Department of Energy
Office of Legacy Management

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Washington, D.C. 20555-0001

Mr. Tom Stoops
Oregon Department of Energy
625 Marion Street
Salem, OR 97301

Dear Mr. Fliegel and Mr. Stoops:

Subject: Water Fluxmeter Pilot Study Status Report

In 2005, the U.S. Department of Energy Office of Legacy Management (DOE-LM) began a pilot study at the Lakeview, Oregon, disposal site to monitor percolation flux through the disposal cell cover.

The enclosed status report provides summaries of (1) background information on the Lakeview disposal site, (2) previous investigations of root intrusion and the permeability of the disposal cell cover, (3) installation methods for water fluxmeters, and (4) the results of percolation flux monitoring and soil moisture monitoring from November 2005 to September 2008. Percolation rates remained high during the 3-year monitoring period but varied some from one year to the next, apparently in response to changes in precipitation patterns, changes in sensor performance, and perhaps to changes in soil permeability. During 2008, one fluxmeter began producing unreliable data and another ceased operating altogether. Tailings moisture content beneath the side slope of the disposal cell remained at or near saturation for the entire 3-year monitoring period.

Please contact me at 970-261-6780 or Ms. Ann Houska at 970-248-6579 if you have questions.

Sincerely,

Jalena Dayvault
Site Manager

Enclosure

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REPLY TO: Grand Junction Office		

LMS/LKD/S04718

Demonstration of Water Fluxmeters at the Lakeview, Oregon, Disposal Site

November 2008

U.S. DEPARTMENT OF ENERGY | Office of Legacy Management

LMS/LKD/S04718

Demonstration of Water Fluxmeters at the Lakeview, Oregon, Disposal Site

Fiscal Year 2008 Progress Report

November 2008

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Acronyms

AEPs	air-entry permeameters
AETL	automatic equilibrium tension lysimeter
CFR	*Code of Federal Regulations*
cm	centimeters
cm/s^{-1}	centimeters per second
CSL	compacted soil layer
DOE	U.S. Department of Energy
ft	foot (feet)
g	gram(s)
HDUs	heat dissipation units
LCEs	leachate collection efficiencies
LM	Legacy Management
LTSM	long-term surveillance and maintenance
LTSP	long-term surveillance plan
m	meter(s)
mL	milliliter(s)
mm	millimeter(s)
NRC	Nuclear Regulatory Commission
PMP	probable maximum precipitation
POC	point of compliance
RRM	residual radioactive material
UMTRCA	Uranium Mill Tailings Radiation Control Act
WCR	water content reflectometer
WFM	water fluxmeter

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Executive Summary

The U.S. Department of Energy (DOE) Office of Legacy Management (LM) is evaluating new technologies for monitoring the performance of disposal cell covers at LM sites and exploring ways to enhance their sustainability. The current monitoring strategy for disposal cells, as specified in long-term surveillance plans, is to periodically sample downgradient groundwater as an indicator of hydrologic performance of the upgradient disposal cell. This retrospective strategy does not provide the early warning necessary to implement corrective actions. Alternatively, directly monitoring and modeling the disposal cell cover could provide an early warning, so that corrective actions could be implemented to protect groundwater.

In 2005, DOE began a pilot study at the LM Lakeview, Oregon, disposal cell to test a new device, a soil water fluxmeter (WFM), that can be used to directly monitor percolation flux through disposal cell covers. This report provides summaries of (1) background information on the Lakeview Disposal Site, (2) previous investigations of root intrusion and permeability of the disposal cell cover, (3) the installation of WFMs, and (4) the results of soil moisture and percolation monitoring from 2005 to 2008.

DOE constructed the Lakeview disposal cell in 1989 under the Uranium Mill Tailings Radiation Control Act of 1978. The cover relies on a compacted soil layer (CSL) to limit radon escape from and water percolation into underlying tailings. From bottom to top, the cover profile consists of a 45-centimeter (cm) CSL, a 15-cm sand drainage layer, and a 30-cm rock-and-soil layer. Shortly after construction, inspectors observed recruitment of native shrubs on the cover from surrounding plant communities. Follow-up investigations determined that mature shrubs growing on the cover were rooted in the CSL, which was a concern because water extraction by roots can desiccate and crack CSLs even when overlying soils are wet.

In 1997 and 1998, air-entry permeameters (AEPs) were used to measure saturated hydraulic conductivity (K_{sat}) in the Lakeview CSL. The mean K_{sat} for 17 AEP tests was 3.0×10^{-5} cm per second (cm/s), 300 times greater than the design target. The highest K_{sat} values were measured near the top of the CSL at locations both with and without roots; the lowest K_{sat} values were measured deeper in the CSL. These results are consistent with findings at other sites. Multiple lines of evidence show that many existing CSLs fall short of low-permeability targets, often soon after construction, and sometimes by several orders of magnitude.

In fall 2005, LM began a pilot study of WFMs. Three WFMs, installed in holes augered through the top slope of the cover and into tailings, capture percolation just below the CSL. Monitoring results in both 2006, a wet year, and 2007, a dry year, show significant percolation through the cover, primarily during winter and spring months. Percolation flux rates remained high in 2008, but patterns were more erratic. The exceptionally high percolation values are likely a consequence of the intentional placement of WFMs in downslope locations where water accumulates in the sand drainage layer.

Patterns of percolation rates changed from one year to the next, apparently in response to precipitation patterns, but also in response to WFM sensor performance and perhaps in response to changes in soil permeability. During the wet 2006 bioclimatic year, percolation rates for all three WFMs peaked in November and December and then tapered off gradually in response to

several wet months followed by several dry months. During the drier 2007 bioclimatic year, percolation rates for two WFMs tended to fluctuate in response to less consistent precipitation events. In contrast, in the third WFM, percolation peaked abruptly early in the wet season and then dropped to zero in early spring. Field checks in the fall of 2007 and again in the spring of 2008 revealed that this third WFM had stopped functioning. Precipitation events during the 2008 bioclimatic year were again somewhat erratic, but the remaining two functioning WFMs responded differently. Percolation rates measured in one of the two remained low but continuous, whereas percolation rates in the other fluctuated greatly in response to precipitation events, suggesting a higher soil permeability.

1.0 Introduction

The primary mission of the U.S. Department of Energy (DOE) Office of Legacy Management (LM) is to protect human health and the environment through effective and efficient long-term surveillance and maintenance (www.lm.doe.gov). Engineered disposal cells, the selected remedy for residual contaminants at many LM sites, were designed in part to limit the percolation of water into interred waste. The current monitoring strategy for disposal cells, as specified in long-term surveillance plans (LTSPs), is to periodically sample downgradient groundwater as an indicator of performance (DOE 2000). This strategy does not provide the early warning necessary to implement corrective actions, such as repairing or renovating covers, and could result in significant increases in long-term surveillance and maintenance (LTSM) costs. Alternatively, if disposal cells are not performing as expected, directly monitoring and modeling the cells' hydrological and ecological performance could provide an early warning, so that corrective actions could be implemented to protect groundwater (DOE 2006).

