Design and Installation of a Disposal Cell Cover Field Test

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ABSTRACT

The U.S. Department of Energy's Office of Legacy Management (LM) initiated a cover assessment project in September 2007 to evaluate an inexpensive approach to enhancing the hydrological performance of final covers for disposal cells. The objective is to accelerate and enhance natural processes that are transforming existing conventional covers, which rely on low-conductivity earthen barriers, into water balance covers, that store water in soil and release it as soil evaporation and plant transpiration. A low conductivity cover could be modified by deliberately blending the upper layers of the cover profile and planting native shrubs.

A test facility was constructed at the Grand Junction, Colorado, Disposal Site to evaluate the proposed methodology. The test cover was constructed in two identical sections, each including a large drainage lysimeter. The test cover was constructed with the same design and using the same materials as the existing disposal cell in order to allow for a direct comparison of performance. One test section will be renovated using the proposed method; the other is a control. LM is using the lysimeters to evaluate the effectiveness of the renovation treatment by monitoring hydrologic conditions within the cover profile as well as all water entering and leaving the system. This paper describes the historical experience of final covers employing earthen barrier layers, the design and operation of the lysimeter test facility, testing conducted to characterize the as-built engineering and edaphic properties of the lysimeter soils, the calibration of instruments installed at the test facility, and monitoring data collected since the lysimeters were constructed.

INTRODUCTION

Final covers at many disposal sites managed by the U.S. Department of Energy (DOE) rely on a compacted soil layer to limit radon flux from the cell. Construction of the radon barrier in these conventional covers was assumed to achieve a low saturated hydraulic conductivity (K_s less than 10^{-9} m/s). However, field investigations of in-service covers have shown that the operating K_s can be much higher than that attained during construction. The higher-than-expected K_s generally can be attributed to (1) unanticipated ecological consequences of biointrusion, desiccation, and freeze-thaw cycling; (2) the retention of borrow soil structure (clods) during construction; and (3) natural soil-formation processes after construction. After several years with these natural processes acting upon the cover materials, the percolation rate into the waste may also be much higher than anticipated, sometimes by several orders of magnitude [1,2,3,4,5,6].

In contrast, studies by DOE, the U.S. Environmental Protection Agency (EPA), and others have shown that water balance covers can be very effective at limiting percolation at arid and semiarid sites [7,8,9,10,11]. Water balance covers consist of thick, fine-textured soil layers that store precipitation in the root zone where it can be removed seasonally by plants [12]. For example, the average percolation rate from the water balance cover at the Monticello, Utah, Disposal Site has been approximately 0.6 mm/yr for more than a decade during which the average annual precipitation has been 358 mm/yr [11]. Furthermore, water balance covers can be designed to accommodate changes in soil hydraulic properties caused by the environmental conditions that damage low-conductivity covers." [13].

Maintenance of conventional covers at DOE disposal sites can be costly. For example, the costs of herbicide spraying have increased at many sites and will likely continue to do so as ecological conditions become more favorable for plant growth. Replacement or rehabilitation of the hydraulic barrier layer at these sites could be much more expensive. Without intervention, however, ecological succession and soil development processes will effectively transform existing conventional covers with low-conductivity radon barriers into water balance covers. Thus, one option is to enhance this transformation process by anthropogenic means. The goal would be to accommodate ecological processes and, thereby, sustain a high level of performance while reducing long-term maintenance costs.

In September 2007, the DOE Office of Legacy Management initiated a cover assessment project to investigate an inexpensive way to improve sustainability and reduce long-term surveillance and maintenance of disposal cell covers. A test facility was constructed at the Grand Junction, Colorado, Disposal Site to evaluate methods for modifying conventional covers in a manner that deliberately accelerates their transformation to water balance covers.

This paper describes historical evaluations of conventional and water balance covers at sites managed by DOE and others, the construction of the test facility at the Grand Junction Disposal Site, testing conducted to characterize the as-built engineering properties of the test cell lysimeters, the calibration of instruments installed at the test facility, and monitoring data collected since the lysimeters were constructed.

EXISTING COVERS

The Grand Junction Disposal Site was constructed for the disposal of uranium mill tailings and other materials associated with the cleanup of the Grand Junction Processing Site and vicinity properties in the city of Grand Junction, Colorado (http://www.lm.doe.gov). All contaminated materials from these sites had been transported to the disposal cell by the end of 1994. About 4.4 million cubic yards of contaminated materials were placed in the cell. Part of the Grand Junction Disposal Cell was completed in 1994; the remainder of the cell will remain open until 2023 to receive additional residual radioactive material.

The final cover at the Grand Junction Disposal Site consists of four layers (Fig. 1): a low-conductivity radon barrier constructed with compacted fine-grained soil overlying tailings; a protection layer constructed with fine-grained soil; a sand-and-gravel bedding layer; and a surface layer of basalt riprap. Measurements of the compacted soil barrier made at two locations with air-entry permeameters [14] in 2003 yielded 7×10^{-7} and 2×10^{-6} m/s, 2 to 3 orders of magnitude above the design target (1×10^{-9} m/s). As a result, percolation may be transmitted into the underlying waste at higher rates than originally anticipated. A Long Term Surveillance Plan (LTSP) serves as the regulatory framework guiding the maintenance of the disposal cell, and at many sites, includes a provision to cut and spray with herbicide all plants that may be considered to threaten the integrity of the disposal cell. This typically includes pants considered to be deep rooted. Many desert phreatophytes naturally occurring in the vicinity of the disposal cells at arid and semi-arid sites fit this description, and there is at present a requirement to eliminate these at least annually. As a result, the cost of controlling vegetation on the Grand Junction Disposal Site cover has increased as deposition of aeolian dust in the riprap layer has created a more favorable habitat for fourwing saltbush and other plants. The riprap layer also acts as a mulch that retains water within the underlying fine-textured soil, enhancing the establishment and growth of vegetation. As a result of these conditions, the performance in terms of limiting infiltration of the cover at the Grand Junction Disposal Site may be diminishing, and the costs of maintenance may increase in the long term as a larger area will need to be controlled under the current LTSP.

