVER DEMONSTRATION PLOTS AT HILL AIR FORCE BASE



TECHNICAL CONSIDERATIONS

The Concept of Water Balance

The fate of meteoric water falling on the surface of a landfill is often referred to as the water balance of the site. A simplified representation of water balance describes *surface runoff and one-dimensional movement of water in the soil profile to the plant* rooting depth. For net rates and amounts, the water balance equation is:

$$dS/dt = (P - Q - ET - L)/dt \qquad \text{(Equation 1)}$$

where dS is the rate of change in soil moisture, P is the precipitation per unit area, Q is the runoff per unit area, ET is the evapotranspiration per unit area, L is the percolation below the root zone per unit area, and t is the unit of time used in solving the equation.

Application of the concept of water balance to design of landfill caps takes advantage of the fact that there are strong interactions between the various components of water balance. For example, a reduction or elimination of the runoff term (Q), increases infiltration of water into the soil, resulting in increased soil moisture storage followed by an increase in ET and/or percolation. Likewise, reducing percolation necessitates that more of the precipitation be partitioned between soil moisture storage, ET, runoff, or that it is diverted laterally using an appropriate barrier technology. The coupled nature of the processes comprising the water balance can be used to advantage in designing landfill caps that minimize or eliminate processes in Equation 1 that contribute to contaminant migration (i.e. percolation) while enhancing other terms (i.e. ET) that do.

The concept of water balance and, especially methods to manipulate it's various components, has served as the basis for several studies to design, test, and evaluate a variety of capping alternatives for radioactive and hazardous waste landfills (Nyhan et al., 1990; Hakonson et al., 1992; Hakonson et al., 1993; Lane, 1984; Lane and Nyhan, 1984).

THE HILL AIR FORCE BASE COVER DEMONSTRATION

Objectives

Los Alamos National Laboratory has investigated the performance of a variety of landfill capping alternatives since 1981 using large field lysimeters to monitor the fate of precipitation falling on the cap surface (Hakonson et al, 1992). The objective of these studies is to provide the risk manager with a variety of field tested capping designs, of various complexities and costs, so that design alternatives can be matched to the need for hydrologic control at the site (Nyhan et al, 1990; Hakonson et al, 1989; Hakonson et al, 1986).

In climates that experience freezing temperatures or drought, the cover may be damaged by the freezing or drying of soil or man-made construction materials. Critical design components of the cover should be placed below the depth of freezing or severe drying. Freezing may also increase the amount of runoff during winter months, since percolation through frozen ground can be reduced.

Biological Factors

Although vegetation is important in controlling erosion and percolation (Nyhan et al, 1984), deep-rooted plants can access buried radionuclides and bring them to the surface of the site (Foxx et al , 1984). Radionuclides in plant tissue can be transported through the food web to humans by herbivorous or nectivorous organisms (Anonymous, 1967). For example, one of the pathways of tritium transport away from a low level waste site at Los Alamos is via the soil moisture to plant nectar to honey bee to honey pathway (Hakonson and Bostick, 1976). Also, tumbleweeds (Salsola kali) growing over the cribs at Hanford, accumulated Sr-90 and then transported the contaminant away from the site as the matured plants blew away from the site after the growing season was over(Klepper et al, 1979).

The importance of preventing buried waste from reaching the ground surface is that erosional processes dominate in the movement of contaminants on the ground surface to biological surfaces. For example, rain splash and/or wind resuspend soil particles (especially the fine silts and clays) and then deposit them on plants (Dreicer et al, 1984; Foster et al, 1985) and animals (Romney and Wallace, 1977; Hakonson and Nyhan, 1980). Field studies (Hakonson and Nyhan, 1980; Watters et al, 1980) with plutonium show that physical deposition of contaminated soil particles on vegetation surfaces is 100-1000 times more important than root uptake in contaminating vegetation with this radionuclide.

The role of burrowing animals in mobilizing buried waste is generally unknown. A limited database (O'Farrell and Gilbert, 1975; Winsor and Whicker, 1980; and Arthur and Markham, 1983) demonstrated that burrowing animals can transport radionuclides vertically in the soil profile and influence water balance and erosion of the cap by changing the physical and hydrologic characteristic of the soil (Aubertin, 1971; Grant et al , 1980; Lysikov, 1982).

REGULATORY CONSIDERATIONS

General Performance Requirements

The regulatory requirements for closure of hazardous and mixed waste landfills are found in 40CFR Parts 264 and 265, Subpart N. Under these regulations, owners/operators of landfills are required to perform landfill closures. The primary requirement of 264.310 and 265.310 is for the owner/operator to design and construct a low-permeability cover over the landfill to minimize migration of liquids into the waste

TABLE 1. ESTIMATED COST OF SOME LANDFILL CLOSURE ALTERNATIVES

ALTERNATIVE	COST/UNIT
EXCAVATE	\$33M/AC
RCRA CAP	\$2M/AC
SOIL/CAPILLARY BARRIER COVER	\$1.5M/AC
BIO-ENGINEERED SOIL/VEG COVER	\$0.1M/AC
SURFACE MGMT W/ EROSION CONTROL	\$0.05M/AC

SELECTION OF ALTERNATIVE SHOULD BE BASED ON HUMAN AND ECOLOGICAL RISK ASSESSMENT

Control of contaminant migration can be achieved with natural or synthetic barriers that can be placed around the waste to control the movement of water and/or gases. Migration barriers can be permeable or impermeable depending on the type of contaminant/s and their mode of transport (note that side wall- and/or under- barrier technology is currently not well developed). The cap placed over the waste is a central feature of most containment strategies and can range from a very simple soil cover to a very complex engineered design that is intended to mitigate both the vertical and lateral flow of water and gases.

Even at this early stage in DOE's cleanup program, it is certain that capping technologies will be heavily used, either alone or in combination with other technologies, to remediate the landfills on DOE property. Capping is a viable cleanup alternative because human and ecological risks are considered to be low at most of these sites (based on known levels of contaminants and preliminary baseline risk assessments) and the regulatory requirements for final closure of old landfills can be met using a well designed cap to isolate the buried waste.

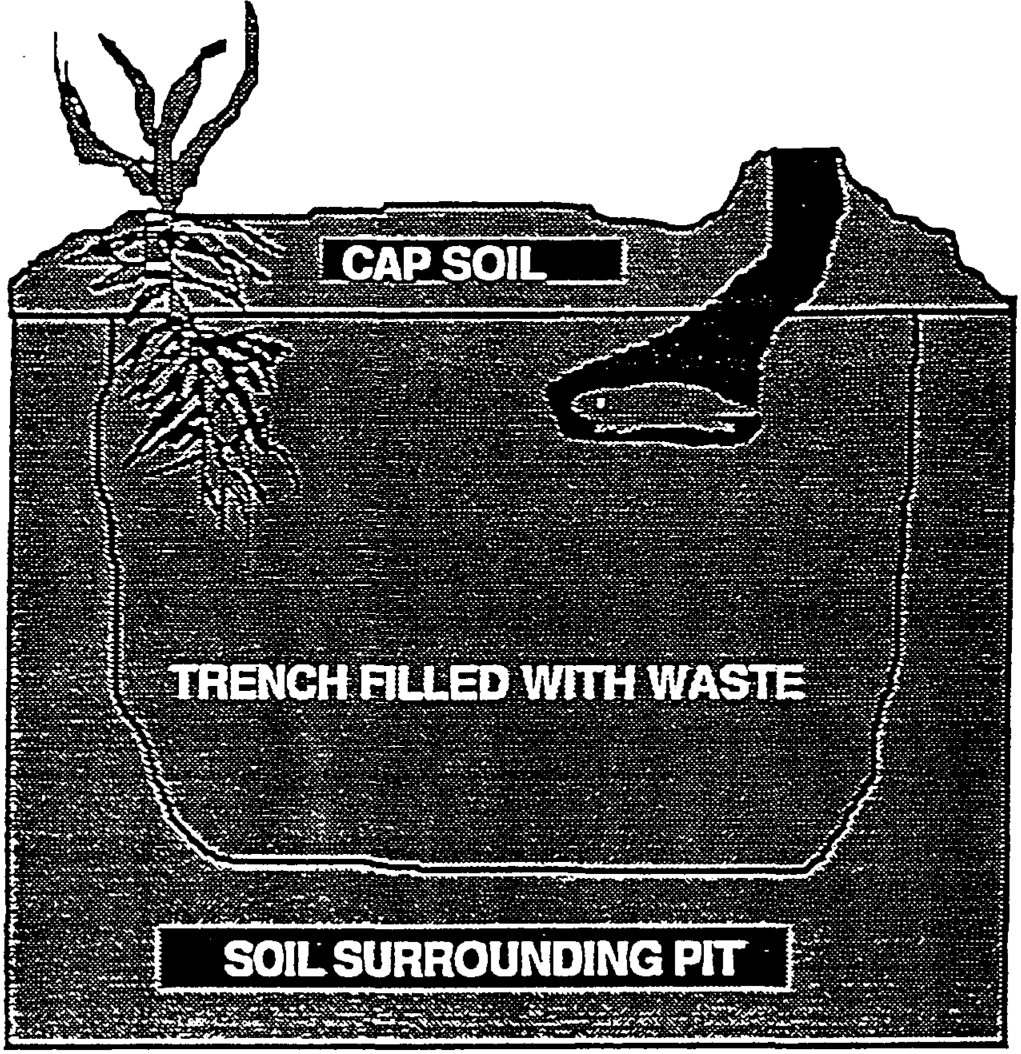
Under ideal conditions, the primary functions of the cap (Figure 1) are to isolate the buried waste from the surface environment and to control hydrologic processes, including erosion, that can cause contaminant migration from the site (Hakonson et al., 1992). Excessive erosional loss of cap soil can expose buried waste leading to the potential for off site transport of contaminants. Likewise, water that infiltrates into the cap soil can lead to enhanced percolation of water and solutes out of the burial environment.

Biological processes, including plant root and burrowing animal intrusion into the waste can also contribute to migration of contaminants from the burial environment (Hakonson et al, 1992; Figure 1). However, the relative importance of biological processes, in either positively or negatively affecting the migration of the waste, is strongly related to their relationship to the hydrologic characteristics of the site (Hakonson et al., 1992).

Cost will always be an important criteria for selecting options for remediating contaminated sites. In general, the objective is to reduce costs to a minimum while satisfying technical, regulatory, and political/social constraints. The technical basis for defining the level of control needed to reduce contaminant migration should be derived from the health and environmental risk assessments.

A comparison of estimated unit costs for construction (i.e. O&M costs not included) of several capping alternatives is compared to the cost of excavating the waste in Table 1. Note that the most costly capping alternative (i.e. the RCRA cap at $4.9M/ha) is still a factor of 15 less expensive than removal of the waste. Additionally, the cost of different capping alternatives can vary by at least a factor of 10 (i.e. from $0.12M - $4.9M), depending on the complexity of the design and, again, the need for reducing risks. Although capping costs are relatively inexpensive compared to other options, they still

FIGURE 1. CONVENTIONAL LANDFILLING PRACTICE



LAUR-93-4469

HYDROLOGIC EVALUATION OF FOUR LANDFILL COVER DESIGNS AT HILL AIR FORCE BASE, UTAH

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K. L. Manies, R. W. Warren,
L. J. Lane, J. S. Kent, and W. Wilson

PREPARED FOR THE DEPARTMENT OF ENERGY
MIXED WASTE LANDFILL INTEGRATED DEMONSTRATION
SANDIA NATIONAL LABORATORY

REPORT TO MEET MILESTONE A1 ON TTP 1212-11
(SELECT BEST BARRIER DESIGN AT HILL AFB).

February 4, 1994

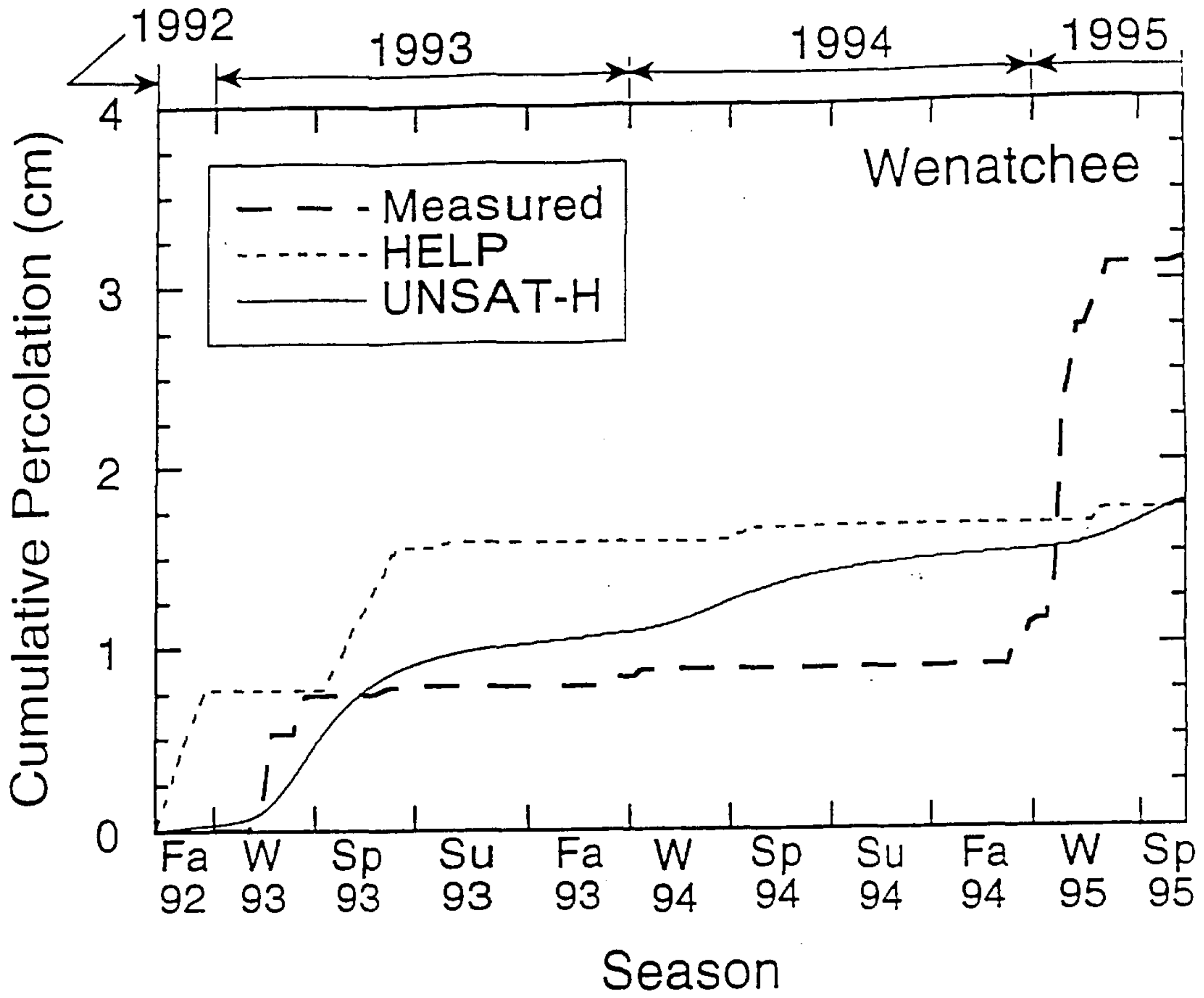
1992
1993
1994
1995
Wenatchee
Measured
HELP
UNSAT-H
Cumulative Percolation (cm)
0
1
2
3
4
Fa 92
W 93
Sp 93
Su 93
Fa 93
W 94
Sp 94
Su 94
Fa 94
W 95
Sp 95
Season

FIG. 12

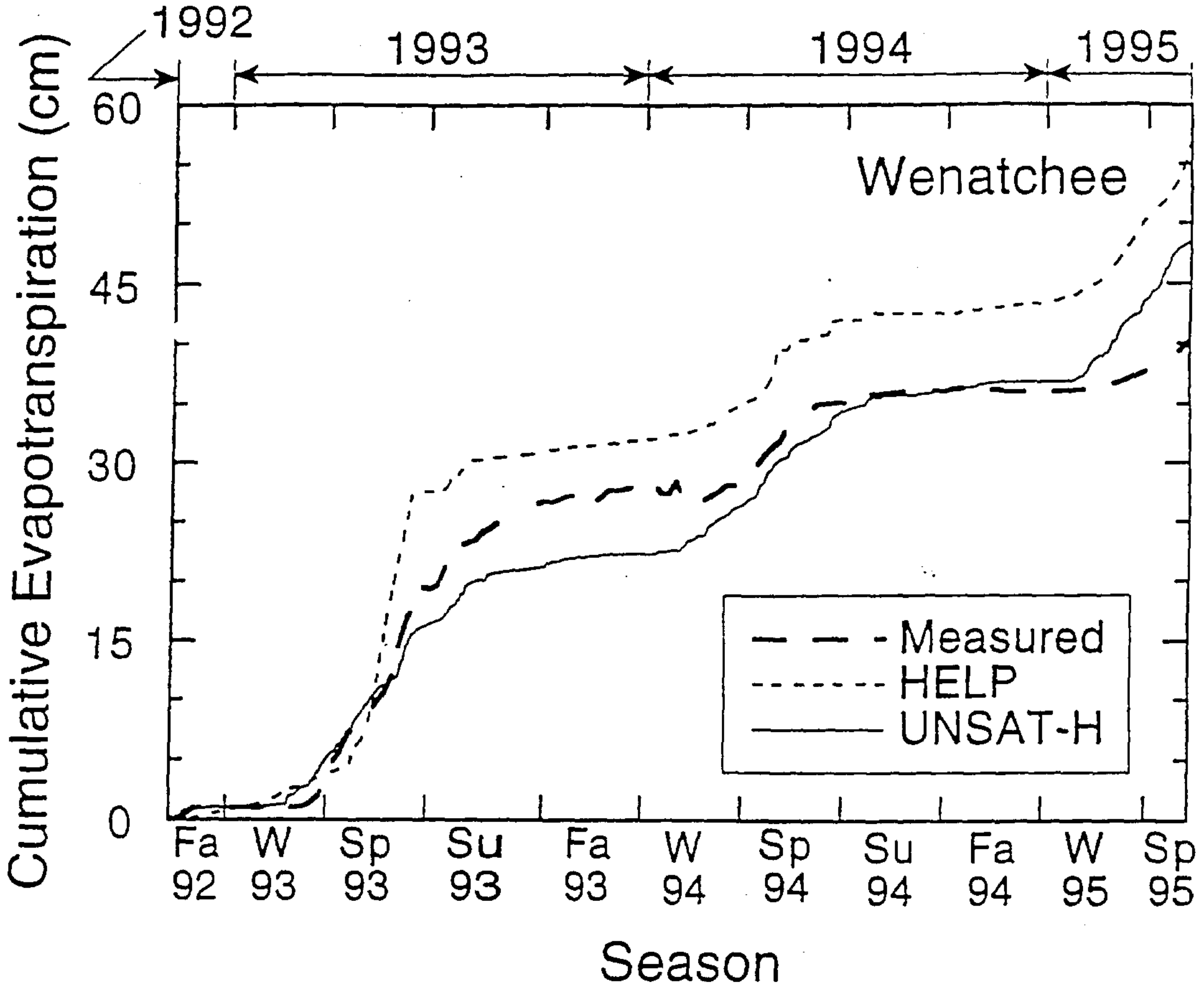
1992
1993
1994
1995
Cumulative Evapotranspiration (cm)
60
45
30
15
0
Wenatchee
Measured
HELP
UNSAT-H
Fa 92
W 93
Sp 93
Su 93
Fa 93
W 94
Sp 94
Su 94
Fa 94
W 95
Sp 95
Season

FIG. 10

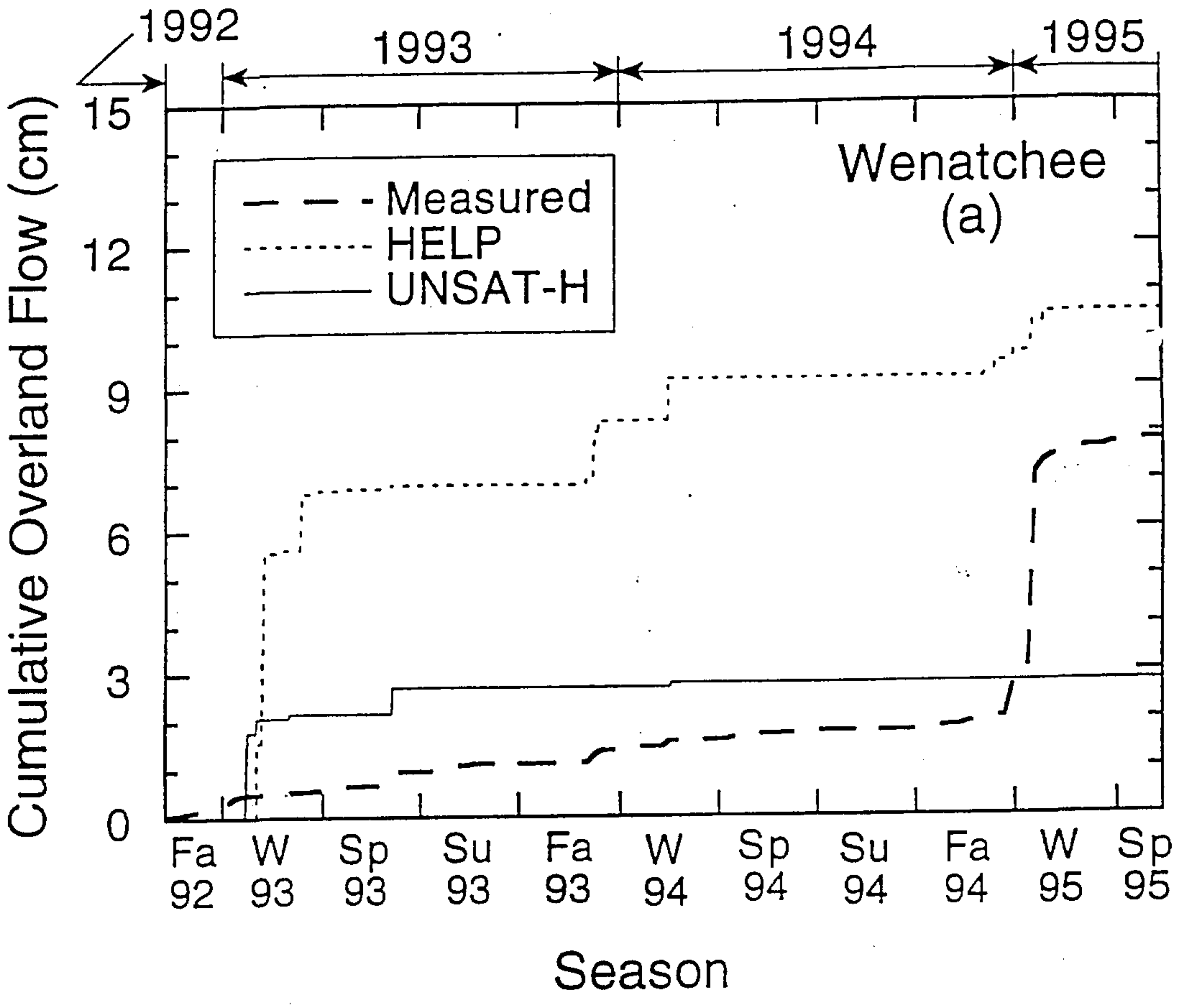
1992
1993
1994
1995
Cumulative Overland Flow (cm)
0
3
6
9
12
15
Measured
HELP
UNSAT-H
Wenatchee
(a)
Fa 92
W 93
Sp 93
Su 93
Fa 93
W 94
Sp 94
Su 94
Fa 94
W 95
Sp 95
Season

FIG. 8

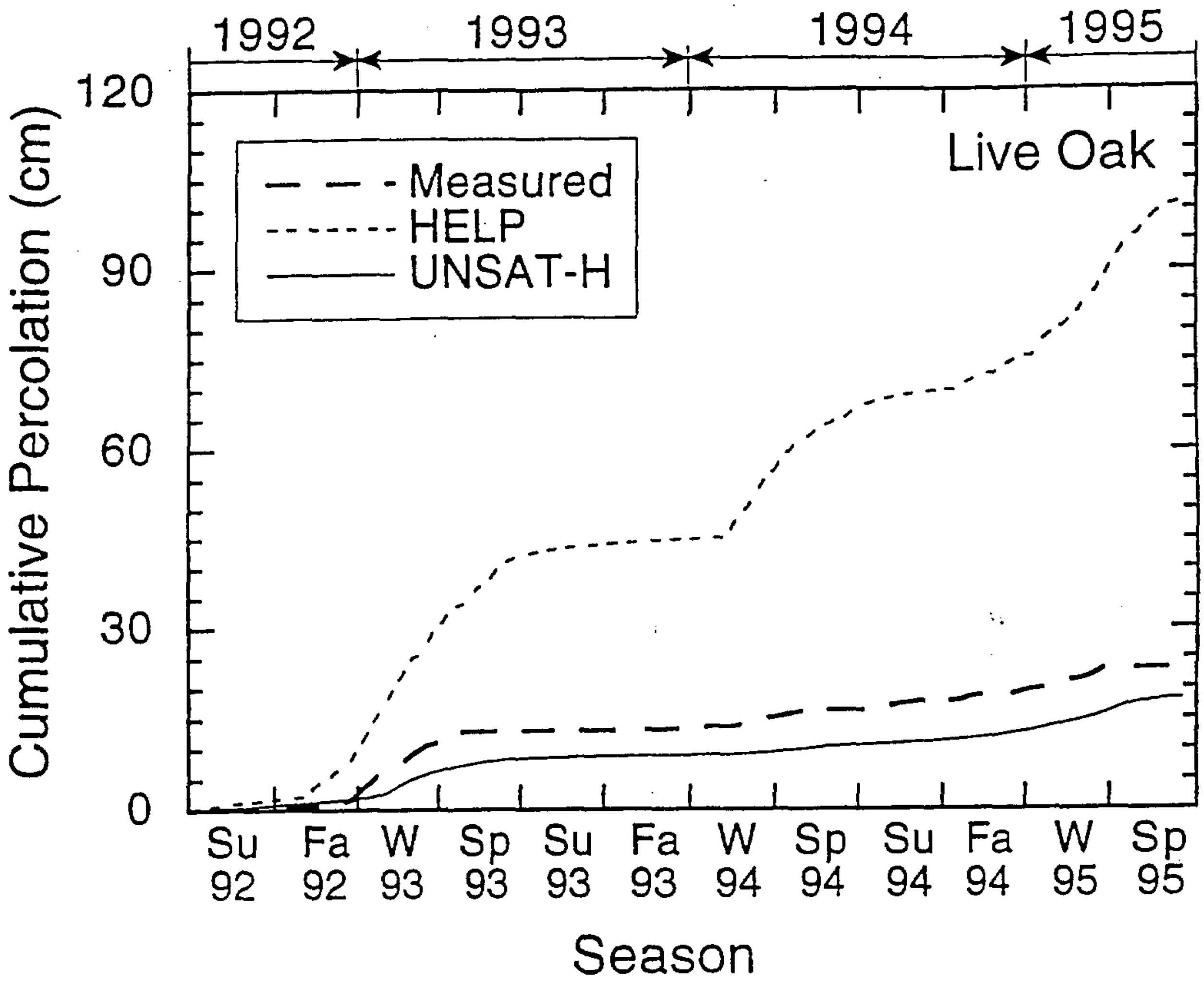
1992
1993
1994
1995
Live Oak
Measured
HELP
UNSAT-H
Cumulative Percolation (cm)
0
30
60
90
120
Su 92
Fa 92
W 93
Sp 93
Su 93
Fa 93
W 94
Sp 94
Su 94
Fa 94
W 95
Sp 95
Season