In 2005, DOE initiated a pilot demonstration of a new device, a water fluxmeter (WFM), as a means for monitoring percolation through disposal cell covers. The pilot demonstration was installed at the Lakeview, Oregon, Disposal Site. The Lakeview disposal cell is a covered landfill constructed by DOE under the Uranium Mill Tailings Radiation Control Act (UMTRCA) of 1978. Previous investigations found that root intrusion and soil formation processes have increased the permeability of the compacted soil layer (CSL) or radon barrier in the cover, raising concerns about higher-than-expected percolation of water into the disposal cell (DOE 2007). WFMs were designed by Pacific Northwest National Laboratory as a way to directly measure both saturated and unsaturated flow through disposal cell covers, and to perform other, similar applications. In contrast, most existing methods for measuring or calculating percolation flux are indirect, unreliable, and fraught with high levels of uncertainty.

This progress report (1) reviews the regulatory background for the site, (2) provides a review of the technical argument for using WFMs instead of alternative methods for measuring percolation flux in covers, (3) describes the environmental setting and design of the cover, (4) reiterates the WFM installation and monitoring methods LM used at Lakeview, and (5) presents percolation and water content monitoring results for September 2005 through August 2008.

2.0 Regulatory Information

Title I of UMTRCA provides for remedial action and regulation of uranium mill tailings at sites that were unlicensed and abandoned as of January 1, 1978. Lakeview is a Title I site. The remedies DOE designed and implemented at Title I sites consisted primarily of engineered disposal cells to contain tailings and other contaminated materials (DOE 1989a). The UMTRCA disposal cells were designed to satisfy cleanup standards promulgated by the U.S. Environmental Protection Agency under Title 40 *Code of Federal Regulations* (CFR) Part 192 and design standards issued by the U.S. Nuclear Regulatory Commission (NRC).

Federal regulations under Title 10 CFR Part 40.27 provided for the licensing, custody, and long-term care of uranium-mill-tailings disposal sites remediated under Title I. The general license became effective when a site-specific LTSP received NRC concurrence. The LTSP explains how DOE, as the long-term custodian, will satisfy the requirements of the general license for the site, including institutional controls, inspections, monitoring, and maintenance. LTSPs, including the one for the Lakeview Disposal Site (DOE 2002), also recommend follow-up investigations when annual inspections detect changes in site conditions that may influence long-term performance (DOE 2000). At Lakeview, follow-up investigations of root intrusion, cover permeability, and percolation were conducted after deep-rooted shrubs were observed growing on the cover during annual inspections.

3.0 Lakeview Disposal Cell Monitoring and Follow-up Investigations

The Lakeview disposal cell is a covered landfill constructed by DOE between 1986 and 1988. The disposal cell is located approximately 11 kilometers northwest of the town of Lakeview in Lake County, Oregon (Figure 1). The disposal cell contains about 668,000 metric tons of uranium mill tailings and other materials hauled from a former uranium-processing site.

Figure 1. Location of Lakeview, Oregon, Disposal Site

3.1 Environmental Setting

The Lakeview disposal cell lies near the northern end of a large playa valley, Goose Lake Valley, at an elevation of 4,950 ft above sea level. The disposal site is underlain by as much as 1,000 ft of Quaternary sands, silts, and lacustrine clays. Depth to groundwater beneath the disposal cell is approximately 100 ft. The potential natural vegetation in the immediate vicinity of the disposal cell is sagebrush-bitterbrush shrub steppe growing in deep, fine-grained soils. Ponderosa pine forests grow in the shallow soils of nearby foothills.

The 6.5-hectare disposal cell was excavated into a hillslope of Quaternary sediment and thus is partially below grade (Figure 2). The excavation was lined with a layer of silt and clay soil compacted with the goal of achieving a saturated hydraulic conductivity (K_{sat}) of less than 10^{-7} centimeters per second (cm/s^{-1}) to limit seepage into the underlying unsaturated sediments (DOE 2002).

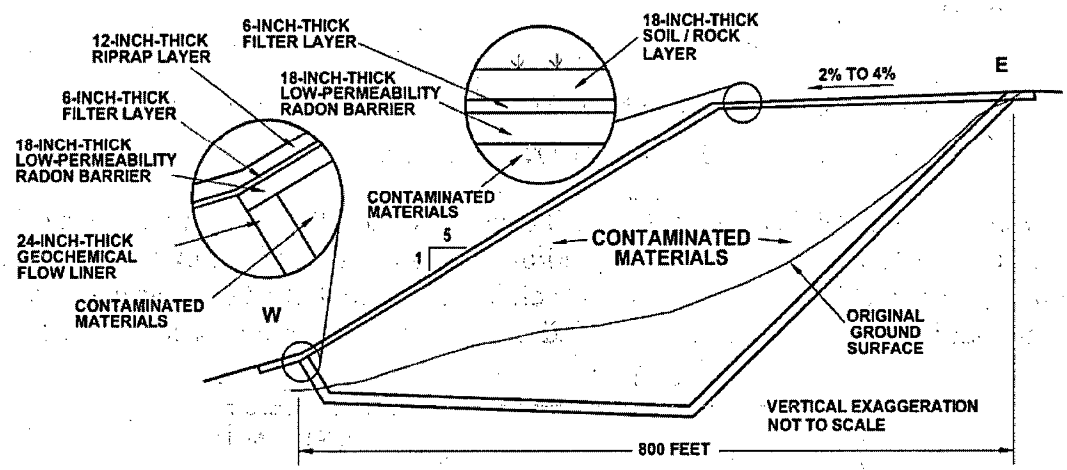

Figure 2. West–East Cross Section of the Lakeview, Oregon, Disposal Cell

3.2 Cover Design

The disposal cell cover consists of four layers, which are, in ascending order, a 45-cm (18-inch) CSL overlying the tailings, a 15-cm (6-inch) coarse sand-and-gravel layer, a 30-cm (12-inch) rock layer, and, only on the top slope, a 15-cm (6-inch) topsoil layer (Figure 2). The design thickness for the CSL was calculated to limit radon flux at the surface of the CSL to less than 20 picocuries per square meter per second. Similar to the liner, the CSL was highly compacted with the goal of achieving a K_{sat} of less than 10^{-7} cm s^{-1} (DOE 2002). UMTRCA design guidance calls for the K_{sat} of the cover CSL to be less than the K_{sat} of the liner CSL to prevent a buildup of water in the disposal cell (DOE 1989b).

The rock riprap layer was designed to protect the underlying CSL and tailings from erosion that could occur during severe storm events. The procedure used for the design determined the size of rock that would be adequate to prevent erosion in the event of runoff produced by a probable maximum precipitation (PMP) event. The PMP event is the theoretical worst storm event possible and, thus, is extremely unlikely to occur. By definition, the PMP is the estimated precipitation depth for a given duration, drainage area, and time of year for which there is virtually no risk of it being exceeded (Wang 1984).

The highly permeable coarse sand-and-gravel layer was designed to act as bedding for the overlying rock layer and as a drainage layer to shed precipitation to the toe slopes of the disposal cell. Rock-lined diversion channels and drains along the toe slopes were designed to dissipate the energy of large-scale runoff events and to direct runoff water away from the disposal cell. On the relatively flat top slope of the disposal cell (approximately 3 percent slope), the rock layer was covered with a 10-to-15-cm-deep layer of soil, creating a rock-soil matrix. The placement of a soil layer on top of the rock layer was not part of the original design. The soil layer was intended as a growth medium for grasses, apparently to improve the aesthetics of the site (DOE 1989b).

