Performance Evaluation of the Engineered Cover at the Lakeview, Oregon, Uranium Mill Tailings Site

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ABSTRACT

The U.S. Department of Energy (DOE) Office of Legacy Management (LM) is evaluating the performance of disposal cell covers at LM sites and exploring ways to enhance their sustainability. The cover of the Lakeview, Oregon, disposal cell relies on a compacted soil layer (CSL) to limit radon escape and water percolation into underlying tailings. The design created habitat favorable for growth of woody plants that sent roots through the CSL. The mean saturated hydraulic conductivity (K_{sat}) of the CSL, measured at 17 locations, was 3.0 x 10^{-5} cm s^{-1}, 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. Water flux meters (WFMs) installed in 2005 to directly measure percolation flux show significant percolation through the cover. Three WMFs began recording percolation in mid-November, 7 days after the start of a prolonged precipitation event, and continued until early June 2006. Percolation flux during this period ranged between 3.1 x 10^{-5} and 8.5 x 10^{-5} cm s^{-1}. The cumulative percolation was greater than total precipitation during the period, probably because of a water-harvesting effect. The WFMs were strategically placed in downgradient positions on the cover top slope where water likely accumulated in a sand drainage layer. Routine monitoring at Lakeview shows that the ground water remains protected. LM plans to evaluate potential effects of high percolation rates in covers to ensure that disposal cells remain protective for the long term.

INTRODUCTION

The U.S. Department of Energy (DOE) Office of Legacy Management (LM) is conducting a pilot demonstration of water flux meters as a means for monitoring percolation rates through the cover at the Lakeview, Oregon, disposal site. The Lakeview disposal cell is one of many constructed by DOE under the Uranium Mill Tailings Radiation Control Act (UMTRCA) of 1978, as amended. Evidence that root intrusion and soil formation processes have increased the permeability of a compacted soil layer (CSL) in the cover raised concerns about the integrity of the disposal cell. Water flux meters are a new technology capable of directly measuring both saturated and unsaturated flow. In contrast, many existing methods for measuring or calculating percolation flux are indirect, unreliable, and fraught with high levels of uncertainty. This paper presents the regulatory background for Lakeview, the environmental setting and design of the cover, results of past root intrusion and permeability studies, and the installation methods and results to date for monitoring percolation with water flux meters.

LEGAL AND REGULATORY REQUIREMENTS

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, Oregon 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.[1] 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 licensing, custody, and long-term care of uranium mill tailings disposal sites remediated under Title I of UMTRCA. The general license became effective when a site-specific Long-Term Surveillance Plan (LTSP) received NRC concurrence. The LTSP explains how DOE, as the long-term custodian, will satisfy requirements of the general license for the site, such as institutional control, inspection, monitoring, maintenance, and other measures that may be necessary to ensure that sites continue to protect public health, safety, and the environment after remediation is completed. LTSPs recommend follow-up investigations when annual inspections detect progressive, slow-acting natural processes that may influence long-term performance of disposal cells.[2] The Lakeview LTSP presents requirements for long-term surveillance and maintenance of the Lakeview site, including annual inspections and follow-up investigations.[3] 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.

LAKEVIEW DISPOSAL CELL LOCATION AND DESIGN

The Lakeview Disposal Cell is a covered landfill constructed by DOE between 1986 and 1988. The disposal cell is located approximately 11 kilometers (7 miles) northwest of the town of Lakeview in Lake County, Oregon (Fig. 1). The disposal cell contains 668,000 metric tons (736,000 tons) of uranium mill tailings, demolished mill structures, and other materials hauled to the site from a former uranium processing site. Between 1958 and 1974, the Lakeview mill extracted uranium from ore mined in the nearby mountains.

Fig. 1. Location of Lakeview, Oregon, disposal site.