FIG. 6

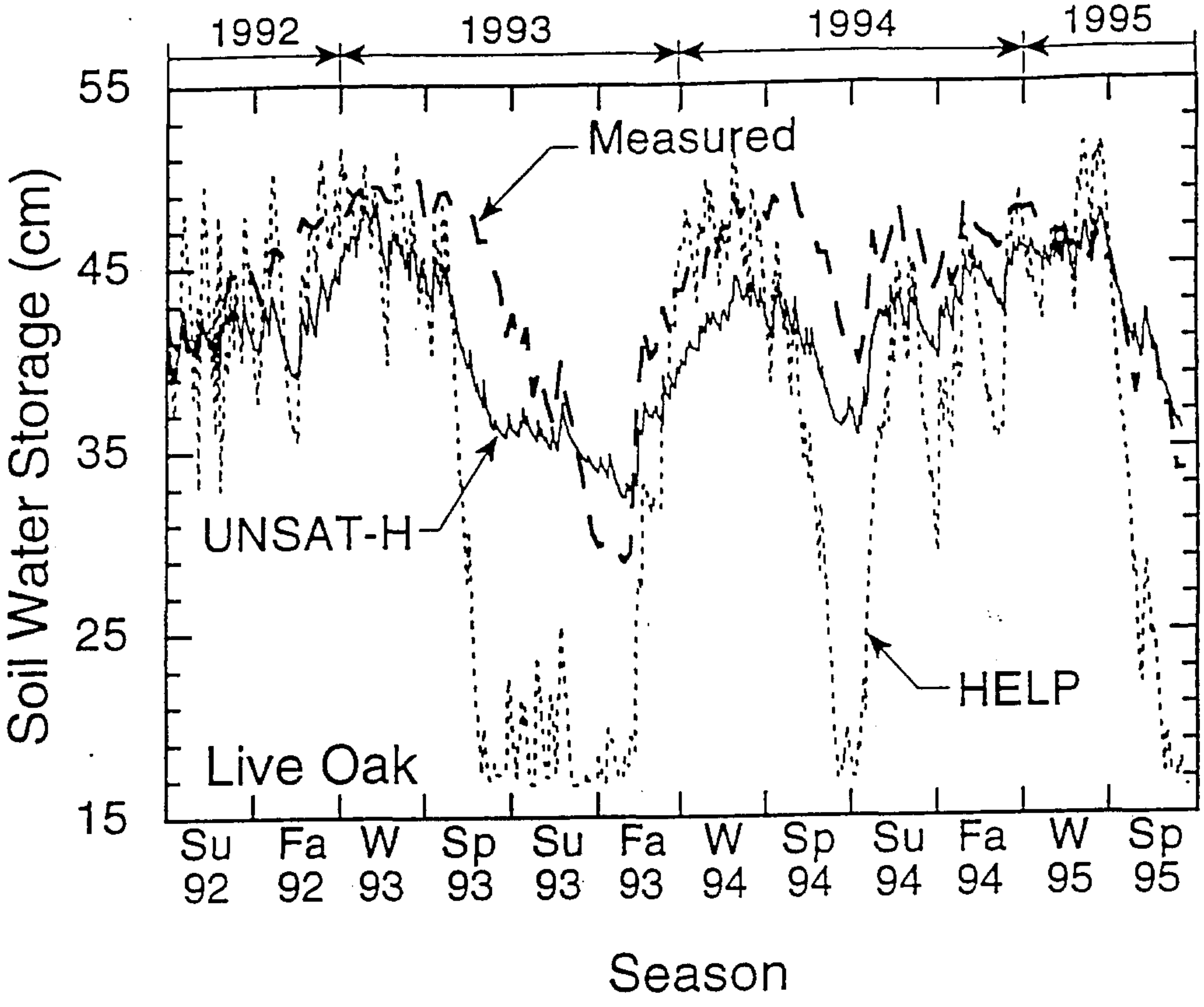
1992
1993
1994
1995
Soil Water Storage (cm)
55
45
35
25
15
Measured
UNSAT-H
HELP
Live Oak
Su 92
Fa 92
W 93
Sp 93
Su 93
Fa 93
W 94
Sp 94
Su 94
Fa 94
W 95
Sp 95
Season

FIG. 4

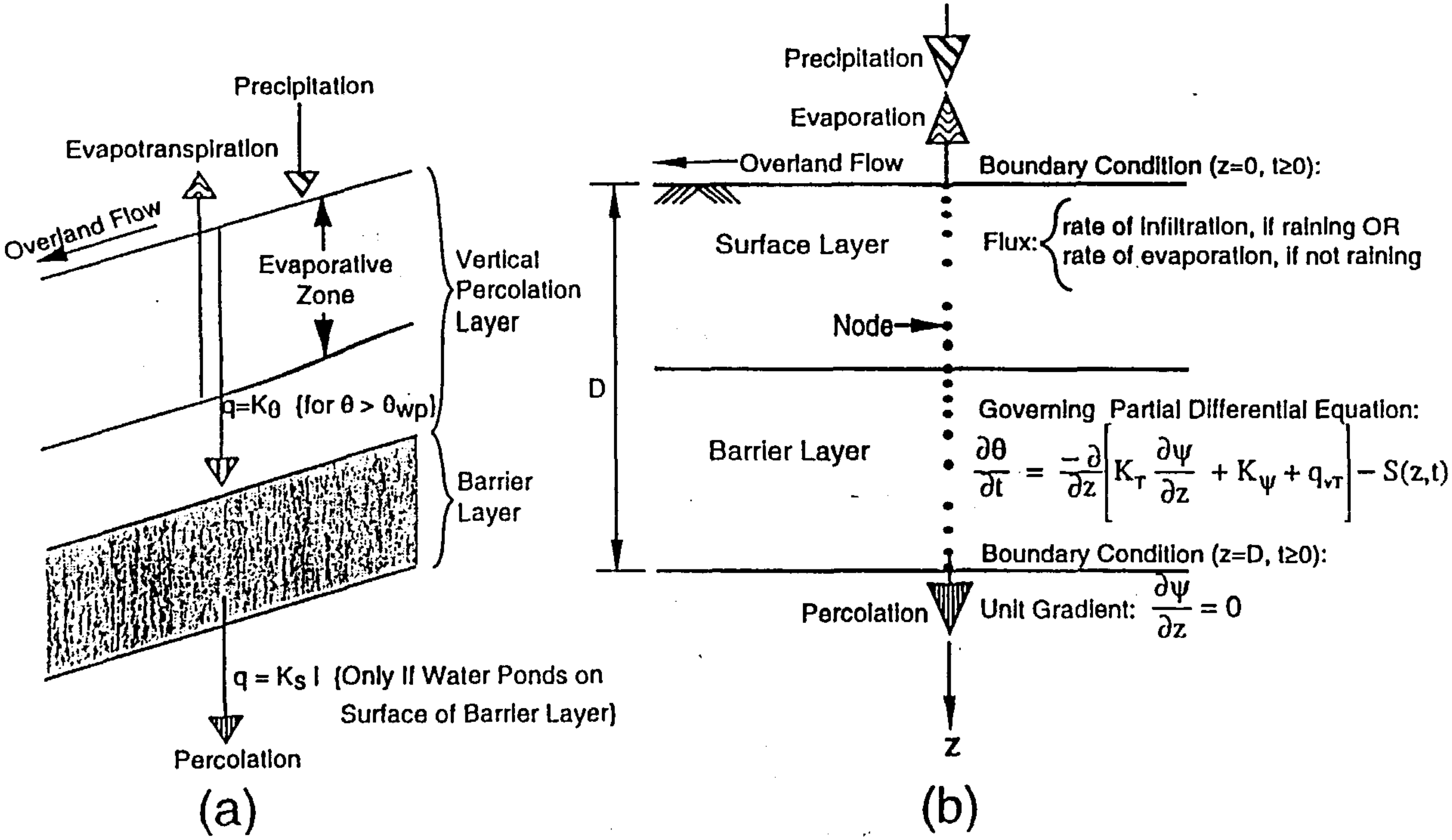

Figure 2. Schematic Representation of Water Balance Computations by HELP (a) and UNSAT-H (b)

Table 2. Initial Abstraction and SCS Runoff Curve Number for Live Oak

Season	Measured Abstraction (cm)	HELP Abstraction (cm)	HELP CN	CN for Better Prediction of Overland Flow	Avg. Increase in Overland Flow[a] (cm)
Spring 1993	0.7	1.8	87.7	95	1.5
Summer 1993	0.7			91	1.0
Fall 1993	0.1			96	1.6
Spring 1994	0.9			89.5	0.8

[a] Avg. increase in overland flow is per storm event

Table 1. Input Parameters for Model Simulations

Parameter	Site/Layer	Input Value	Reference	MODEL Applicable
Soil Properties				
Porosity (cm/cm)	Live Oak: Surface Layer, Barrier Layer Wenatchee: Surface Layer, Barrier Layer	0.40, 0.52 0.40, 0.36	Field Density Test (Lane et al. 1992)	HELP, UNSAT-H
Field Capacity (cm/cm)	Live Oak: Surface Layer, Barrier Layer Wenatchee: Surface Layer, Barrier Layer	0.35, 0.33 0.29, 0.25	Pressure Plate Test (Khire et al. 1994)	HELP
Wilting Point (cm/cm)	Live Oak: Surface Layer, Barrier Layer Wenatchee: Surface Layer, Barrier Layer	0.15, 0.17 0.06, 0.07	On-Site TDR Measurements (Khire et al. 1994)	HELP
Saturated Hydraulic Conductivity (cm/s)	Live Oak: Surface Layer Live Oak: Barrier Layer Wenatchee: Surface Layer Wenatchee: Barrier Layer	1.0×10^{-4} 3.2×10^{-6} 4.5×10^{-5} 2.2×10^{-7}	Laboratory Hydraulic Conductivity Tests (Benson et al. 1993)	HELP, UNSAT-H
Haverkamp Fitting Parameters for Soil Water Characteristic Curve	Live Oak: Surface Layer Live Oak: Barrier Layer Wenatchee: Surface Layer Wenatchee: Barrier Layer	$\alpha = 200$, β (1/cm) = 0.65 $\alpha = 17$, β (1/cm) = 0.40 $\alpha = 80$, β (1/cm) = 0.60 $\alpha = 72$, β (1/cm) = 0.60	Khire et al. (1994)	UNSAT-H
Haverkamp Fitting Parameters for Unsaturated Hydraulic Conductivity Function	Live Oak: Surface Layer Live Oak: Barrier Layer Wenatchee: Surface Layer Wenatchee: Barrier Layer	A = 1, B (1/cm) = 1.45 A = 8, B (1/cm) = 1.15 A = 300, B (1/cm) = 2.2 A = 400, B (1/cm) = 1.3	Khire et al. (1994) Khire et al. (1995)	UNSAT-H
Plant Data				
Evaporative Depth (cm)	Live Oak, Wenatchee	106.5, 75	Schroeder et al. (1994)	HELP
Root Zone Depth (cm)	Live Oak, Wenatchee	24, 23	(Benson et al. 1993)	HELP, UNSAT-H
Percent Bare Area	Live Oak Wenatchee	59 40	Grid Pictures (Benson et al. 1993)	UNSAT-H
Leaf Area Index	Live Oak Wenatchee	2.0 1.0	Expert Opinion	HELP, UNSAT-H
Growing Season (Julian Day)	Live Oak Wenatchee	75-320 105-225	Expert Opinion	HELP, UNSAT-H
Fitting Parameters for Root Density Function	Live Oak Wenatchee	a=0.315, b_1 (1/cm)=0.0773, b_2=0.0755 a= 1.16, b_1 (1/cm)=0.129, b_2=0.02	Fayer and Jones (1990) Fayer and Walters (1995)	UNSAT-H

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Consequently, caution should be employed when interpreting predictions made with these models for sites where snow cover is significant, particularly in arid regions where snow constitutes a significant fraction of annual precipitation.

The writers also caution that less accurate predictions should be expected in general practice because in this study the input data were defined with much greater detail and accuracy than is generally practical. For example, when using different methods to estimate the unsaturated hydraulic conductivity functions, dramatically different water balance predictions can be obtained (Khire et al. 1995). Also, in any design the impacts of deterioration of the cover need to be considered when making water balance predictions. Neither of the models examined in this study include algorithms that simulate the formation of macro-defects that influence the water balance, particularly percolation.

Finally, in practice the designer must choose between simpler, easier to use, less accurate, yet conservative models (e.g., HELP) and more accurate, more complex models (e.g., UNSAT-H) requiring extensive input. A logical choice is to use the simpler model (HELP) to investigate alternatives during an iterative design phase and then to make final checks and predictions using the more complex model (e.g., UNSAT-H). This approach exploits the advantages of both models, and should minimize costs during final cover design and after closure of the landfill.

ACKNOWLEDGMENT

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water contents that were attained as a result of the large quantity of precipitation received during the previous winter.

UNSAT-H over-predicted evapotranspiration by 8.1 cm. Evapotranspiration was primarily over-predicted during winter (Fig. 10), which may be caused by the inability of the model to limit evaporation when the soil is frozen or covered with snow. Unlike Live Oak, however, the over-prediction in winter is compensated by an equivalent under-prediction in spring and summer (Fig. 8a). Consequently, the evapotranspiration predicted by UNSAT-H for Wenatchee is accurate, on average.

Percolation

Measured percolation and percolation predicted by HELP and UNSAT-H for Wenatchee are shown in Fig. 12. Two major pulses of percolation occurred in the field; one during Winter 1993 and another during Fall 1994 - Winter 1995.

HELP also predicted two major pulses of percolation. However, the onset and magnitude of the predicted percolation do not match that occurring in the field. HELP predicted percolation throughout Fall 1992 and Spring 1993, whereas little or no percolation occurred in the field during these periods.

The pulse of percolation predicted by HELP in Spring 1993 corresponded with the sharp decrease in simulated soil water storage (24 cm to 5.1 cm, Fig. 11) that occurred as HELP drained water from soil water storage under a unit gradient. In contrast, the field data suggest that water was removed from the test section more slowly than predicted by HELP (Fig. 11) and primarily by evapotranspiration rather than percolation (Figs. 10, 12).

The large pulse of percolation during Fall 1994 and Winter 1995 occurred partly because of flow through cracks and animal burrows. A crack in the barrier layer was observed in a test pit outside the monitoring area during a investigation in March 1994 (Benson and Khire 1995) and snow filled animal burrows were found in Spring 1995 (Benson et al. 1996a). When the pulse of percolation was observed in early Winter 1995 (January, Fig. 13a), the water content near the

UNSAT-H under-predicted overland flow by 5.1 cm (Fig. 8). Furthermore, like HELP, UNSAT-H predicted most of the overland flow during Winter 1993. One possible reason why UNSAT-H over-predicted overland flow is that the melt water applied as precipitation was too rapid. If rate of application of snow-melt was reduced by stretching the input period (e.g. 7:00 AM to 8:00 PM instead of 10:00 AM to 5:00 PM), the predicted infiltration would have increased and overland flow would had been less.

In Winter 1995, overland flow predicted by UNSAT-H was zero whereas 5.5 cm of overland flow occurred in the field. The primary reason for this discrepancy is UNSAT-H does not have an algorithm to predict freezing of ground. In the field, most of the snow-melt was shed as overland flow because the ground was frozen, whereas UNSAT-H allowed the water to infiltrate during late Fall 1994 and early Winter 1995. Later, the infiltrated water was removed by UNSAT-H via evapotranspiration, which was over-predicted by 4 cm (Fig. 10).

Soil Water Storage

Measured and predicted soil water storage for Wenatchee are shown in Fig. 11. The field data show that soil water storage increases in fall and winter and decreases during spring and summer. These changes in storage are similar to those measured at Live Oak in 1993 (a dry summer), but larger than those measured at Live Oak in 1994 and 1995 (wetter summers). Similar trends exist in the predictions by HELP and UNSAT-H.

Throughout Fall 1992 and partly during Winter 1993, the field soil water storage increased until the test section was nearly saturated (~ 27 cm). HELP also predicted an increase in soil water storage (beginning of Fall 1992), but more rapidly and earlier than in the field. The period of rapidly increasing soil water storage predicted by HELP was followed by a period when virtually no change in soil water storage was predicted (shown by arrow near upper left corner of Fig. 11). No change in soil water storage was predicted because HELP assumed the ground was frozen during late Fall 1992 and early Winter 1993 and shed melt water as overland flow (Fig. 8).

laboratory. Because the soil water characteristic curves are for desorption and daily average water contents were used, the calculated hydraulic gradients are approximate (e.g., the gradient at 27 cm must be positive during some of the wet period, because percolation did occur). Nevertheless, Fig. 11 illustrates that large changes in hydraulic gradient occur in the field, and that for a significant portion of a year the gradient is upward. Because a downward unit gradient is assumed, HELP continually drained water from the soil until the wilting point (θ_{wp}) was reached (see Fig. 4, where θ_{wp} corresponds to soil water storage = 17 cm). In the field, however, percolation ceased at an average water content = 0.38, because the gradient within most of the test section was upward, not downward.

MODEL PREDICTIONS AND FIELD DATA: WENATCHEE

Overland Flow

Measured overland flow and overland flow predicted by HELP and UNSAT-H for the test section at Wenatchee are shown in Fig. 8. The field data show that overland flow at Wenatchee does not have a well-defined seasonal trend. Furthermore, most of the cumulative overland occurred during Winter 1995.

HELP over-predicted overland flow by 2.7 cm. Most of the error in the predicted overland flow occurred during Winters 1993 and 1995. Overland flow was over-predicted during Winter 1993 and under-predicted during Winter 1995. The measured overland flow was very small during Winter 1993 and large during Winter 1995 (Fig. 8).

The primary reason why HELP over- or under-predicted overland flow was an inability to accurately predict whether snow melt occurred and, when melt did occur, whether the melt water infiltrated or was shed as overland flow. The fate of melt-water depends on whether the soil surface is frozen. HELP assumes that the soil surface freezes when the 30-day-average air temperature drops below 0 °C (Schroeder et al. 1994). When the soil is assumed frozen. HELP

Spring 1994, and Spring 1995 is that it over-predicted percolation (see subsequent section on percolation).

The large seasonal fluctuations in soil water storage occurring in the field are captured fairly accurately by UNSAT-H (Fig. 4). Nevertheless, UNSAT-H under-predicted soil water storage during Winter 1993, Winter 1994, and Winter 1995 and over-predicted soil water storage during Summer 1993 and Summer 1994 (Fig. 5). Fayer et al. (1992) found similar under- and over-predictions when they simulated the hydrology of lysimeters at the Hanford site. Fayer (1993) attribute this discrepancy to the influence of hysteresis in the soil-water characteristic curve, which is not incorporated in the model. Fayer (1993) report that incorporating hysteresis, at the expense of significant additional computational effort, results in better predictions of soil water storage

Evapotranspiration

Evapotranspiration at Live Oak back-calculated using Eq. 1 is shown in Fig. 5. The field data show a higher rate of evapotranspiration during spring and summer and a lower rate in fall and winter, which is consistent with changes in temperature, solar radiation, and growing season of the vegetation. Predictions from HELP and UNSAT-H show similar trends.

HELP predicted evapotranspiration very accurately. Evapotranspiration predicted by HELP was 7.1 cm less than the measured evapotranspiration, and the only significant deviation between measured and predicted evaporation occurred within the first year of monitoring. The accurate prediction of evapotranspiration was not expected given that HELP under-estimated overland flow by 74.4 cm. When overland flow is under-estimated, more water infiltrates into the cover and thus more water is available for evapotranspiration. However, actual evapotranspiration cannot exceed potential evapotranspiration (PET) and the evaporation rate is generally close to PET or equals the PET rate for soils having high water content (Hillel 1980). The test section at Live Oak had relatively high water contents during the portions of the monitoring period when evapotranspiration is significant (e.g., spring) and therefore evapotranspiration should have changes in water content occur throughout the entire depth of the compacted clay layers each year (Khire et al. 1994, Meerdink et al. 1996). In addition, plant roots were found in the compacted fine-grained layers (Benson et al. 1993), indicating that water is removed from these layers by transpiration.

Nodal Spacing and Mass Balance Criterion for UNSAT-H

Discritization of the covers in UNSAT-H included 64 nodes along the depth of the test sections (Fig. 2b). A small nodal spacing (< 0.1 cm) was used near the upper and lower boundaries and the interfaces between layers. The spacing became progressively larger away from the boundaries (3 to 4 cm).

The maximum tolerable mass balance error for UNSAT-H was input as 10^{-5} cm per time step. This mass balance criterion resulted in cumulative mass balance errors that were less than 0.05%.

MODEL PREDICTIONS AND FIELD DATA: LIVE OAK

Overland Flow

Accurate predictions of overland flow are important because they affect the volume of water that infiltrates. If the volume of water infiltrating the soil is incorrect, all subsequent flow processes may be incorrect. Overland flow at Live Oak is shown in Fig. 3 with predictions made with HELP and UNSAT-H. Overland flow at Live Oak is generally higher in fall and winter and lower in spring and summer. HELP and UNSAT-H predicted similar seasonal trends (Fig. 3).

HELP under-estimated overland flow by 74.4 cm during the monitoring period, with the largest deviations occurring between Winter 1993 and Spring 1994. The primary factors contributing to the underestimation are (i) overestimation of initial abstraction (i.e., amount of precipitation that occurs before overland flow begins) and interception by the plant canopy and (ii) the use of a fixed SCS runoff curve number (CN) for the entire year.

was to be used to calibrate several hydrologic models that will be used to design landfill covers.

MATERIALS AND METHODS

Plot Construction, Design and Rationale

The purpose of the Protective Barrier Landfill Cover Demonstration was to monitor and compare water balance on the conventional landfill cover design, similar to that used in Los Alamos and the waste management industry for waste disposal (3), with that on three other designs containing engineered barriers. The performance of all four designs was evaluated at dominant downhill slopes of 5, 10, 15 and 25%. These plots were installed during the spring, summer and fall of 1991 in our 8-ha field test facility (7) and were instrumented so that a complete accounting of precipitation falling on the plots could be measured. The plots were constructed and instrumented to provide measures of runoff and interflow, as well as seepage and soil water storage as a function of slope length.

The technology for controlling soil water erosion on all cover designs consisted of applying a 70% surface cover of medium gravel (8.0- to 25-mm diam). Dominant downhill slopes up to 25% were used on the plot surfaces to insure a range of slopes up to the maximum slope that would be allowable for the safe operation of large earth-moving equipment at a landfill.

The Protective Barrier Landfill Cover Demonstration was emplaced on an east-facing 10.7- by 37.5-m parcel of land with crushed tuff backfill on the surface (8). This backfill is used in landfills at Los Alamos as a result of excavating disposal trenches in local Bandelier Tuff, which is then crushed and emplaced around the waste materials. This area was surveyed into four 10.7- m-long areas, each of which received additional crushed tuff to establish the varying downhill slopes. The crushed tuff on each of these pads was then compacted and resurveyed to confirm the desired slopes. A south-facing 4.6-m-wide, 40-m-long ramp that abutted the lower ends of these four east-facing pads was constructed similarly, only with a 2% dominant downhill slope. A set of four 1.0- by 10.0-m plots with common sidewalls was then constructed on the center of each pad, with a distance of 3.05 m between each set of plots. All of the plot walls except the downhill endplates were fabricated using two pieces of plywood (1.27 cm by 1.88 m by 1.22 m) emplaced within a framework consisting of vertically placed iron I beams (2.5 by 5.1 by 0.32 cm) on 1.22 m centers, with channel iron (2.5 by 5.1 by 0.32 cm) top and bottom framing. The endplates were fabricated from 14 gauge sheet metal, and had 7.62-cm and 10.2-cm diam steel half couplings welded into the endplate wall to connect plumbing used for the collection of seepage and interflow, respectively. The interflow collection system consisted of a 1.0-m long, 30.5-cm-deep, 30.5-cm-wide 14 gauge metal trough welded to the inside of the plot's endplate. The runoff collection system was also fabricated using 14 gauge sheet metal and consisted of a 1.0-m long, 15.2-cm-wide trough with a floor that sloped to divert runoff (30.5-cm deep at the low end and only 25.4 cm deep at the high end); this trough was welded to the top of each endplate and had a 15.2-cm-diam steel half coupling welded into the trough wall to connect plumbing used to collect runoff.

A seepage collection system was installed in the bottom of each of the plots and was designed to evaluate seepage as a function of slope length. Sixty-eight 2.02- by 0.76 m pans with a depth of 0.30 m were fabricated from 14 gauge sheet metal. Each pan was designed with a 5.0-cm-tall. 2.02-m-long channel iron foot that was welded to the bottom of the pan; this foot insured a slope on the bottom of the pan for seepage water to flow out of the pan through a standard 1.3-cm-diam standard pipe coupling which was welded into a corner of the pan. Four of these pans were placed end-to-end in the bottom of each plot, and were attached to each other at the top of each pan using a sheet metal clip. An 11.4-cm-wide space was purposely left between each sidewall of the plot and the pan to minimize sidewall effects in this experiment, which might allow water to migrate down the sidewalls of the plot and be incorrectly measured as seepage. Each pan and the rest of the bottom of each plot were then filled with medium gravel (8.0- to 25-mm diam). A sharp

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Title:

HYDROLOGIC STUDIES OF MULTILAYERED LANDFILL COVERS FOR CLOSURE OF WASTE LANDFILLS AT LOS ALAMOS, NEW MEXICO

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soil water is retained in the upper fine-grained layer, making it more available for evapotranspiration. This is helpful because a larger portion of the precipitation received by the landfill cover can then be removed via evapotranspiration during the plant growing season. The second advantage is that the gravel-cobble layer keeps plant roots from growing through the landfill cover and potentially translocating waste materials to the surface of the SLB facility (Hakonson, 1986). Thirdly, the enhanced levels of plant-available water that occur in the upper fine-grained layer result in enhanced plant biomass at the soil surface, which in turn translates to greatly improved soil erosion protection of the landfill cover. The fourth advantage is that snowmelt results in soil water penetrating into the coarse-grained layer and this water can be removed from the landfill cover by drains placed at the base of this layer. This is helpful because a vertical diversion of infiltrating snowmelt (at a time when potential evapotranspiration is low) means less soil water coming into contact with waste materials located beneath the landfill cover.

The data collected in this field experiment was used to field calibrate a simplistic, one-dimensional model (CREAMS) without extensive input parameters (Nyhan, 1990). For the first time, direct measures of all of the water balance components existed from this study to compare with model-simulated values, instead of just comparing observed and predicted soil water content values to evaluate the success of the hydrologic simulation. Ultimately, a multidimensional finite element model will be validated that takes into account soil, plant, and climatic variability. Models like these can be used to optimize configurations of specific landfill cover materials, such as the thickness of the cover. Using this approach, landfill closure designs can be further evaluated for 20 to 30 yr of meteorological conditions to encompass the average and record wet years, so that the effectiveness of the landfill covers can be assessed. The cost effectiveness and practicality of various designs will be evaluated with the help of our site operator, who will have a major input into the selection of a final closure design for low level radioactive and hazardous waste sites.

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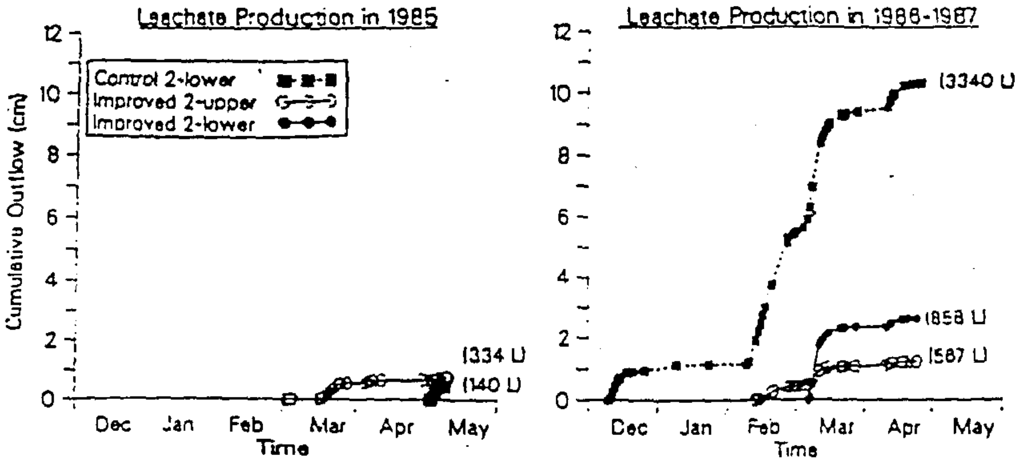

Fig. 7. Cumulative leachate production in the ITP experiment. No leachate production occurred at all other time periods during the year other than those indicated in the figure. The upper drain leachate data, originally on a 3.7- by 10.7-m basis, was multiplied by 0.83 so that it could be expressed on a 3.0- by 10.7-m basis with the rest of the data presented in this figure.

L of leachate, respectively. By the end of the experiment in 1987 the total leachate produced by Plots 1 and 2 was 3239 and 3176 L, respectively. Similar data are not available from the improved plots because Improved Plot 1 did not produce detectable leachate from either drain during the course of the study. This was probably the result of enhanced evapotranspiration on this plot with its larger plant biomass than Improved Plot 2 (see Table 1).

Both the amounts of leachate produced and the seasonability of leachate production varied with the landfill cover design. During the snowmelt events in the spring of 1985, leachate was produced from lateral water flow in the upper drain of Improved Plot 2 from March through early May, and totaled to 0.72 cm (Fig 7). During the first week in May the control plots began producing leachate from their cover profiles that totaled to 0.56 and 0.43 cm, from Plots 1 and 2, respectively. Therefore, by the end of the 1985 events, ~~it appeared that the capillary barrier in the improved~~ plots was satisfactorily diverting soil water laterally in the soil overlying the gravel, because no leachate was produced from the lower drain in these plots, ~~unlike~~ within the control plots (Fig. 7).

In December 1986, leachate production in the control plots began again—almost 600 d after the initial outflow in early May 1985. Control Plots 1 and 2 produced about 0.90 cm of leachate during December and about 1.30 cm in January and March, but the largest amount of leachate was produced in February–April 1987 (7.7 and 8.0 cm in Plots 1 and 2, respectively). In contrast, outflow in the improved plots did not begin until mid-February from the upper drain and in early March from the lower drain. Thus, the capillary barrier conducting water toward the upper drain did perform satisfactorily for about 3 wk (mid-February–early March), but finally failed (the soil above the gravel finally attained saturation with this extremely heavy snowmelt, allowing water to pass into the lower drain in the plot). The end result for the 1986–1987 period was that the control plots produced an average of 10.1 cm of leachate, compared with only 2.6 cm of leachate produced from the lower drain in the improved plot design. Even during this very wet period, the capillary barrier diverted about 1.2 cm of leachate to the upper drain.