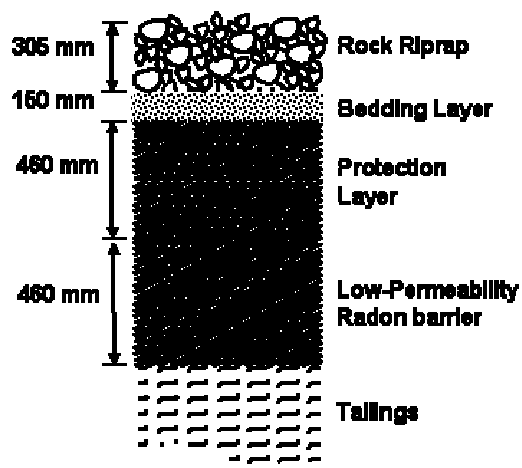


Fig. 1. Profile of Grand Junction Disposal Cell cover.

The conditions observed at the Grand Junction Disposal Site are not unique. Deep-rooted plants began growing on conventional uranium mill tailings covers at several sites within a few years after construction [15]. Roots of woody plants were excavated and found to grow down into or through radon barriers at the Grand Junction; Lakeview, Oregon; Burrell, Pennsylvania; Durango, Colorado; Shiprock, New Mexico; and Tuba City, Arizona, disposal sites [4,6,15]. Taproots typically extended vertically through the riprap and bedding layers and then branched and spread laterally at the surface of the compacted soil barrier, following both the source of water and the path of least resistance to penetration and growth. Secondary and tertiary roots extended vertically into the compacted soil barrier, where they became fibrous root mats following cracks and soil structural planes.

In follow-up investigations of root intrusion, DOE evaluated the effects of plant roots and soil development on in situ K_s of compacted soil layers at Burrell, Lakeview, Shiprock, and Tuba City using air-entry permeameters [14]. At Burrell, the mean K_s was 3.0×10^{-7} m/s where Japanese knotweed roots penetrated the radon barrier, and 2.9×10^{-9} m/s at locations with no plants [4]. The weighted-average K_s for the entire cover, calculated using the community leaf area index for Japanese knotweed, was 4.4×10^{-8} m/s. At Lakeview, the mean K_s for the radon barrier both with and without sagebrush and bitterbrush roots was 3.0×10^{-7} m/s [6]. The highest K_s occurred near the top of the compacted soil barrier; the lowest K_s occurred deeper in the barrier. The mean K_s in the top of the Shiprock radon barrier was 4.4×10^{-7} m/s [5]. Results were higher and more variable where tamarisk and Russian thistle were rooted in the radon barrier. The Shiprock radon barrier was nearly saturated, as measured monthly for 16 months at four locations using a neutron hydroprobe. At Tuba City, K_s of the radon barrier had a mean of 8.7×10^{-8} m/s and ranged from 9.8×10^{-11} to1.2×10^{-6} m/s. In all of the tests mentioned above, dyes indicated that water moved through macropore cracks in the soil structure of radon barriers.

Short-term changes in cover soil properties are not unique to disposal cells for uranium mill tailings. Exhumations of the lysimeters in EPA's Alternative Cover Assessment Program (ACAP) [8] show changes to saturated and unsaturated hydraulic properties over the 4- to 8-year life of the lysimeters. Benson et al. [13] reported in-service K_s for storage and barrier layers between 7.5×10^{-8} and 6.0×10^{-6} m/s regardless of the initial K_s. Alterations in K_s occur in all climates and for barrier and storage layers in all cover types. Wet-dry cycling appears to play a major role in altering K_s. Smaller changes in K_s occurred in storage and barrier layers constructed with soils that have lower clay content, soils that have a fines fraction with a greater proportion of silt-size particles, and soils compacted to lower dry unit weight. Changes in the soil water characteristic curve (SWCC) parameters (α and n) typically were smaller than the changes in K_s (2.2 times smaller for α and 1.1 times smaller for n, on average). Benson et al. [13] reported that the porosity of most earthen storage and barrier layers evaluated in the ACAP study was between 0.35 and 0.45 when exhumed, and predicted that densely compacted earthen storage and barrier layers would loosen over time and become more permeable.

LYSIMETER DESIGN AND CONSTRUCTION

The current study is evaluating cover modification—accelerating and enhancing natural processes already transforming covers. The conceptual design involves deliberately blending the riprap and underlying fine-textured soil by ripping and mixing the rock, bedding, and protection layers, and planting native shrubs in the rip rows. Effectiveness of the treatment will be evaluated by monitoring hydrologic conditions within the cover profile (water content and matric potential) as well as boundary fluxes (runoff, evapotranspiration, and percolation).