The Lakeview disposal cell lies near the northern end of a large playa valley, Goose Lake Valley, at an elevation of 1509 m above sea level. The disposal site is underlain by as much as 305 m of Quaternary sands, silts, and lacustrine clays. Depth to groundwater beneath the disposal cell is approximately 20 m. 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-ha disposal cell was excavated into a hillslope of Quaternary sediment and thus is partially below grade (Fig. 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} cm s^{-1} to limit seepage into the underlying unsaturated sediments.[3]

The disposal cell cover consists of four layers in ascending order: a 45-cm (18-in) CSL overlying the tailings, a 15-cm (6-in) coarse sand-and-gravel layer, a 30-cm (12-in) rock layer, and, only on the topslope, a 15-cm (6-in) topsoil layer (Fig. 2). The design thickness for the CSL was calculated to limit radon flux at the surface of the CSL to less than 20 pCi m^{-2} s^{-1}. 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}.[3] 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.

The rock riprap layer was designed to protect the underlying CSL and tailings from erosion that could occur during severe storm events. The median diameter (D_{50}) of the riprap at the time of construction was 9.9 to 6.9 cm. The D_{50} value is a measure such that 50 percent of the rock by weight is of a certain size or larger. The procedure used for the design determined that rock of this size would be adequate to prevent erosion in the event of runoff produced by a Probable Maximum Precipitation (PMP) event. The PMP is the theoretical worst storm event possible and, thus, has an extremely low probability of occurring. 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.[4]

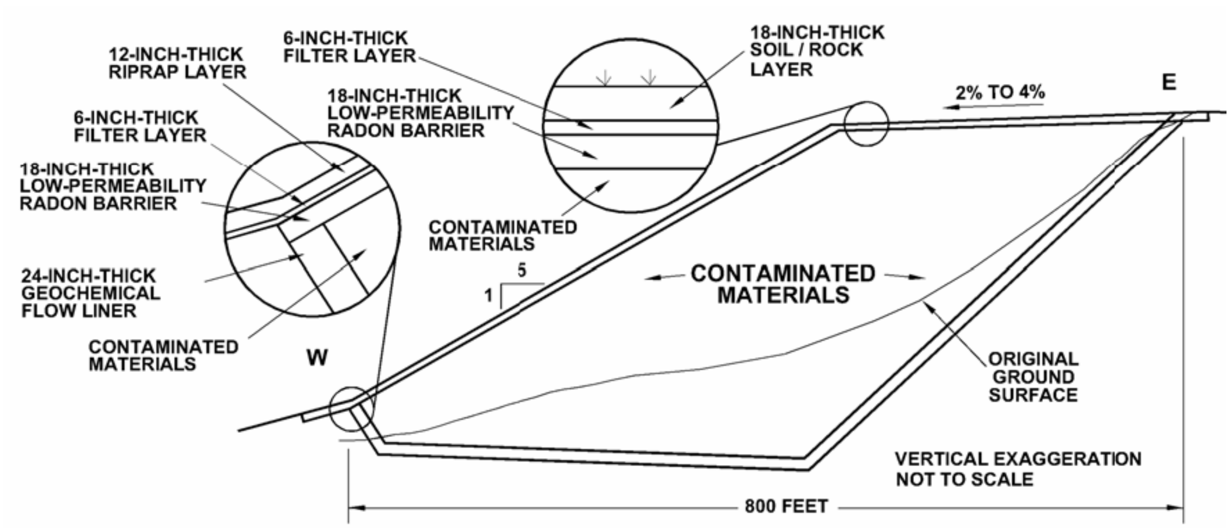

Fig. 2. West-east cross section of the Lakeview, Oregon, disposal cell.

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% slope), the rock layer was covered with a 10-to-15-cm deep layer of soil, creating a rock-soil matrix. Placement of a soil layer on top of the rock layer was not part of the original design. Subsequent small excavations have shown that soil has settled into the interstices of the underlying rock at some locations. At other locations, the soil still partially covers the rock. The soil layer placed over rock on the topslope was intended as a growth medium for grasses, apparently to improve the aesthetics of the site.[5] Although the topsoil was intended to support various rangeland grasses, only a sparse cover of grass was achieved. The soil placed over the riprap is too thin to hold sufficient moisture to support a grass cover similar to surrounding rangeland. Since completion of cell construction, deep-rooted shrubs have established on top of the disposal cell. Grass cover is increasing but remains sparse.