Leachate production estimates presented in Fig. 7 should not be used as an absolutely accurate and final representation of the seepage process in the near-surface areas of Los Alamos shallow land burial (SLB) facilities. The reliance on plastic liners on the floors of the plots and French drains (which drains at near-saturated conditions) tends to temporarily minimize leachate production. As time proceeded in our field experiment, the soil water inventories near the plot floors in both landfill cover designs probably increased to amounts that would have been lower in a natural system without a plastic liner and drain. However, the scope of the experiment only included a comparison of the water balance between the two landfill designs in the field plots, and not a comparison between the plots and natural conditions (an area for future studies).

Evapotranspiration Estimates

Since no runoff occurred in the ITP experiment at any time, we could estimate ET by difference in Eq. [1] and quantitatively estimate all of the parameters of the water balance equation for every time interval for which we had field data. Evapotranspiration rates (Fig. 8) were calculated from these estimates and did show the expected seasonality pattern: low evapotranspiration rates (<0.1 cm/d) in the late fall–winter and peak evapotranspiration rates (>0.2 cm/d) during the spring and summer. Peak evapotranspiration rates occurred during seasons with peak precipitation rates in both cover designs. When these estimates were performed for shorter time periods i.e., biweekly instead of for an entire season, larger variation in evapotranspiration rates was observed with time from all of the plots, since the frequency of precipitation and the amounts of plant-available water were also more variable with time (Fig. 8).

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the landfill cover). Water storage (cm) beneath the cover in the control plots was estimated by calculating the average volumetric water content percentage for the 110-cm depth for the six sampling locations, dividing this number by 100, and multiplying this result by 28 cm, the depth of the crushed tuff beneath the cover.

Soil water storage estimates were also made for the improved cover design for each sampling period. These two plots contained a gravel/cobble layer with a maximum thickness of 137 cm, which was excluded from the inventory estimates, based on the assumption that this layer contained a negligible, constant water-holding capacity. Thus, the soil water storage in the trench cap was estimated by calculating the average volumetric water content percentage for the 20-, 40-, and 60-cm depths (nine sampling locations for the 20- and 40-cm depths, and three sampling locations for the 60-cm depth) dividing this number by 100, and multiplying this result by 70 cm (the average thickness of the porous materials above the biobarrier). Water storage (cm) beneath the landfill cover was estimated by calculating the average volumetric water content percentage for the 220-cm depth for the six sampling locations, dividing this number by 100, and multiplying this result by the average thickness of the tuff backfill beneath the biobarrier, 38 cm.

Evaluation of Plant Biomass and Species Composition

By 26 Aug. 1986, all four plots had a 100% cover of blue grama and western wheatgrass. Ten 10- by 10-cm quadrants were clipped for each of these two plant species on this date, and the oven dry weight per unit area of vegetation (biomass) was determined. Relative plant cover by species was also estimated using two longitudinal transects on each plot, where the percent cover of both grass species was estimated visually in 22 quadrants located 1 m apart on each of the two transects. The relative plant cover estimates and the biomass estimates for each grass species were used to estimate the average biomass of grass species on the plots.

RESULTS AND DISCUSSION

Precipitation Data

The precipitation received by the plots from May 1984 through mid 1987 was generally larger than the average received at Los Alamos from 1911–1986 (Fig. 4). The total precipitation in the fall of 1984 was 12.54 cm, compared with the average (1911–1986) fall precipitation of 8.38 cm. This was followed by above average snowfall in February and March of 1985 (Fig. 4), which resulted in 13.73 cm of precipitation during the winter of 1984–1985 (compared with the 1911–1986 average of only 6.71 cm for winter). This winter was then followed by the second wettest spring on record, with the ITP experiment receiving 15.31 cm of precipitation, 63% more than average for spring from 1911 to 1986.

Whereas the fall of 1985 was not particularly unusual for Los Alamos, 24.69 cm of precipitation was received in the spring of 1986 (Fig. 4), making this a maximum record both for the season and for the month of June. During the plant growing season of 1986, summer rainstorms produced below average precipitation followed by a slightly wetter fall than average. However, during the winter of 1986–1987, record maximum snowfall occurred for the month of January (with 165 cm of snowfall) and February. In contrast, only about 6.4 cm of precipitation occurred in the spring of 1987, compared with the 1911–1986 average of 9.37 cm.

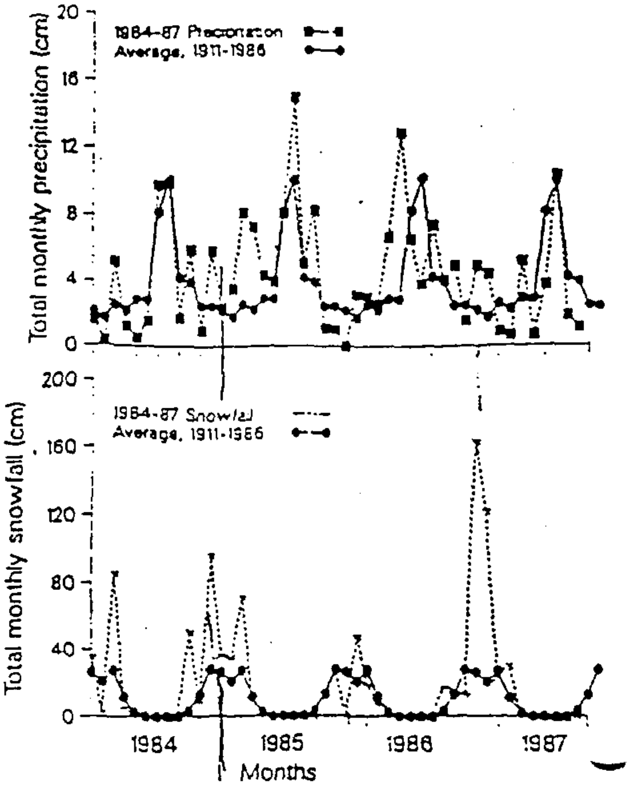

Fig. 4. Distribution of monthly precipitation and snowfall in the ITP experiment compared with the average values for 1911–1986 (Nyhan et al., 1989a).

Soil Water Storage Estimates

The soil water storage data is presented in Fig. 5 and 6, as well as the total precipitation received by the plots weekly and an indication of the maximum soil water storage possible for each portion of the soil profile (the soil would be close to saturation at this value, based on laboratory porosity measurements).

The soil water data collected on the control and the improved plots all show a pronounced increase in water content, with additions of precipitation during the first winter of the field experiment in 1985. The vegetation on all of the plots was fully established by early 1985 and substantial decreases in soil water content during the spring and summer of 1985 were a direct result of evapotranspiration (very little leachate production occurred at these times as we will demonstrate subsequently). Notice that plant roots had withdrawn water out of the landfill covers in both designs, as well as beneath the landfill cover in the conventional cap design (Fig. 5). This latter phenomenon occurred on every growing season, but did not occur on the improved plots (Fig. 6), pointing out the effectiveness of the cobble layer in keeping plant roots confined to the landfill cover soil above the biobarrier.

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A Water Balance Study of Two Landfill Cover Designs for Semiarid Regions

J. W. Nyhan,* T. E. Hakonson, and B. J. Drennon

ABSTRACT

The results from several field experiments on methods to control soil erosion, biointrusion, and water infiltration were used to design and test an enhanced landfill cover that improves the ability of the disposal site to isolate buried wastes. The performance of the improved cover design in managing water and biota at the disposal site was compared for 3 yr with that obtained from a more conventional design that has been widely used in the industry. The conventional cover design consisted of 20 cm of sandy loam topsoil over 108 cm of a sandy silt backfill, whereas the improved design consists of 71 cm of topsoil over a minimum of 46 cm of gravel, 91 cm of river cobble, and 38 cm of sandy silt backfill. Each plot was lined with an impermeable liner to allow for mass balance calculation of water dynamics. Results over a 3-yr period, including 2 wet yr, demonstrated that the improved design reduced percolation of water through the landfill cover by a factor of >4 over the conventional design. This decrease in percolation was attributed to a combination of increased evapotranspiration from the plant cover and the effect of a capillary barrier embedded in the enhanced cover profile in diverting water laterally in the cover. The field data are finally discussed in terms of its usefulness for waste management decisions to be made in the future for both new and existing landfills at Los Alamos, NM, and at other semiarid waste disposal sites.

THE PRIMARY objective of postclosure requirements for waste repositories is to limit the exposure of the general public to radioactive and hazardous wastes for time periods ranging from 100 to 10 000 yr (USNRC, 1982; USEPA, 1980, 1985). Hydrologic processes historically account for most of the performance-related problems (Jacobs et al., 1980; Hakonson et al., 1982b; USDOE, 1980). For example, erosion of the landfill cover can breach the cap and expose waste to the biosphere. Water that infiltrates into the cover can accumulate within the landfill, leach wastes into groundwater, and enhance subsidence with the landfill.

As Fig. 1 implies, the successful performance of the entire landfill is very much a function of interactive processes operating to control water balance within the landfill covers. If we restrict our attention to net rates and amounts, and consider one-dimensional movements of water in the soil profile, then the following equation can be used to represent a simplified water balance:

$$\Delta S = P - Q - ET - L \qquad [1]$$

where

ΔS = change in soil water storage
P = precipitation
Q = runoff
ET = evapotranspiration, and
L = seepage or percolation.

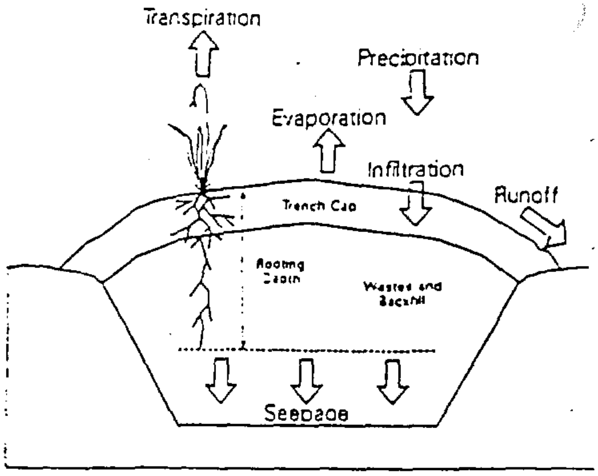

Fig. 1. Hydrology of shallow land burial of waste materials.

Traditional remedial engineering solutions, which do not include analyses of these interactive factors have already led to numerous landfill failures (Hakonson et al., 1982b). Future designs that ignore these interactive factors will certainly reproduce many of the failures of the past (Hakonson et al., 1982b, 1987; Nyhan and Lane, 1986a), and at a very high cost: landfill cover installation costs range from $400 000 to $4 000 000 per ha of landfill (Brandt, 1988; Cook, 1988).

Currently, adequate field data does not exist from carefully instrumented large-scale experiments o [illegible] movement of water and contaminants under uns[illegible]rated conditions to enable a site operator to define and engineer suitable barriers to prevent the migration of waste materials out of a landfill. Our approach to developing an effective landfill cover technology combined the results from individual studies at Los Alamos, NM, on soil erosion (Hakonson et al., 1982a; Nyhan et al., 1983a, 1984a,b; Nyhan and Lane, 1986a,b), on subsidence (Abeele, 1984a,b,c, 1985, 1986; Abeele et al., 1986; Nyhan et al., 1984a), on biointrusion barriers (Pertusa, 1980; Felthauser and McInroy, 1983; Hakonson et al., 1982a,c, 1983; Hakonson, 1986; Nyhan et al., 1984a, 1986), and on capillary barriers (Abeele and DePoorter, 1984; Nyhan et al., 1986) to design and emplace a landfill cover demonstration called the Integrated Test Plot (ITP) experiment. The purpose of the field demonstration was to monitor and compare water balance and biologic intrusion on a conventional landfill cover design with that on an improved design, which was based on the results of the previous studies.

MATERIALS AND METHODS

Plot Construction, Design, and Rationale

The purpose of the cover demonstration was to monitor and compare water balance on the conventional landfill

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became available for evaporation. This result is important because it suggests that the fine-layer water content may be moderated by air flow in the coarse layer. Incorporating diffusion of water vapor from the fine layer into the coarse layer substantially increased the water movement out of the fine layer.

ACKNOWLEDGMENT

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in the base of the gravel layer. The water content of the middle of the topsoil layer changed only very slightly. It can also be observed that a significant amount of water remained within the gravel layer even after a year of air flow. The mechanism of the water content reduction under these conditions appears to be the forcing of water out of the model domain through the seepage faces, due to the increased air pressure. This result indicates that even if the influent air is saturated with water vapor, the flow of air in the coarse layer will move some of the water out of the system.

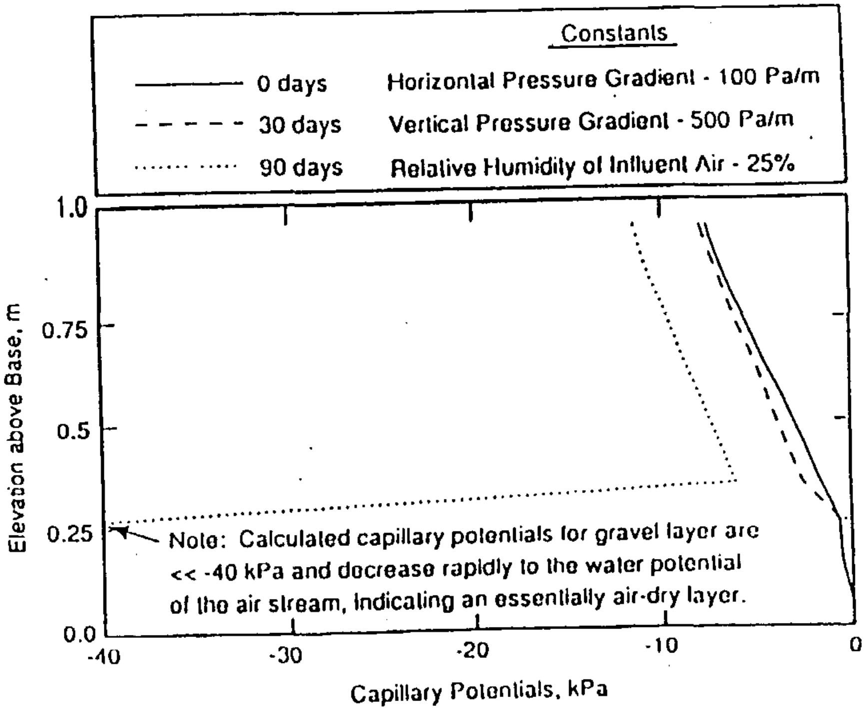
The movement of air and water within the cover was also examined by converting the water-phase pressures to total potentials (sum of the pressure and elevation heads). For this analysis, the simulation used a horizontal pressure gradient of 100 Pa/m, relative humidity of 25%, and a vertical pressure gradient of 500 Pa/m. Capillary water potentials at 0, 30, and 90 days are presented in Figure 9. This figure shows a vertical cross-section (through the cover) located at the midpoint of the model domain (0.5 m from the lateral boundaries). Prior to initiation of air flow, the water phase was essentially at equilibrium within the soil profile. The small water potential differences within the coarse layer resulted from the contrast between the nearly saturated conditions at the base of the gravel layer and the low water content in middle and upper portions of the drained gravel. By 90 days, the coarse layer became nearly dry, the water potential declined sharply at the interface, and a strong downward hydraulic gradient developed.

The numerical simulations reveal that air flow in the coarse layer induced some water movement in the fine layer when the influent air was not saturated with water vapor. The removal of water by evaporation near the fine/coarse layer interface reduced the local water content. When the local hydraulic head decreased, a downward liquid water pressure gradient was established, and water moved toward the fine/coarse layer interface and became available for evaporation. This result is important because it suggests that the fine-layer water content may be moderated by air flow in the coarse layer.

In the simulations discussed above, diffusion of water vapor was not considered. In the TOUGH2 code, the vapor diffusion coefficient is given by

$$D_{va} = \tau\phi S_g \frac{D^{\circ}_{va}}{P}\left(\frac{T+273}{273}\right)^{\theta}, \tag{5}$$

where τ is tortuosity, ϕ is porosity, S_g air-phase saturation, D°_{va} free gas diffusion coefficient (2.13×10^{-5} m^2/s at standard conditions for air/vapor mixtures), θ is a constant 1.80, P is pressure, and T is temperature. Of these variables, only tortuosity and porosity are material properties. Because measured tortuosities were not available, sensitivity analyses were performed to assess the potential significance of vapor diffusion on the rate and amount of water loss from the cover.



Note: Calculated capillary potentials for gravel layer are << -40 kPa and decrease rapidly to the water potential of the air stream, indicating an essentially air-dry layer.

Figure 9. Capillary pressures in cover system at 0, 30, and 90 days.

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can be made for both plots for the data collected at the bottom of the fine sand layer at the maximum slope length tested (9.7 m downslope).

The TDR data for the Clay Loam Capillary Barrier design with the dominant downhill slope of 25% is presented in Fig. 8 to demonstrate the effect of a low-conductivity topsoil on capillary barrier dynamics. The daily interflow data presented in Fig. 2 for this design evaluated on a 5% slope is typical for this design compared with similar data from the plots on the other three slopes. The soil water content data for the bottom of the fine sand layer (25% slope) do not demonstrate multiple large pulses of water coming through the clay loam topsoil (Fig. 8), in contrast to what happened on the capillary and hydraulic barrier plots with the highly conductive loam topsoil (Figs. 5-7). Instead, we observed a pattern indicating a very slow drainage rate of water from the clay loam layer into the underlying fine sand layer, whose soil water content dramatically decreased from September through December 1992 (notice the TDR data at the 9.70 m downslope position), following the decrease in soil water content of the soil layer about 1 month previous to this time period (top portion of Fig. 8).

USEFULNESS OF STUDY AND FUTURE RESEARCH

The most practical comparisons among the four landfill cover designs for a semiarid region, in terms of their usefulness to the burial site operator, should be the overall performance comparison of the water balance parameters for the duration of this field study. Ultimately, the site operator wants a design for a specific slope and slope length that minimizes long-term runoff and seepage and maximizes interflow and evapotranspiration. These water balance parameters are interdependent and need to be evaluated in the field using techniques and field data similar to those in this study.

Only 15 months of data is presented in this manuscript for this study, yet we are already struggling to keep up with data analysis. Many of the commonly used computer software programs and hardware do not have the capacities to handle such large data sets, so we are in the process of connecting our measurement systems for water flow and TDR to a local area net of computers to solve this problem. This will allow us to perform routine system diagnostic checks on our hydrologic sensors and to calculate water balance estimates on this entire data set. Once this is accomplished, we can evaluate important issues such as the time scale necessary to adequately describe a landfill cover design for waste management purposes. Coupled with this effort will be a major activity to develop field-calibrated hydrologic models that then can be used to evaluate future performance of the designs, such as the effect of a 100-year precipitation event on the design. The cost effectiveness and practicality of various designs can then be evaluated with the help of burial site operators and regulators, who will have major inputs into the selection of a final closure design for low-level radioactive and hazardous waste sites.

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topsoil exhibited maximum daily interflow rates of only 0.034 cm with only 0.71 cm of interflow occurring during this time period. Most of this large difference in interflow can probably be attributed to the fact that the clay loam has a low conductivity (8), compared to the loam topsoil, which limited the flow of soil water into the fine sand layer in this design.

The estimates of interflow and seepage on all 16 plots for the 15 months of this study are summarized in Table I. This data shows that all of the capillary and hydraulic barriers are preventing seepage at all slopes and slope lengths tested in the study. Total interflow for the 15 months of the study ranged from 3.4 to 6.1 cm on all of the EPA and capillary barrier designs containing the loam topsoil. In contrast, the conventional design, which did not contain an engineered barrier, produced seepage in almost every case tested and most of this seepage occurred from February through April of 1992, during and following a relatively dry winter (Fig. 1).

For the Conventional design evaluated on the 5% slope, this 15-month total seepage occurred in the seepage collection system located 3.64-5.66 m downslope (0.21 cm), 5.66-7.68 m downslope (0.37 cm), and 7.68-9.70 m downslope (2.86 cm). This design only produced seepage 5.66 to 9.70 m downslope with a 15% slope, and 7.68 to 9.70 m downslope with a 25% slope.

Runoff occurred on these unvegetated plots from December 1991 through February 1992, as a result of snowmelt and during May and August 1992, as a result of thunderstorm activity. The total runoff from all 16 plots is summarized in Table II for the 15 months of the study. The largest daily runoff (0.54 cm) occurred on the EPA design with the 25% slope after a 2.16-cm precipitation event on August 24, 1992.

No consistent relationship exists between slope and runoff for either the clay loam topsoil used on the Clay Loam Capillary Barrier design or the loam topsoil used on all the other designs. Less than 15% of this total runoff (Table II) usually came from snowmelt events during the first winter of the study, but this is not surprising since almost 30% of the total precipitation for the entire 15 months was received in May and August, 1991 (Fig. 1).

Soil Water Data

Each of the 212 locations throughout the 16 plots was monitored for soil water content once every six hours from November 1991 through December 1992, resulting in several 60-megabyte monthly computer files of TDR waveforms. This waveform data was then reduced to soil water content data.

Soil water data is presented for several layers of the Conventional design evaluated at a position 9.7 m downslope in the plots with dominant downhill slopes of 5% (Fig. 3) and 15% (Fig. 4). The water content of the loam topsoil is presented in the top half of each of these two figures, representing the readings of a horizontally-emplaced pair of waveguides within the 15-cm deep topsoil (at an actual depth of 5 to 10 cm).

The topsoil water content data from these two plots can be used to demonstrate the influence of aspect on snowmelt dynamics during the short daylight periods of the winter when the sun is at a low angle on the horizon. For the plot with the 15% slope (Fig. 4), the volumetric water content rises from 14.2% on December 10, 1991 (at 6:20 am), to 27.9% on December 11 (at 2:44 PM), as a result of a snow event that accounted for 2.4 cm of precipitation added to the surface of the site. The volumetric water content steadily decreased to 7.1% on December 15 (at 5:08 am). All of this happened as the snow melted on the surface of this high-aspect plot, unlike what happened on the plot with the 5% slope (Fig. 3). This plot retained snow cover and only demonstrated a small increase in volumetric water content to 19.0% on December 11, 1991 (at 2:44 PM).

The bottom portions of Figures 3 and 4 contain the soil water content data for the crushed

<1 x 10^{-9} m/s. Since the plastic FML would last less than 35 years (11), this feature of the EPA design was omitted in our EPA design to evaluate the worst possible case. The results of previous research on mixtures of local crushed tuff and sodium-saturated bentonite (5,6) indicated that a 1:10 (W:W) mixture of finely ground Aquagel (Baroid Drilling Fluids, Farmington, NM) and crushed tuff should easily provide us with the low conductivity required for this layer. This mixture was prepared in a cement truck by adding 10 45.4-kg bags of dry Aquagel to 4.54 metric tons of <6.4-mm diam crushed tuff that had been screened and dried using an asphalt batch plant. This dry mixture was mixed for 40 minutes, approximately 200 liters of water was added (for dust control and to optimize compaction), followed by an additional 30 minutes of mixing. A 15-cm-deep lift of mixture was finally added to each plot. After compaction this lift was covered to prevent the mixture from drying, and this lift was sprayed with water before adding the next 15-cm lift of mixture to promote the uniformity of the entire 61-cm layer.

Two designs contained capillary barriers varying only in the type of soil used in the uppermost layer. One of the designs contained 61 cm of the same loam mixture used in the previous designs, whereas the other design contained 61 cm of a local clay loam backfill classified (30) as a Lithic Aridic Haplustalf (clayey, mixed, mesic family) and used in two previous studies (8,9). These soils were emplaced on top of 76 cm of a fine sand (0.05-to 0.425-mm particle diam) made in the sand classifier/blender described previously. The fine sand was specifically chosen to complement the underlying medium-sized gravel in terms of optimizing both the hydraulic conductivity and water-holding properties of the capillary barrier (27).

Measurement of Seepage, Interflow, Runoff, and Precipitation

Runoff, interflow, and seepage were collected in 100 100-liter tanks housed in two instrument trailers that were heated in the winter to allow year-round hydrologic measurements. Water levels in each tank was measured with a microprocessor-controlled ultrasonic liquid level sensor (model DCU-7, Lundahl Instruments, Logan, UT) mounted in the top end of a 1.5-m-long stilling well (5.1-cm diam PVC pipe) attached to the inside of the tank. The sensor output was connected to one of five multiplexer boards (model CIO-MUX32, CyberResearch, New Haven, CT) located in five junction boxes. This multiplexer board was organized as a pair of 16-to-1 multiplexers. The output of each multiplexer was connected by way of shielded flat cable to a digitizer card (model CIO-AD08, CyberResearch, New Haven, CT) in a computer with a widely used personal computer motherboard (model 386N33, Hauppauge Computer Works, Inc., Commack, NY) and a 200 megabyte hard drive (model ST1239A, Seagate Technology, Scotts Valley, CA). Two digitizer cards served the ten multiplexers in this system, in which the digitizer cards accepted 4 and 6 analog inputs, one from each multiplexer.

The computer was used to capture and store the water level data from each tank and to activate the draining of the tank when it was nearly full by actuating a 5.1-cm-diam electrically-actuated ball valve (115 volt alternating current Electromni model, Asahi/America Inc., Medford, MA) mounted in the bottom of the tank. The digital output card in the computer (model PCL 722, CyberResearch, New Haven, CT) was organized as six channels of 24 bits each, with five channels being connected to five relay driver boards (model DB-3737, PERX, Inc., San Mateo, CA) located in the junction boxes. Thus, the computer read the water levels in the 100 tanks and made the decision to actuate the valves and repeated this loop at a rep rate of approximately 1.5 hertz. The water levels in the tanks were routinely recorded hourly, but much more frequently when the tank was emptying and when it was nearly full. This data was routinely copied into a single large file every 24 hours.

Precipitation was measured using a tipping bucket rain gauge and a long-term event recorder (Weathermeasure Corp., Sacramento, CA).

Measurement of Soil Water Content

Time domain reflectometry (TDR) is used to measure soil water content. Lateral flow from the surface and the barrier layers is not measured. Because the hydraulic conductivity of all the soil layers is very low and the soils are rarely saturated (Khire et al. 1994), little lateral flow occurs. Benson et al. (1994) indicate that error in the water balance incurred by ignoring the lateral flow is less than 1.5% at Live Oak and much smaller in Wenatchee. Climatic and hydrologic data have been obtained continuously since June 1992 for the test section at Live Oak and since November 1992 for the test section at Wenatchee. Benson et al. (1996a) provide a comprehensive summary of the data.

Percolation, overland flow, and soil water contents are measured directly. To compute the soil water storage, soil water contents are integrated over the depth of a test section. Evapotranspiration (E_t) is computed by subtracting daily overland flow (O_f), percolation (P_r), and the change in the soil water storage (ΔS_w) from daily precipitation (P) as shown in Eq. 1:

$$E_t = P - O_f - P_r - \Delta S_w \qquad (1)$$

OVERVIEW OF HELP (Version 3.01) and UNSAT-H (Version 2.0)

HELP Model

Schroeder et al. (1994) provide a detailed description of the algorithm HELP uses to route water into different components of the water balance. The portion of the methodology relevant to earthen final covers is herein discussed briefly. A schematic showing how HELP handles the water balance is shown in Fig. 2a.

HELP requires that each layer of a landfill cover be specified as a vertical percolation layer, barrier soil liner, lateral drainage layer, or geomembrane liner depending on the function and hydraulic properties of the layer. In a vertical percolation layer, unsaturated flow of water occurs in the vertically downward direction. A barrier layer (soil liner) has low saturated hydraulic conductivity and is assumed to always be saturated. Percolation from the barrier layer is assumed

Unsaturated Water and Heat Flow (UNSAT-H, Fayer and Jones 1990), developed at Pacific Northwest Laboratory, is also used to make water balance predictions.

Although HELP and UNSAT-H are both water balance models, their formulations are distinctly different. HELP employs simplified schemes to model the routing of water through soil layers and removal of water via overland flow and evapotranspiration and contains databases describing meteorological conditions, vegetation, and saturated and unsaturated soil properties. HELP is operated interactively and a simulation typically requires little processing time on a desktop computer because simplified algorithms are employed. In contrast, UNSAT-H uses a finite-difference implementation of a modified form of Richards' equation that describes unsaturated flow in soil layers and water removal by transpiration. The boundary conditions employed to solve Richards' equation specify how precipitation is partitioned into overland flow and percolation and how water is removed by evaporation. Extensive meteorological data and data describing unsaturated soil properties and characteristics of the vegetation are required by UNSAT-H, and no databases are included that provide this information. UNSAT-H is run in a batch mode (non-interactively) and requires extensive processing time even on high-speed workstations (some simulations require several days to finish).