Testing the procedure on the existing cover was not practical. Thus, two identical test sections including large-scale lysimeters simulating the as-built cover were constructed adjacent to the disposal cell. One of these test sections (Lysimeter R) will be modified, and the other (Lysimeter C) will be monitored as a control that simulates the existing cover. The test sections were constructed in late summer and fall 2007 and currently are acclimating to ambient environmental conditions. The lysimeters are modeled after EPA's ACAP [8]. Fig. 2 shows a cross section the test cell lysimeter. Each 10 meter [m] × 20 m lysimeter has instrumentation for monitoring percolation from the base of the cover, a runoff collection system, a collection of instruments used to monitor state variables within the cover profile, and a weather station to monitor meteorological conditions. This system permits direct monitoring of precipitation, runoff, soil water storage, and percolation, and calculation of evapotranspiration as the difference. Each test section includes a 10-m-wide buffer zone around the lysimeter.

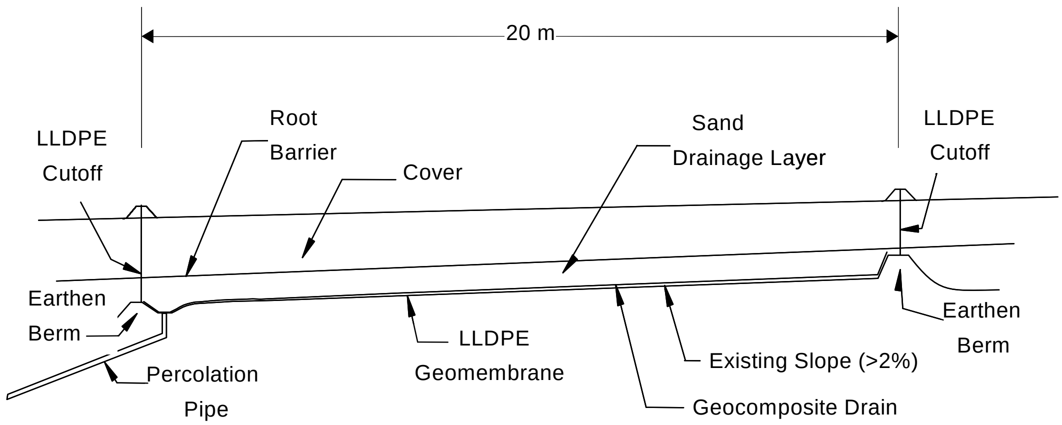


Fig. 2. Cross section of the test cell lysimeter used to monitor water balance variables.

Lysimeter Construction

The test sections were constructed using earthen materials identical to those in the disposal cell cover. The radon barrier and the protection layer were constructed with moderately plastic clay having a Unified Soil Classification System (USCS) designation of CL. The radon barrier was underlain with a 460-mm-thick layer of road base gravel (broadly graded alluvium with a USCS classification of SW) that was stockpiled on site when the full-scale cover was constructed. This lower layer of road base gravel simulates the transition layer in the disposal cell. The bedding layer beneath the riprap was also constructed with road base gravel. Riprap for the surface was obtained from a stockpile on site left over from the construction of the full-scale cell. Heavy equipment similar to that used for the full-scale cover was employed for construction.

The construction of two identical lysimeters required an area approximately 65 m by 45 m (approximately 3,000 m^2). The completed test facility was approximately 3 m tall and was sloped at 3H:1V around the perimeter. The top deck was sloped at 2 percent, a slope identical to that of the full-scale cover. Procedures for the construction of an ACAP test cell described in Benson et al. [16] were followed for construction.

The test facility was constructed north of the existing disposal cell. This area was surveyed, cleared and grubbed, and approximately 0.3 m of topsoil was stripped using a Case 821 frontend loader. The stripped soil was stockpiled in an adjacent area for use in revegetation after construction. After stripping, the exposed subgrade was proof-rolled, and the dry unit weight and water content were measured.

Silty clay with cobbles, stockpiled nearby during full-scale construction, was used as compacted random fill for the foundation of the test facility. Moisture was added to the stockpile beforehand to improve compaction. The moisture-conditioned material was transported to the test pad in 10 m^3 dump trucks, spread with a Bobcat T250 skid loader, and compacted with a Rhino 66 vibratory padfoot compacter (75 mm shank). Approximately 0.6 m of the silty clay fill was placed. This layer was overlain with a veneer of granular road base to provide a smooth working platform for the construction of the lysimeters.

Each lysimeter was constructed using 1.5-mm-thick linear low-density polyethylene (LLDPE) geomembrane with texturing on both sides. LLDPE geomembrane was used because of its flexibility, ductility, and puncture resistance. LLDPE geomembrane was used to form the base and sidewalls of each lysimeter. However, the upper portion of the sidewalls of Lysimeter R was constructed with 0.1 mm polyethylene sheet to ensure that ripping through the sidewalls could be accomplished during the modification phase of the project. Methods described in Benson et al. [16] were used to form and weld the lysimeter walls and to install the sump in the base for the collection of percolation water to be measured.

The floor of the lysimeter was overlain with a geocomposite drainage layer (geonet sandwiched between two non-woven geotextiles) that collects percolation from the base of the cover profile and directs the percolation to a collection sump and a collection basin. Pipes used to convey percolation from the sump to the basin were placed in trenches and buried in road base.

Placement of Cover Soils

The cover soils were placed in the same sequence used for the construction of the actual cover on the disposal cell. Road base material for the transition layer was transported from stockpiles to the test pad in 10 m^3 dump trucks and spread in 0.3 m loose lifts with a Bobcat skid loader. Lift thickness was monitored with a laser level set to a 2 percent grade. The material was placed over the entire test facility (i.e., within the lysimeters, between the lysimeters, and in the perimeter area). The final thickness of the transition layer was determined using conventional surveying techniques and a transit equipped with an electronic distance meter.