ROOT INTRUSION

Shortly after construction of the Lakeview disposal cell, inspectors began observing encroachment by deep-rooted shrubs. The rock armor reduces evaporation [6], increases water storage deeper in the cover profile [7], 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.[8,9] At Lakeview, these conditions favor establishment and survival of sagebrush, rabbitbrush, and bitterbrush, which also dominate plant communities surrounding the site.

Inspectors were concerned that roots of these shrubs were growing through the cover and into underlying tailings. Roots can transport contaminants to aboveground shoots and stems.[10] Plants rooted in uranium mill tailings may contain elevated levels of molybdenum, polonium-210, radium-226, selenium, thorium-230, and uranium.[11,12,13,14,15] Typically, levels of uranium mill tailings constituents in plant tissues are low, but soil-plant concentration ratios can vary markedly among plant species. Therefore, analytical results for one species are not necessarily transferable to another species. Roots may also alter tailings chemistry as they decompose and release exudates that mobilize metals.[16]

Radon-222 can be actively transported into the atmosphere through the transpiration stream of plants that are rooted in uranium mill tailings.[17,18] Decayed roots also create conduits through CSLs, increasing water infiltration and radon diffusion. Sensitivity analyses show that radon diffusion is much higher in drier soils. Radon barriers are most effective when soil pores are filled with water. Hence, drying of radon barriers by plants could potentially increase radon flux rates.

Root intrusion can also physically degrade covers. Evidence suggests that covers with compacted soil layers such as at Lakeview are vulnerable to desiccation and cracking from wet-dry cycles, freeze-thaw cycles, and biointrusion.[19,20] Macropores left by decomposing plant roots can act as channels for water and gases to rapidly bypass the soil mass in compacted soil layers. 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 [21], indicating that the rate of water extraction by plants may exceed the rehydration rate of the compacted clay. In addition, roots can clog lateral drainage layers[22], potentially increasing rates of infiltration through the underlying compacted soil. Later covers designed for uranium mill tailings included a protective layer overlying the CSL to mitigate effects of wet-dry cycles, freeze-thaw cycles and biointrusion.[23]

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. Tap roots 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). Tap roots 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.

PERMEABILITY OF THE COMPACTED SOIL LAYER

DOE began to evaluate the effects of shrub root intrusion on the permeability of the CSL in the Lakeview cover in 1999. 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}.[3]

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. The AEPs were designed and manufactured by Daniel B. Stephens and Associates, Inc., for use on engineered clay layers and other low-permeability clay soils.[24,25] Each AEP, which is based on a design by Bouwer [26], consists of a round, 30-cm-deep permeameter ring, air-tight polycarbonate plate, standpipe, graduated water reservoir, and vacuum gauge.

Permeameter rings were driven into the CSL with a slide hammer after removal of overlying materials. Polycarbonate plates were sealed to the ring tops, standpipes and water reservoirs were attached to the standpipes, and the reservoirs were filled with water. Dye was added to the reservoir water to trace wetting fronts and preferential flow paths. The two-stage test consisted of (1) measuring the rate of water-level drop in the reservoir and (2) measuring the pressure (tension) with the vacuum gauge after shutting off the water supply and allowing water to redistribute. The vacuum gauge measurement was needed to calculate the air-entry or bubbling pressure of the soil. Saturated hydraulic conductivity (K_{sat} in centimeters per second) was calculated using the Bouwer method [26] as

$$K_{sat} = [2 \cdot dH/dT \cdot L \cdot (R_{ws}/R_{sr})2]/[H_f + L - (0.5 \cdot P_a)] \quad \text{(Eq. 1)}$$

where dH = change in head,
dT = change in time,
L = depth of soil surface to wetting front,
R_{ws} = radius of water-supply reservoir,
R_{sr} = radius of AEP soil ring,
H_f = last head reading,
P_a = $P_{min} + G + L$,
P_{min} = gauge pressure at air entry (negative value), and
G = height of gauge above the soil surface.