Because their formulations and input requirements differ significantly, predictions made by HELP and UNSAT-H are likely to differ in accuracy. Some studies conducted by others (Peyton and Schroeder 1988, Barnes and Rodgers 1988, Peters et al. 1986, Gee and Kirkham 1984, and Thompson and Tyler 1984) have attempted to assess the accuracy of HELP. However, in most studies, key input data were not measured and/or ambiguities existed in the field data that preclude making definitive conclusions regarding model accuracy (Khire 1995). An assessment of the accuracy of UNSAT-H has not been made using large-scale field data, particularly for covers designed as resistive barriers, an (e.g., Fayer et al. 1992). The term "resistive barrier" used here, originally coined by Schulz et al. (1988), refers to earthen barriers that employ a layer of compacted fine-grained soil or a geosynthetic (geosynthetic clay liner or geomembrane as barrier layer) as the primary means to limit flow.

Soil Water Characteristic Curves

Water contents corresponding to field capacity and wilting point were obtained from soil-water characteristic curves developed using pressure-plate extractors. Benson et al. (1993) describe the procedure in detail. Khire et al. (1994) present the soil water characteristic curves for the soils used in this study. The Haverkamp function for the soil water characteristic curve (Haverkamp et al. 1977) was fit to the soil water characteristic data for each soil using a computer program described by Khire et al. (1994). The Haverkamp function is:

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{\alpha}{\alpha + \psi^{\beta}} \tag{3}$$

where θ is the volumetric water content, the subscripts s and r correspond to saturated and residual conditions, and α and β are fitting parameters. The Haverkamp function was used because it provided a good fit to the data and can be directly input to UNSAT-H. Haverkamp parameters for the cover soils from Live Oak and Wenatchee are listed in Table 1.

Unsaturated Hydraulic Conductivity Function

Unsaturated hydraulic conductivity functions were measured in the laboratory by Meerdink et al. (1996) and in the field by Khire et al. (1994). These hydraulic conductivity functions, which were both determined using the instantaneous profile method, agree well (Meerdink et al. 1996, Khire et al. 1995). The Haverkamp unsaturated hydraulic conductivity function was fit to the unsaturated hydraulic conductivity data for the surface and barrier layers using the program described by Khire et al. (1994). The Haverkamp function has the form:

$$\frac{K_v}{K_s} = \frac{A}{A + \psi^{B}} \tag{4}$$

UNSAT-H Model

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 and Jones 1990, Fayer et al. 1992), but is used only for water balance simulations in this study. UNSAT-H simulates water flow through soils by solving Richards' partial differential 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. The form of Richards' equation solved by UNSAT-H is (Eq. 2):

$$\frac{\partial \theta}{\partial \psi}\frac{\partial \psi}{\partial t} = \frac{-\partial}{\partial z}\left[K_T \frac{\partial \psi}{\partial z} + K_\psi + q_{vT}\right] - S(z,t) \qquad (2)$$

where ψ is matric suction, t is time, z is the vertical coordinate, θ is volumetric water content, K_ψ is unsaturated hydraulic conductivity, $K_T = K_\psi + K_{v\psi}$, where $K_{v\psi}$ is isothermal vapor conductivity, q_{vT} is thermal vapor flux density, and S(z, t) is a sink term representing water uptake by vegetation. Thermal vapor flux density (q_{vT}) is computed by applying Fick's law to vapor diffusion. Hysteresis of the soil water characteristic curve is not considered.

A schematic showing how UNSAT-H computes the water balance is shown in Fig. 2b. UNSAT-H separates precipitation falling on a landfill cover into infiltration and overland flow. Overland flow occurs when water applied to the soil surface exceeds the infiltration capacity of the soil profile immediately prior to or during rainfall. Thus, the fraction of precipitation shed as overland flow depends on the saturated and unsaturated hydraulic conductivities of the soils constituting the final cover. UNSAT-H does not consider absorption and interception of water by the plant canopy and the effect of slope and slope-length when computing overland flow.

Water that infiltrates moves upward due to evaporation or downward as a consequence of gravity and matric potential (Fig. 2b). When the upper boundary is selected as a flux boundary,

Khire, M. (1995) Field Hydrology and Water Balance Modeling of Final Covers for Waste Containment. Ph.D. Dissertation, University of Wisconsin-Madison.

Khire, M., Meerdink, J., Benson, C., and Bosscher, P. (1995) Unsaturated Hydraulic Conductivity and Water Balance Predictions for Earthen Landfill Final Covers. *Soil Suction Applications in Geotechnical Engineering Practice*, GSP No. 48, ASCE, 38-57.

Khire, M., Benson, C., and Bosscher, P. (1996a) Water Balance Modeling of Earthen Final Covers at Humid and Semi-Arid Sites. *J. of Geotechnical Engineering*, in press.

Khire, M., Benson, C., and Bosscher, P. (1996b) Capillary Barriers in Semi-Arid & Arid Climates: II. Design Variables and the Water Balance. *J. of Geotechnical Engineering*, in review.

Meerdink, J., Benson, C., and Khire, M. (1996) Unsaturated Hydraulic Conductivity of Two Compacted Barrier Soils. *J. of Geotechnical Engineering*, ASCE, 122(7), 565-576.

Morris, C. and Stormont, J. (1996) Design of Capillary Barriers for Waste Site Containment, Proc. of the 3rd International Symposium on Environmental Geotechnology, Vol. 1, H-Y Fang and H. Inyang, Eds., 513-522.

Nyhan, J., Hakonson, T., and Drennon, B. (1990) A Water Balance Study of Two Landfill Cover Designs for Semiarid Regions. *J. of Environmental Quality*, 19, 281-288.

Nyhan, J., Langhorst, G., Martin, C., Martinez, J., and Schofield, T. (1993) Hydrologic Studies of Multilayered Landfill Closure of Waste Landfills at Los Alamos. *Proc. of 1993 DOE Environmental Remediation Conference*, Augusta, GA.

Schulz, R., Robert, R., and O'Donnell, E. (1989) Control of Water Infiltration Into Near Surface LLW Disposal Units, Annual Report. US Nuclear Regulatory Commission, NUREG/CR-4918, Vol. 3.

Stormont, J. (1995) The Performance of Two Capillary Barriers During Constant Infiltration. *Landfill Closures*. ASCE GSP No. 53, J. Dunn and U. Singh, Eds., 77-92.

addition, the annual change in soil water storage (ΔS max) is larger for the resistive barrier, primarily because significant changes in water content occur at all depths in the resistive barrier, whereas most storage in the capillary barrier occurs in the surface layer.

Evapotranspiration is the most significant component of the water balance at this semi-arid site (~80% of precipitation). Evapotranspiration is a function of soil water storage and energy available to evaporate soil water. Evapotranspiration is low during fall and winter, due to low air temperatures and solar radiation. During spring, as solar radiation and air temperature increase and the growing season begins, evapotranspiration increases rapidly. Evapotranspiration ceases when the water supply in the barrier is exhausted. For example , evapotranspiration persisted into fall in 1993 and 1995 because water was available. In 1994, however, less water was available and evapotranspiration ceased in mid-summer.

A key element of design for either barrier type is ensuring that adequate evapotranspiration will exist to remove water stored during the critical wet period (winter at this site). If evapotranspiration is inadequate, water will annually accumulate in the barrier, and percolation will occur (Morris and Stormont 1996). At this site, evapotranspiration was adequate, because soil water storage was reduced to conditions corresponding to residual water content each summer.

Percolation

Percolation for the resistive and capillary barriers is shown in Fig. 6. During the three year monitoring period, the resistive barrier transmitted 3.3 cm of percolation (5.1% of precipitation), whereas the capillary barrier transmitted 0.5 cm of percolation (0.8% of precipitation).

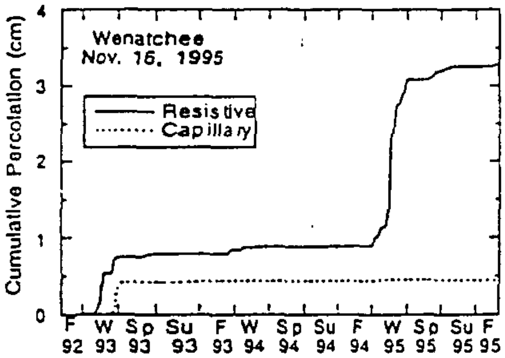

Figure 6. Percolation from the Resistive and Capillary Barriers

Significant percolation from the capillary barrier occurred only during Winter 1993 when the record snow fall was received. If the surface layer of the capillary barrier had been thicker (i.e., providing additional storage capacity), percolation from the capillary barrier would have been nearly zero (Khire 1995).

Percolation from the resistive barrier in 1993 and 1994 occurred when the wetting front reached the base of the test section towards the end of winter (Figs. 4, 6). At the end of Winter 1995, however, percolation occurred before the wetting front reached the base (Khire et al. 1996b). Percolation also increased dramatically in 1995. The primary reason for this change is new preferential flow through vertical cracks, which apparently formed as the barrier desiccated the previous summer (Benson and Khire 1995, Khire et al. 1996a). Animal burrows, found during field reconnaissance in Spring 1995, may also have contributed to the increase in percolation.

SUMMARY AND PRACTICAL IMPLICATIONS

Water balance data have been described in this paper from two test sections representing resistive and capillary barriers. The data show that the capillary barrier effect can be realized at field scale and that capillary barriers can be more effective in restricting percolation in semi-arid and arid the barrier layer. In the capillary barrier, water that enters the surface layer remains in that layer rather than move downward into the sand. As a result, water is more easily removed from the capillary barrier via evapotranspiration, because it is located near the surface.

FIELD WATER BALANCE OBSERVATIONS

Overland Flow

Cumulative overland flow for the resistive and capillary barriers is shown in Fig. 3a. Overland flow is essentially the same for the resistive (12.6% of precipitation) and capillary barriers (11.9% of precipitation). The primary reason for this similarity is believed to be the combined influence of hydraulic conductivity of the surface layer and density of vegetation on both test sections.

The hydraulic conductivity of the surface layer of the capillary barrier is approximately one order of magnitude higher than that for the resistive barrier (Fig. 3). Thus, water should infiltrate more easily in the capillary barrier. However, vegetation on the capillary barrier is less abundant than on the resistive barrier. The percent bare area (area bare of plants/total area) for the capillary barrier is 83%, whereas for the resistive barrier it is 40% (Benson et al. 1993). Dunne and Dietrich (1980) report that the average runoff velocity decreases and the residence time increases as the density of vegetation increases. Consequently, overland flow is lower for slopes having denser vegetation. Apparently the effects of higher hydraulic conductivity and less abundant vegetation for the capillary barrier compensate, and result in essentially the same overland flow as occurs on the resistive barrier.

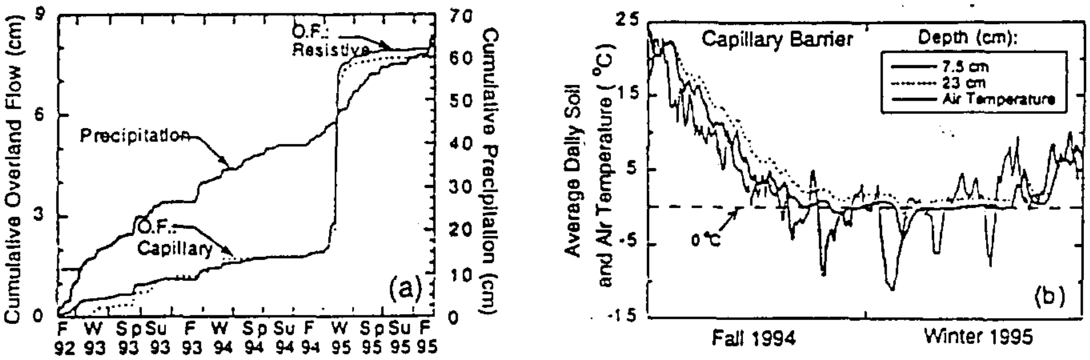

Fig. 3. Overland Flow and Precipitation (a) and Soil and Air Temperature for Capillary Barrier (b).

Overland flow for both test sections was exceptionally high during late Fall 1994 and early Winter 1995. The primary reason for this behavior is that the ground surface was frozen during late Fall 1994 and most of the early part of Winter 1995 (Fig. 3b), which limited infiltration. Thus, simulations conducted during design should account for freezing of the surface layer, and its effect on overland flow.

Soil Water Content

Volumetric water contents for the resistive and capillary barriers are shown in Fig. 4. For both test sections, the water contents show a periodic behavior. An increase in water content occurs in fall and winter, followed by reductions in spring and summer.

In the resistive barrier, water contents increase gradually at all depths during the winter, and exhibit a time lag with depth corresponding to the slow downward movement of a diffuse wetting front (Fig. 4a). These gradual increases in water content are consistent with the unsaturated hydraulic properties of the soils used to construct the resistive barrier. That is, these soils exhibit gradual changes in water content and hydraulic conductivity as matric suction changes. In addition, because the unsaturated hydraulic conductivity of the barrier layer is greater than that for the surface layer (when $\psi > 0.6$ m), water readily moves from the surface layer into the barrier layer.

Different behavior occurs in the capillary barrier during winter seasons (Fig. 4b). The water content of the surface layer increases gradually as the layer accumulates ("stores") water. The

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Water Use by the Four Plant Species under Irrigation

The above results demonstrated that all four species can remove water from a waste trench cap to a depth of at least 2.2 m, and they indicate that any of the species could use all of the water that might be stored in the soil during a very wet year. To test that postulate, we supplemented natural precipitation on one plot of each species. Our estimate of the maximum precipitation that might fall while plants are dormant is 277 mm (see Depth of Fill Soil Required, below). However, it is possible that snow accumulation or runoff resulting from irregular topography might result in storage of more than 277 mm, if a sufficient depth of soil was present. Thus, to estimate the maximum amount of water that crested wheatgrass and Great Basin wildrye plots could use, we irrigated stands of those species so that they received about 600 mm of water in 1987. In 1988 they received between 460 and 500 mm water. The irrigated sagebrush plot received about 366 mm each year,and the streambank wheatgrass plot received about 366 mm in 1987 (plants on that plot were replaced by Great Basin wildrye after the 1987 season).

In 1987, ET from all irrigated plots except that with streambank wheatgrass exceeded 366 mm (Fig. 4). Streambank wheatgrass plants on the irrigated plot had suffered considerable mortality as a result of plot leveling the previous fall (necessitated by subsidence), otherwise ET from that plot likely would have exceeded 366 mm. Evapotranspiration from the irrigated Great Basin wildrye plot was 636 mm, some 2.8 times the average annual precipitation.

In the fall of 1987, all of the plants from two of the plots were removed prior to determination of the drained upper limit (see Methods, above). Upon completion of those experiments, we transplanted crested wheatgrass onto one of the plots and Great Basin wildrye onto the other to again assess the capacity of these species to use water during the first season after being transplanted. Evapotranspiration from plots of both species was more than 400 mm in 1988 (Fig. 4). Evapotranspiration from the newly transplanted Great Basin wildrye plot was nearly identical to that of the original Great Basin wildrye plot (Fig. 4).

Water Loss from Plots without Vegetation

Figure 5 provides a comparison through four growing seasons of soil profiles of the two bare plots with that of a plot supporting a stand of sagebrush. In the fall of 1984, 1 yr after the trenches were filled and compacted, soil moisture was approximately 17% by volume throughout the profile on both bare plots (Fig. 5a, b). The wetting front reached 0.6 m in the spring of 1985, and by the fall of 1985 there was a large increase in the amount of water in storage throughout the profile on both plots. Water content at the bottom of Plot b was well above the drained upper limit (ca. 28%) by the fall of 1985 (Fig. 5b). In subsequent years, the bottom meter of soil on both plots was at or above the drained upper limit, and it is likely that there was substantial drainage from the bottom of the profile (Fig. 5a, b).

Relatively little water was lost from these bare plots by evaporation. Even in the fall, water content at 0.2 m was at or above 20% (Fig. 5a, b). In contrast, water content on the sagebrush plot was at about 15% throughout the profile by the fall of 1985, and in subsequent falls it was uniformly at 10 to 11% (Fig. 5c). It is impossible to separate losses by evaporation from those due to drainage for these bare plots. The area between the spring and fall lines above the point of intersection at the top of each profile indicates the maximum amount of water that might have been lost by evaporation (Fig. 5a, b), although it is likely that some of this change in water content was due to drainage. These data suggest that evaporation might extract water from a bare plot to a maximum depth of about 1 m. Nevertheless, the amounts lost would be small relative to a vegetated plot.

The data in Fig. 5 show that bare soils may quickly reach the drained upper limit, and the influx of water from normal precipitation likely will result in deep drainage. It is evident that vegetation is essential to remove water from the entire soil cap and thereby empty the storage reservoir each year.

Depth of Fill Soil Required

Estimates of the lower limit of extraction ranged from 10 to 12% (e.g., Fig. 3), and there was little difference in the lower limit of extraction among the plant species (Anderson et al., 1987). We estimate that the lower limit of extraction averages 11%. Our estimate of the drained upper limit for this soil is 28%. The difference in these values, 17%, is the effective moisture storage capacity of this soil.

If a good cover of perennial plants is present, precipitation received during the middle and latter portions of the growing season will be evaporated or transpired within a short time; therefore, it is unnecessary to plan for storage of the total annual precipitation. We assumed that any precipitation falling during June, July, August, and September would be lost by evapotranspiration and not stored in the soil. Thus, we took the maximum October to May total from the 40-yr record for the Central Facilities Area (277 mm) to estimate a minimum fill soil requirement. If 277 mm water infiltrated the soil, 1.6 m of fill soil would be required to store it, given a storage capacity of 17%. However, the wetting front in a soil will extend below that portion of the profile that is at the drained upper limit (e.g., Fig. 3, 6c). Our data indicate that the wetting front from 277 mm of water might reach 1.8 m. Additionally, soil subsidence or deep snow accumulation could increase the depth of infiltration in local areas. Therefore, we recommend a minimum fill soil depth of 2 m for the INEL. A substantial portion of precipitation that falls while plants are dormant will be lost by evaporation or sublimation, so a fill soil of 2 m should be quite conservative.

Simulations of the soil water balance parameters using two computer models calibrated for the climate and soils at the INEL predicted that water would drain from a 1.2 m soil cap in very wet years, whereas the models predicted that a cap of 1.8 m prevented intrusion even during the wettest years (Laundré, 1990). These results are consistent with our estimate of the minimum depth of fill soil required.

entire year. The area between adjacent lines in Fig. 3c is proportional to the amount of water extracted from the soil by the vegetation during that time interval. The bulk of the available water was consumed during May and June, and nearly all of the water available to plants was used by 28 June.

Water Use by the Four Plant Species under Natural Precipitation

When the trench plots were established, the fill soil was moderately moist. That, coupled with above average precipitation, made water plentiful during the first growing season after transplanting or seeding. Total evapotranspiration (ET) that season exceeded the mean annual precipitation for the INEL (221 mm) on all plots (Fig. 4).

An example of the pattern of water use through the first 3 yr following planting is shown in Fig. 3. During the first growing season, crested wheatgrass plants extracted water from the soil to a depth of 1.6 m, and plants on the replicate plots removed an average of 243 mm of water from the soil. Evapotranspiration from the plots averaged 443 mm (Fig. 4), and essentially all of the available moisture was used by the end of the season (Fig. 3a). The recharge wetting front reached depths of 0.6 m in 1985 and 0.8 m in 1986, and there was very little change in the moisture profile below 1 m after 1984 (Fig. 3b, c).

Great Basin wildrye extracted less moisture (185 mm) from the soil during the first growing season after transplanting than did crested wheatgrass, but water was extracted to a depth of 2.2 m, showing that roots had grown to that depth. Average growing season ET from the Great Basin wildrye plots was 385 mm (Fig. 4). In the second growing season, Great Basin wildrye removed large amounts of water from throughout the profile, and by the end of that season the soil was uniformly dry to about 10% throughout the profile. Subsequently, patterns of recharge and extraction were similar to those for the crested wheatgrass plots.

Transplanted sagebrush plants extracted the least water (91 mm) during the first growing season, and only to a depth of 1 m. Average ET from these plots in the 1984 growing season was 291 mm (Fig. 4). Sagebrush roots extracted water from throughout the profile in the second season, and by the end of the third season, the soil was uniformly dry throughout the profile (Fig. 5c).

Streambank wheatgrass, which was started from seed, extracted water to a depth of 1.2 m during the first growing season, removing 186 mm of water from the soil; ET was 386 mm (Fig. 4). Thus, in its first growing season a species started from seed reduced the amount of water in soil storage sufficiently to provide storage for the next winter-spring recharge period. Plants extracted water from throughout the profile during the second growing season, and the profile was uniformly dry to about 10% moisture by volume by the end of the third season.

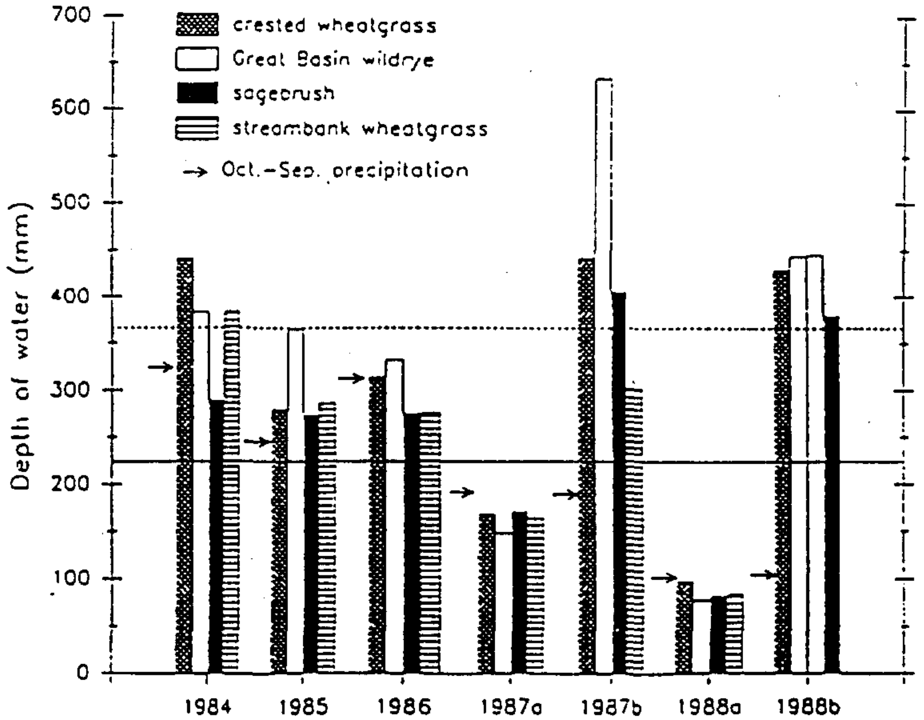

Fig. 4. March–September evapotranspiration from plots supporting monocultural stands of four plant species (*bars*). Data for 1984–1986 are means of replicate plots. In 1987 and 1988, one plot (*a*) of each species received natural precipitation while the other (*b*) received supplemental irrigation (see Methods). Arrows show total October–September precipitation for each growing season. Dotted line shows mean annual precipitation for the INEL (221 mm); dashed line shows maximum annual precipitation received at INEL since data collection began in 1950 (366 mm). In the fall of 1987, vegetation on the irrigated crested wheatgrass and streambank wheatgrass plots was removed to facilitate estimation of the drained upper limit (see Methods). Subsequently, mature crested wheatgrass and Great Basin wildrye plants were transplanted onto the plots. Thus, for 1988, plants on one irrigated Great Basin wildrye plot and the irrigated crested wheatgrass plot were planted the previous fall. All other data were from plants established in 1984.

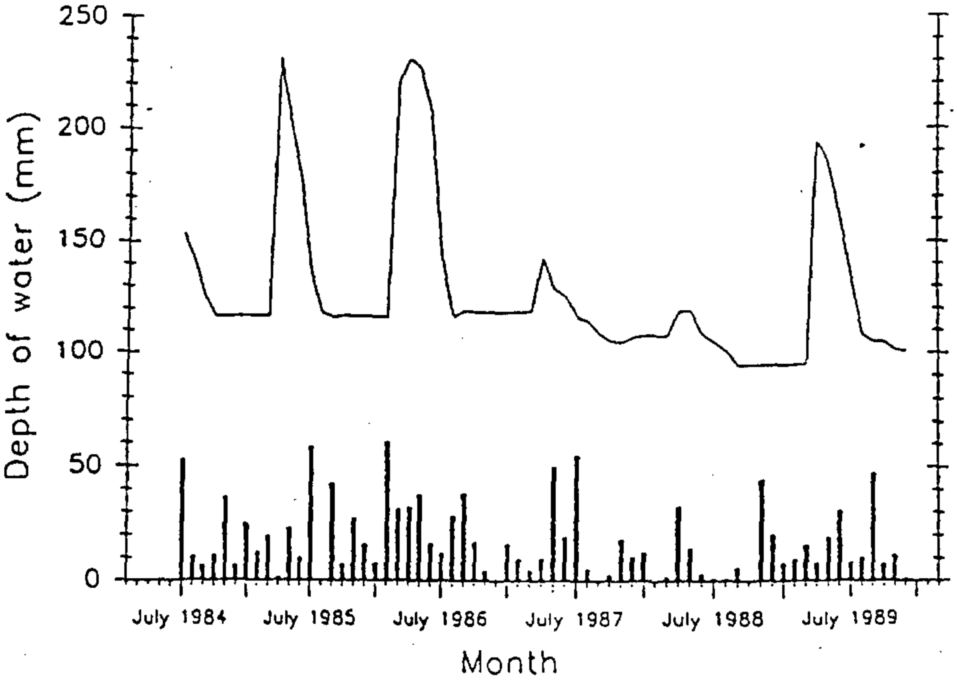

Fig. 2. Amount of water stored in 1.2 m of soil supporting a natural sagebrush–grass community at the Idaho National Engineering Laboratory (*solid line*) and monthly precipitation (*bars*) over 5.5 yr.

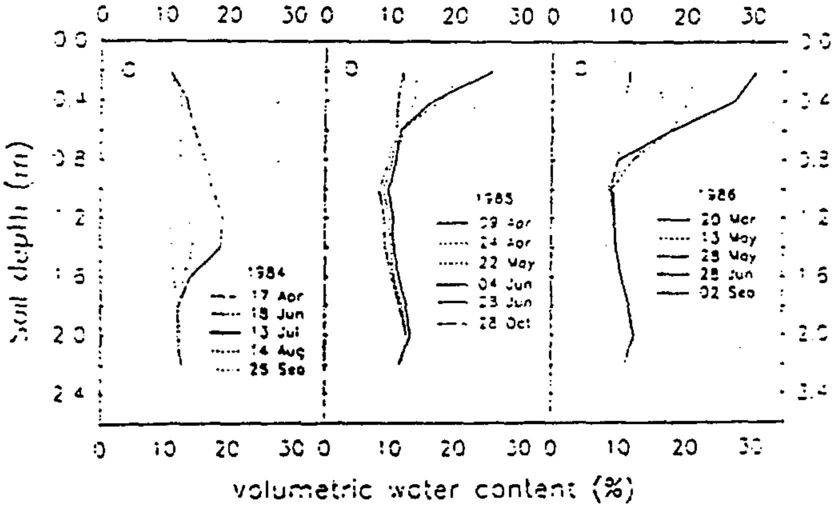

Fig. 3. Soil moisture profiles for a stand of crested wheatgrass on a simulated waste trench plot. Each line depicts moisture content as a function of depth in the soil for a particular sampling date. Data for the first two dates in 1984 were from gravimetric determinations at depths of 0.3, 0.6, 0.9, and 1.2 m. All other data are mean values from measurements at 0.2-m depth intervals in three or four neutron access tubes (redrawn from Anderson et al. 1987).

Precipitation is not closely correlated with the amount of water stored in the soil for two reasons (i) precipitation falling in late fall or winter may not infiltrate the soil if it falls as snow and/or the soil is frozen, and (ii) precipitation that falls in late spring, summer, or early fall is returned to the atmosphere by evapotranspiration and does not enter storage. Minimum water contents in 1988 and 1989 were lower than in the 3 previous years (Fig. 2), apparently as a consequence of low precipitation and moisture recharge in those years.

Seasonal Changes in a Soil Moisture Profile

Typical changes in moisture throughout a soil profile during a growing season are shown in Fig. 3c. In the fall of 1985, the soil was uniformly dry with a water content of about 10% throughout the profile (Fig. 3b, 28 October). On 20 Mar. 1986, the maximum amount of water in the soil for that year was recorded. At that time, the wetting front had reached 0.8 m. Below that depth, soil water content was essentially unchanged through the water moves in the opposite direction in response to the vapor pressure gradient from the wet cell surfaces to the relatively dry atmosphere. This evaporative loss of water, transpiration, accounts for nearly all of the water taken up by the roots. When soil water is in short supply, plants can curtail water loss by closing their stomata, but stomatal closure limits the supply of CO_2, which in turn reduces photosynthesis.

Over a growing season, plants can use an enormous amount of water if it is plentiful. For example, irrigated alfalfa (*Medicago sativa* L.) in southern Idaho can extract nearly 12 mm of water from the soil in a single day; mean water use of an alfalfa crop for a 120-d growing season was about 8 mm d^{-1} (Wright and Jensen, 1972), which was equivalent to roughly four times the average annual precipitation of the area. We show herein that an irrigated stand of Great Basin wildrye [*Leymus cinereus* (Scribn. & Merr.) A. Love], a robust native bunchgrass, used more than 630 mm of water during one growing season at the INEL, which is 2.8 times the mean annual precipitation for the area.

