Monitoring the Performance of an Alternative Landfill Cover at the Monticello, Utah, Uranium Mill Tailings Disposal Site

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ABSTRACT

The U.S. Department of Energy Office of Legacy Management (DOE) and the U.S. Environmental Protection Agency (EPA) collaborated on the design and monitoring of an alternative cover for the Monticello uranium mill tailings disposal cell, a Superfund site in southeastern Utah. Ground-water recharge is naturally limited at sites like Monticello where thick, fine-textured soils store precipitation until evaporation and plant transpiration seasonally return it to the atmosphere. The cover at Monticello uses local soils and a native plant community to mimic the natural soil water balance. The cover is fundamentally an evapotranspiration (ET) design with a capillary barrier.

A 3-hectare drainage lysimeter was embedded in the cover during construction of the disposal cell in 2000. The lysimeter consists of a geomembrane liner below the capillary barrier that directs percolation water to a monitoring system. Soil water storage is determined by integration of point water content measurements. Meteorological parameters are measured nearby. Plant cover, shrub density, and leaf area index (LAI) are monitored annually.

The cover performed well over the 7-year monitoring period (2000-2007). The cumulative percolation was 4.2 mm (0.6 mm yr^{-1}), satisfying an EPA goal of an average percolation of <3.0 mm yr^{-1}. Almost all percolation can be attributed to the exceptionally wet winter and spring of 2004-2005 when soil water content slightly exceeded the water storage capacity of the cover. The diversity, percent cover, and LAI of vegetation increased over the monitoring period, although the density of native shrubs that extract water from deeper in the cover has remained less than revegetation targets.

DOE and EPA are applying the monitoring results to plan for long-term surveillance and maintenance and to evaluate alternative cover designs for other waste disposal sites.

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INTRODUCTION

The U.S. Department of Energy Office of Legacy Management (DOE) and the U.S. Environmental Protection Agency (EPA) collaborated on the design and construction of a disposal cell to contain uranium mill tailings at the DOE Monticello, Utah, Disposal Site (www.lm.doe.gov/land/sites/ut/monticello/monticello.htm). This study addresses the use of an engineered earthen cover to reduce percolation of precipitation into the underlying tailings. Many conventional covers designed for uranium mill tailings disposal cells rely on the low hydraulic conductivity of a compacted soil layer to limit infiltration and percolation. An alternative design approach is to manipulate the cover ecosystem with the goal of enhancing soil water storage and plant evapotranspiration. The performance of the alternative design depends on interaction of the climatology, soil hydrology, and plant ecology of the site.

This paper reviews (1) the history and regulatory background of the Monticello Disposal Site, (2) the environmental setting and design of the Monticello cover, (3) the design and installation of a 3-hectare (ha) (7.5-acre) lysimeter embedded in the cover, and (4) water balance and vegetation monitoring results from the lysimeter since 2000. Results of studies using small weighing lysimeters and large caisson lysimeters that led to the final cover design for Monticello were reported in previous Waste Management Conference Proceedings [1, 2].

HISTORY AND REGULATORY REQUIREMENTS

Monticello is a small town located in the southeastern corner of Utah in San Juan County (Figure 1). Vanadium Corporation of America constructed the original Monticello mill in 1942 with Federal Government funding to provide vanadium during World War II. Beginning in the mid-1940s and ending in 1960, the mill processed vanadium and uranium ores from across the Colorado Plateau. Concentrated vanadium ore was shipped off site for use in the hardening of steel. Concentrated uranium ore was shipped off site for use in the production of nuclear weapons components. Processing of the ores resulted in the generation of tailings that were stored at the site. The mill processed nearly one million Mg of uranium ore and produced more than 2.5 million m^3 of tailings and other contaminated materials before its closure. The tailings contain high concentrations of a variety of metals and radioactive materials that pose a risk to human health and the environment.