Clay for the radon barrier was moisture-conditioned at the stockpile, using a water truck, and transported to the test facility in 10 m^3 dump trucks. The clay was spread in 200 mm loose lifts, using a skid loader, and compacted with a Rhino compactor. Vibration was not used when compacting the clay. Loose lift and final placement thickness were controlled during construction with a laser level set to a 2 percent grade. Identical methods were used to place and compact the clay within, between, and around the perimeter of the lysimeters. The final thickness was determined by elevation difference between the surveyed ground surface elevations obtained after each layer was constructed, using conventional surveying techniques.

The protection layer was constructed using methods similar to those used to construct the radon barrier. However, the loose lifts were more than 300 mm thick, and compaction was achieved by driving dump trucks over the protection layer. The same methods were used inside, between, and around the perimeter area of the lysimeters. The final layer thickness was determined by elevation differences, using conventional surveying techniques.

The bedding layer was constructed with granular road base that was placed using the same methods employed for the transition layer. The bedding layer was 150 mm thick. Riprap from on-site stockpiles was placed directly on the bedding layer and spread to a final lift thickness of 300 mm.

Compaction

The as-built dry unit weight and water content of each layer were measured using a nuclear gage in accordance with ASTM D 6938. A technician from a local geotechnical testing laboratory conducted the nuclear gage testing. Table I summarizes the compaction test data.

Table I. Water Content and Dry Unit Weight of Each Layer of Test Lysimeters

Layer	Water Content (%)		Dry Unit Weight (kN/m^3)	
	Test Section C	Test Section R	Test Section C	Test Section R
Frost Protection	16.8 ± 1.5	16.1 ± 0.6	16.9 ± 0.5	17.0 ± 0.1
Radon Barrier	14.6 ± 0.2	17.1 ± 0.5	18.1 ± 0.1	17.5 ± 0.2
Transition	2.9 ± 0.2	2.9 ± 0.2	19.9 ± 0.3	19.2 ± 1.0

The geotechnical laboratory determined compaction curves for the road base and clay corresponding to standard Proctor (ASTM D 698). The clay has a maximum dry unit weight of 17.3 kN/m^3 at optimum water content (14.5%). The road base has a maximum dry unit weight of 18.2 kN/m^3 at optimum water content (13.6%).

To mimic full-scale construction, compaction control was not conducted on the transition or bedding layers. The radon barrier was compacted to 103 percent of maximum dry unit weight and 1.5 percent wet of optimum, on average. These conditions are ideal for remolding clay clods, eliminating interclod voids, and achieving a barrier with low K_s [17]. The protection layer was compacted to 93 percent of maximum dry unit weight without a water content criterion.

MATERIALS CHARACTERIZATION

Samples were collected from the transition layer, radon barrier, protection layer, and bedding layer during construction. Disturbed samples of the coarse-grained road base in the transition layer were collected with shovels and placed in sealed 20 L buckets. Undisturbed block samples were collected from the radon barrier and protection layer using the procedure in ASTM D 7015. Cylindrical polyvinyl chloride (PVC) sampling rings, with a height and diameter of 360 mm, were used to collect the block samples. Large block samples were collected to provide a realistic assessment of the field K_s at the time of construction [16,18,19].

All of the samples were shipped to the Wisconsin Geotechnics Laboratory at the University of Wisconsin–Madison for analysis of particle size distributions, Atterberg limits, and compaction characteristics. The clay is moderately to highly plastic, consists almost entirely of fines (94 percent), and contains no gravel or cobbles. The road base is a very broadly graded, coarse-grained material with comparable amounts of sand and gravel, a modest amount of fines, and no cobbles.

Saturated Hydraulic Conductivity

The K_s of each block sample was measured in a flexible-wall permeameter using the falling-headwater–rising-tailwater method described in ASTM D 5084. Prior to testing, disturbed soil was trimmed from the surfaces until the specimen had a diameter of 305 mm and an aspect ratio of 1.0. Testing was conducted using an average effective stress of 35 kPa, a hydraulic gradient of 10, and a backpressure of 350 kPa. Table II summarizes the saturated hydraulic conductivities of the block samples from the protection layer and radon barrier.

Table II. Saturated Hydraulic Conductivity of Samples from RECAP Lysimeters

Test Section	Layer	Water Content (%)	Dry Unit Weight (kN/m^3)	Sat. Hydraulic Conductivity (m/s)
C	Frost Protection	22.4	15.2	1.8×10^{-6}
C	Frost Protection	21.7	16.4	1.6×10^{-10}
R	Frost Protection	15.1	18.1	1.3×10^{-10}
R	Frost Protection	19.4	16.3	3.8×10^{-8}
C	Radon Barrier	21.3	16.2	6.3×10^{-10}
C	Radon Barrier	14.6	17.8	7.4×10^{-9}
R	Radon Barrier	19.0	17.0	7.4×10^{-11}
R	Radon Barrier	20.6	16.3	9.6×10^{-11}

The K_s of the road base was measured in a large-scale rigid-wall permeameter custom-made for this study. Tests were conducted using the constant-head method described in ASTM D 5856, using a hydraulic gradient of 1. The permeameter had a diameter of 356 mm to accommodate the large particles contained in the road base. Test specimens were prepared by compacting the road base in the permeameter in three lifts of equal thickness using a wooden tamper until the dry unit weight of the test specimen was equal to the average dry unit weight measured in the field (19.6 kN/m^3). For a given layer, the two field samples were composited due to the similarity in the particle size distribution.