3.3 Root Intrusion

Because the topsoil layer is too thin to hold sufficient moisture, only a sparse cover of grass grows on the cover. Shortly after the cover's construction, inspectors began observing deep-rooted shrubs. The rock armor likely reduces evaporation (Groenevelt et al. 1989), increases water storage deeper in the cover profile (Kemper et al. 1994), and, consequently, creates habitat for deep-rooted shrubs. This has been DOE's experience at most arid and semiarid UMTRA sites that have covers armored with a surface layer of rock (Burt and Cox 1993; Waugh 2004). At the Lakeview Disposal Site, these conditions favor the establishment and survival of sagebrush, rabbitbrush, and bitterbrush, which also dominate plant communities surrounding the site.

Root intrusion is of concern because roots can transport contaminants to aboveground shoots and stems (Hakonson et al. 1992). Roots may also alter tailings chemistry as roots decompose and release exudates that mobilize metals (Cataldo 1987). Radon-222 can be actively transported into the atmosphere through the transpiration stream of plants that are rooted in uranium mill tailings (Lewis and McDonell 1990; Morris and Fraley 1989). Decayed roots also create conduits through CSLs, increasing water infiltration and radon diffusion. Radon barriers are most effective when soil pores are filled with water. Hence, the drying of radon barriers by plants could increase radon flux rates.

Root intrusion can also physically degrade covers. Evidence suggests that covers with CSLs, such as the cover at Lakeview, are vulnerable to desiccation and cracking from wet-dry cycles, freeze-thaw cycles, and biointrusion (Melchoir 1997; Kim and Daniel 1992). Macropores left by decomposing plant roots can act as channels for water and gases to rapidly bypass the soil mass in CSLs. Plant roots also tend to concentrate in and extract water from compacted clay, causing desiccation and cracking. This degradation can occur even when overlying soils are nearly saturated (Hakonson 1986), indicating that the rate of water extraction by plants may exceed the rehydration rate of the compacted clay.

In 1997, roots of five mature shrubs (two rabbitbrush, two sagebrush, and one bitterbrush) growing on the top slope of the disposal cell cover were excavated. Taproots of all specimens extended vertically through the rock-soil surface layer and the coarse-sand drainage layer down to the surface of the CSL (radon barrier). Taproots branched and spread laterally at the CSL surface. Secondary and tertiary roots extended vertically into the CSL, where they became fibrous root mats following cracks and structural planes in the CSL.

3.4 Permeability of the CSL

In 1999, DOE began to evaluate the effects of shrub root intrusion on the permeability of the CSL in the Lakeview cover. Permeability can be defined, qualitatively, as the ease with which water can penetrate or pass through a soil mass or layer (http://www.soils.org/sssagloss/). As an indicator of permeability, K_{sat} is a quantitative measure of the ability of a saturated soil to transmit water when subjected to a hydraulic gradient. It can be thought of as the ease with which pores of a saturated soil permit water movement. One of the design targets for the Lakeview CSL was a K_{sat} of less than 10^{-7} cm s^{-1}.

Air-entry permeameters (AEPs) were used to measure in situ K_{sat} and preferential flow in the Lakeview CSL that can be attributed to root intrusion and soil formation processes (Stephens et al. 1988; Havelena and Stephens 1992). See Waugh et al. (2007) for detailed descriptions of the installation, operation, and results of AEP tests at Lakeview.

AEPs were used to compare the K_{sat} of the CSL for the following combinations of conditions on the Lakeview cover in an effort to better understand causal factors: (1) the CSL with and without roots, (2) upper and lower depths in the CSL, and (3) the CSL on the top slope compared with the CSL on the side slope. The upper CSL on the top slope had the highest K_{sat} values whether roots were present or not (Table 1). The lowest K_{sat} values were measured deeper in the CSL on the side slope. K_{sat} values for 16 of the 17 tests were between 1 and 3 orders of magnitude greater than the design target. The mean (geometric) K_{sat} for all AEP tests was 3.0×10^{-5} cm s^{-1}, 300 times greater than the design K_{sat} of $<1.0 \times 10^{-7}$ cm s^{-1}.

Table 1. Results of Air-Entry Permeameter Tests of In Situ Saturated Hydraulic Conductivity (K_{sat}) of the CSL (Radon Barrier) in the Lakeview Disposal Cell Cover

Conditions Tested	K_{sat} (cm s^{-1})	Test Date	K_{sat} (Geometric Mean)
Side slope/upper CSL	2.0×10^{-5}	June 1998	2.1×10^{-5}
	6.9×10^{-5}	June 1998	
	6.8×10^{-6}	June 1998	
Side slope/lower CSL	1.6×10^{-6}	June 1998	8.1×10^{-6}
	8.5×10^{-6}	June 1998	
	1.4×10^{-5}	June 1998	
Top slope/roots/upper CSL	6.4×10^{-5}	July 1997	1.0×10^{-4}
	1.3×10^{-4}	July 1997	
	1.4×10^{-4}	June 1998	
	1.0×10^{-4}	June 1998	
Top slope/roots/lower CSL	2.9×10^{-5}	June 1998	3.4×10^{-5}
	3.9×10^{-5}	June 1998	
Top slope/no roots/upper CSL	5.1×10^{-5}	July 1997	9.2×10^{-5}
	1.1×10^{-4}	July 1997	
	2.1×10^{-4}	June 1998	
	6.3×10^{-5}	June 1998	
Top slope/no roots/lower CSL	6.9×10^{-7}	June 1998	6.9×10^{-7}
Mean for all tests			3.0×10^{-5}

These results are consistent with findings at other sites with landfill covers that rely on CSLs to limit the percolation and leaching of contaminants. Multiple lines of evidence, including U.S. Environmental Protection Agency and DOE field studies, laboratory studies, and monitoring data, show that many existing CSLs fall short of the low-permeability targets, often at the time of, or shortly after, construction, and sometimes by several orders of magnitude (Daniel 1994;

Melchoir 1997; Benson et al. 1999; Benson 2001; Albrecht and Benson 2001; Albright et al. 2004). Several reasons are cited in the literature:

- Unanticipated ecological consequences of designs that encourage biointrusion (Hakonson 1986, 1992; Suter et al. 1993; Bowerman and Redente 1998; Waugh et al. 1999; Waugh 2004).
- Compaction either dry or wet of optimum during construction (Daniel 1994; Benson et al. 1999).
- Desiccation cracking (Boyton and Daniel 1984; Daniel 1994; Albrecht and Benson 2001).
- Differences between laboratory- and field-determined hydraulic conductivities (Daniel 1984; Benson et al. 1999).
- Freeze–thaw cracking (Kim and Daniel 1992; Benson and Othman 1993).
- Differential settlement (Jessberger and Stone 1991; LaGatta 1992; Daniel 1994).
- Retention of borrow soil structure (clods) during construction and pedogenesis (soil-development processes) after construction (Benson and Daniel 1990; Benson 1999; Albright et al. 2004; Waugh 2004).