METHODS

Study Area

The INEL occupies 2315 km^2 of cold desert rangeland at an average elevation of about 1500 m on the upper Snake River Plain in southeastern Idaho. The continental climate of this area is characterized by large daily and seasonal temperature fluctuations (Fig. 1). During summer, low humidities, clear skies, and high temperatures result in high evaporative demand during the day; at night, radiation cooling to clear skies often results in temperatures within a few degrees of freezing. Winters are cold, with 2 to 3 mo having mean temperatures below freezing (Fig. 1). Topsoils usually remain frozen from mid to late November through February or early March. Snow cover typically persists for at least 2 to 3 mo. The average annual temperature is 5.5 °C, and the frost free period is about 90 d.

The INEL lies in the rainshadow of numerous mountain ranges to the west. Mean annual precipitation is 221 mm and, on average 36% falls early in the growing season (April–June; Fig. 1). Typically, precipitation exceeds potential ET from October through May (Fig. 1, vertical hatching), and potential ET exceeds precipitation from June through September (Fig. 1, stippled area).

The study was conducted at the INEL Field Station (43° 36'N, 112° 54'W). Natural vegetation at the study site is dominated by big sagebrush (*Artemisia tridentata* Nutt.) and perennial grasses (Anderson and Holte, 1981; Anderson et al., 1987). The soils are Xerollic Calciorthids.

Plant Species

Three species of grasses and one shrub were chosen for study:

Crested wheatgrass [*Agropyron desertorum* (Fisch. ex Link) Schult.]. This naturalized bunchgrass has been used extensively in the western USA for rangeland rehabilitation (see Anderson and Shumar, 1989). Stands of crested wheatgrass persist as virtual monocultures at the INEL (Marlette and Anderson, 1986). This species currently is used to establish plant cover on shallow-land burial sites at the INEL.

Great Basin wildrye. This native bunchgrass is found throughout the Intermountain West on deep soils or disturbed sites. At the INEL, Great Basin wildrye often occurs in pure stands in depressions or low-lying areas where deep soils have accumulated. Individual plants are large, growing to 2 m in height. As noted earlier, stands of this species can have high seasonal water use. Unlike other native grasses, Great Basin wildrye continues to actively photosynthesize and transpire after seed ripening, well into late summer in years when water is available. These characteristics seemed ideal for water management on waste burial sites.

Streambank wheatgrass [*Elymus lanceolatus* (Scribn. and

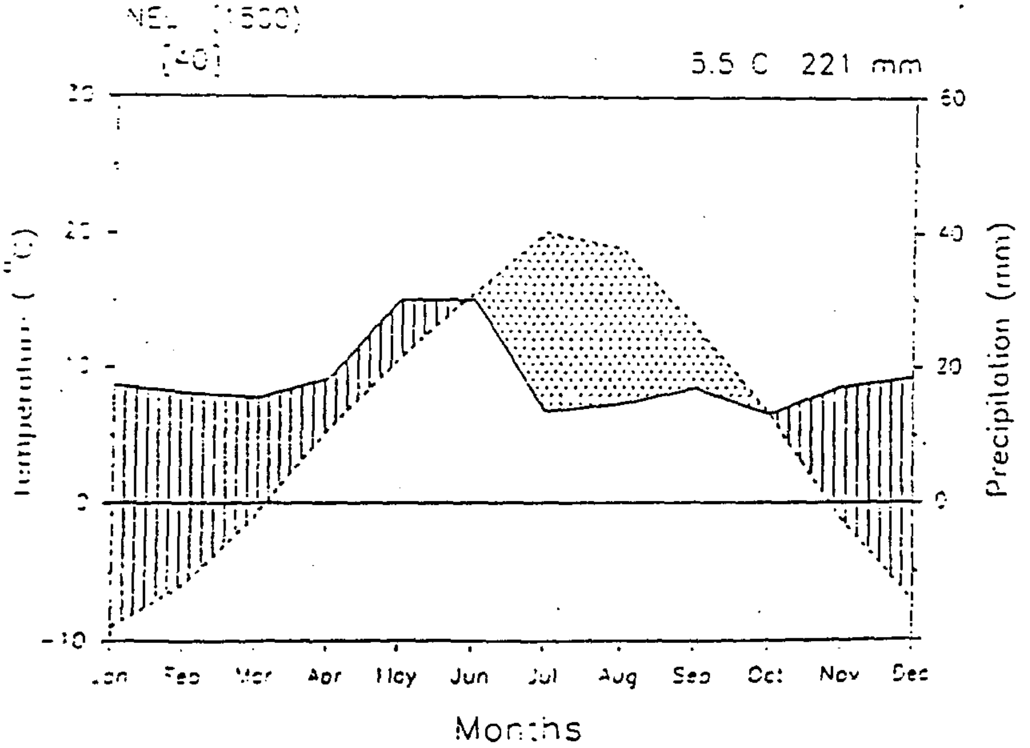

Fig. 1. Climate diagram (*sensu* Walter et al. 1975) for the Idaho National Engineering Laboratory (INEL) based on data for 40 yr from the Central Facilities Area (NOAA. 1950–1989, unpublished data). Solid line depicts mean monthly precipitation; *dashed line shows mean monthly temperatures. Vertical hatching indicates periods when precipitation generally exceeds potential evapotranspiration. Stippled area indicates periods when potential evapotranspiration generally exceeds precipitation. The INEL lies at an average elevation of about 1500 m. Average annual temperature is 5.5 °C; average annual precipitation is 221 mm.*

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design contained 61 cm of a Hackroy clay loam classified as a Lithic Aridic Haplustalf (clayey, mixed, mesic family) and used in two previous studies (Nyhan et al., 1984, 1990a). These soils were emplaced on top of 76 cm of a fine sand (0.05-to 0.425-mm diam) made in the sand classifier/blender described previously. The fine sand was specifically chosen to complement the underlying medium-sized gravel in terms of optimizing the relationship between the hydraulic conductivity and the water-holding properties of the capillary barrier (Wohnlich, 1990).

Measurement of Seepage, Interflow, Runoff, and Precipitation

Runoff, precipitation, and seepage were collected year-round from December 1991 through July 1995, as well as interflow (flow occurring along the length of each plot through the medium sand layer in the EPA Design, the fine sand layer in the two designs with capillary barriers, and the crushed tuff layer of the Conventional Design). Water levels in each 100-liter tank used to collect these data were measured with a microprocessor-controlled ultrasonic liquid level sensor (model DCU-7, Lundahl Instruments, Logan, UT) connected to a multiplexed, automated system described previously (Nyhan et al., 1993). The water levels in the tanks were routinely recorded hourly, but much more frequently when the tank was either emptying or when it was nearly full. Precipitation was measured using a weighing rain gauge and a long-term event recorder.

Measurement of Soil Water Content

Soil water content was routinely monitored once every six hours from December 1991 through July 1995, at each of 212 locations throughout the 16 plots using Time Domain Reflectometry (TDR) techniques with the help of an automated and multiplexed measurement system. Volumetric water content was measured with a pair of stainless steel waveguides (60-cm long, 3-mm diam soil moisture probes; model number 6860, Campbell Scientific, Logan, UT), which are buried parallel and 5 cm apart in the soil and are connected to a 26-m length of RG-8/U coaxial cable. TDR waveguides were emplaced in the Conventional Design at depths of 5-10, 20-80, and 80-86 cm, in the EPA Design at depths of 1-61, 61-91, 96-102, and 92-152 cm, and in the two designs containing capillary barriers at depths of 1-61, 66-126, and 126-132 cm. These TDR waveguides were normally emplaced at downslope locations of 2.63, 4.65, 6.62, and 8.69 m for each soil depth, except at the deepest depths in the Conventional Design and the designs containing the capillary barriers, where they were emplaced at downslope locations of 3.64, 5.66, 7.68 and 9.70 m (to coincide with the bottom end of each of the four seepage pans installed in the bottom of each field plot).

Water Balance Calculations

Daily water balance calculations were performed by determining the daily change in soil water inventory, by summing the daily amounts of precipitation, seepage, interflow, and runoff, and then determining the amount of daily evaporation by difference. As an independent check on these evaporation estimates, evaporation was also estimated from eddy heat flux data collected from a fast-response hygrometer mounted at a height of 12 m on a 92-m meteorological tower at Los Alamos; daily values were estimated from field data collected at 15-minute intervals.

In order to further evaluate the water balance data, daily shortwave radiative energy received by field plots with slopes of 5, 10, 15, and 25% was estimated from pyranometer data collected at a height of 1.2 m from the same meteorological tower described above at the same sampling frequencies. The influences of slope and seasonality of shortwave radiative energy were calculated using the SOLARFLUX model (Rich et al., 1995).

RESULTS AND DISCUSSION

Estimates of Precipitation and Soil Water Inventory

The overall significance of each year's water balance data can best be explained by understanding the spatial and temporal occurrence of precipitation around Los Alamos (Bowen. 1990). Bowen showed that mean annual precipitation is 32.8 cm at White Rock, the only station close to the Protective Barrier Landfill Cover Demonstration with a data base longer than the data collected in this field study. We determined that 2.94-year, 5.56-year, and 20-year events occurred in 1992, 1993, and 1994, respectively.

constructed and instrumented to provide measures of runoff and interflow, as well as seepage and soil water storage as a function of slope length.

The Protective Barrier Landfill Cover Demonstration was emplaced on an east-facing slope similar to the aspect of many of the local landfills where this technology will be applied. The area was surveyed into four pads, each of which received crushed tuff to establish the varying downhill slopes. Four 1.0- by 10.0-m plots with common sidewalls were then constructed on the center of each pad (Nyhan et al., 1993). A seepage collection system was installed in the bottom of each of the plots consisting of four metal pans filled with medium gravel (8.0- to 25-mm diam) overlain with a high conductivity MIRAFI geotextile used in previous field studies (Nyhan et al., 1990a); an 11-cm-wide space was left between the sidewalls of the plot and the pan to minimize sidewall effects.

The hydrologic properties of soils used in the field study are presented in Table 1. The soils were analyzed for porosity and for hanging column and thermocouple psychrometric moisture retention characteristics (Klute, 1986). Constant head determinations of saturated hydraulic conductivity were performed as well as pressure plate extractor determinations of moisture retention characteristics (ASTM, 1993). Van Genuchten's RETC code (van Genuchten, 1991) was

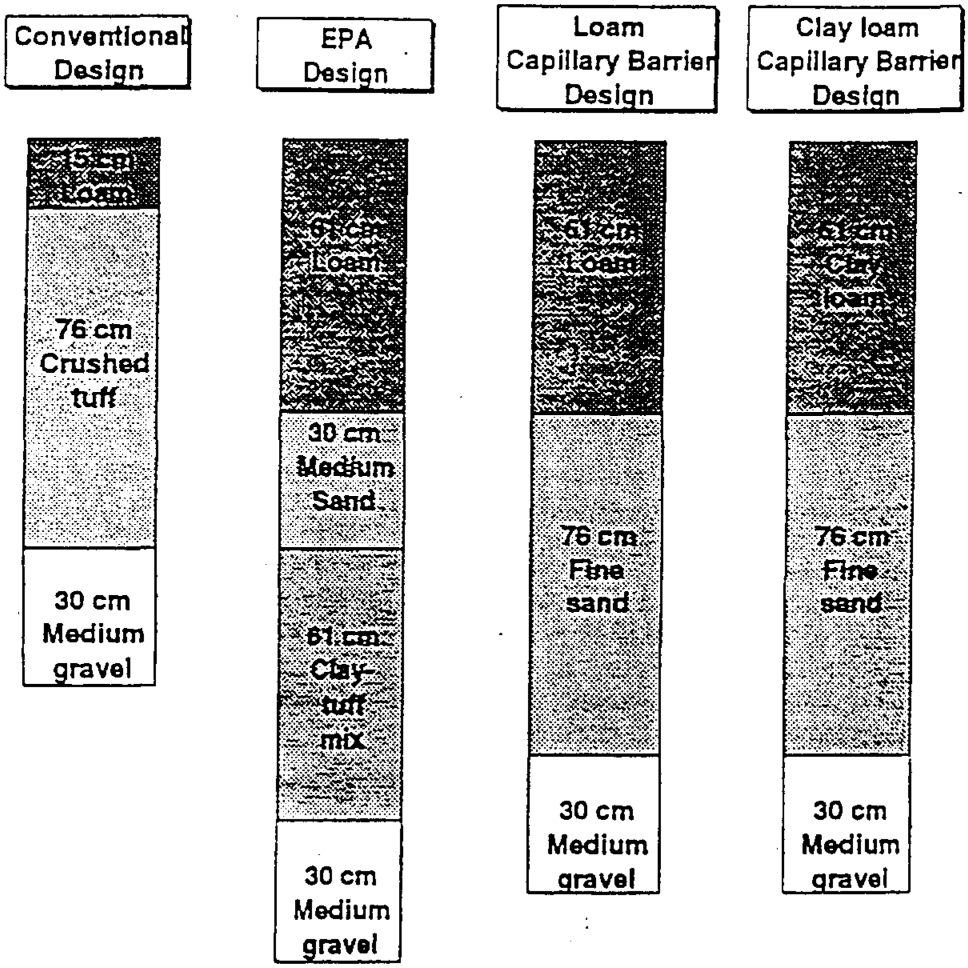

Figure 1. Descriptions of soil layers in the four landfill cover designs at the Protective Barrier Landfill Cover Demonstration. Dashed lines represent a high conductivity geotextile installed at the interfaces between soil layers.

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Title:

A WATER BALANCE STUDY OF FOUR LANDFILL COVER DESIGNS VARYING IN SLOPE FOR SEMIARID REGIONS

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February 9-12, 1997
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Los Alamos
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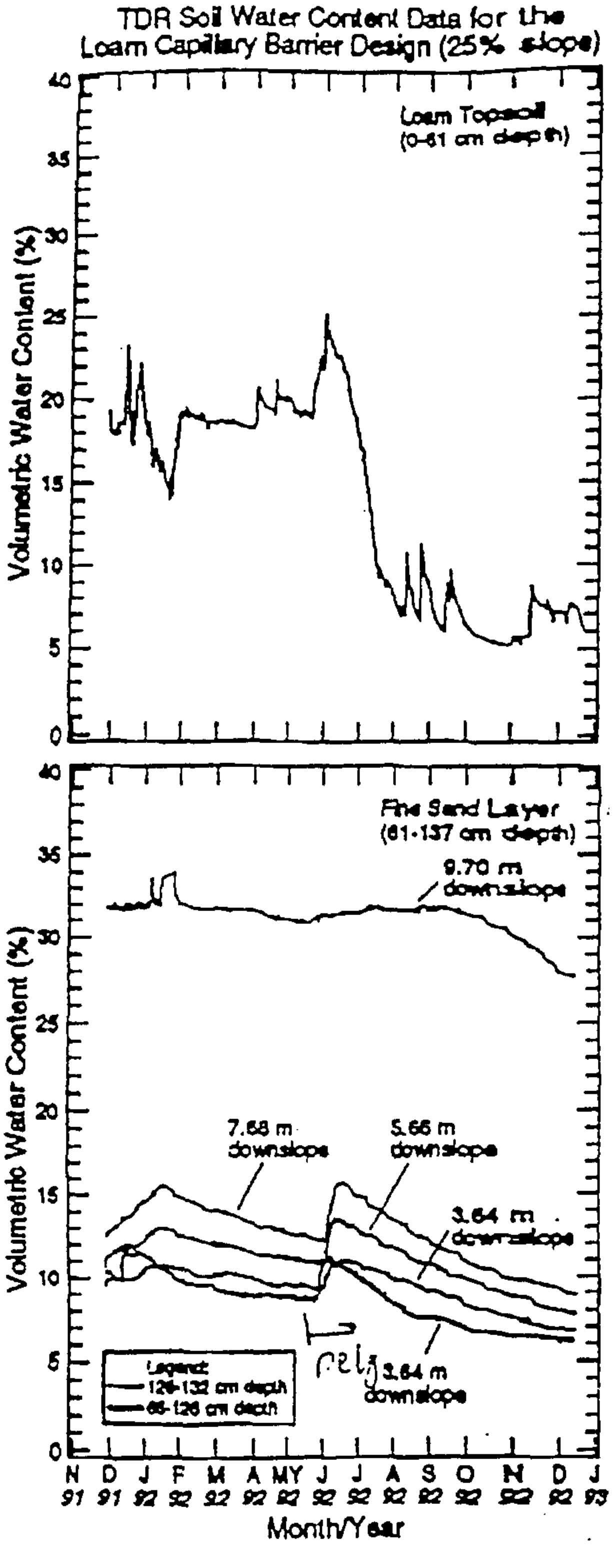

$p = O_f + E_t + \Delta S + P_r + L_f$

ΔS = ~~0.1X61 cm~~ (-ve)

0.06 – 0.19

(ΔS = 0.05 X 76) -ve

0.39 0.72

Top of slope

Always dryest

0.06 - 0.1

Fig. 7. TDR Soil Water Content Data Collected For the Loam Capillary Barrier Landfill Cover Design With the 25% Dominant Downhill Slope At the Protective Barrier Landfill Cover Demonstration.

parameters for the root length density function. Khire (1995) reports that water balance predictions made by UNSAT-H are not particularly sensitive to the shape of the root density function.

Hydrologic and Meteorological Data

Energy reflection by the ground surface is described by the surface albedo. HELP has a "built-in" albedo of 0.23 (Schroeder et al. 1994). For UNSAT-H, a soil surface albedo of 0.2 was used for both test sections, which is consistent with albedos recommended by Chudnovskii (1966) and Benson et al. (1996b).

SCS runoff curve numbers recommended by HELP were used for both test sections. The curve numbers recommended by HELP depend on the saturated hydraulic conductivity, condition of vegetation, slope, and slope-length. HELP recommended curve numbers of 87.7 and 89.5 for Live Oak and Wenatchee, respectively.

Meteorological input for HELP includes daily precipitation, average daily air temperature, daily solar radiation, quarterly relative humidity, and average yearly wind speed. Climatic input for UNSAT-H includes daily and hourly precipitation, daily maximum and minimum air temperatures, daily solar radiation, average daily dew point, and average daily wind speed. The data collected on-site (Khire et al. 1994) were used as input to HELP and UNSAT-H.

Unlike HELP, UNSAT-H does not have a snow-melt algorithm. Hence, precipitation in the form of snow has to be "melted" before it is input to UNSAT-H. For calculating daily snow-melt, the restricted degree-day radiation balance approach (Kustas et al. 1994) was used. In this method, daily snow melt (M) is computed using Eq. 6 (Kustas et al. 1994):

$$M = a_r T_d + m_Q R_n \tag{6}$$

where a_r is the restricted degree-day factor ranging between 0.20 to 0.25 cm/°C, T_d is the average daily air temperature above the base temperature (base temperature assumed 0 °C in this study), m_Q is a conversion constant equal to 0.026 W/m^2, and R_n is the net solar radiation. To calculate

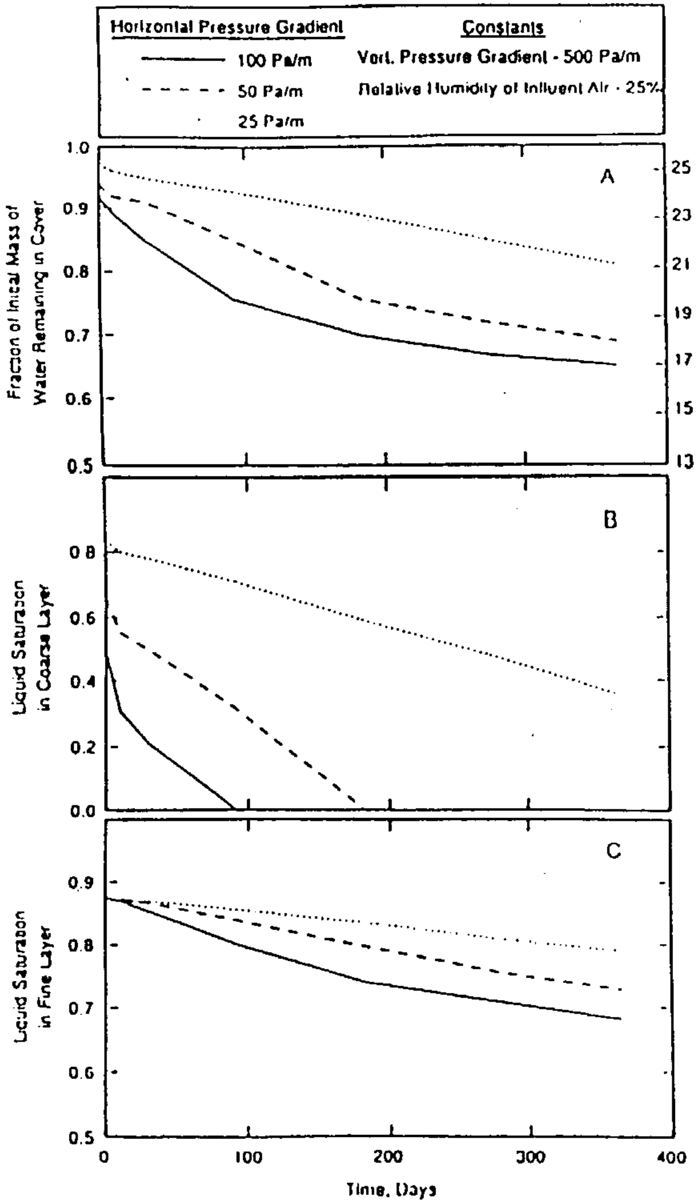

Figure 6. Effect of horizontal pressure gradient on: A, fraction of initial mass of water remaining in cover; B, liquid saturation in coarse layer; and C, liquid saturation in fine layer.

able because, as the horizontal air-pressure gradient increased, the rate and cumulative volume of air flow over time through the cover also increased. Consequently, the rate and amount of water evaporation within the cover would be expected to increase. The vertical pressure gradients employed in these simulations were 500 Pa/m. The results at other vertical pressure gradients were virtually identical and are not shown.

The effects of various horizontal pressure gradients on water saturation within the cover are also presented in Figure 6. Increasing the horizontal pressure gradient had a significant effect on the water content of both the fine and the coarse layers. As can be seen on Figure 6B, increases in the horizontal pressure from 25 to 50 Pa/m resulted in the virtually complete removal of water within the gravel layer within 6 mo. Increasing the gradient under these conditions to 100 Pa/m decreases the drying time to approximately 3 mo. In Figure 6C, the effects of increased air-pressure gradients on the water content of the topsoil layer are presented. The moisture content of the topsoil layer was reduced after about 30 days of air flow. By comparing Figures 6B and 6C, it can be observed that the rate of drying of the topsoil layer was initially a function of the horizontal pressure gradient. The rate of water removal declined as the drying front moved into the fine layer. Once the coarse layer was dry, the rate of water loss in the fine layer was essentially independent of the horizontal pressure gradient.

The effects of varying relative humidity of the influent air (from 25 to 100%) on the total water content of the cover are presented in Figure 7A. These simulations employed a 100 Pa/m horizontal gradient and a 500 Pa/m vertical gradient. The influence of relative humidity on water saturations in the middle of the fine layer and at the base of the coarse layer are presented in Figure 7B and 7C, respectively. These results clearly confirm that the drier the influent air is, the more water can be evaporated and removed from the system. Efficiency, (i.e., the rate of water removal) is greater for the coarse layer, and efficiency declines with time for both layers.

Figure 8 presents results for the case where the influent air stream is saturated with water vapor. In this case, almost all reductions in water content occurred during the first 10 days. A direct, almost linearly proportional relationship exists between air-pressure gradients and liquid mass removal. An examination of Figures 8B and 8C reveals that virtually all the mass removed from the cover was liquid originally present

$$k_{rg} = \left(1 - S^{*}\right)^{1/2}\left(1 - S^{*\frac{1}{\lambda}}\right)^{2\lambda}, \text{ respectively.} \tag{4}$$

The thermal properties for all material types were estimated from values presented by de Marsily (1986). The material properties employed in the modeling are presented in Table 1. Within each of the cover layers, the soil physical properties were assumed to be homogeneous and isotropic.

Table 1. Properties of materials used in numerical studies

Material type	Water content, θ_s	Water content, θ_r	α 1/Pa	λ	Intrinsic permeability, m²	Heat capacity, J/kg°C	Thermal conductivity, W/m°C
Topsoil	0.40	0.09	$1.21 \times 10^{[illegible]}$	0.476	$8.86 \times 10^{[illegible]}$	886.0	2.2 wet 1.0 dry
10-20 Sand	0.28	0.04	$1.60 \times 10^{[illegible]}$	0.698	$1.38 \times 10^{[illegible]}$	800.0	1.4 wet 1.4 dry
Pea Gravel	0.42	0.01	$5.03 \times 10^{[illegible]}$	0.543	$3.50 \times 10^{[illegible]}$	800.0	3.2 wet 0.5 dry

INITIAL AND BOUNDARY CONDITIONS

The boundary conditions employed in the modeling included specified pressure, temperature, and air-phase mass fractions. A no-flow boundary was employed at the base of the coarse gravel layer to simulate the presence of an impermeable liner below the pea gravel. Horizontal and vertical air flow through the cover was induced by establishing various horizontal and vertical pressure gradients across the gravel layer and between the gravel and the ground surface. The vertical boundaries of the topsoil and the intermediate 10-20 sand were simulated as no-flow boundaries. The ground surface and vertical boundaries of the gravel layer were simulated as seepage faces by specifying a capillary pressure of zero a[illegible]rfect mobility for both phases. This condition permits the flow of both water and air across these boundaries. The location of the model boundary conditions is also shown on Figure 3.

The magnitude of the vertical and horizontal pressure gradients considered are consistent with an engineering study of dry barrier cover systems for the western United States (Stormont et al., 1994). The pressure gradient within the cover depends on a number of factors, including: climatic conditions, desired water-removal rates, spacing of injection and withdrawal pipes, and pressure losses in the pipes. For hectare-sized landfill covers (100 m by 100 m) in the western United States, dry barrier systems were designed with pressure drops ranging from 10 Pa/m to 100 Pa/m. These pressure drops are readily achievable with commercially available blowers, which can develop over 5 kPa total pressures. Given the pressurization of the coarse layer, we imposed vertical air-pressure differences between the gravel layer and the ground surface of 500, 1500, and 2500 Pa to investigate the influence of the vertical air-pressure gradient on the removal of water from the cover system. These pressure gradients were established by increasing the pressure of the influent air stream in the basal coarse layer above the atmospheric pressure specified at ground surface. The influence of the horizontal pressure gradient was evaluated in conjunction with each of the vertical pressure gradients by imposing additional horizontal pressure differences across the gravel layer through which the air stream entered and exited the model domain. Gradients of 25, 50, and 100 Pa/m were investigated. Each horizontal and vertical pressure-gradient scenario was simulated with the influent air stream at 25, 50, 75, or 100% relative humidity.

The initial condition was established by simulating drainage from a condition of near-saturation throughout the entire cover to an equilibrium soil water content distribution at ambient, static, air-pressure conditions. A typical distribution of the resulting initial water-phase saturations within the landfill cover is shown in Figure 4. The water content of the fine-textured topsoil layer increased from a relative saturation of approximately 0.8 at the ground surface to greater than 0.95 at its base. The water content of the 10 to 20 sand and the upper 0.2 m of the coarse gravel layer were slightly greater than their residual saturation moisture contents. However, the water content at the base of the coarse layer was close to saturation, due to the presence of the impermeable boundary underneath. These initial conditions [illegible]esent a moisture content distribution which might be expected to oc[illegible] in the

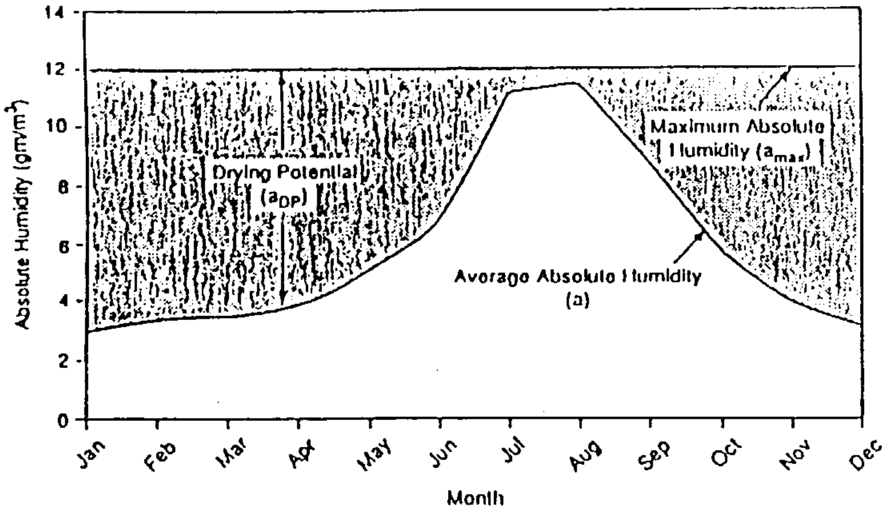

Figure 2. Drying power of same air equilibrated with 13°C soil in terms of absolute humidity.

ing drainage from an initial condition of near-saturation throughout the entire cover to an equilibrium distribution of soil water content at ambient, static air-pressure conditions. A series of simulations were then conducted with the influent airstream at various horizontal and vertical air-pressure gradients and relative humidities. The effects of vapor diffusion and coupled heat flow on water movement within the cover system were also investigated.