As expected, the fine-grained radon barrier and protection layer have much lower K_s than the coarse-grained road base used in the transition and bedding layers. The K_s of the protection layer ranged from 1.3×10^{-10} to 1.8×10^{-6} m/s, while the K_s of the radon barrier ranged from 7.4×10^{-11} to 7.4×10^{-9} m/s; hence, the protection layer is also more permeable and more variable than the radon barrier. The higher hydraulic conductivity and variability of block samples from the protection layer are likely due to its lower in-place dry unit weight and its lack of water content control. The highest K_s in the protection layer corresponded to the specimen with the lowest dry unit weight.

Three of the four specimens from the radon barrier had very low K_s (less than 10^{-10} m/s), which reflects the high compaction water content and moderate to high plasticity of the clay [17,18]. One specimen had K_s greater than 10^{-9} m/s. This specimen had compaction water content less than optimum water content, a condition that is known to result in macrostructure and higher K_s [17]. The geometric mean K_s of the four block samples from the radon barrier (both lysimeters) is 4.3×10^{-10} m/s, close to the average K_s reported in a survey of more than 100 as-built clay barriers in North America (4.8×10^{-10} m/s, [20]).

The K_s of the road base material was very uniform (1.1×10^{-3} to 1.5×10^{-3} m/s). The similarity of the hydraulic conductivities is consistent with the similarity in the particle size distributions of the road base samples. Thus, compositing samples from a given layer in a lysimeter was appropriate.

Soil Water Characteristic Curves

SWCCs for the radon barrier, the protection layer, and the road base were measured using the procedures described in ASTM D 6836. SWCCs for the radon barrier and the protection layer were measured in pressure plate extractors custom-made for this project. The test specimens were trimmed from specimens used for K_s testing. For the road base material, test specimens were compacted into large-scale hanging columns, which were 300 mm in diameter and custom-made for this study, until the average dry unit weight measured in the field was achieved.

All of the custom-made equipment conformed to the criteria in ASTM D 6836. Tests conducted on specimens from the radon barrier and the protection layer were conducted using Methods B and D in ASTM D 6836. Tests conducted on the road base were conducted using Method A in ASTM D 6836.

All of the SWCCs were parameterized using van Genuchten's equation:

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[\frac{1}{1 + (\alpha\psi)^n} \right]^m \qquad \text{(Eq. 1)}$$

where θ_s is the saturated hydraulic conductivity (K_s), θ_r is the residual water content, ψ is the soil matric suction, α and n are the van Genuchten shape parameters, and $m = 1-1/n$. The SWCCs for the protection layer and radon barrier are shown in Fig. 3, and the parameters are summarized in Table III.

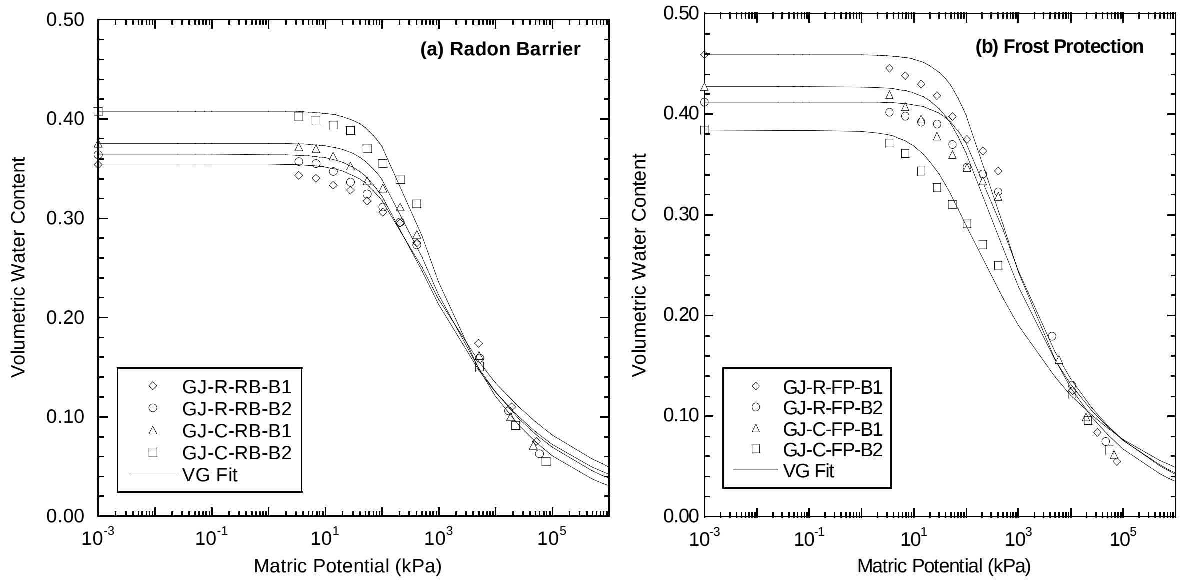


Fig. 3. SWCCs for (a) the radon barrier (RB) and (b) the frost protection layer (FP). R designates Lysimeter R, and C designates Lysimeter C.

Table III. van Genuchten Parameters for Samples from test cell Lysimeters.