4.0 Status of the WFM Pilot Demonstration

This section reiterates WFM installation methods and presents monitoring results for September 2005 through August 2008.

4.1 WFM Installation Methods

Five locations on the Lakeview disposal cell were selected for installation of WFMs: three on the top slope of the cover and two on the side slope. A meteorological station was also set up on the top slope. Rather than locating WFMs randomly, WFMs were strategically placed at locations where the cover was considered to be most vulnerable to percolation. The objective was to demonstrate installation and monitoring, not to estimate average percolation flux rates for the entire cover. The three top-slope WFMs (WFM1, WFM4, and WFM5) were located in a downgradient position where water-harvesting effects (the accumulation of water in the drainage layer of the cover from precipitation up slope) were considered to be greatest. The two other WFM stations (WFM2 and WFM3) were to be placed as far down the side slope as possible without losing communication with the meteorological station.

A summary of installation steps for WFMs in the Lakeview cover follows:

1. The upper rock-and-soil layer and underlying sand-and-gravel bedding layer at five locations on the disposal cell cover (Figure 3) were peeled back, using a backhoe, to expose the top of the CSL. At each location, excavated rock riprap and bedding layer materials were stockpiled separately on tarps for later reconstruction of the cover above the WFM.
2. A small-diameter hole was augered into the tailings material below the CSL at each location. Cuttings of tailings were placed in 3.8-liter (5-gallon) buckets for radiological evaluation. Materials excavated down to 2 meters (m) below the CSL exhibited readings not significantly

greater than background (1,650 disintegrations per minute/100 cm^2) using an FH406-L/FHZ-732 instrument combination. Low-activity readings were expected because less-contaminated materials from the evaporation pond and peripheral areas at the processing site were placed above more-contaminated tailings when the disposal cell was filled.

3. A 1.5-m-deep, 15-cm-wide test hole was hand-augered through the CSL and into underlying tailings at each WFM location. CSL and tailings materials were stored separately in 3.8-liter buckets to maintain field moisture contents. A volume sampler was used to acquire soil samples every 15 cm in the CSL and every 30 cm in the underlying tailings as the hole was augered. Volume samples were used to determine soil dry-weight bulk density and moisture content. These data were used to calculate lift mass, which was needed to reconstruct the tailings and cover layers to match the original compaction. At both side slope locations (WFM2 and WFM3), test holes became filled with water because tailings were saturated. WFMs cannot be submerged; hence, WFMs were not installed in the side slope.
4. The 15-cm-wide holes were reamed with a 30-cm-wide hand auger to a depth of about 1 m. Again, excavated CSL and tailings materials were stored in 3.8-liter buckets to maintain field moisture contents.
5. The tipping calibrations (volume of water per tip) in the WFMs and the calibration and sample collection tubes were checked. WFMs were prepared for installation by placing gravel to a depth of 10 to 15 cm in the bottom of each hole to allow percolation water to drain.
6. WFMs were placed and backfilled. The WFM funnel was filled to a depth of at least 2 cm with diatomaceous earth to prevent soil from filtering down through the funnel and to create good contact with wick fibers. Tailings materials were then placed in the funnel above the diatomaceous earth, in lifts that matched the initial bulk density, to a depth of 20 cm. The CSL above was also reconstructed in lifts to match the initial dry-weight bulk density.
7. After the divergence column on the top of the WFM and the hole above the WFM were backfilled, a falling-head technique was used to determine field K_{sat} following the methods of Bagarello et al. (2004). Paired K_{sat} tests were conducted, one overlying the reconstructed CSL above the WFM and the other adjacent to it on an undisturbed section of the CSL. The purpose was to measure the effects of the WFM installation on the hydraulic properties of the CSL.
8. The 15-cm-thick sand-and-gravel layer and the 30-cm-thick rock-and-soil layer were reconstructed within each pit. A preprogrammed datalogger (Campbell Scientific model CR205) was installed on a tripod, and WFMs were wired to it.
9. A meteorological station installed near the center of the disposal cell top slope included instrumentation for precipitation (Texas Electronics TE535WS-L), air temperature and relative humidity (Vaisala HMP-45C), wind speed and direction (Met One 034B-L), and solar radiation (Li-Cor LI200X-L).

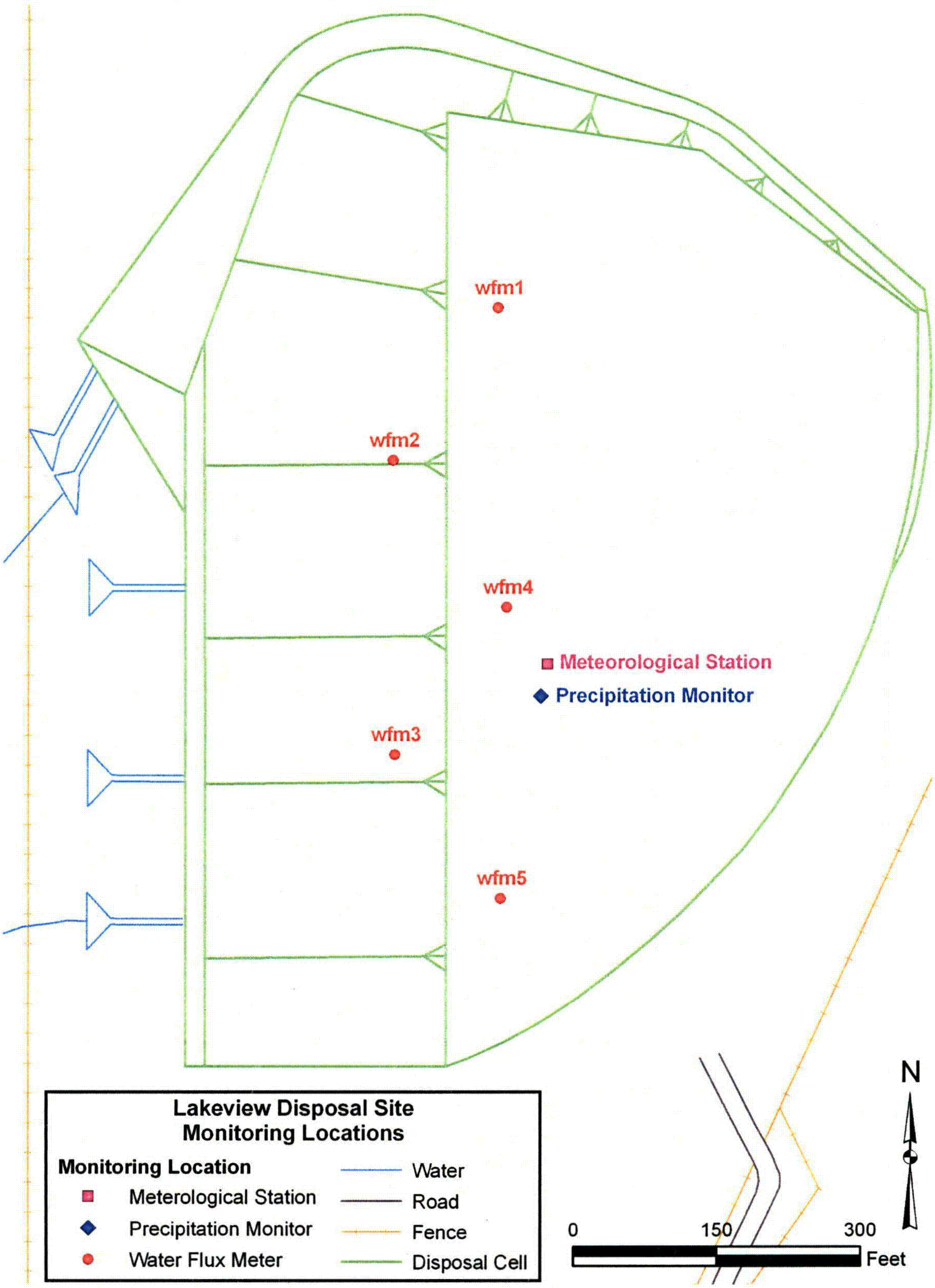

Figure 3. Illustration of Lakeview Disposal Cell Showing Locations for a Meteorological Station and Five WFM Installations on the Top Slope and Side Slope