The Monticello Mill Tailings Site was placed on the National Priorities List (Superfund) in 1989 because of the risks associated with mill tailings and related contaminated materials. Tailings at the former millsite and nearby contaminated properties were cleaned up, as required by the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). DOE, EPA, and the State of Utah Department of Environmental Quality (UDEQ) entered into a Federal Facilities Agreement that specified DOE as the lead Federal agency responsible for cleanup at the millsite, and EPA and UDEQ as regulatory oversight agencies. The disposal cell design was subject to both minimum technology guidance for hazardous waste disposal facilities [3] under subtitle C of the Resource Conservation and Recovery Act of 1976 (RCRA), and design guidance for radon attenuation and 200-1000-yr longevity [4] under the Uranium Mill Tailings Radiation Control Act of 1978 (UMTRCA). Construction of the tailings disposal cell was completed in 2000.

DOE initiated long-term surveillance and maintenance (LTS&M) activities in 2001 with regulatory oversight by EPA Region VIII and UDEQ [5]. LTS&M activities include routine inspection, operation, and maintenance of the disposal cell; annual site inspections; and CERCLA 5-year reviews (begun in 1997) to monitor and document the effectiveness of the selected remedies.

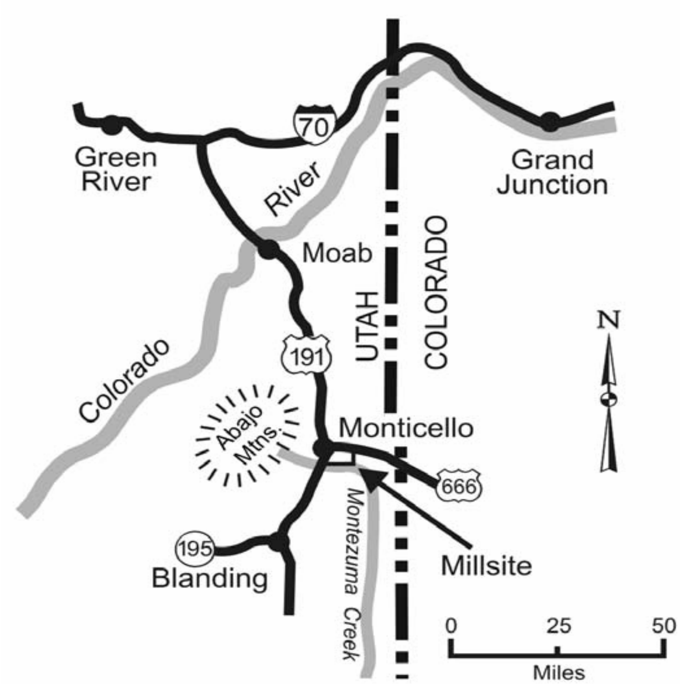

Fig. 1. Location of the Monticello Millsite in southeastern Utah.

CLIMATE, SOILS, AND VEGETATION

Monticello is semiarid with cold, windy winters and mild summers. The 58-yr (1948–2006) average annual precipitation is 390 mm (15.4 in). The average minimum January temperature is -10.5 °C, and the average July maximum temperature is 28.9 °C. Three seasons occur with respect to soil-water balance: November through March, the season of deep infiltration and moisture accumulation in soils (precipitation averages 160 mm); April through June, a moisture-depletion period when plants are most active (precipitation averages 60 mm); and July through October, a season of near-surface moisture accumulation and depletion resulting from monsoonal convection storms (precipitation averages 170 mm). Annual snowfall averages 160 to 170 cm.

The clay loam to sandy loam soils (*Monticello very fine sandy loam*) within the footprint of the Monticello disposal cell formed in Pleistocene loess [6]. The potential natural vegetation in this soil consists primarily of western wheatgrass (*Pascopyrum smithii*), Sandberg bluegrass (*Poa secunda*), blue grama (*Bouteloua gracilis*), mountain big sagebrush (*Artemisia tridentata* subsp. *vaseyana*), and rubber rabbitbrush (*Ericameria nauseosa*), and typically has a canopy coverage of 50% to 60%.