Lysimeter	Layer	θ_s	θ_r	α (kPa^{-1})	n
C	Bedding	0.25	0.05	0.81	1.60
R	Bedding	0.25	0.00	1.91	1.28
C	Frost Protection	0.43	0.00	0.013	1.24
C	Frost Protection	0.38	0.00	0.036	1.20
R	Frost Protection	0.46	0.00	0.0092	1.28
R	Frost Protection	0.41	0.00	0.0073	1.26
C	Radon Barrier	0.38	0.00	0.0071	1.26
C	Radon Barrier	0.41	0.00	0.0057	1.30
R	Radon Barrier	0.35	0.00	0.0087	1.22
R	Radon Barrier	0.36	0.00	0.0092	1.24
C	Transition	0.25	0.04	1.13	1.42
R	Transition	0.25	0.05	0.88	1.56

The difference between α in the road base (transition and bedding layers) and α in the clay (protection layer and radon barrier) reflects the different pore size distributions of these materials (Table 1). The clay has much smaller pores and, therefore, much higher air entry suction (lower α) than the road base material. The radon barrier also has lower α than the protection layer, which reflects the smaller pores obtained when compacting the clay to a higher dry unit weight. The control on compaction water content employed during the radon barrier's construction also resulted in a narrower range of α relative to the protection layer (0.0071–0.0092 kPa^{-1} vs. 0.0073–0.013 kPa^{-1}). Both the clay and the road base have an *n* value that is less than 2, which indicates the broad distribution of pores characteristic of compacted clays [21] and broadly graded, coarse-grained soils. The low residual water content obtained for both materials (0.00 for clay; 0.04-0.05 for the road base) indicates that sufficient equilibration time was permitted when measuring points on the dry end of the SWCC.

Edaphology

The success of cover modification will depend, in part, on the edaphic properties of cover soil layers [12]. Edaphology is the branch of soil science concerned with the influence of soils on living things, particularly plants. Initiating a favorable succession trajectory for plants, and reliable transpiration rates, will require the characterization and possible enhancement of edaphic properties. Soils excavated and stockpiled to construct the Grand Junction Disposal Cell cover and the test sections formed in colluvium and alluvium derived from basalt residuum and weathered clayey shale. The native soils, classified as aridisols, include typic natrargids (soil profiles include a horizon with columnar structure and >15% of the CEC saturated with sodium) and typic calciorthids (soil profiles include a horizon with >15% calcium carbonate and/or at least 5% calcium sulfate). Below is a summary of physical and chemical properties of test section soils that may influence plant establishment and succession. Values (Table IV) are for soil layers sampled during construction of test sections and analyzed by the Colorado State University Soil Testing Laboratory.

Soil physical properties that most influence plant ecology are particle size distribution (texture), dry unit weight (bulk density), and particle aggregation (structure). In general, soil texture and structure influence the distribution and availability of water for plants, root growth, and cation exchange capacity—the quantity of cations that can be adsorbed on negatively charged soil solids. CEC influences the availability of plant nutrients. Blending the loamy sand bedding layer with the silt loam protection layer should produce a layer with favorable plant-available water (see above discussion of soil water retention characteristics). High bulk density values for frost protection and radon barrier layers may hinder root growth. Achieving a bulk density similar to the undisturbed borrow source (1.3 - 1.4 g cm^{-3}) is a goal of this test work. Frost protection and radon barrier layers initially had massive structure—few cracks within soil aggregates—as reflected in low Ks values (see above). A goal of ripping is to create a more blocky structure which should enhance permeability, root development, and plant health.

Soil chemical properties that most influence plant establishment and development are pH, type and concentration of soluble salts, and availability of plant nutrients. Frost protection and radon barrier soils are slightly alkaline, typical for the area, and variably sodic. Sodic soils can adversely affect plant metabolism and indirectly affect root growth by increasing soil dispersion and hindering structural development. Effects of elevated sodium on soil aggregate structure may be offset by the presence of gypsum. Salinity levels are well within tolerance limits for native vegetation in the area and high CEC values reflect the high clay content. Nitrate levels appear to be variably elevated, phosphorus levels are low, and potassium levels are typical for the area.

Overall, high bulk density, which we hope to lower by ripping, and elevated sodium levels, which may be offset by the presence of gypsum, could otherwise adversely influence the establishment and development of a favorable plant community. We will continue to evaluate these and other edaphic properties during the course of the study.

Table IV. Summary of Key Edaphic Properties of Test Section Soil Layers.[a]

Soil Layer	pH	Salts (mmho/cm)	CEC meq/100 g	Nitrate-N (ppm)	Phosphorus (ppm)	Potassium (ppm)
Bedding	7.8 - 8.7	1.4 - 3.5	15.1 - 21.5	0.6 - 12.5	3	62 - 81
Frost protection	7.8 - 8.2	2.7 - 4.9	30.6 - 34.5	0.7 - 4.2	2 - 5	170 - 246
Radon Barrier	7.8 - 8.4	1.7 - 4.8	43.3 - 48.2	1.2 - 16.5	2 - 9	198 - 310

Soil Layer	% Sand	% Silt	% Clay	Texture[b]	SAR[c]	Bulk Density (g cm^{-3})
Bedding	81 - 83	12 - 15	4 - 5	Loamy sand	2 - 8	-
Frost protection	15 - 23	56 - 67	10 - 25	Silt loam	6 - 21	1.73
Radon Barrier	8 - 19	33 - 35	47 - 59	Clay	6 - 12	1.79

[a] Value ranges for n=4 samples taken from test sections during construction.
[b] USDA soil texture classification system.
[c] Sodium absorption ratio = $Na/(Ca+Mg/2)^{1/2}$ in meq/L.