4.2 Percolation Monitoring Results

WFM data show significant percolation through the Lakeview cover (Figure 4) since the pilot study was installed in 2005.

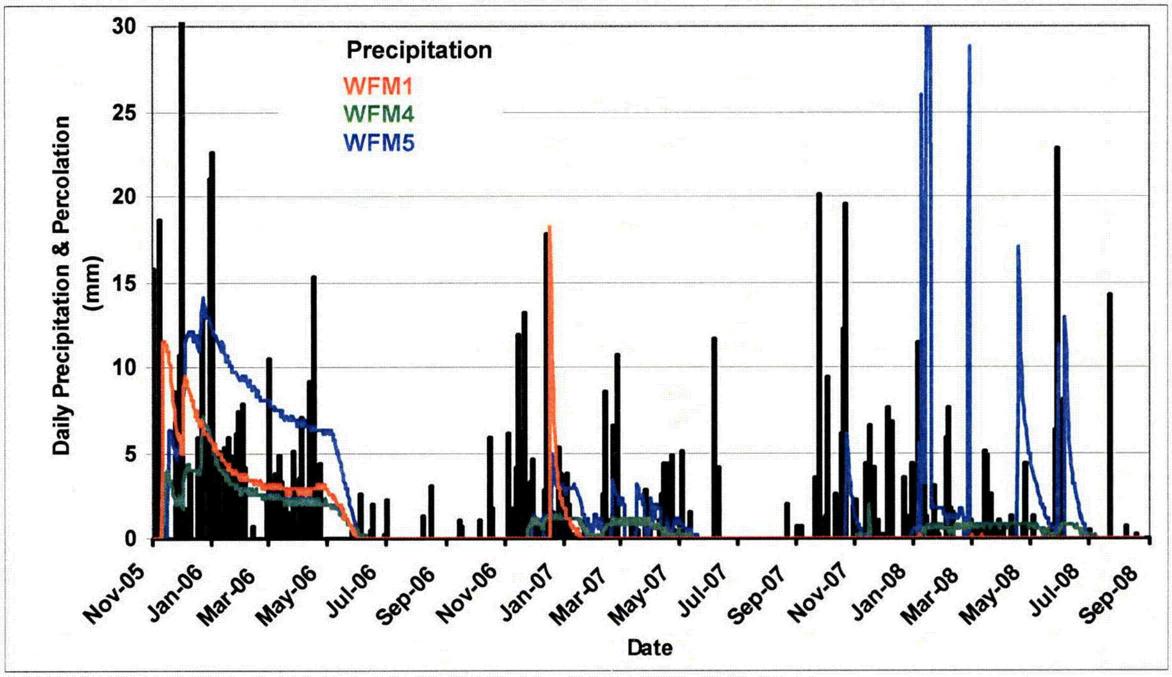

Figure 4. Daily Precipitation on the Disposal Cell (Black Bars) and Daily Percolation as Measured in WFMs Installed below the Top Slope of the Cover at the Lakeview Disposal Site (See Figure 3.)

Total precipitation for the bioclimatic year (November 2005 through October 2006) was 415 millimeters (mm) (16.3 inches), or about 113 percent of the long-term mean (368 mm). The three WFMs installed in tailings below the top slope cover began recording percolation in mid-November 2005, 7 days after the start of a prolonged period of above-normal precipitation. Percolation continued in all three WFMs until early June 2006. No percolation was recorded between June 2006 and October 2006. Percolation rates between November 2005 and June 2006 ranged between 3.1×10^{-5} and 8.5×10^{-5} cm/s^{-1} for the three WFMs. Total precipitation for the 2006 wet season (November 2005 through June 2006) was much wetter than average: 408 mm (16 inches), or about 128 percent of the long-term mean (318 mm).

Cumulative percolation for the wet season (November 2005 through June 2006) exceeded the total precipitation in all WFMs, ranging between 140 percent and 375 percent of precipitation. Strategic placement of the three WFMs near the lower edge of the top slope, where the cover is most vulnerable to percolation, may be the reason for the exceptionally high percolation volumes. The coarse sand-and-gravel drainage layer is likely shedding some water, as designed, causing water to accumulate downgradient in the bedding layer; hence, the CSL likely remains saturated long after a precipitation event ceases. Earlier tests indicated that the K_{sat} of the cover ranges between about 10^{-6} and 10^{-4} cm/s^{-1}; so, if the cover remains saturated because of water harvesting from up slope, then the WFM percolation flux values appear to be reasonable. The mean cumulative percolation for the bioclimatic year was 996 mm, or about 270 percent of precipitation.

The bioclimatic year November 2006 through October 2007 was drier than normal: 260 mm (10.2 inches), or about 71 percent of the long-term mean. The 2007 wet season (November 2006 through June 2007) was also drier than 2006 and drier than the long-term mean. The Lakeview Disposal Site received 222 mm (8.7 inches) of precipitation, about 70 percent of the long-term mean, during the wet season. Nonetheless, even during this dry year, the mean percolation measured in the three WFMs was 186 mm, or about 58 percent of precipitation. The 2008 bioclimatic year was again drier than the long-term mean precipitation. The site received 285 mm (11.2 inches), or about 77 percent, of the long-term mean. The mean percolation for the three WMFs during the 2008 bioclimatic year was 444 mm, or about 121 percent of precipitation.

Patterns of percolation rates changed from one year to the next, apparently in response to precipitation patterns, but also in response to WFM sensor performance and perhaps in response to changes in soil permeability. During the wet 2006 bioclimatic year, percolation rates for all three WFMs peaked in November and December and then tapered off gradually in response to several wet months followed by several dry months. During the drier 2007 bioclimatic year, percolation rates for WFMs 4 and 5 tended to fluctuate in response to less consistent precipitation events. In contrast, percolation rates measured in WFM1 peaked abruptly early in the set season and then dropped to zero in early spring. Field checks in the fall of 2007 and again in the spring of 2008 revealed that the WFM had stopped functioning. Precipitation events during the 2008 bioclimatic year were again somewhat erratic, but the remaining two functioning WFMs responded differently. Percolation rates measured in WFM4 remained low but continuous, whereas in WFM5, percolation rates fluctuated greatly in response to precipitation events, suggesting a higher soil permeability.