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) CSL with and without roots, (2) upper and lower depths in the CSL, and (3) the CSL on the top slope compared with the side slope. For AEP tests on the top slope, a trench approximately 1.5 m wide by 3 m long was excavated at various locations where a mature sagebrush or rabbitbrush was rooted in the CSL. The rock-soil matrix layer and drainage layer were excavated and placed on tarps in separate piles. Four AEP tests were conducted in each location: two where roots penetrated the CSL and two directly adjacent where the CSL was free of roots. At each location, two AEP tests were conducted in the upper (0 to 20-cm depth) and two in the lower (20 to 40-cm depth) portions of the CSL. Because no shrubs were present on the side slope, only two AEP tests were conducted in each trench, one at the 0 to 20-cm depth and one at the 20 to 40-cm depth in the CSL.

Table I presents the results of the AEP tests. The upper CSL on the top slope had the highest K_{sat} values whether roots were present or not. 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 x 10^{-5} cm s^{-1}, 300 times greater than the design K_{sat} of <1.0 x 10^{-7} cm s^{-1}.

The dye patterns in these tests suggest that preferential flow paths often follow preexisting structural planes (between clods). Horizontal dye patterns are evidence of freeze-thaw cracking after construction. These results are consistent with findings at other sites with landfill covers that rely on CSLs to limit percolation and leaching of contaminants. Multiple lines of evidence, including U.S. Environmental Protection Agency and DOE field studies, laboratory studies, and

Table I. 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)	*Test Date*	K_{sat} (geometric mean)
Side slope/upper CSL	2.0 x 10^{-5}	June 1998	2.1 x 10^{-5}
	6.9 x 10^{-5}	June 1998	
	6.8 x 10^{-6}	June 1998	
Side slope/lower CSL	1.6 x 10^{-6}	June 1998	8.1 x 10^{-6}
	8.5 x 10^{-6}	June 1998	
	1.4 x 10^{-5}	June 1998	
Top slope/roots/upper CSL	6.4 x 10^{-5}	July 1997	1.0 x 10^{-4}
	1.3 x 10^{-4}	July 1997	
	1.4 x 10^{-4}	June 1998	
	1.0 x 10^{-4}	June 1998	
Top slope/roots/lower CSL	2.9 x 10^{-5}	June 1998	3.4 x 10^{-5}
	3.9 x 10^{-5}	June 1998	
Top slope/no roots/upper CSL	5.1 x 10^{-5}	July 1997	9.2 x 10^{-5}
	1.1 x 10^{-4}	July 1997	
	2.1 x 10^{-4}	June 1998	
	6.3 x 10^{-5}	June 1998	
Top slope/no roots/lower CSL	6.9 x 10^{-7}	June 1998	6.9 x 10^{-7}
Mean for all tests			3.0 x 10^{-5}

monitoring data, show that many existing CSLs fall short of their low-permeability targets, often at the time of or shortly after construction, and sometimes by several orders of magnitude.[27,19,28,29,30,31] Several reasons are cited in the literature:

- Unanticipated ecological consequences of designs that lead to biointrusion.[21,10,32, 33,34,9]
- Compaction either dry or wet of optimum during construction.[27,28]
- Desiccation cracking.[35,27,30]

- Differences between laboratory and field-determined hydraulic conductivities.[27,28]
- Freeze-thaw cracking.[36,37]
- Differential settlement.[38,39,27]
- Retention of borrow soil structure (clods) during construction and pedogenesis (soil formation processes) after construction.[40,29,31,9]

STATUS OF THE WATER FLUX METER DEMONSTRATION

Because of concerns about the potential effects of high percolation rates with respect to long-term stewardship risks and costs, LM explored state-of-the-science methods and technologies for measuring and estimating percolation through disposal cell covers. Most existing methods for measuring or calculating percolation flux are indirect, unreliable, and produce highly uncertain results.[41,42,43,44] A new device called a water flux meter (WFM), developed by Pacific Northwest National Laboratory, is a promising exception.[42,45] LM decided to conduct field tests in a disposal cell cover after WFMs became commercially available in 2004. LM installed WFMs in the Lakeview cover during fall 2005.

This section presents a summary of installation methods, monitoring results, and calibration activities between September 2005 and September 2006.