NUMERICAL CODE

The simulations were conducted using the TOUGH2 numerical code. TOUGH2 is capable of simulating the multidimensional coupled flow of multiphase fluids in porous and fractured media (Pruess, 1991). It employs an integrated, finite-difference, numerical approach to the solution of the governing flow equations. Details of the application of TOUGH2 to simultaneous water/air flow is described by Oldenburg and Pruess (1993) for evaluating capillary barriers.

MODEL DOMAIN AND GRID

We developed our numerical model to be consistent with the conventional cover for the closure of hazardous-waste landfills or similar units, as defined by the U.S. Environmental Protection Agency (EPA) technical guidance (USEPA, 1989). The EPA recommends a multilayer final cover design composed of three layers, with allowance for optional layers. The basic three layers, from top to bottom, are:

- Topsoil Layer—A layer of either armored or vegetated surface and 60 cm of soil. The armored surface is designed to minimize erosion and to promote drainage off the cover. Vegetation reduces percolation by transpiration.
- Drainage Layer—A layer of either soil or a geosynthetic material that will promote lateral drainage, with a lateral slope of at least 3%. If soil is used, it should be at least 30 cm thick and have a minimum hydraulic conductivity of 10^{-2} cm/sec.
- Low-Permeability Layer—A two-component layer to minimize the infiltration of water through the cover into the underlying waste. The layer consists of a geomembrane of at least 20-mil (0.5-mm) thickness overlying a 60-cm-thick compacted soil layer with a maximum hydraulic conductivity of 10^{-7} cm/sec.

An illustration of the geometry we evaluated is given in Figure 3. The numerical simulations utilized the drainage layer as the dry barrier layer. Between the topsoil and the gravel drainage layer, a 10-cm-thick sand layer is used as a filter to prevent migration of fines into the gravel. The bottom of our model is defined by the geomembrane, which is assumed to be impermeable. The geomembrane will isolate the air-dried layer from the clay-based layer; this is important because drying the clay would impair its performance. Because the geomembrane is considered impermeable, our model is restricted to the top three layers of the multicomponent design. The layers were not sloped in these simulations.

The horizontal dimension of 1 m was selected to simulate a "unit width" of the cover. As configured, the grid is essentially a two-dimensional cross-section through a segment of a cover. A series of model simulations were conducted to evaluate the effects of various cell sizes on computational time and on accuracy of the results. The grid employed in the cover modeling was selected to have cell sizes which provided reasonably similar results with respect to other grids with smaller cell

provided this project by the University of Maryland's Experiment Station, Beltsville Unit staff, notably Peter Godwin.

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WATER REMOVAL FROM A DRY BARRIER COVER SYSTEM

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Key words: *Landfill cover, air flow, dry barrier, water movement, numerical analysis*

ABSTRACT

A dry barrier is a layer of soil that is dried by air flow. Incorporating a dry barrier within a landfill cover system adds an additional component to the water balance of the cover, increasing the available storage within. As covers typically include multiple, laterally continuous layers with contrasts in material properties, air flow is channeled through relatively coarse, air-permeable layers within the cover. Systems can be active, using blowers and fans, or passive, exploiting atmospheric phenomena.

We performed a numerical analysis of a three-layer landfill cover design (topsoil, sand, and gravel) to investigate the mechanisms of water movement induced by air flow. The simulations were conducted using the TOUGH2 numerical code. Initial conditions were established by simulating drainage from conditions of near saturation throughout the entire cover to an equilibrium distribution of soil water content at ambient, static, air-pressure conditions. A series of simulations were then conducted with the influent airstream at various horizontal and vertical air-pressure gradients and relative humidities. Pressure gradients readily established with commercially available equipment resulted in virtually complete removal of water from the gravel layer within 6 mo for hectare-sized landfills.

Although there was very little drying in the fine layer due to advective air flow, the removal of water by evaporation near the fine/coarse layer interface reduced the local water content and hydraulic head. Water therefore moved toward the fine/coarse-layer interface, becoming available for evaporation. This is important because it suggests that the fine-layer water content may be moderated by air flow in the coarse layer.

INTRODUCTION

Surface covers are mandated for closure of many types of waste-disposal units, including landfills, surface impoundments, waste piles, and some mine tailings. Covers can vary from a simple soil cover to multi-

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Innovative Cover Design for 2:1 Slopes Complying With California Closure Criteria

by

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A.S. Dellinger, P.E.; Member, ASCE[2]

Background

Closure of inactive landfills, while preventing harmful effects to the environment, is a challenge facing all landfill engineers. The need to balance closure costs with the benefits associated with environmental mitigation must be considered when designing landfill final covers.

California is recognized as having some of the most stringent environmental standards in the United States. These standards, coupled with seismic stability requirements, necessitate creative and innovative landfill cover designs.

The City of Los Angeles is responsible for developing final closure plans for the Toyon Canyon Sanitary Landfill, a 0.36 square kilometer (90 acre) canyon fill site with refuse depths of 88 m (290 feet) on average. The front face (sloped area) of Toyon Canyon Landfill encompasses 0.16 square kilometers (40 acres), with 10 benches or terraces; bench heights range from 9 to 12 m (30 to 40 feet). This site ceased waste disposal in 1985, with disposal of 14.5 million metric tons (16 million tons) of refuse, but has yet to implement a final cover system. The challenge in designing a final cover system for this landfill was placement of cover material which satisfied permeability limits while meeting seismic slope stability needs. What makes this site unique is the presence of slopes at 2:1 (2h:1v); current manufacturers of cover products cannot satisfy seismic stability factors of safety (FS) for placement on slopes with angles exceeding 26 degrees.

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monitoring equipment was designed for measuring the components of water balance and additional ancillary variables. All monitoring equipment was also designed with a backup for each.

The water balance equation to be used is:

$$E = P - I - R - D - \Delta S; \text{(Equation 2)}$$

where, precipitation (P), surface runoff (R), lateral drainage (D), evapotranspiration (E), soil water storage (S), and percolation or infiltration (I) are the six water balance variables. With the exception of 'E', estimates of all terms in Equation 2 will be obtained with the monitoring systems. Evapotranspiration will be estimated by solving Equation 2 for 'E'. Other measurement variables include erosion, precipitation, relative humidity, barometric pressure, soil temperature with depth, vegetation biomass and cover, and wind speed and direction. Most of the physical attributes will be measured with automated monitoring systems to provide continuous data (see figure 5).

Soil Moisture: Time Domain Reflectometry (TDR) and an associated data acquisition system will be used to provide a continuous record of soil moisture status at various plan locations and depths in each cover profile. The soil moisture will be measured using TDR. PVC pipes were installed strategically in the covers to be used as ports to allow for the use frequency domain reflectometry as a backup. The process of sending pulses and observing the reflected waveform is called TDR. A waveform traveling down a coaxial cable or waveguide is influenced by the type of material surrounding the conductors. If the dielectric constant of the material is high, the 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 medium being measured.

Soils with a high water content lengthen the propagation time and this is reflected as an apparent increase in the distance traveled by the pulse. Soils with a high water content and a high electrical conductivity rapidly attenuate the voltage pulse before it is reflected back to the source. If the attenuation is great enough there is no return signal and the probe cannot be used. This is essentially what happened when commercially available probes were tested in soils representative of the barrier layer in the Compacted Clay Cover – no useful signal was reflected back. The high density, water content and sodium bentonite addition made TDR a challenge to use. Because of the problems with the commercially available TDR systems, a system was designed to overcome these problems. The design began with perhaps the single most important element and weak link - the probe. Such things as: rod length, rod spacing, number of rods (2 or 3), coating the rods (with several different types of coatings, coating thicknesses, and surface preparation), total coax cable lengths, rod diameter, low loss coaxial cable, and inserting diodes were experimented with to perfect the probes.

The final design yielded excellent waveforms under the most trying of circumstances. 256 probes were fabricated, installed in the three covers, and multiplexed (SDMX50 by Campbell Scientific) back to a set of Cable Testers (Tektronix 1502B). After fabrication of the probes but prior to their installation, each probe was individually calibrated. This calibration process was extremely lengthy and time consuming. Each probe as it would be assembled in the field was inserted in representative soil under a range of moisture contents to develop an algorithm that would yield an accurate moisture content. The TDR system was calibrated to measure the soil moisture content to within +/- 1% of actual moisture content.

Soil Temperature: Thermocouples placed strategically throughout each cover will measure the soil temperature. This data will be used to assist with evapotranspiration studies and for monitoring frost penetration and its affect on the hydraulic conductivity of the soils.

Runoff and Erosion: Runoff and erosion will be measured on an event basis. Surface runoff water will be collected with a gutter system located at the bottom of each slope of each cover. The collected water will be routed to instrumentation that quantifies it. All instrumentation is set up so as to have redundancy in case of a failure in the primary measurement. A data acquisition system is linked to the instrumentation to automatically record and store data. Sediment will be separated from runoff in a settling tank located downstream from the runoff measuring system to provide total soil loss for each runoff event.

Percolation and Interflow: Subsurface flows will be measured. Lateral drainage from each drainage layer will be collected using underdrain systems placed at the bottom of each slope of each cover. The water will be routed to instrumentation that quantifies it. The instrumentation is linked to a data acquisition system to continuously record flow events. Percolation through the barrier layer for each cover will be collected using a geomembrane under a geonet that routes the water to an underdrain collection system. Both percolation and interflow will be routed via drains to the flow monitoring system. Measurement redundancy is built into the system to reduce the chances of losing data due to equipment failure or power loss and to verify correctness of results obtained. To avoid problems with inclement weather, all monitoring instrumentation is housed in a shelter.

Meteorology: A complete weather station was installed at the ALCD site. Precipitation, air temperature, wind speed and direction, relative humidity, and solar radiation will be continuously recorded. The meteorological measurements will be made with automated equipment coupled to the data acquisition system.

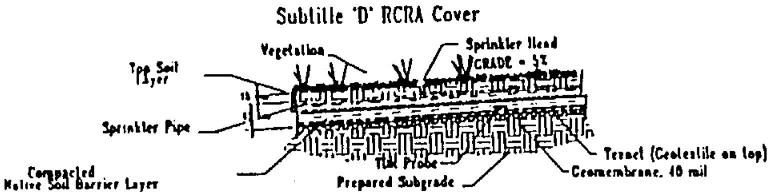

Figure 3 - Soil Cover typical section.

The third cover is called a Geosynthetic Clay Liner (GCL) cover (see figure 4). It is identical to the Compacted Clay Cover installed with one exception. The compacted clay barrier layer was replaced by a single manufactured sheet known as a GCL. Therefore the GCL is the bottom layer covered with a geomembrane, drainage layer and vegetation layer, respectively. The GCL sheet installed is a composite of two nonwoven geotextile fabrics sandwiching a layer of bentonite. The hydraulic conductivity of the GCL is 5×10^{-9} cm/sec.

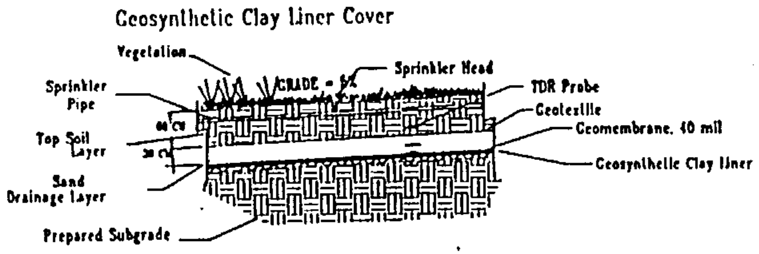

Figure 4 - GCL Cover typical section.

Apart from the three covers installed, two smaller test pads were also constructed adjacent to the test pads. The test pads are 7.3 m by 7.3 m. One pad is a Subtitle 'C' compacted clay barrier layer with the other being a Subtitle 'D' compacted soil barrier layer. They were constructed exactly like the barrier layers in the full size test plots. A double-ring infiltrometer was installed on each test pad to measure in-situ hydraulic conductivity (ASTM D5093). These infiltrometers will be left in-place to measure hydraulic conductivity throughout the duration of the experiment.

Phase I Construction Quality Assurance

A detailed Quality Assurance (QA) Plan was prepared for this demonstration. It adheres closely to that recommended by the EPA (EPA, 1993). The major purpose of this QA process was to provide documentation for those individuals who were unable to observe the entire construction process (e.g., representatives of regulatory agencies, etc.) so that these individuals can make informed judgments about the quality of construction of the ALCD. QA procedures and results were thoroughly documented.

Daily Inspection Reports were prepared that included information about work that was accomplished, tests and observations that were made, and descriptions of the adequacy of the work that was performed. Daily Summary Reports provided a chronological framework for identifying and recording all other reports and aided in tracking what was done and by whom. Inspection and Testing Reports noted field observations, results of field tests, and results of laboratory tests performed on- or off-site. These observations took the form of notes, charts, sketches, or photographs, or a combination of these. Problem Identification and Corrective Measures Reports identified and recorded fixes of problems with material or workmanship that did not meet the requirements of the plans, specifications, or QA Plan. Drawings of Record ('as-built' drawings) were prepared and continually updated to document actual field installations. Final Documentation and Certification took the form of a final report that included all of the aforementioned.

Key meetings were essential to the successful construction of the ALCD. These meetings included a pre-bid meeting held prior to bidding of the contract, a pre-construction meeting held in conjunction with a resolution meeting after the contract was awarded but prior to the start of actual construction activities.

The pre bid meeting was used to discuss the QA Plan and resolve differences of opinion before the project was let for bidding. It also gave the bidders a chance to ask questions and problems which were therefore rectified early on. The resolution / pre-construction meeting allowed for lines of communication, review of construction plans and specifications, emphasize the critical aspects of a project necessary to ensure proper quality, begin planning and coordination of tasks, and anticipate any problems that might cause difficulties or delays in construction. It also allowed for the review of the QA Plan, to make sure that the responsibility and authority of each individual was clearly understood, where procedures to resolve construction problems were established. Periodic progress meetings were held at the job site. These meetings were helpful in maintaining lines of communication, resolving problems, identifying action items, and improving overall quality management.

Materials Quality Assurance was of utmost importance. Materials and their installation were tested to ensure compliance with the design and recorded throughout the construction process. These items included such things as plasticity index, sieve analysis, maximum size stone or debris, placement and compaction, moisture content, bond between lifts, in-situ hydraulic conductivity (ongoing), out for review first to a group of technical peers that were independent of the project and deemed industry experts. This review helped ensure the technical validity of the designs to be constructed in Phase I. Comments were gathered from the reviewers and included in the designs.

This revised test plan was then sent to regulatory representatives from Environmental Departments from many of the western states including New Mexico, Arizona, California, Nebraska, Nevada, South Dakota, Texas, and Utah. It was also sent to representatives from the EPA Regions VI and VIII offices. Comments from this review were also incorporated into the design package.

Politicians and thus regulators are becoming more sensitive to special interest groups concerns and are therefore encouraging participation with these groups when permitting projects. The ALCD has received endorsement by a committee from a western states' and federal government initiative to accelerate and improve clean up of federal lands. This initiative originated in 1992, when the Western Governors Association, the Secretaries of Defense, Energy, and Interior, and the Administration of the Environmental Protection Agency formed a federal advisory committee to cooperate on the cleanup of federal waste management sites in the region. This committee, known as the Committee to Develop On-Site Innovative Technologies (DOIT Committee), has sought the guidance of key players to help identify, test and evaluate more cooperative approaches to deploying promising innovative waste remediation and management technologies in order to clean up federal waste sites in an expeditious and cost-effective manner.

The DOIT Committee's primary goal with regard to the ALCD is to assist with the eventual acceptance of new technologies that come from the demonstration and inclusion of landfill permitting in an inter-state reciprocity program the Committee is attempting to finalize.

Yet, another review process included sending a general overview of the demonstration to members of the DOIT Committee and special interest groups identified by the DOIT Committee. These interest groups included representatives from such entities as environmental activist groups like the Sierra Club, Indian tribes, government agencies, neighborhood associations, local businesses, engineering firms, and politicians. Over 1000 groups received a package. Comments were forwarded through the Western Governors Association for consideration. The majority of these comments centered on questions rather than comments and on praise for getting them involved early in the process. Much interest was invoked as a result of this. Periodic meetings were held with these representatives of some of the special interest groups, Western Governor's Association, regulatory agencies (predominantly from New Mexico), New Mexico State Legislature, and Sandia National Laboratories. These meetings kept interested parties apprised of advancements, progress, and answered questions and concerns. These meetings continue on about a bimonthly basis.

Demonstration Description

The ALCD is a series of large-scale landfill test covers constructed side-by side for comparison. (see figure 1). Future test cover construction will continue this side-by-side arrangement. The various covers will be compared based on their performance, cost, and ease of construction.

The ALCD is not intended to showcase any one particular cover system. It is intended to compare and contrast different cover systems in a dry environment. Information gained from the demonstration can then be used by others when choosing between cover designs or when applying for the permitting of one of the cover systems.

Figure 1 - ALCD Test Covers

The covers are each 13 m wide by 100 m long. The 100 m dimension was chosen because it is fairly representative of hazardous and mixed waste landfills found throughout the DOE complex (approximately 2 acres in surface area).

General site preparation included bringing utilities (water and power) to the site for the instrumentation and stress testing. The site was cleared and grubbed after which the top 15 cm of topsoil was excavated and stockpiled. This topsoil was reused as the top 15 cm of the covers. The covers were designed so that the site cut excavations were approximately equal to the soil requirements for the covers. The subgrade below each cover was compacted to 95% of maximum dry density (ASTM D698). The only soil hauled in from off-site used in the construction of the covers was the bentonite added to the barrier layer in the Compacted Clay Cover and the sand for the drainage layers. All covers were constructed with a 5% slope in all layers.

Phase I Cover Descriptions

The Compacted Clay Cover installed was designed to meet minimum requirements from Subtitle 'C' regulated landfills (EPA, 1991). It is 1.5-meters thick. The typical profile for this cover consists of three layers (see figure 2). The bottom layer is a 60 cm thick barrier layer. The barrier layer's primary purpose is to prevent the downward movement of water into underlying waste. It was constructed of native soil mixed with 6% bentonite. The bentonite was required because the native

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Alternative Landfill Cover Demonstration

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Abstract

The Alternative Landfill Cover Demonstration is a large-scale field test to compare and document the performance of alternative landfill cover technologies of various costs and complexities for interim stabilization and/or final closure of landfills in arid and semi-arid environments. Test plots of traditional designs recommended by the US Environmental Protection Agency (EPA, 1991) for both RCRA Subtitle 'C' and 'D' regulated facilities have been constructed. These will serve as baselines for comparison to alternative covers. The alternative covers designed specifically for dry environments will be constructed in 1996. The covers will be tested under both ambient and stressed conditions. All covers will be instrumented to measure water balance variables and soil temperature. An on-site weather station will record all pertinent climatological data.

A key to acceptance of an alternative environmental technology is seeking regulatory acceptance and eventual permitting. The lack of acceptance by regulatory agencies is a significant barrier to development and implementation of innovative cover technologies. Much of the effort on this demonstration has been toward gaining regulatory and public acceptance. The demonstration is working with regulatory authorities and public interest groups toward the possibility of interstate permitting of alternative landfill cover technologies.

Introduction

The Departments of Energy and Defense have begun a clean-up of their facilities that is expected to cost hundreds of billions of dollars. These cost estimates, however, are based on "state-of-the-art" technologies, of which many are inadequate. Consequently, work has begun on the development or improvement of environmental restoration and management technologies. One particular area being researched is landfill covers. As part of their ongoing environmental restoration activities, the US

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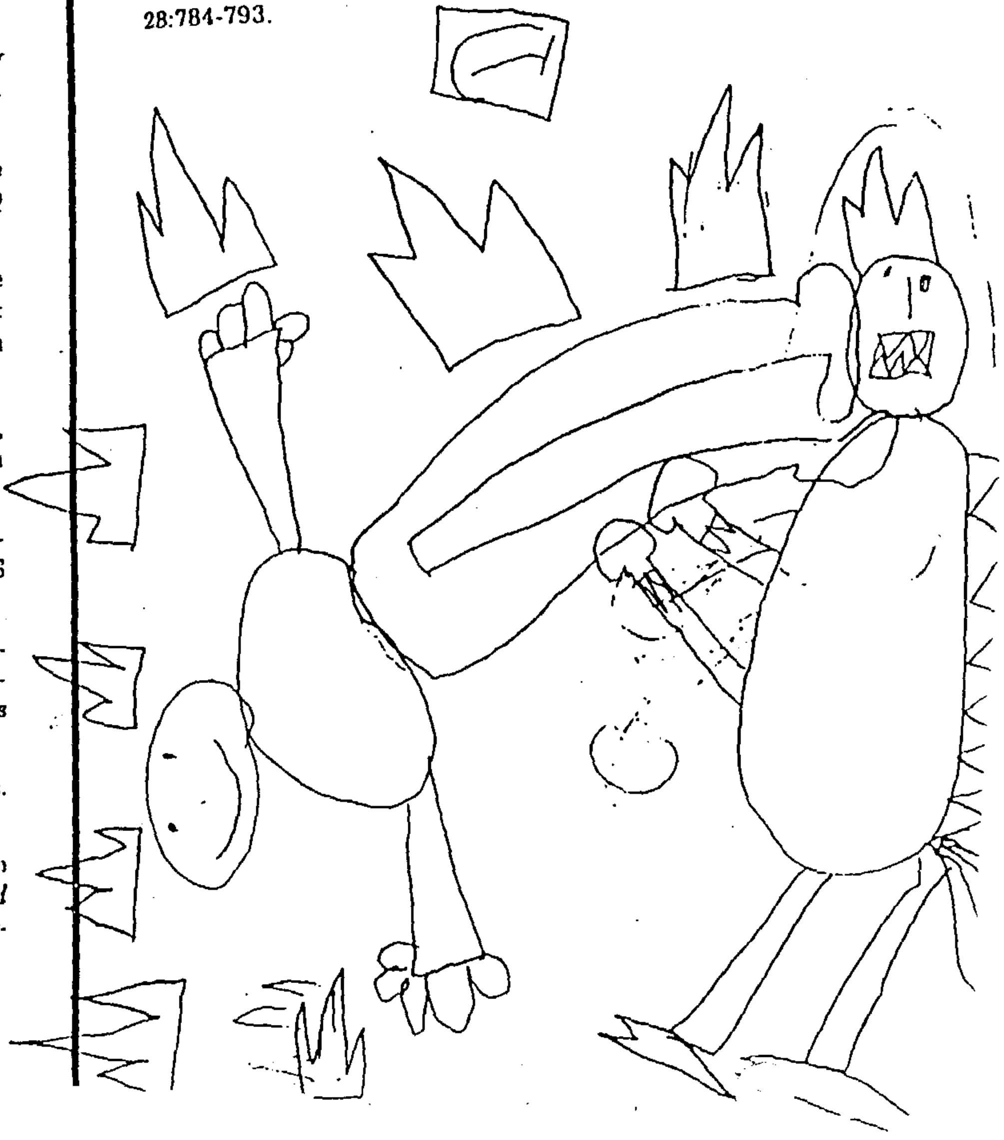

2. Develop data on field performance of alternative materials to those in the CSL. Geosynthetic clay liners and asphaltic barriers are two examples of materials that show great promise as alternatives.
3. Determine how much differential settlement surface barriers can withstand before their ability to limit infiltration is compromised. Because the available information is meager, until more data are developed, surface barriers are likely to be restricted to sites with little or no anticipated settlement. When the amount of settlement that a surface barrier can withstand is defined, then the barriers can be used over a greater range of site conditions.
4. Document performance in the field. There is not much information on field performance, and most published case histories point to failures rather than to successes. To use surface barriers reliably, field performance data on individual components of the barriers, and on the barrier itself, must be documented.

CONCLUSIONS

This paper has summarized the basic principles employed for design of surface barriers. The most important conclusions relate to the barrier layer within the surface barrier. The main conclusions are as follows:

- Compacted clay-rich soil liners by themselves are not the best type of material to use for a hydraulic barrier because the clay is vulnerable to damage from wet-dry cycles, freeze-thaw (at some sites), and differential settlement.
- A GCL is a better overall choice than compacted, low-permeability soil for many sites because it can better resist wet-dry cycles, freeze-thaw conditions, and differential settlement.
- Alternative barrier materials, including asphalt and GCL, appear to be promising and warrant further study.
- Geomembranes are thought to have service lives of up to several hundred years or more. Despite this relatively long service life, geomembranes may not provide long enough protection for some radioactive waste sites. However, their low cost and high degree of effectiveness for at least several hundred years (when the waste is most radioactive) make geomembranes potentially viable materials even if only for redundancy.

- The EPA-recommended surface barrier (sometimes called "RCRA cap") has evolved over time, but it is not a technology that has been proved to work well. Many more failures than successes have been reported in the literature. Whether the RCRA cap will work well over the long term remains to be determined, but there is reason to believe that many caps will fail to meet design expectations.
- There is a lack of field performance data for surface barriers. Perhaps the single greatest research and development need is to document field performance and publish more case histories of successes in surface barriers.

In summary, this paper has addressed the problems, solutions, and future needs for surface barriers. The problems are: (1) Great reliance has been placed on low-permeability, compacted soil barriers, but the performance of such materials may be compromised by desiccation- or settlement-induced cracking. (2) Geomembranes may work well for several centuries but cannot be relied upon for surface barriers with longer design lives. (3) The literature is not rich with examples of surface barriers that have performed effectively. To the contrary, there are many examples of failures, leading one to conclude that current technology for surface barriers is unproved.

The solutions are to make greater use of natural processes for control of erosion and infiltration of water and to use alternative barrier materials. Future needs are, primarily, to determine how much differential settlement surface barriers can withstand, and to develop field performance data to determine and document how well surface barriers can perform under realistic conditions.

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measured much greater tensile strains without cracking in many GCL, probably due to the beneficial reinforcing effects from the geotextiles or geomembrane in the GCL. In any case, the available data indicate that GCL can withstand much greater tensile deformation than normal compacted soils without cracking, which is a very favorable characteristic for surface barriers. Geosynthetic clay liners are considered to be superior to CSL in terms of resistance to damage from differential settlement.

Construction Issues. The construction issues that might be considered in an equivalency analysis include puncture resistance, effect of subgrade condition on constructability, ease of placement, speed of construction, availability of materials, requirements for water, air-pollution effects, weather constraints, and quality-assurance requirements. In most respects, the GCL enjoys advantages over CSL in terms of ease of construction. The only potential problem warranting discussion is puncture resistance of GCL.

Geosynthetic clay liners are thin and, like all thin liner materials, are vulnerable to damage from accidental puncture during or after construction. Thick CSL cannot be accidentally punctured. Some GCL are capable of self-sealing around certain punctures, e.g., penetration of the GCL by a sharp object, such as a nail. The swelling capacity of bentonite gives GCL this self-healing capability. Of greater concern than penetration of the GCL by an object after construction is accidental puncture during construction. For example, if the blade of a bulldozer accidentally punctures the GCL during spreading of cover material, the GCL would probably not self-seal at the puncture.

The puncture resistance of GCL will generally not be equivalent to that of CSL. However, this does not mean that a GCL cannot meet or exceed the performance objectives of a CSL. Quality-assurance and quality-control procedures can be established and implemented to make the probability of puncture during construction extremely low. In surface barriers, one or two accidental punctures would probably not have a major impact on the overall performance of the barrier layer. In a bottom liner system subjected to a continuous head of liquid, a different conclusion might be drawn about the significance of undetected and unrepaired damage to a GCL from puncture. Ultimately, site-specific conditions and quality-assurance procedures will be critical in dealing with the issue of puncture and in establishing equivalency of a GCL to a CSL for a particular project.

CASE HISTORIES OF SURFACE BARRIERS

Field Test Plots Illustrating Desiccation Problems

Some designers have assumed that a CSL can be protected from desiccation with a thin layer of cover soil. Montgomery and Parsons (1989) describe field experiments in which three test plots were constructed and monitored for 3 yr. A 1.2-m-thick layer of low-permeability, compacted clay soil was covered with either 150 mm or 450 mm of topsoil at a temperate site in the northern United States. After 3 yr, excavations were made into the compacted soil. The condition of the two plots was about the same: The upper 200 to 250 mm of clay was weathered and blocky, cracks up to 12 mm wide extended up to 1 m into the clay; roots penetrated up to 250 mm into the clay in a continuous mat, and some roots extended up to 750 mm into the clay. Clearly, neither 150 mm nor 450 mm of topsoil was enough to protect the clay adequately.