5.0 WFM Calibration

Because percolation values were exceptionally high, it was important to check the calibration of WFMs and compare results with independent data. The results were scrutinized in several ways. So far, all methods indicate that these values are reasonable, given the conditions of the study.

5.1 Laboratory Calibration of WFMs

WFMs function as wicking lysimeters. Water passing through a soil layer contacts a wicking material that has a matrix potential similar to the soil. Water passes through the wick and drips into a small tipping bucket gauge (like a rain gauge). For these units, the water collection system consists of an auto siphon that drains (tips) every 10 milliliters (mL) into a tipping spoon that sits below the siphon and records a similar count as a redundant record. The datalogger records tips. The factory calibration is 10 mL/tip for the auto siphon. This value is used in the datalogger program. LM scientists checked the auto-siphon calibrations using WFMs stored in the laboratory and confirmed the 10 mL/tip value. Laboratory WFMs were also connected to a CR205 datalogger (like the ones at Lakeview) to verify that the program accurately records tip volume.

5.1.1 Permeability of the CSL

When WFMs were installed, the compaction or bulk density of the CSL was determined before holes were augered, and then the CSL was reconstructed above the WFMs to match the initial bulk density. After CSL profiles were reconstructed, the infiltration of the rebuilt CSL and the undisturbed CSL were compared using a falling-head method. Average results of these tests were 6×10^{-5} and 4×10^{-5} cm/s^{-1} for rebuilt and undisturbed CSLs, respectively. These values are well within the range of K_{sat} values determined previously for the Lakeview CSL.

5.1.2 Lag Time Calculation

WFMs first recorded percolation through the cover about 7 days after a major rainfall event in November 2005. Given the 45-cm CSL in the Lakeview cover, the 7-day lag time is equivalent to a saturated flow rate through the CSL of 7.5×10^{-5} cm/s^{-1}. This flow rate calculated from the lag time is well within the expected range based on actual WFM flux measurements (3.1×10^{-5} and 8.5×10^{-5} cm/s^{-1}), infiltration tests (6×10^{-5} and 4×10^{-5} cm/s^{-1}), and previous K_{sat} tests.

5.1.3 Field Calibration of WFMs

WFMs are calibrated periodically in the field by adding a known volume of water to a calibration line that extends to the surface and using results recorded with the datalogger to check the number of auto-siphon tips. The three WFMs at Lakeview were calibrated in this manner at least annually since November 2006. Results show that WFM1 and WFM5 initially recorded tips with ± 5 percent of the known water volume. WFM4 recorded about 70 percent of the volume of water injected through the calibration lines. In January 2007, WFM1 stopped recording while WFM4 and WFM5 continued measuring percolation until mid-May 2007. Calibration tests conducted in June 2007 and again in November 2007 and March 2008 confirmed that WFM1 was no longer functioning.

These field calibrations of the WFMs support the previous observations of high percolation rates on the mid-slope portion of the cover. A significant portion of the infiltration water from winter rains and snowmelt is draining and not lost back into the atmosphere via evapotranspiration. Water from the crown of the barrier appears to be moving downslope and creating excess percolation in the vicinity of the WFMs.

6.0 Soil Moisture Monitoring

6.1 Water Content Reflectometer (WCR) Calibrations

Soil moisture sensors called WCRs were placed in the cover profile on the side slope and above WFMs on the top slope as a means for monitoring soil water storage, wetting fronts, and percent saturation. Dataloggers were programmed using factory calibrations for the WCRs. Because of the low specific gravity of tailings materials and the CSL, LM scientists decided to develop calibration curves specifically for these materials.

A WCR consists of two parallel rods attached to an electronic signal generator. A pulsed wavelength traveling down a waveguide is influenced by the type of material surrounding the conductors. If the dielectric constant of the material is high, the signal propagates more slowly. Because the dielectric constant of water is much higher than most other materials, a signal within a wet or moist medium propagates more slowly than in the same medium when dry. The WCR measures the effective dielectric as a pulse transit time, which in turn is calibrated against water content. A manufacture's calibration is supplied with the sensor, but the LM Applied Science and Technology (AS&T) project usually checks the calibration against specific site soil conditions since salinity and other soil properties, such as mineralogy and specific gravity, can influence the calibration.

Calibrations for Campbell Scientific CS625 WCRs were determined for the CSL and tailings materials at Lakeview. Three reflectometer readings were taken for each compacted sample. Readings were averaged and plotted against the average volumetric moisture content determined for each compacted soil sample. Linear regressions are shown in Figure 5 and Figure 6. Table 2 presents target dry density for each soil along with densities and water contents achieved during sample preparation. Calibration results are given in Table 3.

Coefficients for the calibration equation presented in Table 2 were determined from the linear regression:

$$\theta = mT + b$$

where θ and T are the volumetric moisture content and reflectometer period, respectively. T_{min} is computed by determining the reflectometer period corresponding to a zero volumetric moisture content, $T_{min} = -b / m$.

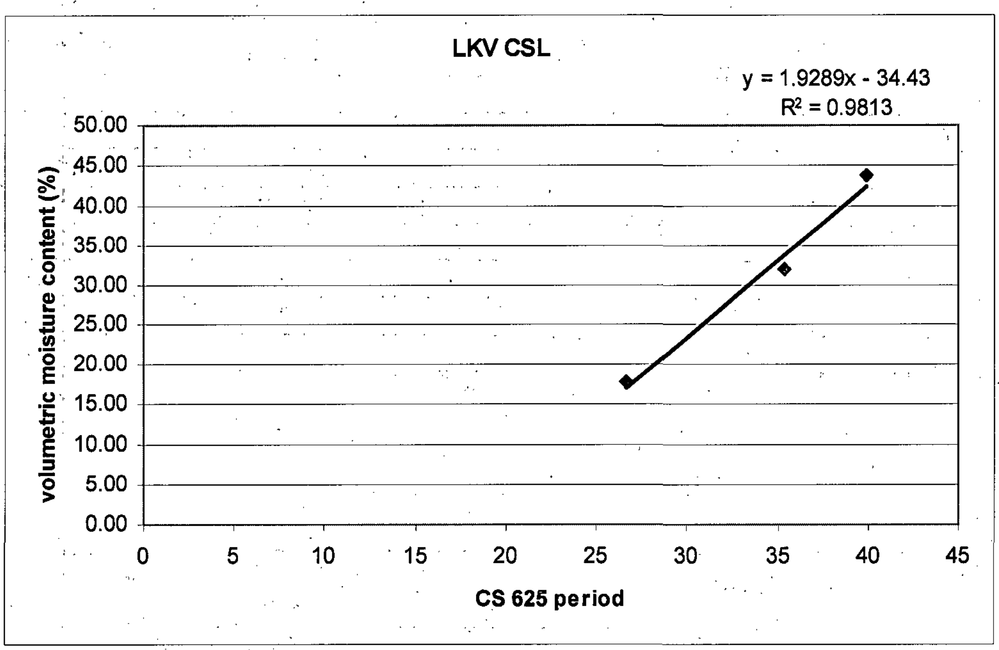

Figure 5. CS625 WCR Linear Regression for the Lakeview CSL.