Water Flux Meter Installation

Five locations on the Lakeview disposal cell were selected for installation of WFMs, three on the top slope and two on the side slope of the cover. A meteorological station and rain gauge were 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 WFM 5) 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) was considered to be greatest. The two other WFM stations (WFM2 and WFM3) were 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/soil layer and underlying sand/gravel bedding layer at five locations on the disposal cell cover 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 m below the CSL exhibited readings not significantly greater than background (1650 dpm/100 cm^2) using an FH406-L/FHZ-732 instrument combination. Low activity readings were anticipated 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-diameter 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 filled with water because tailings were saturated. WFMs cannot be sumerged, hence, WFMs were not installed in the side slope.
4. The 15-cm-diameter holes were reamed with a 30-cm-diameter hand auger to a depth of about 1.0 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 drainage of percolation water.
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.[44] 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 sand/gravel layer and the 30-cm rock/soil layer were reconstructed within each pit. A pre-programmed datalogger (Campbell Scientific model CR205) was installed on a tripod, and WFMs were wired to the datalogger.
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).

Monitoring Results

WFM data from Lakeview show significant percolation through the cover (Fig. 3). The three WFMs installed below the top slope cover began recording percolation in mid-November, 7 days after the start of a prolonged precipitation event. Percolation continued in all three WFMs until early June 2006. No percolation was recorded between June 2006 and October 2007. Percolation rates over the 7-month period ranged between 3.1×10^{-5} and 8.5×10^{-5} cm

s^{-1} for the three WFMs. Cumulative percolation for all WFMs exceeded the total rainfall, ranging between 140% and 375% of precipitation.

These percolation flux values are exceptionally high. A possible explanation is related to the strategic placement of the three WFMs near the lower edge of the top slope where the cover is most vulnerable to percolation. The coarse sand/gravel bedding/drainage layer is likely shedding some water as designed, and water is accumulating downgradient, possibly causing the bedding layer and CSL to remain 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}; hence, if the cover remains saturated because of water shedding from upslope, then the WFM percolation flux values appear to be reasonable.

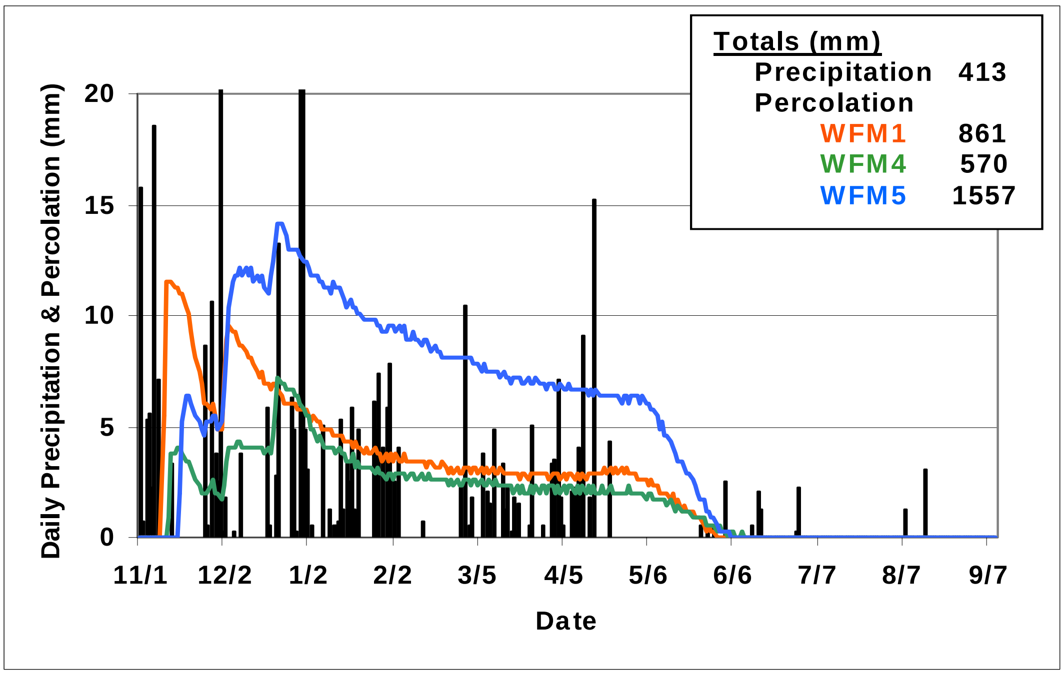

Fig. 3. Precipitation on the disposal cell and percolation through the cover as measured in WFMs at the Lakeview Disposal Site.