Corser and Cranston (1991) describe test plots in which a layer of low-permeability, compacted soil (a soil-bentonite blend) was covered with either (1) a 600-mm layer of topsoil, (2) an unprotected geomembrane, or (3) a geomembrane overlain by 450 mm of topsoil. The site was located in a relatively arid part of California. In less than a year, significant drying and cracking occurred in the plots with soil cover alone or the geomembrane cover alone, but no significant desiccation occurred in the soil covered with both a geomembrane and soil. However, the tests were short-term, and long-term drying may have eventually occurred even with the geomembrane and soil overburden. Nevertheless, the studies of Montgomery and Parsons (1989) and Corser and Cranston (1991), taken collectively, illustrate that the best and, perhaps, only practical way to protect a relatively wet, low-permeability, compacted soil liner from desiccation from the surface is to cover the soil liner with both a geomembrane and a layer of cover soil. To provide less protection is inappropriate if the designer's intention is for the compacted soil liner to remain moist. A geomembrane may not be necessary if an extremely thick layer of cover soil is used, or if the soil liner is designed to withstand drying without cracking (Daniel and Wu, 1993), but the cover layer would have to be so thick that, for some projects, soil alone would be impractical.

where k is the hydraulic conductivity, H is the depth of liquid ponded on the liner, and T is the thickness of the liner. The water pressure on the base of the liner is assumed to be atmospheric pressure in equation (1).

TABLE 2. Differences between geosynthetic clay liners and compacted soil liners.

Characteristics	Geosynthetic clay liner	Compacted soil liner
Materials	Bentonite, adhesives, geotextiles, and geomembranes	Native soils or blend of soil and bentonite
Thickness	Approximately 12 mm; consumes very little landfill volume	Typically 300 to 600 mm; consumes more landfill volume
Hydraulic conductivity	≤1 to 5 × 10^{-9} cm/sec	≤1 × 10^{-7} cm/sec
Speed and ease of construction	Rapid, simple installation	Slow, complicated construction
Ease of quality assurance (qa)	Relative simple, straightforward, common-sense procedures	Complex qa procedures requiring highly skilled and knowledgeable people
Vulnerability to damage during construction from dessication and freeze-thaw	GCL are essentially dry; GCL cannot desiccate during construction; not particularly vulnerable to damage from freeze-thaw	Compacted clay liners are nearly saturated; can desiccate during construction; vulnerable to damage from freeze-thaw
Vulnerability to damage from puncture	Thin GCL is vulnerable to puncture	Thick compacted clay liner cannot be punctured accidentally
Vulnerability to damage from differential	Can withstand much greater differential settlement than compacted clay liner	Cannot withstand much differential settlement without cracking
Availability of materials	Materials easily shipped to any site	Suitable materials not available at all sites
Cost	Reasonably low, highly predictable cost that does not vary much from project to project	Highly variable—depends greatly on characteristics of locally available soils
East of repair	Easy to repair with patch placed over problem area	Very difficult to repair; must mobilize heavy earth-moving equipment if large area requires repair
Experience	Limited due to newness	Has been used for many years
Regulatory approval	Not explicitly allowed in most regulations—owner must gain approval on the basis of equivalency in meeting performance objectives	Compacted clay liners are usually required by regulatory agencies

Equation (1) is applicable only for flow through the bentonite component of a GCL; if the GCL contains a geomembrane, water flux will be controlled by water vapor diffusion through the geomembrane component. The geomembrane component, if present, should be considered in the equivalency analysis and in computation of water flux. The simplest way to do this is to adjust the hydraulic conductivity of the GCL to reflect the presence of a geomembrane. (Equation (1) applies to a compacted soil liner (CSL) or GCL liner alone, not to composite liners involving one or more separate geomembrane components.)

The flux ratio for water, F_w, is defined as the flux through the GCL, divided by the flux through the CSL:

$$F_w = \frac{v_{GCL}}{v_{CSL}}, \tag{2}$$

or

$$F_w = \frac{k_{GCL}}{k_{CSL}} \; \frac{T_{CSL}}{T_{GCL}} \; \frac{H+T_{GCL}}{H+T_{CSL}}. \tag{3}$$

If the flux ratio is 1, then the GCL is equivalent to the CSL in terms of steady water flux. For example, for a situation with $H = 0.3$ m and a GCL with $k_{GCL} = 1 \times 10^{-11}$ m/sec, $T_{GCL} = 0.007$ m, and a CSL with $k_{CSL} = 1 \times 10^{-9}$ m/sec and $T_{CSL} = 0.6$ m, then F_w from equation (3) equals 0.3. This means that there would be less water percolation through the GCL than through the CSL; thus, equivalency is established for these conditions.

Alternatively, one can assume that water flux through the GCL is equal to the water flux through a CSL (i.e., $F_w = 1$):

(4)

and compute the required hydraulic conductivity of the GCL by substitution in equation (4):

$$k_{GCL} \frac{H + T_{GCL}}{T_{GCL}} = k_{CSL} \frac{H + T_{CSL}}{T_{CSL}}, \tag{5}$$

Hydraulic Conductivity. In general, the hydraulic conductivity of the bentonite component of GCL varies between about 1×10^{-11} and 1×10^{-8} m/sec, depending on the compressive stress. The higher the compressive stress, the lower the hydraulic conductivity. There are some differences between the hydraulic conductivities of the various GCL but, except for bentonite-geomembrane composite GCL (for which the geomembrane will significantly reduce the overall hydraulic conductivity), the differences do not appear to be very large. The available data on GCL are summarized by Schubert (1987), Daniel and Estornell (1990), Scheu et al. (1990), Daniel (1991), Eith et al. (1991), Shan and Daniel (1991), Estornell and Daniel (1992), Grube (1992), Daniel et al. (1993), and Daniel and Boardman (1993).

For a surface barrier, a confining stress on the order of 10 to 30 kPa is reasonable. Laboratory hydraulic conductivity tests performed on back-pressure-saturated test specimens in flexible-wall permeameters indicate that the hydraulic conductivity of the bentonite component of GCL in this range of compressive stress is approximately 1 to 4×10^{-11} m/sec. Estornell and Daniel (1992) measured the hydraulic conductivity of GCL in large tanks. The tests were specifically set up to simulate conditions of low overburden stress that are typical of surface barriers and to test very large specimens with overlaps. Of the 10 tests for which hydraulic conductivities were measured, the average value was 4.6×10^{-11} m/sec (normal averaging) or 2.2×10^{-11} m/sec (logarithmic averaging). Based on all the data, a reasonable assumption is that a GCL can be supplied with a hydraulic conductivity for a surface barrier application $\leq 1 \times 10^{-11}$ to 5×10^{-11} m/sec.

Studies of the hydraulic properties of overlapped seams performed by Estornell and Daniel (1992) indicate that the overlapped seams in GCL self-seam in the manner described by the manufacturers. For geotextile-encased, needle-punched GCL with additional bentonite along the overlap, the bentonite appears to swell on hydration and plug voids in the geotextiles in the overlap. For the geotextile-encased, adhesive-bonded GCL that have been tested, the bentonite appears to ooze out through the openings in the geotextile and to allow the material to self-seal. For bentonite-geomembrane composite GCL, the bentonite swells on hydration, seals at the bentonite-polyethylene interface, and effects self-seaming at the overlap. Thus, based on the available data, it is reasonable to assume that, with proper quality contr[illegible] the field, seams will self-seal.

Shear Strength. "Internal shear strength" refers to the strength of the material when sheared through the midplane of the bentonite. Published shear strength data are provided in Shan and Daniel (1991) and Daniel et al. (1993).

Dry bentonite is much stronger than water-saturated bentonite. For dry GCL, or slightly damp GCL, the angle of internal friction (even for materials that are not internally reinforced) is approximately 35. For unreinforced GCL, the angle of internal friction drops to about 10 for fully saturated bentonite.

For GCL that are needle-punched or sewn together, the internal reinforcement makes the material's internal shear strength much less sensitive to the strength of the bentonite contained between the attached geotextiles. However, the reader is cautioned that, for surface barriers, the GCL may be exposed to prolonged shearing stresses for periods of years, decades, or even centuries, and that the long-term shearing resistance should be carefully considered.

"Interfacial shear strength" refers to the shearing strength between two adjacent components of a surface barrier. The GCL may be placed against soil, a geomembrane, or a geotextile. Because the range of possible materials at an interface is unlimited, the actual interfacial shearing properties are usually determined on a project-specific basis. It is the author's experience that the internal shear strength will often govern the design because, with proper selection of materials, relatively high interfacial strengths can usually be obtained.

Whether or not shear strength is of concern for a particular surface barrier depends on the slopes and other site-specific details. The designer, however, should carefully consider the implications of shear strength when consideration is given to use of GCL. For many surface barriers on relatively flat ground, shear strength will not be an important concern.

Durability. Shan and Daniel (1991) studied the effects of punctures on a geotextile-encased, adhesive-bonded GCL. The effects of punctures on the hydraulic conductivity of the GCL were studied by drilling or cutting circular holes into the dry GCL, setting the punctured GCL up in flexible-wall permeameters, and permeating the GCL slowly until steady flow was achieved. Small (25-mm-dia) punctures made in the dry material self-sealed on hydration of the bentonite. These tests illustrate the self-healing capability of bentonite.

tions and also in several surface barriers for hazardous materials, radioactive materials, and nonhazardous solid waste.

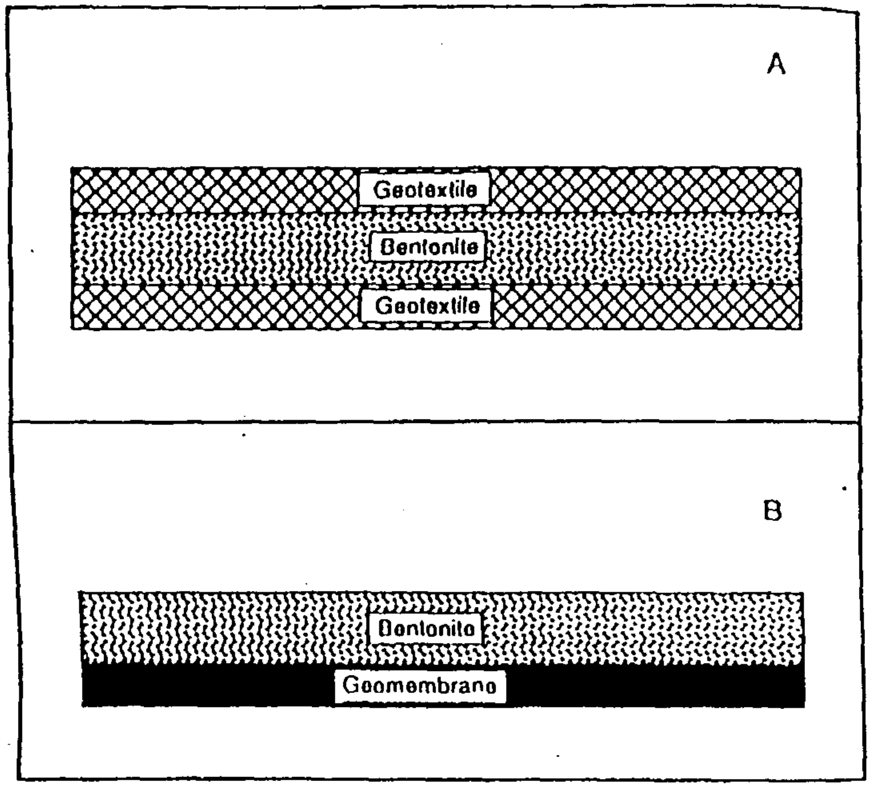


Figure 7. Two basic types of geosynthetic clay liners: A, bentonite sandwiched between two geotextiles; B, bentonite glued to geomembrane.

Four geosynthetic clay liners are currently manufactured in North America: Bentofix*, Bentomat*, Claymax*, and Gundseal*. The GCL fall into the broad categories shown in Figure 7, as follows: bentonite sandwiched between two geotextiles (Bentofix, Bentomat, and Claymax); bentonite mixed with an adhesive and glued to a geomembrane (G[illegible]seal).

The GCL are sketched in Figure 8. Bentofix and Bentomat consist of bentonite sandwiched between a woven and nonwoven geotextile that are needle-punched together. Claymax 200R consists of bentonite mixed with glue and sandwiched between two woven geotextiles. Claymax 500SP consists of bentonite mixed with glue and sandwiched between two woven geotextiles that are sewn together. The purpose of stitching the two geotextiles together is to provide additional internal reinforcement and greater shear strength. Special geotextiles can be selected to "custom design" the GCL to a particular application. Gundseal is made by mixing bentonite with an adhesive and attaching the bentonite layer to a polyethylene geomembrane. Gundseal can be supplied with either HDPE or VLDPE.

Except for shear-strength considerations, the geosynthetics may be considered a "carrier material" for the thin layer of bentonite. If the geosynthetic were to degrade, the hydraulic integrity of the bentonite would not be harmed.

All GCL are manufactured in panels, approximately 4 to 5 m wide and approximately 25 to 60 m long. The panels are placed on rolls at the factory and are unrolled at the time of installation. The mass of the roll varies, depending on size and materials, from about 600 to 2000 kg.

The panels are typically overlapped 75 to 300 mm and are said to be "self-sealing" at the overlaps. A sketch of the overlapped zones is shown in Figure 9. With geotextile-encased, needle-punched GCL, sodium bentonite is placed along the overlap (Figure 9A) at a rate of approximately 0.8 kg/m. The bentonite penetrates the pores of the geotextiles and is said by the manufacturers to cause the materials to self-seam when the bentonite hydrates. With geotextile-encased, adhesive-bonded GCL, no additional bentonite is needed (Figure 9B). The material is said to self-seal upon hydration at the overlaps through expansion of bentonite out through the openings of the geotextile in the overlap area.

With GCL containing a geomembrane, the GCL can be placed with the bentonite facing upward or, as shown in Figures 9C and 9D, downward. If the GCL will be used by itself as a composite geomembrane-clay liner, the geomembrane would face upward. If a separate geomembrane is to be placed on the GCL, the bentonite would face upward. The material is said to be self-sealing at overlaps with no need for any mechanical seam at the o[illegible]p (Figure 9C). However, if one wants [illegible] form a conmay crack. Even in relatively humid regions, occasional droughts can cause cracking in soils to depths in excess of 1 m. The soil tends to swell when wetted, but full "self-healing" is not likely when the compressive stress acting on the soil is low, as in surface barriers (Boynton and Daniel, 1985). Designing CSL at arid sites to resist damage from desiccation is discussed by Daniel and Wu (1993).

Freeze-Thaw. When water freezes, moisture is drawn to the freezing front, which can cause shrinkage cracks from desiccation as well as cracking from the expansion and contraction of the water as it freezes and thaws. Polygonal cracks may form in compacted soils. Examples of damage done by freeze-thaw are given by Kim and Daniel (1992) and Benson and Othman (1993). There is some evidence that soil-bentonite mixtures may not be as vulnerable to damage from freeze-thaw as compacted native soils (Wong and Haug, 1991). In general, however, it is considered prudent to bury a low-permeability, compacted soil liner deep enough to ensure that it is not subjected to freeze-thaw.

Differential Settlement. LaGatta (1992) has summarized available data on the tensile strains that compacted soils can undergo before they fail in tension (i.e., crack) (Table 1). The published data indicate that most compacted soils cannot withstand tensile strains greater than 0.1 to 1.0% without cracking. The question, then, is how likely is it that tensile strains greater than 0.1 to 1.0% will develop in surface barriers?

It is convenient to define *distortion* as the differential settlement, , that occurs over a distance L (Figure 6), or /L. Distortion in a surface barrier stretches the barrier layer and, as a result, tends to produce tensile strains in the components of the barrier. Murphy and Gilbert (1985) computed the relationship between distortion and tensile strain for cover components; the maximum distortion /L associated with a tensile strain of 0.1% to 1% is 0.05 to 0.1.

Jessberger and Stone (1991) performed centrifuge tests on 35- to 45-mm-thick prototype clay liners to be used for surface barriers. A "trap door" beneath the liner was deformed to produce settlement like that expected in a surface barrier. Flow rates through the soil were measured as a function of the distortion in the liner. It was found that the flow rate through the clay remained low until the distortion reached /L = 0.1, at which point the flow rate increased dramatically. Tension cracks were noted in later examinations of the material. Thus, the experiments reported by Jessberger and Stone support the findings from Murphy and Gilbert (1985); i.e., compacted soil liners in surface barriers cannot withstand /L distortions greater than approximately 0.05 to 0.1 without cracking.

TABLE 1. Published data on the tensile strain at failure for clay soils (from LaGatta, 1992).

Reference	Type or Source of Soil	Water Content (%)	Plasticity Index (%)	Tensile Strain at Failure (%)
Tschebotarioff and DePhilippe (1953)	Natural Clayey Soil	19.9	7	0.80
	Bentonite (Montmorillonite)	101	487	3.4
	Illite	31.5	34	0.84
	Kaolinite	37.6	38	0.16
Leonards and Narain (1963)	Portland Dam Portland, CO	16.3	8	0.14
	Rector Creek Dam Napa, CA	19.8	16	0.16
	Woodcrest Dam Riverside, CA	10.2	Nonplastic	0.18
	Shell Oil Dam ' entura, CA	11.2	Nonplastic	0.07
	Willard Test Dam Embankment, UT	16.4	11	0.20

What does this level of distortion mean in practical terms? Suppose that one observes a circular crater with a diameter of 10 m in a surface barrier. What is the maximum settlement at the center of the crater before significant cracking would be expected in a compacted soil liner? The horizontal distance from the edge to center of the crater, L, is 5 m, and 0.05 to 0.1 times L yields a maximum allowable settlement (Δ) of 0.25 to 0.5 m. It is the author's experience that many surface barriers placed over compressible materials undergo this magnitude of distortion or larger. In such cases, it may be pointless to construct an

Erosion Layer. The erosion layer is typically used to support growth of vegetation. The EPA recommends that the universal soil loss equation be used to estimate rates of water erosion from the surface barrier; for wind erosion, they recommend an alternative equation (USEPA, 1993). No specific guidance is provided on allowable rates of soil loss. The soil should be selected to provide a good growth medium for surface vegetation. Loamy soils with adequate organic content are generally preferred.

A vegetative cover is recommended for MSWLF. Locally adapted perennial plants that are resistant to drought and temperature extremes are recommended. Roots should not disrupt the underlying low-permeability layer. The use of deep-rooted plants and shrubs is not recommended. Careful timing of seeding is critical to germination in most climates.

The main criticism of the author for the EPA's recommendations concerning the erosion layer is the recommended minimum thickness of 150 mm. Field experience has shown that native grasses have roots that typically extend to greater depths, and rill erosion commonly occurs to local depths >150 mm. In the author's experience, 150 mm is not nearly thick enough for the erosion layer; a minimum thickness of 450 to 600 mm would be much more appropriate.

Infiltration Layer. The infiltration layer must be at least 450 mm thick and should consist of earthen material that has a hydraulic conductivity less than or equal to the hydraulic conductivity of any bottom liner system or natural subsoils. If there is no bottom liner, or if the bottom liner is of poor quality, the infiltration layer must have a hydraulic conductivity 1 × 10' m/sec. No explanation of or justification for the latter value is provided in EPA's background document (USEPA, 1993). If the bottom liner contains a geomembrane, the infiltration layer must also contain a geomembrane. The surface of the infiltration layer should be sloped at an inclination of at least 3% but no more than 5%, after allowance for settlement. The EPA recommends the computer program HELP (Hydrologic Evaluation of Landfill Performance) for evaluating alternative designs (USEPA, 1993).

In some respects, the rules are confusing and appear to be conflicting. For instance, the rules explicitly state that the infiltration layer must have a permeability that is no greater than that of any bottom liner. If the [illegible]om liner consists of a geomembrane overlying [illegible] mm of low-permeability compacted soil with a saturated hydraulic conductivity ≤1 × 10' m/sec (the standard bottom liner system for MSWLF regulated under subtitle D of RCRA), it would seem that the surface barrier should also have a soil component with a saturated hydraulic conductivity 1 × 10' m/sec. However, the guidance document specifically states that for such a bottom liner system, the infiltration layer need consist only of a geomembrane overlying 450 mm of soil with a hydraulic conductivity ≤1 × 10' m/sec. It is not clear what the rationale is for allowing soil with a hydraulic conductivity 1 × 10' m/sec in the surface barrier when the soil component of a bottom liner has a hydraulic conductivity ≤1 × 10' m/sec. The EPA's recommendation has been strongly criticized (Austin, 1992).

The earthen material used for the infiltration layer should be free of rocks, clods, debris, rubble, roots, and other materials that may increase the hydraulic conductivity of this layer. Problems with frost action and desiccation are mentioned in USEPA (1993), but no requirements are stated for burial of the layer below the depth of frost penetration or seasonal moisture change.

If a geomembrane is used as an infiltration layer, the geomembrane should be at least 0.5 mm thick, or thicker, if necessary, for welding (e.g., a minimum thickness of 1.5 mm is recommended for high-density polyethylene in order to produce high-quality seams).

Alternative Layers. The director of the applicable state regulatory agency in an EPA-approved state may approve alternative surface barriers, provided its performance is equivalent to the EPA criteria in terms of minimizing infiltration and erosion. No specific examples are provided in the background document (USEPA, 1993), other than to repeat much of what EPA has already stated about surface barriers for hazardous-waste disposal facilities.

Criticisms. The EPA's rules for MSWLF went into effect on October 9, 1993. The new regulations have been criticized by some as being insufficiently stringent. In a summary article by Austin (1992), many of these criticisms are listed and explained. A 150-mm-thick erosion layer is consider inadequate for many sites over the long term by one expert. Several experts note that the requirement of 1 × 10' m/sec is far below what is technologically achievable and they are at a loss to justify this value. Offi[illegible] from EPA note that the regulations were written

If there is potential for particles from the overlying layer to clog the drainage layer, a filter should separate them. The filter may be soil or a geotextile; design criteria are given by USEPA (1989).

If the drainage material is a geosynthetic (e.g., geonet, geocomposite, or geotextile), the geosynthetic drainage material should provide an in-plane transmissivity that is equivalent to or better than the transmissivity provided by 300 mm of soil having a hydraulic conductivity ≥1 × 10^{-4} m/sec.

Low-Permeability Layer. The surface barrier is required to provide long-term minimization of the migration of liquids through the surface barrier. Also, the cover over a waste-disposal unit is required to have a permeability less than or equal to the permeability of the bottom liner system or natural subsoils present. The EPA recommends a geomembrane/soil composite liner that is similar in concept, but not necessarily identical in materials, to a typical composite bottom liner. The two components (geomembrane and low-permeability soil layer) are considered to function together as one system. The geomembrane stops the movement of nearly all liquid through it, except for liquid that diffuses through the geomembrane (usually considered to be a trivial amount) and liquid that migrates through any defects in the geomembrane (including pinholes but, primarily, tiny imperfections in welded seams). The primary purpose of the low-permeability soil component is to minimize leakage through any imperfections in the geomembrane or its seams. The EPA believes that the recommended composite barrier is the best one practicable, in most cases, to minimize percolation of water through the surface barrier. The geomembrane and low-permeability soil components are thought to complement each other so that the long-term effectiveness of the two components together is better than each alone.

The EPA recommends that the low-permeability layer be located below the maximum depth of frost penetration. They also recommend that the geomembrane be at least 0.5 mm thick, that it should be placed without surface unevenness (to facilitate drainage of water in the overlying layer), and that the geomembrane should be in direct contact with a smoothed surface on the underlying low-permeability soil layer. Also, penetrations through the geomembrane should be minimized.

When the EPA originally began recommending composite geomembrane/soil barriers for waste containment units in the early 1980s, th

considered the geomembrane to be a relatively short-lived component. They believed that the low-permeability soil would provide for long-term minimization of flow through the composite barrier. However, with increasing knowledge of the characteristics of geomembranes, and development of relatively stable and long-lived polymers (such as high-density polyethylene), the EPA believes that geomembranes can provide long-term containment. (The life of geomembranes is discussed later in this paper.)

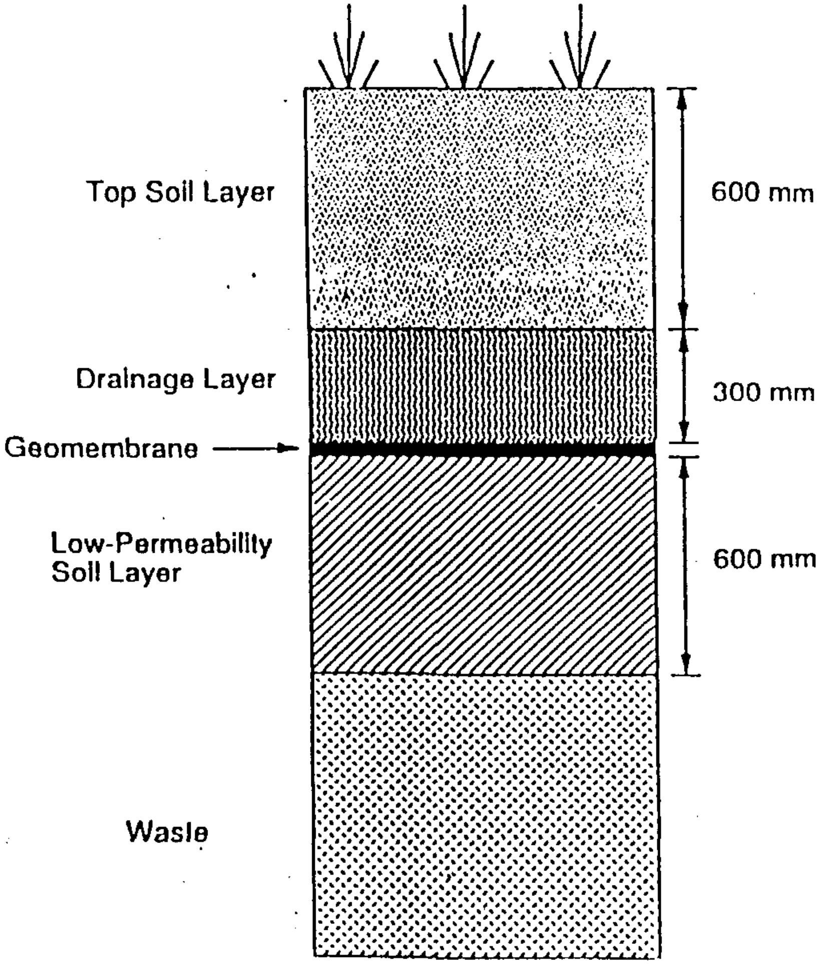
The EPA recommends that the low-permeability soil component consist of a minimum of 600 mm of compacted, low-permeability soil with an in-place saturated hydraulic conductivity of 1 × 10^{-9} m/sec or less. The soil must be free of large clods, large rocks or stones, rubbish, roots, or other materials that would tend to provide preferential flow paths or puncture the overlying geomembrane.

A written construction quality assurance (CQA) plan is recommended for both the geomembrane and low-permeability soil. Experience has shown that most leaks in geomembranes are the result of inadequate construction quality control (CQC) or CQA. It is for this reason that EPA places strong emphasis on CQA (e.g., USEPA, 1989; Daniel and Koerner, 1993). The EPA recommends construction of a test fill prior to actual construction of the low-permeability soil component of a surface barrier (USEPA, 1989). The purpose of the test fill is to verify that the soil can be constructed to an in-place saturated hydraulic conductivity that is no greater than 1 × 10^{-9} m/sec. The EPA believes that the construction of a test fill utilizing the soil, equipment, and procedures to be used in construction of the low-permeability layer will ensure that design specifications are attainable with the available materials and equipment. (The test fill need not be constructed on the contaminated site.)

Gas Vent Layer. The function of a gas vent layer (Figure 4) is to control combustible or toxic gases released from buried wastes or other contaminated materials. For a hazardous-waste landfill, the facilities that are likely to require a gas vent layer are codisposal facilities that receive organic waste material, such as that found in municipal waste, which produces gas upon decomposition, in addition to hazardous waste. However, certain volatile chemicals may also be of concern.

The EPA recommends that the gas vent layer be at least 300 mm thick and that it be located between the barrier layer and the waste.

1989). The usual cover design recommended (Figure 3) is commonly used both for design of new, hazardous-waste disposal facilities and for covers over remediation projects regulated under EPA's Superfund program. It incorporates a top layer (which doubles as the surface layer and protection layer), a drainage layer, and a geomembrane/soil composite liner. There is no mention of a gas collection layer or foundation layer in this design. An alternative design recommended by EPA (Figure 4) includes cobbles at the surface, a biotic barrier, and a gas collection layer.



Figur Recommended surface barrier for hazardous-waste d al facility (after USEI 89).