MONITORING SYSTEM

The lysimeters were equipped with a system for monitoring water balance and state properties. Surface runoff collected by diversion berms and percolation collected in the lysimeter sump are conveyed via Sch 40 PVC pipe to collection basins. Water collected in the percolation and runoff basins is monitored with a pressure transducer and a float switch. The flow of water into the percolation tank is monitored with a high-capacity tipping bucket. The tipping buckets and the pressure transducers were calibrated in accordance with the methods in Benson et al. [16].

Water content is measured using CS 616 water content reflectometers (WCRs) manufactured by Campbell Scientific, Inc. The WCRs are installed in two nests located along the centerline at the upper and lower quarter points of each lysimeter. Each nest contains seven probes that are used to monitor the transition layer (two probes), radon barrier (two probes), protection layer (two probes), and bedding layer (one probe). The soil-specific calibration of the WCRs was conducted using the method described in Benson and Wang [22], which includes temperature compensation. The calibration equation has the form:

$$\theta = \frac{-(b_1 - a_1T) + \sqrt{(b_1 + a_1T)^2 - 4a_2T(a_0T + b_0 - P)}}{2a_2T} \quad \text{(Eq. 2)}$$

where P is the period reported by the WCR, T is the soil temperature at the probe location, and a_0, a_1, a_2, b_0, and b_1 are calibration parameters. Calibration was conducted on samples of the radon barrier, protection layer, and road base that were composited after conducting the hydraulic properties tests. Specimens used for calibration were prepared at the average dry unit weight of each material that was measured in the field.

Matric suction (ψ) in the cover profile was monitored with CS 229 thermal dissipation sensors (TDSs) manufactured by Campbell Scientific, Inc. The TDSs were calibrated following the procedure in Sawangsuriya et al. [23], which is based on the non-dimensional parameterization proposed by Flint et al. [24]. The calibration equation has the form:

$$\psi = \psi_o \qquad T^* = 1 \qquad \text{(Eq. 3a)}$$

$$\psi = \frac{\psi_o}{T^{*\frac{1}{\lambda}}} \qquad T^* < 1 \qquad \text{(Eq. 3b)}$$

where T^* is the normalized temperature drop and ψ_o is the air entry suction for the ceramic element in the TDS. The normalized temperature drop is computed as:

$$T^* = \frac{\Delta T_d - \Delta T}{\Delta T_d - \Delta T_s} \qquad \text{(Eq. 4)}$$

where ΔT_d is the temperature drop for a dry TDS, ΔT_s is the temperature drop for a saturated TDS, and ΔT is the temperature drop at a given ψ. A unique calibration for each TDS was conducted. However, compilation of the data showed that a single calibration could be applied to all sensors. This calibration has ΔT_d = 3.94 °C, ΔT_s = 1.41 °C, ψ_o = 12 kPa, and λ = 0.43.

Meteorological data (precipitation, air temperature, relative humidity, wind speed and direction, and solar radiation) are measured with a meteorological station mounted on the test facility. A Campbell Scientific, Inc., CR21X datalogger mounted at the meteorological station is used to collect data from the meteorological sensors as well as all other sensors installed at the test facility. Data are recorded hourly under quiescent conditions. However, when water elevations in the basins change more rapidly (e.g., during heavy precipitation), data are recorded as frequently as every 15 s. A comprehensive data quality assurance review is conducted quarterly to ensure the integrity of the data and to identify problems (potential and actual) in the monitoring system. Wiring for the datalogger and sensors was oriented to facilitate the ripping of Lysimeter R without damaging the instrumentation.

MONITORING DATA

Monitoring data have been collected from the test lysimeters since 15 November 2007. Water balance data are summarized graphically in Fig. 4. Through 24 October 2010, total precipitation has been 620 mm and the average annual precipitation has been 207 mm.

Water Balance

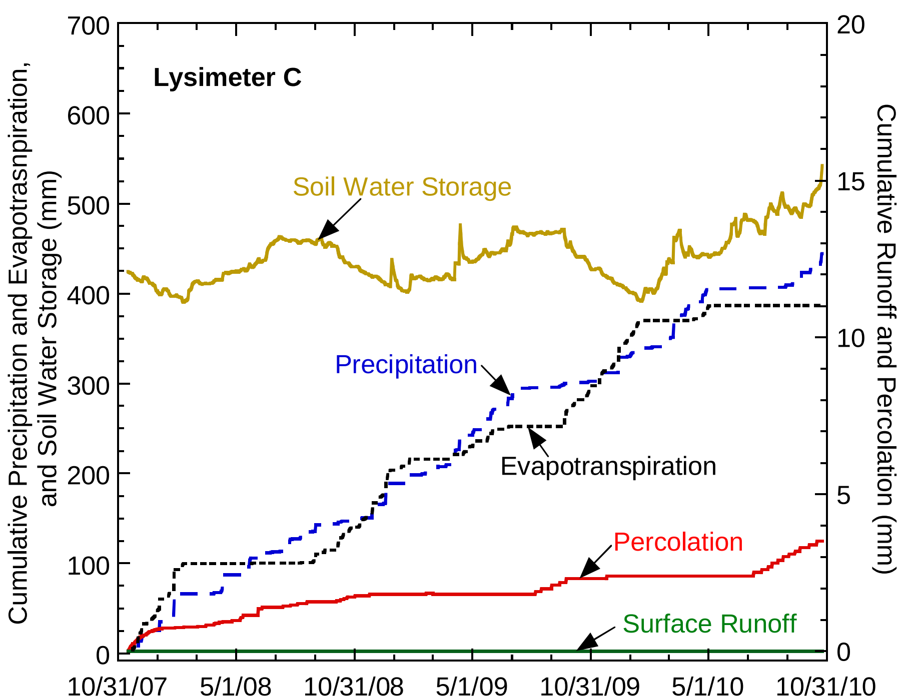
Evapotranspiration has been the dominant flux from both lysimeters, percolation has been very small (less than 4%), and there has been only trace of runoff (0.1 mm in 2010). In 2008, the first complete year of monitoring, both lysimeters transmitted 1.1 mm of percolation and had no runoff; Lysimeter C emitted 155 mm of surface evaporation, and Lysimeter R emitted 158 mm of surface evaporation. Throughout the entire monitoring period, Lysimeter C has transmitted 3.5 mm of percolation, and Lysimeter R has transmitted 12.2 mm.