COVER DESIGN AND MONITORING OBJECTIVES

Conventional and Alternative Covers

Most conventional cover designs include compacted soil layers (CSLs) to impede percolation into underlying contaminated materials [3, 4]. Although design targets and performance standards for CSLs vary, the typical goal is a saturated hydraulic conductivity less than 1×10^{-7} cm/s. Multiple lines of evidence (including EPA and DOE field studies, laboratory studies, and monitoring data) show that many existing CSLs in covers fall short of the low-conductivity targets, often at or shortly after construction, and sometimes by several orders of magnitude [7, 8, 9, 10, 11, 12, 13, 14]. Several reasons are cited:

- Unanticipated ecological consequences of designs that encourage biointrusion [14, 15, 16, 17, 18, 19].
- Compaction either dry or wet of optimum during construction [9, 20].
- Desiccation cracking [7, 12].
- Differences between laboratory and field-determined saturated hydraulic conductivities [9, 20].
- Freeze-thaw cracking [21, 22].
- Differential settlement [9, 23, 24].
- Retention of borrow soil structure (clods) during construction and pedogenesis (soil development processes) after construction [9, 11, 13, 14, 19].

Advances in the science of cover performance and lessons learned from monitoring conventional covers contributed to the development of alternatives to the low-conductivity designs for uranium mill tailings [25]. In many arid and semiarid ecosystems, relatively low precipitation, high potential evapotranspiration (ET), and thick unsaturated soils limit recharge [26]. Alternative covers that mimic this natural water conservation, sometimes called ET covers [27, 28], may provide long-term hydrologic isolation of subsurface contaminants, thereby reducing long-term risk [29]. Alternative covers can also be viewed as a type of enhanced natural attenuation—a sustainable manipulation of natural processes that limits contaminant migration [30].

Covers that rely on this store-and-release principle consist of thick, finer-textured soil layers that store precipitation in the root zone where it can be removed seasonally by ET [31]. Capillary barriers, composed of coarse-textured sand and gravel placed below this soil “sponge,” can enhance soil water storage capacity and limit unsaturated flow [32, 33, 34]. Available water storage capacity has been defined as the difference between the total amount of water retained in a soil at field capacity (*drained upper limit*) and the amount of water remaining when the soil dries to the permanent wilting point for plants (*lower limit of extraction*) [35]. At the permanent wilting point, soil water tensions become too high for plants to remove more water.

The sustainability of ET covers relies, in part, on the establishment and resilience of a diverse plant community [36]. Changes in the plant community will influence soil water movement, ET rates, and the water balance of a cover. However, plant community dynamics are complicated and effects are difficult to predict. Even in the absence of large-scale disturbances, seasonal and yearly variability in precipitation and temperature will cause changes in species abundance, diversity, biomass production, and soil water extraction rates on covers [37]. Investigations of natural analogs can provide insight as to how ecological processes may influence sustainability of alternative covers [19, 39]. Evidence from natural analogs can improve our understanding of vegetation responses to climate change and disturbances; effects of vegetation dynamics on ET, soil hydraulic conductivity, soil erosion, and animal burrowing; and effects of soil development processes on water storage, hydraulic conductivity, and site ecology.

Monticello Cover Design

The final cover for Monticello is a composite design that surpasses the EPA minimum technology guidance for hazardous waste disposal facilities regulated under RCRA Subtitle C [3] and exceeds UMTRCA radon attenuation requirements [4]. The design includes a CSL (or radon barrier) directly above the tailings that is overlain with an HDPE (high-density polyethylene) geomembrane. The cover was also designed to mimic the favorable ecology and water balance of deep eolian soils that occur in the landscape surrounding the disposal site. An EPA goal for the Monticello ET cover is sustainability—to even perform better over time—increasing the probability of satisfying the UMTRCA 200 to 1000-yr design life. This paper focuses on the performance of the Monticello ET cover components independent of the CSL and geomembrane.