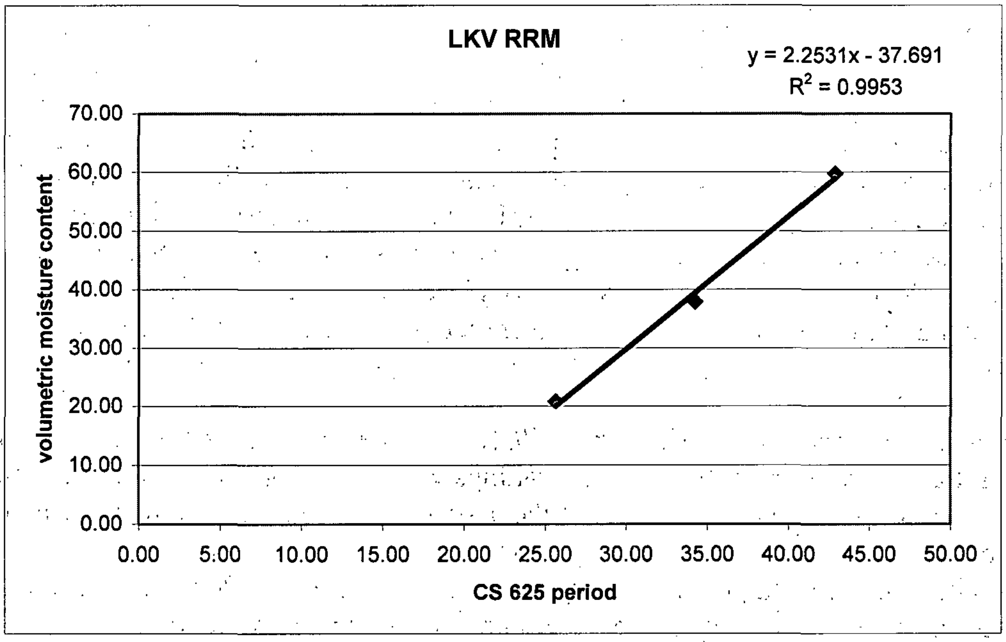

Figure 6. CS625 WCR Linear Regression for the Lakeview Residual Radioactive Material (RRM) or Tailings Material

Table 2. Target Dry Density, Achieved Compaction and Water Content, and Computed Volumetric Water Content for Lakeview CSL and RRM Soils

Site	Target Dry Density (g cm^{-3})	Compaction Achieved		Computed Volumetric Moisture Content, θ(%)[a]
		Dry Density, ρ_d (g cm^{-3})	Water Content w_c (g g^{-1})	
Lakeview CSL				
point 1	1.29	1.21	14.1	17.7
point 2	1.29	1.29	24.4	31.8
point 3	1.29	1.28	33.4	43.8
Lakeview RRM				
point 1	0.78	0.77	25.8	20.1
point 2	0.78	0.73	48.3	37.9
point 3	0.78	0.81	64.1	53.7

[a]$\theta = w_c \rho_d / \rho_w$; where ρ_w is the density of water, 1.0 g/cm^{-3}

Table 3. Calibration Equations for Lakeview CSL and RRM Soils

Soil Material	Calibration Equation[a]
Lakeview CSL	$\theta = 1.929\ (T - 17.85)$
Lakeview RRM	$\theta = 2.253\ (T - 16.73)$

[a]Calibration equation is $\theta = \alpha\ (T - T_{min})$
Where variables are defined as:
θ = volumetric moisture content (g g^{-1})
T = period (μs)

6.2 Side Slope Moisture Monitoring

Test holes augered to a depth of 2 m at two WFM locations in the side slope (Figure 3) rapidly filled with water because the tailings were saturated (Figure 7). Since they cannot be submerged, WFMs were not installed in the side slope. Instead, at both side slope locations, WCRs were installed in the cover and tailings to monitor soil moisture and percent saturation. WCRs were placed in the bedding layer just above the CSL, at 30 to 60 cm in the CSL, and at 30 to 60 cm and at 200 to 230 cm in the upper part of the tailings.

The results of soil moisture monitoring show that the volumetric water content of the gravel bedding layer remains low, as would be expected, but is responsive to precipitation events (Figure 8). The results also show seasonal fluctuation in moisture content of the CSL and the near-surface layer of the tailings, also in response to precipitation (Figure 9). However, at a depth of about 2 m (6 to 7 ft), the tailings remained saturated for the entire monitoring period from November 2005 to August 2008.

Figure 7. Photograph of Water Standing in a Test Hole Augered through the CSL and 2 m into Tailings on the Side Slope of the Lakeview Disposal Cell

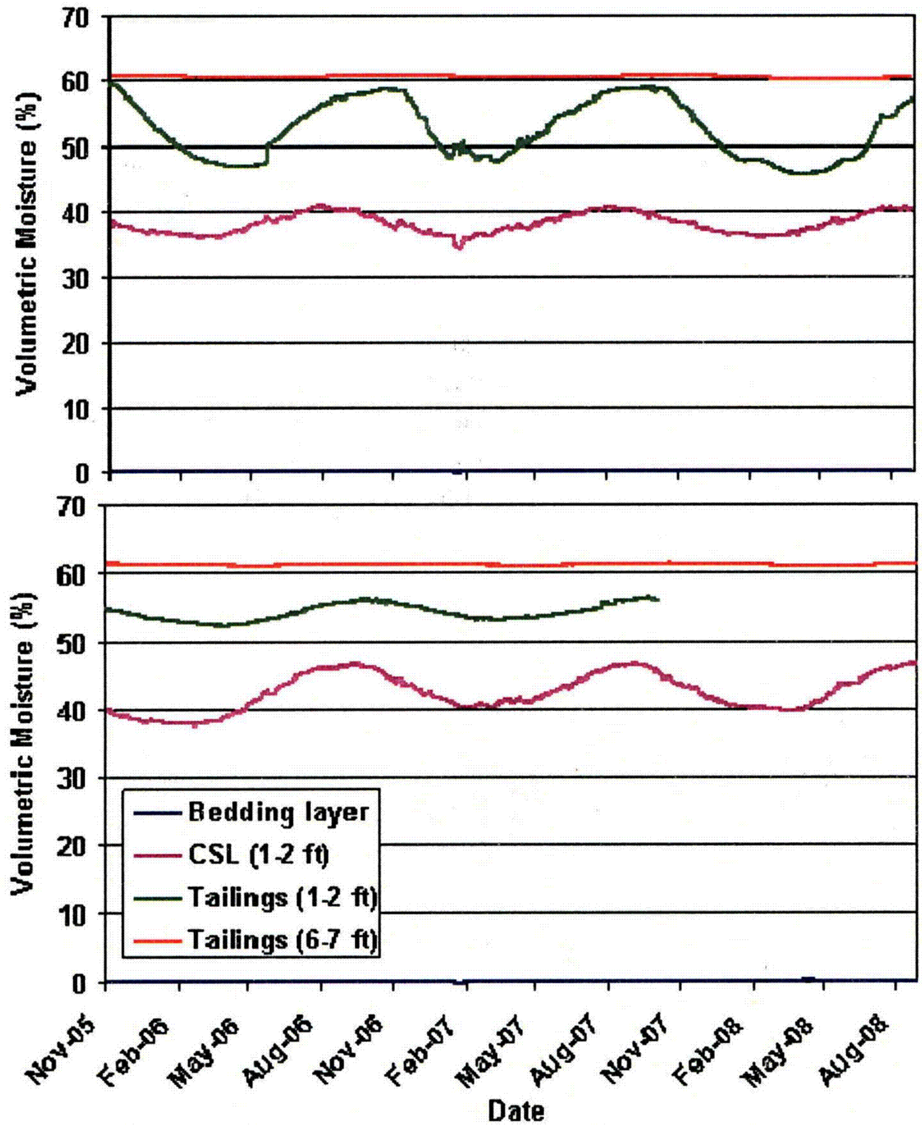

Figure 8. Soil Water Content in the CSL, and Tailings at Two Locations on the Side Slope of the Lakeview, Oregon, Disposal Cell