Water Flux Meter Calibration

Because percolation values were exceptionally high (percolation exceeded total rainfall during the period), 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.

Laboratory Calibration of WFMs

WFM 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 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.

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, 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.

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.

Field Calibration of WFMs

WFMs can be calibrated after placing them in a soil profile by periodically 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 autosiphon tips. The three WFMs at Lakeview were calibrated in this manner in November 2006. Results show that WFM1 and WFM5 recorded tips with $\pm$ 5% of the known water volume. WFM4 recorded about 70% of the volume of water injected through the calibration lines. These latest 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 down slope and creating excess percolation in the vicinity of the WFMs.

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 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, created channels and planes of weakness that caused preferential flow of water under saturated conditions.

This project demonstrates use of a new device called a water flux meter—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 of 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.

WFM data from Lakeview show significant percolation through the cover. 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. The cumulative percolation was exceptionally high, 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 down gradient, causing the drainage layers and CSL to remain saturated for an extended period at WFM locations.

ACKNOWLEDGMENT

This work was performed under DOE contract number DE-AC01-02GJ79491 for the U.S. Department of Energy Office of Legacy Management.

REFERENCES

1. U.S. Department of Energy, “Technical Approach Document, Revision II,” UMTRA–DOE/AL–050425.0002, Albuquerque Operations Office, Albuquerque, New Mexico (1989a).
2. U.S. Department of Energy, “Guidance for Implementing the Long-Term Surveillance Program for UMTRCA Title I and Title II Disposal Sites,” Grand Junction Office, Grand Junction, Colorado (2000).
3. U.S. Department of Energy, “Long-Term Surveillance Plan for the U.S. Department of Energy Lakeview Uranium Mill Tailings Disposal Site, Lakeview, Oregon,” GJO–2002–353–TAC (GJO–LKV 1.1), Grand Junction Office, Grand Junction, Colorado (2002).
4. B-H.M. Wang, Estimation of Probable Maximum Precipitation: Case Studies, “Journal of Hydraulic Engineering,” 110 (10):1457–1472 (1984).
5. U.S. Department of Energy, “Remedial Action Plan and Site Design for Stabilization of the Inactive Uranium Mill Tailings Site at Lakeview, Oregon, Appendix B of the

Cooperative Agreement No. DE–FC04–84AL20534," UMTRA–DOE/AL–050510.0000, Albuquerque Operations Office, Albuquerque, New Mexico (1989b).