The ET cover design for Monticello (Figure 2) relies on the water-storage capacity of a 163-cm, fine-textured soil and rock layer (sponge) overlying a 38-cm, sand capillary barrier layer to retain precipitation until it is seasonally removed by vegetation (solar pumps) [39, 40]. Theoretically, water movement into the sand should occur only if water accumulation at the soil/sand layer interface approaches saturation and tensions decrease sufficiently for water to enter the larger pores of the sand layer. Hydraulic performance can be evaluated as the probability that, over time, ET is sufficient to prevent water accumulation in the soil sponge from exceeding the storage capacity.

Other components of the Monticello design either facilitated construction or were included to enhance long-term performance. A geotextile fabric maintains the fine-grained soil/coarse sand layer discontinuity during construction and until soil aggregation can occur by natural pedogenic processes [41]. The combination of vegetation and the surface gravel admixture controls erosion. Vegetation and organic litter disperse raindrop energy, shield underlying fine soils, increase infiltration, reduce surface water flow and surface wind velocity, bind soil particles, and filter sediment from runoff [42]. Gravel mixed into the surface helps control erosion when vegetation is sparse (following construction, fires, drought, etc.), mimicking conditions that lead to the formation of natural gravel pavements. The gravel admixture also helps disperse raindrop energy, shield underlying fine soils, and reduce flow velocity. Gravel mulches increase near-surface water storage, enhancing seedling emergence. Hence, the gravel admixture controls both wind and water erosion [43, 44] and, functioning as a mulch, enhances seedling emergence and plant growth [45].

The Monticello design includes frost protection, deterrents for biointrusion, and other attributes for plant growth. The topsoil layer has physical and hydraulic properties similar to the rest of the soil sponge, but also contains the nutrients, propagules, and microorganisms (e.g., mycorrhizae) needed to establish a sustainable plant community. The soil depth is more than adequate to protect underlying RCRA components (CSL and geomembrane) from frost damage [46]. The soil sponge thickness is the primary biointrusion deterrent. Water retention in the soil sponge should limit deep root penetration, and the layer exceeds the depth of most burrowing vertebrates in the area. A 30.5-cm layer of cobble-size rock above the capillary barrier is an added deterrent should deeper burrowers, such as coyotes, enter the area. Fine-textured soil fills the interstices of this rock layer, preventing it from behaving like a second capillary barrier.

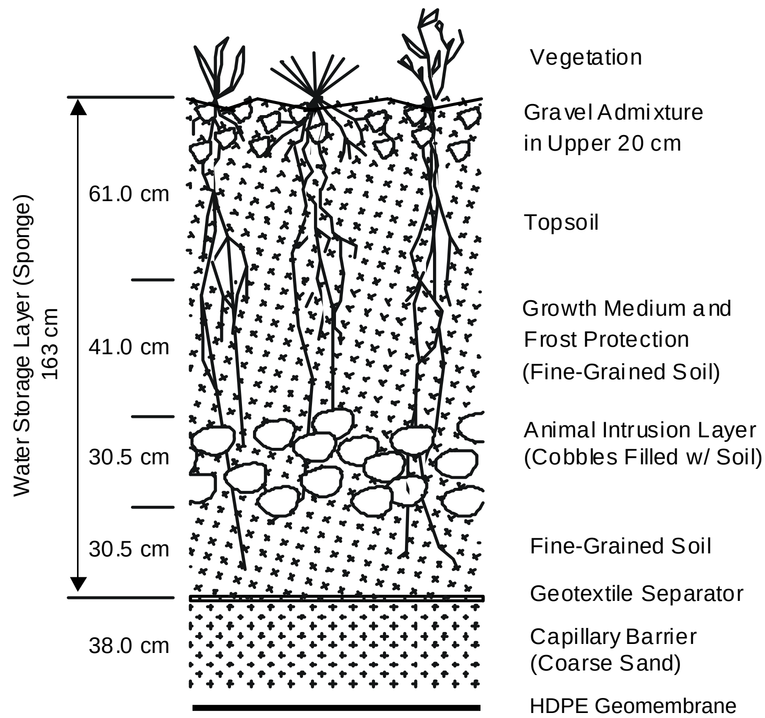

Fig. 2. Monticello ET Cover Profile.