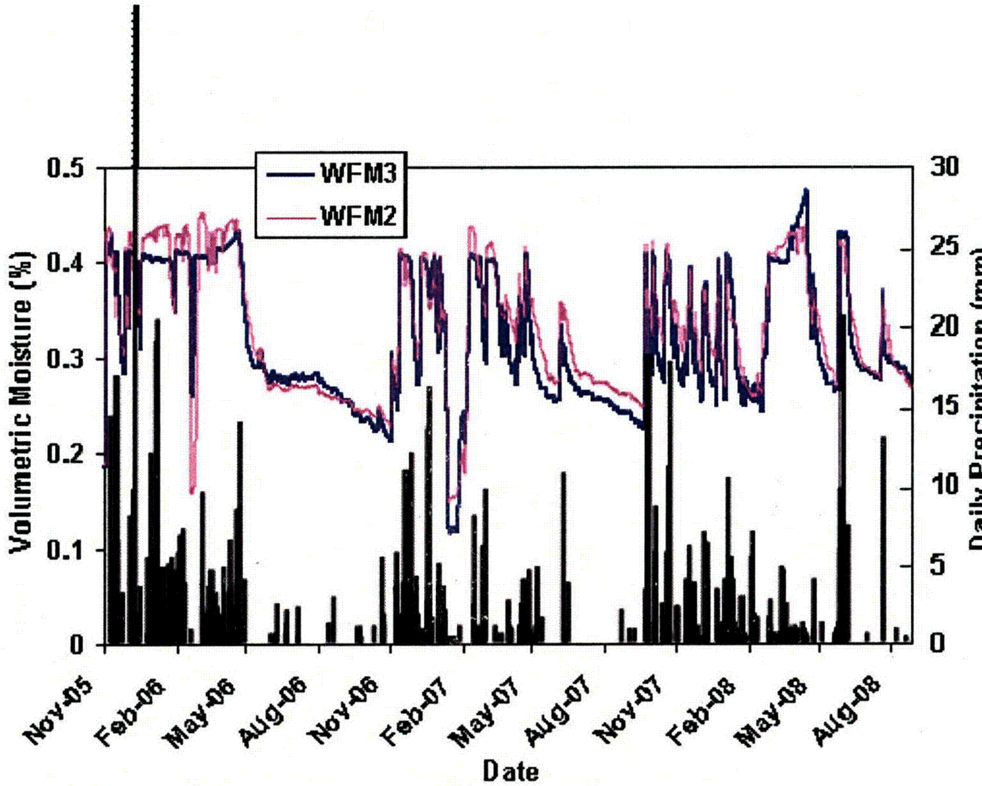

Figure 9. Daily Precipitation (bars) and Soil Water Content in the Bedding Layer of the Cover at Two Locations on the Side Slope of the Lakeview, Oregon, Disposal Cell

6.3 Slope Stability

Evidence of saturated tailings at WFM2 and WFM3 (Section 8.2) suggests that a phreatic water surface occurs approximately 5.5 m below the side slope crest, which led to a cursory evaluation of the side slope's stability.

Original slope stability analyses performed by Morrison Knudson (MK) Engineering were reviewed. The slope stability was initially analyzed assuming poorly draining materials and using slope stability charts (Duncan and Wright 2005). Results from the MK analysis indicated a stable condition. However, the approach did not account for effects of seismic loading. Hence, an analytical approach based on a limit-equilibrium computer program PC STABL5 (Carpenter 1986) was used as an alternative (PC STABL5 is the latest version of the code STABL originally used by MK). Material and seismic parameters put into the program were identical to the original analysis, but they included a phreatic surface at 5.5 m. Using a "factor of safety" less than 1, this analysis indicates that the slope may be unstable under seismic conditions.

7.0 Summary

The disposal cell cover at the Lakeview Site relies on the low permeability of a CSL to limit water percolation and radon escape, and on an overlying rock-and-soil layer to prevent erosion. Since the early 1990s, inspectors have observed recruitment of native shrubs from surrounding plant communities on the top slope of the cover. The surface layer of rock acts as a mulch, limiting evaporation, increasing water storage at greater depths, and creating habitat favorable for the growth of the native shrubs.

Follow-up investigations determined that mature shrubs growing on the cover are rooted in the CSL. Shrub growth on the cell cover is of concern because roots that penetrate tailings can absorb contaminants into shoots and leaves, actively draw radon-222 gas (dissolved in water) in the transpiration stream, and alter soil chemistry. Water extraction by roots can desiccate compacted clay layers even when overlying soils are wet.

Field tests conducted by LM scientists have shown that the K_{sat} of the Lakeview CSL is about 300 times greater than the design target. Root intrusion and natural soil formation processes, which occur both in the engineered CSL and in the borrow soils excavated to build the CSL, apparently created channels and planes of weakness that caused preferential flow of water under saturated conditions.

This project demonstrates the use of the new WFM device—a passive-wicking lysimeter—to directly measure percolation flux through the Lakeview cover. Three WFMs were installed in the top slope of the Lakeview disposal cell during fall 2005. WFMs were placed in holes augered into the upper tailings material just below the radon barrier. WFMs could not be installed in the side slope of the cover because the tailings were saturated and the installation holes rapidly filled with water; however, WCRs were installed in the side slope to monitor moisture content and percent saturation.

The results of the pilot study support the concept that WFMs can be installed in existing disposal cell covers to directly monitor percolation flux. Alternative, more-conventional methods for estimating percolation carry high levels of uncertainty. However, the WFMs may have a relatively short operating life. One of the three WFMs employed in the test failed within 2 years of its installation.

WFM and WCR data from Lakeview show significant percolation through the cover and saturation of the tailings. The three WMFs installed below the top slope cover began recording percolation through the cover in mid-November, 7 days after the start of a prolonged precipitation event. Percolation was continuous in all three WFMs until early June 2006, following a wetter-than-average winter and spring. Percolation occurred more sporadically between November 2006 and June 2007, a winter that was much drier than average, with less than a fifth of the cumulative percolation that occurred the previous winter. However, tailings remained saturated beneath the side slope for the entire 3-year monitoring period.

The cumulative percolation was exceptionally high during the 3-year monitoring period—greater than total precipitation for the period. The high percolation rates likely occurred because the WFMs were strategically placed in downgradient locations where there may be a water-harvesting effect. The bedding layer is likely shedding some water, which accumulates downgradient, causing the drainage layers and CSL to remain saturated for an extended period at WFM locations.

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