6. P.H. Groenevelt, P. Van Straaten, V. Rasiah, and J. Simpson, Modification in Evaporation Parameters by Rock Mulches, "Soil Technology," 2:279–285 (1989).
7. W.D. Kemper, A.D. Nicks, and A.T. Corey, Accumulation of Water in Soils Under Gravel and Sand Mulches, "Soil Science Society of America Journal," 58:56–63 (1994).
8. C.J. Burt, and S.W. Cox, An Assessment of Plant Biointrusion on Six UMTRA Project Disposal Cells, in "Proceedings of Waste Management Number 2," American Nuclear Society, Tucson, Arizona (1993).
9. W.J. Waugh, Designing Sustainable Covers for Uranium Mill Tailings, pp. 157–173, W.R. Keammerer and J. Todd (eds.), in "Proceedings of High Altitude Revegetation Workshop, No. 16," Information Series No. 99, Colorado Water Resources Research Institute, Colorado State University, Fort Collins, Colorado (2004).
10. T.E. HAKONSON, L.J. LANE, and E.P. SPRINGER, Biotic and Abiotic Processes, pp. 101–146, in "Deserts as Dumps? The Disposal of Hazardous Materials in Arid Ecosystems," C.C. Reith and B.M. Thompson (eds.), University of New Mexico Press, Albuquerque, New Mexico (1992).
11. F.V. Clulow, M.A. Mirka, N.K. Dave, and T.P. Lim, ^{226}Ra and Other Radionuclides in Water, Vegetation, and Tissues of Beavers (*Castor canadensis*) from a Watershed Containing U Tailings Near Elliot Lake, Canada, "Environmental Pollution," 69:277–310 (1991).
12. D.R. Dreesen, and J.M. Williams, Mobility and Bioavailability of Uranium Mill Tailings Contaminants, "Environmental Science Technology," 16:702–709 (1982).
13. L.R. Hosner, H.J. Woodard, and J. Bush, Growth and Selenium Uptake of Range Plants Propagated in Uranium Mine Soils, "Journal of Plant Nutrition," 15:2743–2761 (1992).
14. S.C. Lapham, J.B. Millard, and J.M. Samet, Health Implications of Radionuclide Levels in Cattle Raised Near Uranium Mining and Milling Facilities in Ambrosia Lake, New Mexico, "Health Physics," 56:327–340 (1989).
15. P.M. Markose, I.S. Bhat, and K.C. Pillai, Some Characteristics of ^{226}Ra Transfer from Soil and Uranium Mill Tailings to Plants, "Journal of Environmental Radioactivity," 21:131–142 (1993).
16. D.A. Cataldo, C.E. Cowan, K.M. McFadden, T.R. Garland, and R.E. Wildung, "Plant Rhizoshpere Processes Influencing Radionuclide Mobility in Soil," PNL–6277, Pacific Northwest National Laboratory, Richland, Washington (1987).
17. B.G. Lewis, and M.M. MacDonell, Release of Radon-222 by Vascular Plants: Effect of Transpiration and Leaf Area, "Journal of Environmental Radioactivity," 19:93–97 (1990).
18. R.C. Morris, and L. Fraley, JR., Effects of Vegetation, A Clay Cap, and Environmental Variables on Rn-222 Fluence Rate from Reclaimed U Mill Tailings, "Health Physics," 56:431–440 (1989).
19. S. Melchoir, In-Situ Studies of the Performance of Landfill Caps (compacted soil liners, geomembranes, geosynthetic clay liners, capillary barriers), "Land Contamination Reclamation," 5:209–216 (1997).
20. W.H. Kim, and D.E. Daniel, Effects of freezing on the hydraulic conductivity of compacted clay, "Journal of Geotechnical Engineering," 18:1083–1097 (1992).

21. T.E. Hakonson, "Evaluation of Geologic Materials to Limit Biological Intrusion into Low-Level Radioactive Waste Disposal Sites," LA–10286–MS, Los Alamos National Laboratory, Los Alamos, New Mexico (1986).
22. U.S. Department of Energy, "Vegetation Growth Patterns on Six Rock-Covered UMTRA Project Disposal Cells," DOE UMTRA Project Office, Albuquerque Operations Office, Albuquerque, New Mexico (1992).
23. G.M. Smith and P.E. Rager, Protective layer design in landfill covers based on frost penetration, "Journal of Geotechnical Engineering and Geoenvironmental Engineering," 128:794-799 (2002).
24. D.B. Stephens, M. Unruh, J. Havlena, R.G. Knowlton, Jr., E. Mattson, and W. Cox, Vadose Zone Characterization of Low-Permeability Sediments Using Field Permeameters, "Ground Water Monitoring Review," 8:59–66 (1988).
25. J.A. Havlena, and D.B. Stephens, Vadose Zone Characterization Using Field Permeameters and Instrumentation, in "Proceedings of the Symposium on Groundwater and Vadose Zone Investigations," American Society for Testing and Materials, San Diego, California, January 30–February 1, 1991 (1992).
26. H. Bouwer, Rapid Field Measurement of Air Entry Value and Hydraulic Conductivity of Soil as Significant Parameters in Flow System Analysis, "Water Resources Research," 2:729–738 (1966).
27. D.E. Daniel, Surface Barriers: Problems, Solutions, and Future Needs, pp. 441–487, in G.W. Gee and N.R. Wing (eds.), "In-Situ Remediation: Scientific Basis for Current and Future Technologies," Battelle Press, Columbus, Ohio (1994).
28. C.H. Benson, D.E. Daniel, and G.P. Boutwell, Field Performance of Compacted Clay Liners, "Journal of Geotechnical and Geoenvironmental Engineering," 125:390 (1999a).
29. C. Benson, T. Abichou, W. Albright, G. Gee, and A. Roesler, Field Evaluation of Alternative Earthen Final Covers, "International Journal of Phytoremediation," 3(1):1–21 (2001).
30. B. Albrecht, and C. Benson, Effect of Desiccation on Compacted Natural Clays, "Journal of Geotechnical and Geoenvironmental Engineering.," American Society of Civil Engineers, 127(1), pp. 67–76 (2001).
31. W.H. Albright, C.H. Benson, G.W. Gee, A.C. Roesler, T. Abichou, P. Apiwantragoon, B.F. Lyles, and S.A. Rock, Field Water Balance of Landfill Final Covers, "Journal of Environmental Quality," 33:2317–2332 (2004).
32. G.W. Suter Ii, R.J. Luxmoore, and E.D. Smith, Compacted Soil Barriers at Abandoned Landfill Sites Are Likely To Fail in The Long Term, "Journal of Environmental Quality," 217–226 (1993).
33. A.G. Bowerman, and E.F. Redente, Biointrusion of Protective Barriers at Hazardous Waste Sites, "Journal of Environmental Quality," 27:625–632 (1998).
34. W.J. Waugh, S.J. Morrison, G.M. Smith, M. Kautsky, T.R. Bartlett, C.E. Carpenter, and C.A. Jones, "Plant Encroachment on the Burrell, Pennsylvania, Disposal Cell: Evaluation of Long-Term Performance and Risk," GJO–99–96–TAR, U.S. Department of Energy, Grand Junction, Colorado (1999).
35. S.S. BOYTON, and D.E. DANIEL, Hydraulic Conductivity Tests on Compacted Clay, "Journal of Geotechnical Engineering," 111:465–478 (1984).