Monitoring Objectives and Parameters

The primary EPA monitoring objective is to demonstrate that annual average percolation from the ET cover is less than 3 mm [47]. Percolation is considered the critical measurement parameter for the study. Secondary monitoring objectives are to collect data appropriate for the development of landfill cover design guidance and to improve numerical modeling methods [47]. Thorough understanding of processes that control water balance and movement within the cover ecosystem is necessary to meet this objective. Secondary monitoring parameters encompass three dominant factors influencing cover performance:

- Climate: Air temperature, relative humidity, wind speed and direction, solar radiation, and precipitation.
- Soils: Changes in water status and inherent hydrologic and engineering parameters
- Vegetation: Changes in plant species composition, canopy cover, shrub abundance, and leaf area index (LAI).

LYSIMETER CONSTRUCTION AND MONITORING

Performance of alternative covers and related ecological parameters fluctuate on a seasonal and yearly basis and can best be evaluated using lysimetry. Sampling and monitoring at Monticello focus on the components of the soil water balance (precipitation, changes in soil water storage, percolation, runoff and evapotranspiration), soil hydraulic properties, and plant establishment and abundance.

Soil Water Balance Monitoring

The water balance the Monticello cover was monitored using a 3-ha drainage lysimeter. Water balance monitoring included input of precipitation, and outputs of evapotranspiration, percolation (or drainage) through the capillary barrier, and runoff. The lysimeter was isolated from runon. Precipitation (*Pt*), percolation (*Pc*), runoff (*Ro*), and water storage changes (ΔS) are measured directly, and evapotranspiration (*ET*) is estimated by difference:

$$ET = Pt - Pc - Ro + \Delta S \qquad \text{(Eq. 1)}$$

All parameters are recorded as linear units (mm) of water.

Drainage lysimeters offer the only direct means for measuring percolation at field scale and, coupled with additional soil instrumentation, allow comprehensive evaluation of the soil-water balance of alternative cover designs [48]. Lysimeters have been used for many years to evaluate irrigation needs and, more recently, to test the hydrologic performance of landfill covers [13, 33, 39, 49].

The 3-ha drainage lysimeter at Monticello, installed during construction of the 16-ha (40-acre) topslope of the Monticello disposal cell, functions as a large-scale water collection system. The HDPE geomembrane placed below the ET cover (Figure 2) made creation of the water collection system possible. The lysimeter was formed by welding an HDPE flap to the geomembrane that directs percolation water to a sump at the lower corner of the 3-ha facet of the cover. Surface runoff is collected in a 10 m × 20 m test plot formed with treated lumber sidewalls and installed within the 3-ha embedded lysimeter. Surface flow is collected in a concrete sump at the low end of the runoff plot.

Percolation and surface runoff are routed by pipes from the sumps into basins equipped with instrumentation (pressure transducer, tipping bucket, and float switch) capable of measuring flows with a precision better than 1 mm/yr. A discussion of the flow measurement system and its precision can be found in Benson et al. [50]. Soil water content is measured by vertical arrays of time domain reflectometry (TDR) probes in three nests located at quarter points along a downslope transect through the embedded lysimeter. Soil water storage is determined by integration of the TDR point water-content measurements. Meteorological parameters (precipitation, air temperature, relative humidity, solar radiation, wind speed, and wind direction) are measured at an on-site weather station and compared to meteorological data from a nearby National Weather Station (NWS).

Figure 3 displays time series of soil water balance parameters in the Monticello ET cover from July 1, 2000 through October 15, 2007. Total percolation measured in the embedded lysimeter was 4.2 mm over the 7-year monitoring period (0.6 mm yr^{-1}), satisfying the EPA goal of an annual average percolation of <3.0 mm yr^{-1}. In contrast, annual percolation in a conventional low-conductivity cover monitored with water flux meters at the Lakeview, Oregon Disposal Site, which has a climate and ecology similar to Monticello, was 100 to over 1000 times higher [14].