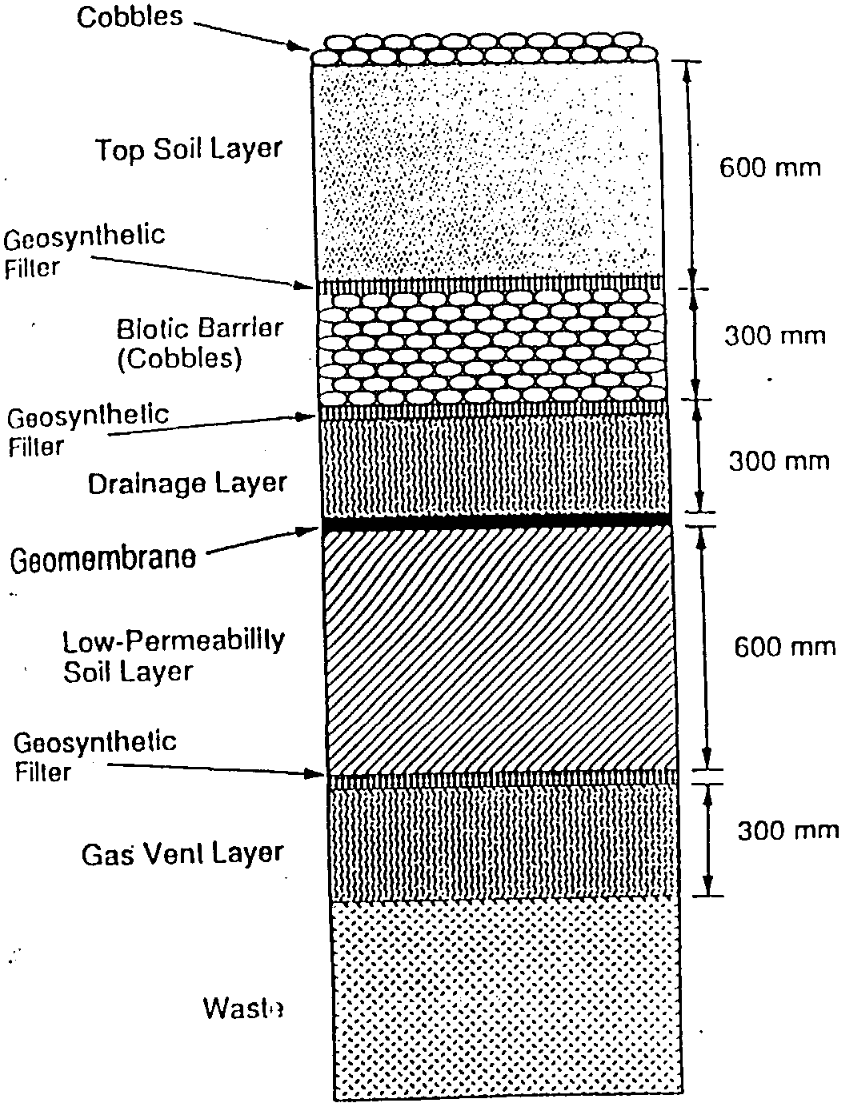


Figure 4. Alternative recommended surface barrier for hazardous-waste disposal facility (after USEPA, 1989).

biointrusion protection layer primarily for radioactive waste-disposal sites, but not for other types of sites. This is because uptake of dangerous compounds by plant roots and burrowing animals is a problem primarily with radioactive materials.

If the protection layer is placed directly on a barrier layer, a plane of potential seepage exists at the interface. The risk of instability is particularly acute following prolonged periods of heavy rain if no drainage layer is provided beneath the protective layer. The engineer must ensure an adequate factor of safety against slippage at this and all other interfaces in the surface barrier. If the originally designed surface barrier does not have an adequate factor of safety, several steps may be taken to increase it. These include: (1) use of different materials (stronger soils, or materials such as textured geomembranes with higher strength along the interface); (2) addition of a drainage layer; (3) flattening of slopes; or (4) reinforcement of cover soils with geogrids or high-strength geotextiles.

Drainage Layer

A drainage layer is sometimes placed below the protective layer and above the barrier layer (Figure 1). There are three reasons why a drainage layer might be desirable: (1) to reduce the head of water on the barrier layer, which minimizes infiltration; (2) to drain the overlying protection layer, which increases the water-storage capacity of the protection layer; (3) to reduce pore water pressures in the cover soils, improving slope stability.

Materials typically used for drainage layers are:

- sand or gravel with either a soil filter or a geotextile filter;
- a thick geotextile, which serves as both a drain and a filter;
- a geonet, with a geotextile filter/separator;
- a geocomposite drain, consisting of a polymeric drainage core and an overlapping geotextile filter/separator.

Selection of material type is usually based on economics and design life. All the materials listed above will work reasonably well in the short term. [illegible] covers with limited design lives (e.g., <30 yr), all these materials are considered technically adequate, and the final selection is

often based on economics. Thin, geosynthetic materials will usually prove the most economical; however, the design life of geosynthetic materials is limited, and the greater the surface area per unit mass, the shorter the life of a geosynthetic. Thus, geotextiles, which have a relatively large ratio of surface area to unit mass, will not last as long as geomembranes, which have a much lower ratio of surface area to mass. For covers with design lives of more than a few decades, natural mineral materials (i.e., sand or gravel) would almost always be used for the drainage material.

Caution is especially urged about two details. First, water must discharge freely from the drainage layer at the base of the surface barrier (Figure 2). If the outlet plugs or is of inadequate capacity, the toe of the slope will become saturated, developing excess pore water pressure, and may become unstable. Drainage pipes that commonly surround a site at its low elevations must have adequate capacity and cannot be allowed to plug. Similarly, for surface barriers that are expected to last indefinitely, a drainage pipe is probably not a viable design element since it can deteriorate or plug.

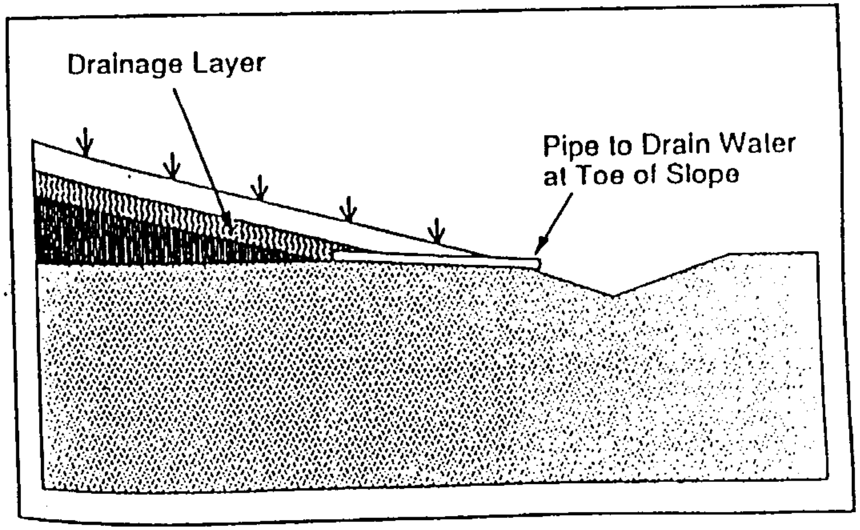


Figure 2. Drainage outlet at edge of surface barrier.

INTRODUCTION

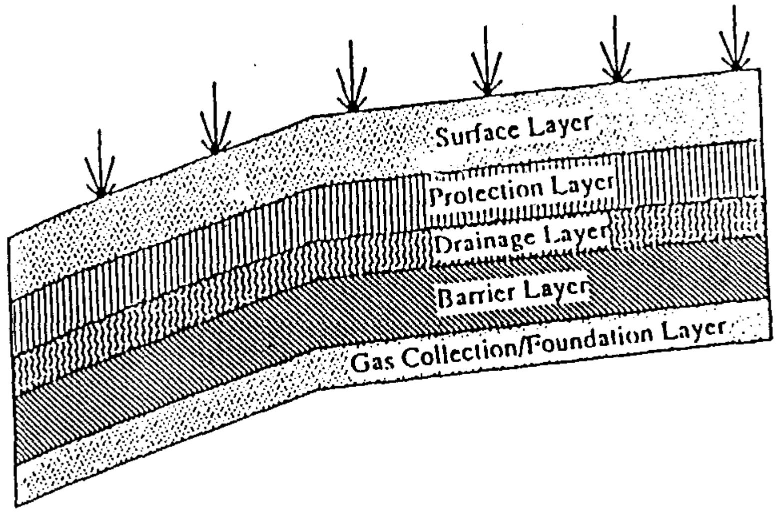
Surface barriers are a critical component in management of liquid and gas movement into and out of contaminated soils, buried wastes, and other sources of subsurface contamination. The main functions of a surface barrier are to separate the contaminated material from the surface environment, to restrict infiltration of water into the contaminated materials, and (in some cases) to control release of gas from the contaminated material. If the objective is prevention of pollution to ground water, then one of the obvious strategies is to try to minimize the amount of liquid available to leach or transport subsurface pollutants. If there is no leachate, there is little or minimal potential for pollution of ground water.

In succeeding sections, the basic components of an engineered surface barrier will be identified; U.S. Environmental Protection Agency (USEPA) regulations concerning surface barriers will be described; and materials that are often employed will be discussed in detail. Also, case histories will be reviewed, and recommendations will be presented for resolving the critical technical issues that limit the use of surface barriers and that require further research and development.

SURFACE BARRIERS

Most engineered surface barriers in the United States are composed of multiple components. As shown in Figure 1, the components of a surface barrier can be grouped into five categories: (1) surface layer, (2) protection layer, (3) drainage layer, (4) barrier layer, and (5) gas collection or foundation layer. Not all components are needed for all surface barriers. For example, a drainage layer might not be needed for a surface barrier located in an arid region. Similarly, a gas collection layer may be required for some surface barriers but not others. Furthermore, some layers may be combined—for instance, the surface layer and protection layer may be combined into a single layer of soil that forms the upper part of the surface barrier.

The materials typically used for an engineered surface barrier are also shown in Figure 1. They include natural earth materials, geosynthetics, and other materials, for example, asphalt.



Layer	Description of Layer	Typical Materials
1	Surface Layer	Topsoil; Geosynthetic Erosion Control Layer; Cobbles; Gravel Admix
2	Protection Layer	Soil; Recycled or Reused Waste Material; Cobbles
3	Drainage Layer	Sand or Gravel; Geonet or Geocomposite
4	Barrier Layer	Compacted Clay; Geomembrane; Geosynthetic Clay Liner; Waste Material; Asphalt
5	Gas Collection Layer and/or Foundation Layer	Sand or Gravel; Soil; Geonet or Geotextile; Recycled or Reused Waste Material

Figure 1. Five possible components of engineered surface barrier.

Surface Layer

The material that is by far most commonly used for the surface layer is soil. Soils have the advantages of local availability and providing a

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Khire et al. (1994b) was easier to construct and less costly than the prescriptive resistive barrier.

Sufficient data regarding the performance of monolayer barriers have not yet been gathered. Nevertheless, the study by Geologic Associates (1993) suggests that *monolayer barriers may be effective in some regions.* Field tests including large-scale measurements of percolation are needed before definitive conclusions regarding monolayer barriers can be drawn.

Capillary Barriers: Hydraulic Conductivity of the Surface Layer

Capillary barriers perform better if the saturated hydraulic conductivity of the surface layer is lower. Nyhan et al. (1993) report that percolation from a capillary barrier constructed with a clay-loam surface layer had 11 times less percolation than an identical capillary barrier constructed with a loam surface layer. The capillary barrier constructed with a clay-loam surface layer also shed more water as overland flow.

Capillary Barriers: Storage Capacity of the Surface Layer

The surface layer of a capillary barrier must be designed to have adequate storage capacity such that significant flow into the coarse-grained layer does not occur. This is particularly important in regions where snow accumulates, because large pulses of percolation can occur if the surface layer has inadequate capacity to store water that infiltrates during snow melt (Wing and Gee 1994, Khire et al. 1994a,b). In regions where snow accumulates, the critical storage capacity should be defined using the storage capacity required in the spring when snow melt occurs. Thus, the design year for regions where snow accumulates should correspond to the year with maximum snow accumulation.

Desiccation Cracking and Biota Intrusion

The surface layer of a capillary barrier must not crack or the effectiveness of the barrier will be compromised. Thus, caution must be exercised when selecting soils for the surface layer. Suitable soils are likely to be clayey silts, silty sands, and some sandy clays. Clay-rich soils should be avoided if possible, because clays shrink and crack when dried (Montgomery and Parsons 1990). If clays are used, they should be placed at low water contents to minimize desiccation cracking (Kleppe and Olson 1984, Daniel and Wu 1993). Furthermore, *if significant potential exists for the surface layer to shrink and crack on drying, then a three layer capillary* barrier may prove to be a more effective alternative (Yeh et al. 1994).

Barriers constructed with thick layers of fine-grained soil must be protected from intrusion by biota. Burrows or tunnels created by animals or deep root holes can become preferential flow paths (Khire et al. 1994b). Thus, biota barriers should be included in any design where preferential flow through a fine-grained layer will compromise performance of the cover.

Vegetation

Field data show that test sections designed to yield greater evapotranspiration do not necessarily perform as intended (Montgomery and Parsons 1990, Hakonson et al. 1994). Furthermore, dense vegetation or species that are not native can be difficult to sustain on capillary barriers (Khire et al 1994a,b). Thus, designers should be cautious regarding the benefits that can actually be accrued through enhanced vegetation.

SUMMARY

Field data from several sites have confirmed that earthen final covers designed as capillary barriers can be effective final covers in semi-arid and arid regions. In some cases, where the soils needed for construction are available on site, earthen covers of this type can be less costly than prescriptive covers designed as *resistive barriers. Less data are available regarding monolayer barriers, but some of* the data collected to date suggest that these covers may also be effective. More data must be collected, however, before a definitive conclusion can be drawn.

The field data also indicate that several factors have a strong influence on the performance of alternative earthen covers. For capillary barriers, these factors include saturated hydraulic conductivity and storage capacity of the fine-grained layer, lateral diversion capacity, and resistance to desiccation cracking. Desiccation cracking is also an issue with monolayer barriers, as are preferential pathways created by intrusion of biota. Finally, the field data also suggest that additional *evapotranspiration expected due to enhanced vegetation may not be realized.* Considering these factors during design will likely result in an earthen barrier that is more likely to perform as expected.

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(300 mm thick), and a layer of clay loam amended with bentonite (600 mm thick). The saturated hydraulic conductivity of the loam-bentonite layer was 3.4 x 10^{-8} m/s. The test sections designed as capillary barriers had the same layering, except one was seeded with grass, whereas the other was seeded with grass and shrubs to enhance evapotranspiration. Both capillary barriers had 1500 mm of sandy loam topsoil over 300 mm of washed gravel (~ 10 mm diameter). A non-woven geotextile was placed between the layers to limit migration of sand and fines into the gravel so that a sharp capillary interface could be preserved. A thin gravel cover was placed on each capillary barrier test section to reduce erosion.

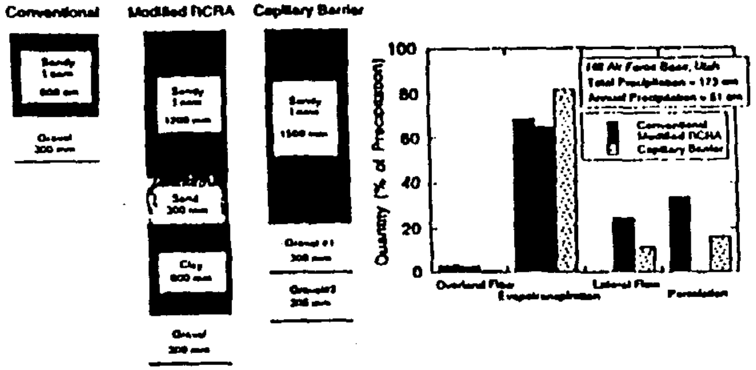

Fig. 9 Test Sections and Water Balance Data from Hankonson et al. (1994)

The test sections were studied for 46 months, during which 1730 mm of precipitation (28% snow) was received. The long-term average precipitation is 510 mm/yr. A summary of the data is shown in Fig. 9. Percolation from the modified-RCRA prescriptive cover was the least (0.006% of precipitation), whereas percolation from the conventional prescriptive cover was greatest (24% of precipitation). Both capillary barriers produced percolation that was approximately 15% of the precipitation. Percolation from the capillary barriers was large because snow accumulated on the test sections, which overwhelmed their capacity for storage and diversion.

The greatest overland flow was obtained for the conventional cover (3.4% of precipitation), whereas the least was obtained for the capillary barrier with grass (0.8% of precipitation). Overland flow for the capillary barrier with grass and shrubs was 1.3% of precipitation, and for the RCRA design it was 5.5% of precipitation.

Evapotranspiration was largest for the capillary barrier with grass (84% of precipitation) and smallest for the RCRA design (65% of precipitation). Surprisingly, the shrubs added to the capillary barrier had no beneficial influence on evapotranspiration (83% of precipitation).

Lateral flow was greatest for the RCRA design (25% of precipitation). No lateral flow was recorded for the conventional prescriptive cover. Lateral flow also occurred in the capillary barriers, being 11% for the cover vegetated only with grass only and 7% for the cover vegetated with grass and shrubs. However, Hakonson et al. (1994) do not describe through which layers lateral flow occurred.

Khire et al. (1994b)

Khire et al. (1994b) describe the water balance of two final cover test sections (resistive and capillary barriers) constructed adjacent to each other in a semi-arid climate (East Wenatchee, Washington; annual precipitation = 230 mm). The two test sections (Fig. 10a) are 30 m x 30 m in areal extent and are located on a landfill side slope. The prescriptive resistive barrier is constructed with a compacted silty clay barrier 600 mm thick and a silty clay surface layer 150 mm thick. The capillary barrier has a sand layer 750 mm thick overlain by a surface layer of silt 150 mm thick. The capillary barrier was constructed without a geotextile separator between the fine- and coarse-grained layers. Examination of the interface between the layers has shown, however, that a distinct interface exists. Benson et al. (1994) provide a detailed description of how the test sections were constucted and instrumented.

Khire et al. (1994b) report that the capillary barrier has been more effective than the resistive barrier in restricting percolation (Fig. 10b). Percolation from the capillary barrier has been 0.6% of precipitation, whereas percolation from the resistive barrier has been 4.4% of precipitation. Overland flow and *evapotranspiration from both test sections have been similar, being 15% and 65% of* precipitation, respectively.

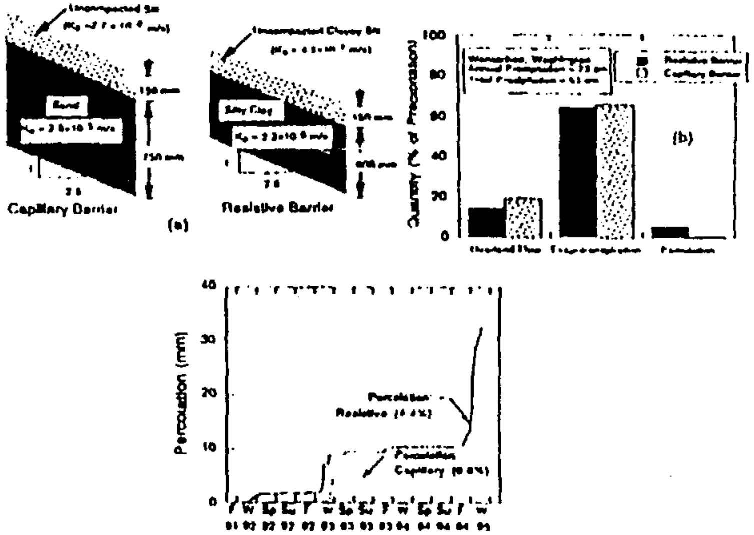

Fig. 10 Test Sections (a), Water Balance (b), and Cumulative Percolation (c) from Khire et al. (1994)

Khire et al. (1994b) report findings regarding snow accumulation similar to those by *Wing and Gee (1994); that is, the capillary barrier can be ineffective when* snow accumulates on the cover and the subsequent melt overwhelms the storage and diversion capacity of the fine-grained layer. For example, approximately the same amount of precipitation was recorded during the winters of 1992-93 and 1993-94. However, in 1992-93, 1.68m of snow accumulated on the test sections. When the *snow melted in late February 1993, the fine grained layer became saturated and rapid*

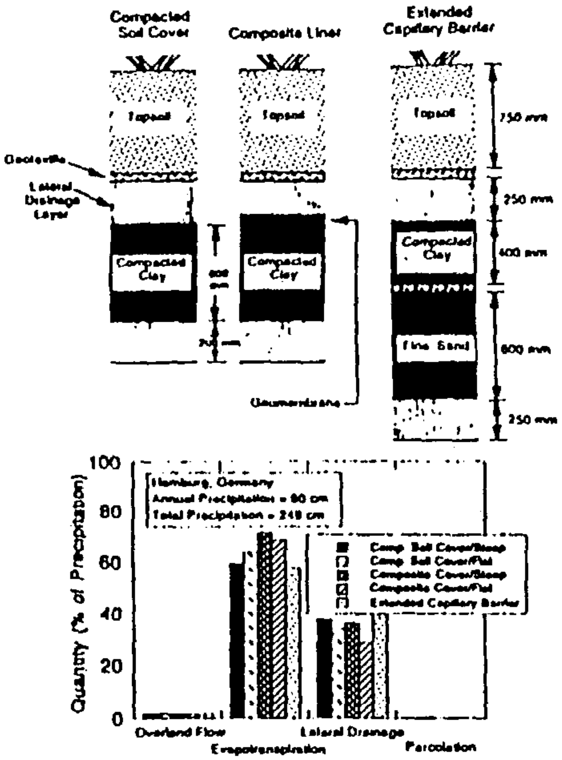

Fig. 5. Water Balance Data from Melchoir et al. (1994)

Data were collected for 4 years. Lysimeters were used for measuring percolation, diversion berms were used for collecting overland flow, and water contents were measured with neutron probes. Meteorologic data consisted of rain, air temperature, and relative humidity. A summary of the data is contained in Fig. 6.

Percolation observed from the two resistive barriers was similar, although slightly more percolation emanated from the resistive barrier with a thicker topsoil layer (4.8% of precipitation, compared to 3.6%). Apparently, the additional evapotranspiration expected from the thicker topsoil layer was not realized. The capillary barrier also did not perform as designed. The upper clay layer became extensively cracked and allowed rapid infiltration of water into the sand layer; however, the sand layer removed a large fraction of the infiltrating water via lateral flow. The lower clay layer remained intact and percolation through it continued at a relatively steady rate (4.6% of precipitation).

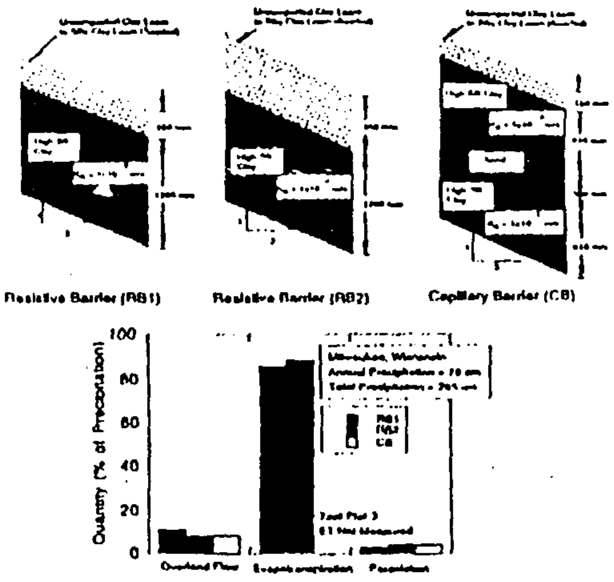

Fig. 6. Test Sections and Water Balance Data from Montgomery and Parsons (1990)

Nyhan et al. (1990)

Nyhan et al. (1990) compared the hydrology of a prescriptive cover to that of an alternative capillary barrier at a site in Los Alamos, New Mexico. Two test sections 3 m x 10.7 m in plan view were constructed. The test section simulating a prescriptive cover consisted of a 200-mm-thick surface layer comprised of sandy loam underlain by 1080 mm of crushed tuff backfill. The capillary barrier consisted of 710-mm-thick surface layer of sandy loam underlain by 460 mm of gravel (5-10 mm diameter). The gravel was underlain by a 910-mm-thick biota barrier consisting of cobbles. Crushed tuff backfill was placed below the biota barrier.

The data indicate that the alternative capillary barrier was more effective in limiting percolation than the prescriptive cover (Fig. 7); percolation produced by the prescriptive cover was four times higher than percolation from the capillary barrier. Furthermore, evapotranspiration from the capillary barrier (96% of precipitation) was larger than evapotranspiration from the prescriptive cover (88% of precipitation). It was also observed that plant species different from those originally seeded eventually covered the test sections.

Nyhan et al. (1993)

Nyhan et al. (1993) studied the water balance of four landfill cover test sections constructed at Los Alamos National Laboratory. The test sections consisted of the following cover designs: conventional prescriptive cover, EPA-recommended prescriptive cover, loam capillary barrier, and a clay-loam capillary barrier (Fig. 8).

studies that have been conducted to evaluate the performance of alternative covers. Some, but not all of the studies have been conducted in semi-arid or arid climates. However, from each study lessons can be learned that can be applied when considering, designing, or evaluating an alternative cover for a semi-arid or arid environment.

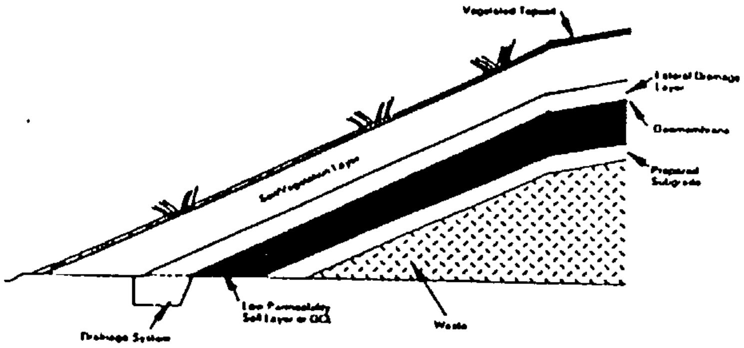

Fig. 1 Prescriptive Final Cover.

WATER BALANCE OF EARTHEN COVERS

Alternative earthen covers generally exploit the unique characteristics of unsaturated flow, the storage capacity of fine-grained soils, and the natural capacity of plants to remove water entering the cover during wet periods. These factors are linked by the water balance, which accounts for movement of water into, within, and out of a final cover. The water balance consists of precipitation (P) in the form of snow, rain, or ice; overland flow (O); soil water storage (S); evaporation from the surface (E); transpiration by vegetation (T); lateral drainage (L); and percolation from the base (P_r) (Fig. 2). In some cases, evaporation and transpiration are combined as evapotranspiration (E_t).

In algebraic form, the water balance can be described by the following equation:

$$P_r = P - O - S - E - T - L \qquad (1)$$

The form of Eq. 1 indicates that percolation can be minimized by enhancing overland flow, soil water storage, evaporation, transpiration, or lateral drainage. Of these factors, soil water storage and lateral drainage are easier to optimize during design. For example, soil water storage can be increased by selecting surficial soils containing a greater percentage of fines or by increasing the thickness of the cover, whereas lateral drainage can be increased by adding a wicking layer (Yeh et al. 1994) or employing a layer with anisotropic hydraulic conductivity (Stormont 1995). Evaporation can be enhanced by selecting soils having unsaturated hydraulic conductivity (K_ψ) that changes gradually with matric suction (ψ) (Khire et al. 1995). Fine-grained soils typically have this type of unsaturated hydraulic conductivity function (Hillel 1980, Meerdink 1994). Transpiration can be enhanced by careful selection of vegetation and manipulating the extent and density of the plant canopy (Rockhold et al. 1995)

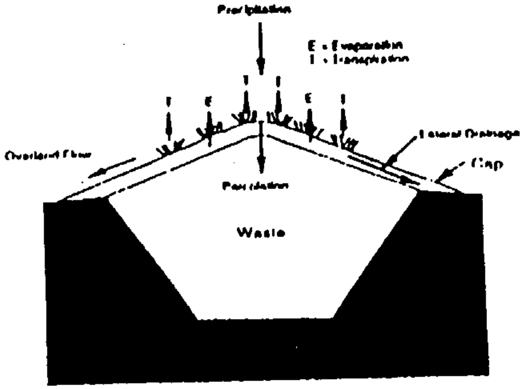

Fig. 2. Water Balance of Landfill Final Cover.

Design of an alternative earthen cover for a semi-arid or arid environment entails manipulating soil water storage capacity, lateral drainage, transpiration, and evaporation such that an acceptable value for percolation occurs in a worst case design year (e.g., year where rainfall or snowfall is abnormally high and temperature and solar radiation are abnormally low). In particular, the cover is designed such that it has adequate capacity to store or divert water that infiltrates during late fall and winter and sufficient vegetation and evaporative potential to remove the stored water during spring, summer, and early fall. Two types of earthen covers that are designed on this principle are capillary barriers and monolayer soil barriers. In some cases, these barriers are used in conjunction with a resistive barrier.

Capillary Barriers

In their simplest form, capillary barriers employ a fine-grained layer over a coarse-grained layer (Fig. 3a). Flow across the interface of these layers is restricted under unsaturated conditions because the unsaturated hydraulic conductivity of the coarse-grained layer is much lower than the unsaturated hydraulic conductivity of the fine-grained layer (Fig. 3b) (Hillel 1980). Thus, the fine-grained soil can store or divert water that infiltrates into the cover, and yet flow into the coarse-grained layer is restricted. More elaborate designs employing multiple layers having contrasting grain size are also possible. These covers employ the capillary barrier principle to divert infiltrating water via lateral flow while ensuring that deep percolation does not occur (Nyhan et al. 1993, Yeh et al. 1994).