Both lysimeters are beginning to show deterioration of the radon barrier (Fig. 4). Percolation records for both lysimeters have followed a more intermittent or stair-step pattern at times (e.g., 2009), which is commonly associated with formation of preferential flow paths [2,3]. In 2010, the percolation rate increased appreciably, especially for Lysimeter R, which transmitted 9.1 mm of percolation (Lysimeter C transmitted 1.2 mm during the same period). However, 2010 was the wettest year during the monitoring period. Thus, lower percolation rates may be realized in the future when precipitation is less.

Water Contents and Matric Suctions

Data for water contents and suctions for the bedding layer and the upper portion of the protection layer in both lysimeters displayed relatively large swings in water content in response to infiltration during precipitation events and surface evaporation. In contrast, subtle variations in water content occurred within the radon barrier and the transition layer in both lysimeters. The riprap and the bedding layer appear to be functioning as an inverted capillary barrier that limits water removal from most of the radon barrier and the interim cover layer in both lysimeters. Modest oscillations in matric suction in the lower portion of the protection layer, the radon barrier, and the bedding layer also support the presence of an inverted capillary barrier at the surface of the lysimeter.

Comparisons of water contents in upper and lower nests of WCR probes in each lysimeter indicate that conditions are reasonably uniform at a given depth. Moreover, the uniformity increases with depth: the water contents recorded by the deepest probes (in the transition layer) in the upper and lower nests of each lysimeter are nearly identical. Comparing the two lysimeters' respective water contents also indicates that both are behaving essentially the same. This similar behavior is consistent with the similarity in the water balance quantities described above. The only significant difference was the higher peak water contents in Lysimeter C during the first winter and spring of the monitoring program.



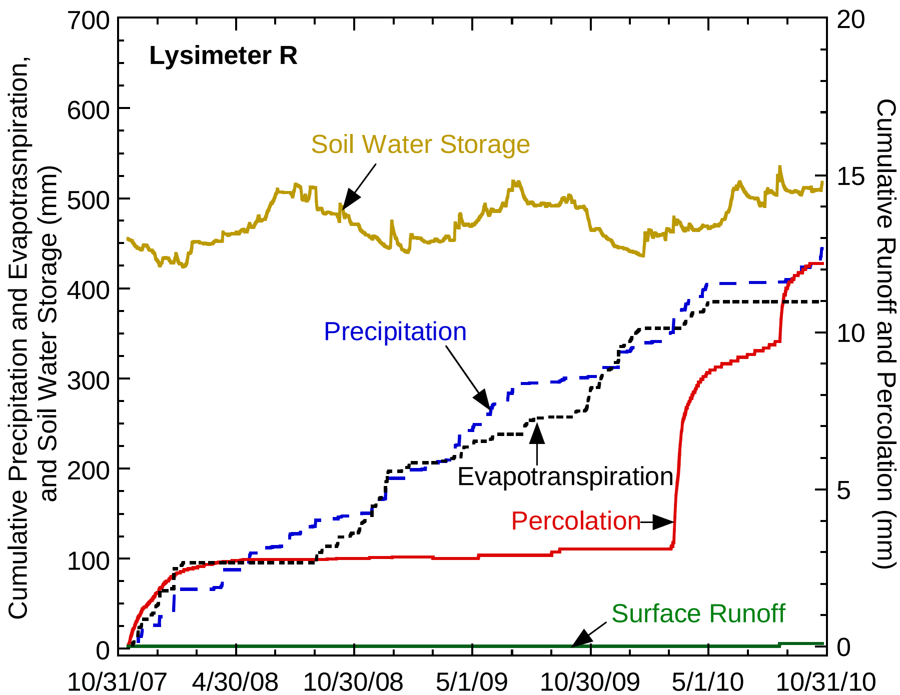


Fig. 4. Water balance quantities for Lysimeters C and R at the Grand Junction Disposal Cell from November 15, 2007, to March 29, 2009.

NATURAL ANALOGS

Geomorphological and ecological evidence from a natural analog site, called Beaver Gulch, near the Grand Junction Disposal Site [25] supports the concept of ripping and blending the riprap, bedding layer, and underlying protection layer, and planting native shrubs in the rip rows. Studies of natural analogs provide clues, from present and past environments, that point to possible long-term changes in engineered covers [26]. Analog studies involve the use of logical analogy to investigate natural materials, conditions, or processes that are similar to those known or predicted to occur in some component of an engineered cover system. As such, analogs can be thought of as uncontrolled, long-term experiments. Evidence or clues from Beaver Gulch suggest that a vegetated rock and soil cover would be adequate to control erosion and limit percolation over hundreds to thousands of years. Rock varnish, lichenometry, soil morphology, and plant community characteristics indicate the slope's stability and relative age, long-term water movement through the soil profile, and the trajectories of plant succession.

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