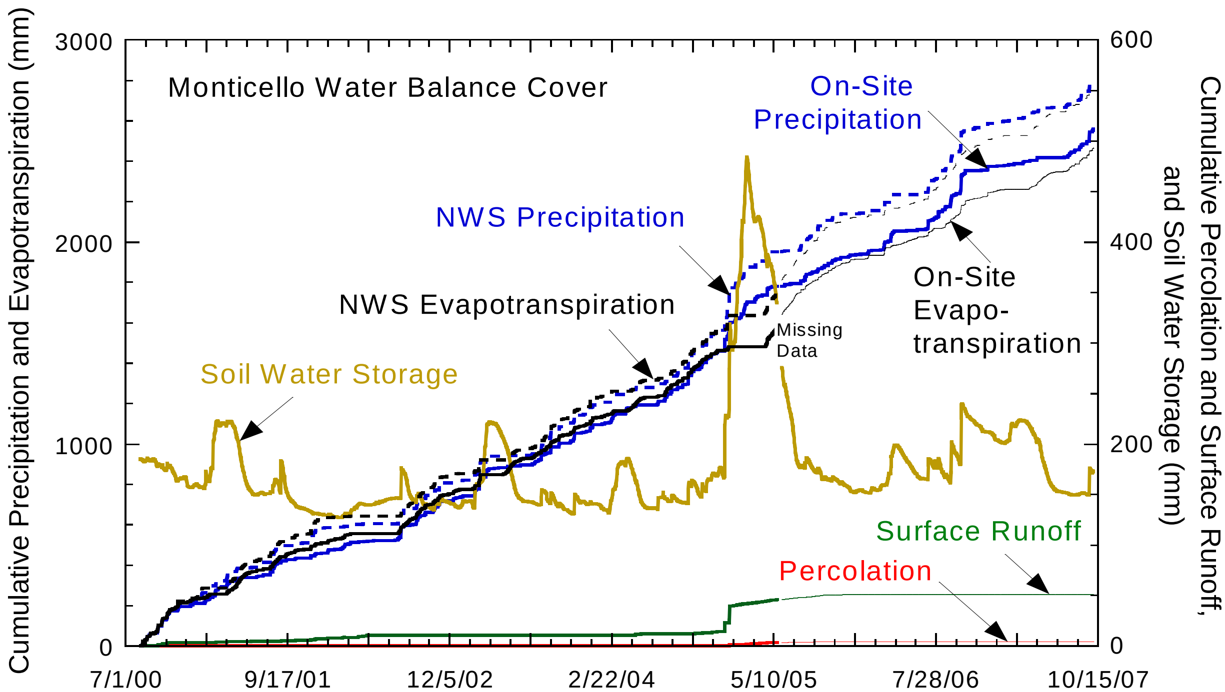

Fig. 3. Water balance of the ET cover at the Monticello, Utah, Disposal Site.

Almost all percolation measured in the embedded lysimeter occurred during the exceptionally wet winter-spring of 2004-2005; there was no percolation in the ET cover during the first 4 years of monitoring. Most of the surface runoff (40 of 51 mm) during the 7-year period also occurred during 2004-2005. Total precipitation for the 6-month period, September 2004 through February 2005—531 mm (20.9 in)—was greater than 250% of the long-term average (211 mm or 8.3 in; 1948-2007). January 2005 precipitation (172 mm; 7.01 in) was the highest January total and the second highest monthly total on record for the Monticello NWS station.

The cyclical soil-water storage time series (Figure 3) reflects the amount and seasonality of precipitation and evapotranspiration. Seasonal high and low water storage occurred in mid-to-late spring and mid-to-late fall, respectively. An overall drying trend from 2000 through 2001 can be attributed to less than average precipitation in 2001 (228 mm; 59% of average) and greater water extraction as plants matured. Soil water storage remained low from 2002 to 2004, fluctuating between seasonal lows of around 125 mm and highs of around 225 mm.