36. K.C. Kim, and C.H. Benson, "Water Content Reflectometer Calibrations for Final Cover Soils," Geo Engineering Report 02–12, Geo Engineering Program, University of Wisconsin-Madison, Madison, Wisconsin (2002).
37. C.H. Benson, and M.A. Othman, Hydraulic Conductivity of Compacted Clay Frozen and Thawed In Situ, "Journal of Geotechnical Engineering," 119:276–294 (1993).
38. H.L. Jessberger, and K. Stone, Subsidence Effects on Clay Barriers, "Geotech," 41:185 vol. 194 (1991).
39. M.D. Lagatta, "Hydraulic Conductivity Tests on Geosynthetic Clay Liners Subjected to Differential Settlement," M.S. Thesis, University of Texas, Austin, Texas (1992).
40. C.H. Benson, and D.E., Daniel, Influence of Clods on Hydraulic Conductivity of Compacted Clay, "Journal of Geotechnical Engineering," 116(8):1231–1248 (1990).
41. G.W. GEE, and D. HILLEL, Groundwater Recharge in Arid Regions: Review and Critique of Estimation Methods. "Hydrological Processes," 2:255-266 (1988).
42. G.W. Gee, A.L. Ward, T.G. Caldwell, and J.C. Ritter, A Vadose Zone Water Fluxmeter With Divergence Control, "Water Resources Research," 38(8):35–41 (2002).
43. Gee, G. W., J. M. Keller and A. L. Ward. 2005. Measurement and prediction of deep drainage from bare sediments at a semi-arid site. *Vadose Zone J.* 4: 32-40.
44. G.W. Gee, Z.F. Zhang, W.H. Albright, S.W. Tyler, and M.J. Singleton, "Chloride Mass Balance: Cautions in Predicting Increased Recharge Rates, *"Vadose Zone Journal,"* 4:72-78 (2005).
45. G.W. Gee, Z.F. Zhang, and AL. Ward, A Modified Vadose Zone Water Fluxmeter With Solution Collection Capability, "Vadose Zone Journal," 2: 627–632 (2003).
46. V. Bagarello, M. Iovino, and D. Elrick, A Simplified Falling-Head Technique for Rapid Determination of Field-Saturated Hydraulic Conductivity, "Soil Science Society of America Journal," 68:66–73 (2004).