Water storage spiked at about 480 mm during the exceptionally wet winter-spring of 2004-2005, exceeding the drained upper limit of 440 mm, as determined in caisson lysimeters (see section on Soil Sampling and Analysis), causing percolation. Plant evapotranspiration extracted soil water to a lower limit of about 150 mm following the 2005 spike, and again in 2007, which was 25 mm greater than the extraction limit prior to the spike. Higher soil water content near the bottom of the cover profile, after the spike, was the reason for the elevated extraction limit. Poor shrub establishment and hence poor root water extraction likely caused water accumulation near the bottom of the profile. A wet summer monsoon season—315 mm (12.4 in) for July-October;

almost twice the long-term average—kept the seasonal low water storage elevated in 2006, decreasing the available water storage capacity.

Soil Sampling and Analysis

Soil hydraulic properties and soil edaphic (plant growth) properties were evaluated in 2000 and 2006, respectively. Four loose soil samples (20-L buckets) and four undisturbed samples were collected to evaluate hydraulic properties of all layers (Figure 2) at three locations during construction of the embedded lysimeter in 2000. At each location, two of the undisturbed samples were collected using thin-wall sampling tubes (76 mm diameter), and two were collected as hand-carved blocks (200 mm diameter and length). The disturbed samples were analyzed for particle size distribution (ASTM D 422), Atterberg limits (ASTM D 4318), and compaction characteristics (ASTM D 698). The undisturbed samples were also tested to determine saturated hydraulic conductivities (ASTM D 5084 or D 5856) and soil water characteristic curves (SWCC) (ASTM D 6836).

Complete hydraulic property results of all tests are contained in Gurdal et al. [51]. This section only addresses particle size and parameters needed to calculate soil water storage capacity. Soil particle size was classified for each ET cover layer, as follows, using the Unified Soil Classification System: Gravel admixture (GL), topsoil (CL), fine-grained soil (CL), animal intrusion layer (GP), and capillary barrier (SP).

The total storage capacity, or drained upper limit, was determined two ways: (1) calculated from SWCCs using the method in Khire et al. [52], which accounts for the additional storage in an overlying finer layer provided by the textural contrast at the capillary break, and (2) measured directly in large caisson lysimeters [2]. The lower bound, geometric mean, and upper bound for soil water storage capacity, calculated from SWCCs, were 480, 513, and 558 mm, respectively. These calculations of storage represent the total water stored in the soil profile rather than available water storage capacity (the difference between the drained upper limit and the lower limit of extraction). The drained upper limit as measured directly in the caisson lysimeters was 440 mm. The difference may be attributable either to soil spatial variability, irregularities in the soil-sand interface at the capillary break, or to soil structural development and preferential flow in the caissons.

Soil edaphic properties, sampled in 2006, included soil bulk density, fertility, structure, and texture. The following preliminary results (Table I) represent only the upper portion of the soil profile. A more comprehensive evaluation of soil morphology and related hydraulic properties will be completed in 2008.

Soil fertility, texture, and bulk density are not likely inhibiting plant growth; values are within normal ranges and the ET cover soils are similar to a nearby analog site (similar soils but with a mature sagebrush-dominated plant community). At both locations, soil pH is slightly alkaline, soil conductivity is typical for semiarid sagebrush steppe, and organic matter content reflects decay of leaf litter. Concentrations of soil macronutrients (nitrogen, phosphorus, and potassium) and micronutrients (sulfate, zinc, iron, manganese, copper, calcium, magnesium, sodium, and boron) are also similar and within typical ranges. Soil texture classes and near-surface bulk density (compaction) values are also similar.

Table I. Soil fertility, texture, and bulk density for the topsoil layer in the embedded lysimeter and at an analog site with similar soil[a].

Fertility	pH	Salts (mmho/cm)	Organic Matter LOI- %	Nitrates (ppm)[b]	Phosphorus (ppm)	Potassium (ppm)
ET Cover	8.3	0.26	1.1	0.25	8.5	142
Analog Site	8.2	0.29	1.3	0.30	8.0	190

Texture and Bulk Density	% Sand	% Silt	% Clay	Texture[c]	% Coarse Fragments[d]	Bulk Density
ET Cover	35	29	36	Clay loam	5-30	1.45
Analog Site	34	34	32	Clay loam	5-30	1.41

[a] Mean values for n=10; 5 samples at 15 cm and 5 samples at 30 cm depths.
[b] Parts per million.
[c] USDA classification system.
[d] Estimates, by volume, made in the field.

Lack of soil structural development and its possible effects on water movement may be contributing to poor shrub establishment on the ET cover (see section on Vegetation Establishment and Monitoring). Only weak structural development was observed in near-surface horizons on the ET cover. In the sagebrush analog area, all the soil profiles contained well-developed argillic horizons (zones of translocated clay accumulation that had strong blocky structure). The well-developed structure of analog soils may cause preferential flow of precipitation, which enhances habitat for shrubs that rely on deep moisture to compete with grasses and forbs, and for seed production at the end of a summer of moisture depletion.

Vegetation Establishment and Monitoring

Revegetation goals for the Monticello cover included plants that (1) are well-adapted to the engineered soil habitat, (2) are capable of high transpiration rates, (3) limit soil erosion, and (4) are structurally and functionally resilient. Diverse mixtures of native and naturalized plants are thought to maximize water removal and remain resilient given variable and unpredictable changes in the environment resulting from pathogen and pest outbreaks, disturbances (overgrazing, fire, etc.), and climatic fluctuations. In contrast, the exotic grass plantings common on engineered covers are genetically and structurally rigid, are vulnerable to disturbance or eradication by single factors, and require continual maintenance.

The Monticello cover was seeded and planted in September 2000 with a mixture of grasses, forbs, and shrubs (Table II), in an attempt to mimic the potential natural vegetation of native borrow soils, based on characterization of reference plant communities. The monitoring objective was to satisfy revegetation acceptance criteria established for the site [54]. Species composition, percent cover, shrub density, and LAI have been measured since 2001. Sampling methods included ocular point intercept [55] and quadrat [56] methods for plant cover, a point-quarter-distance method for shrub density [57], and a radiometric method using an LAI-2000 (www.licor.com) for measuring LAI (ratio of leaf area to ground surface area), measured in mid-summer.

From 2001 to 2003, plant cover was dominated by weedy species; cover of desirable grasses and forbs remained less than half of the criteria, and shrub density barely exceeded one tenth of the criteria (Table III). By 2004 and 2005, plant cover had improved considerably, although success

Table II. Species and seeding rates as planted on the Monticello cover.

Scientific Name	Common Name	Variety	Origin	#PLS/Acre[a]
Achillea millefolium	White yarrow		NZ[b]	0.12
Achnatherum hymenoides	Indian ricegrass	Nezpar	CAN	2.00
Pascopyrum smithii	Western wheatgrass	Rosana	WA	3.00
Artemisia tridentata ssp. *tridentata*[c]	Basin big sagebrush		UT	0.10
Artemisia tridentata ssp. *vaseyana*[c]	Mountain big sagebrush		UT	0.10
Artemisia tridentata ssp. *wyomingensis*[c]	Wyoming big sagebrush		UT	0.05
Aster tanacetifolia	Prairie aster		CA	0.05
Astragalus cicer	Cicer milkvetch	Oxley	CAN	1.60
Bromus marginatus	Mountain bromegrass	Bromar	WA	4.00
Elymus lanceolatus	Thickspike wheatgrass	Critana	WA	3.00
Ericameria nauseosa	Rabbitbrush		UT	1.50
Erigeron speciosus	Aspen daisy		UT	0.15
Hesperostipa comata	Needle and thread grass		WY	2.00
Linum lewisii	Lewis blue flax	Appar	WA	2.00
Pleuraphis jamesii	Galleta grass	Viva	TX	1.00
Purshia tridentata	Antelope bitterbrush		ID	1.00
Sphaeralcea coccinea	Scarlet globemallow		UT	0.50
Sphaeralcea grossulariifolia	Gooseberry leaf globemallow		UT	0.50

[a] #PLS/Acre=pounds of pure live seed per acre.
[b] Text on seed label reads "NZ," but the seed probably came from Nevada rather than New Zealand.
[c] Containerized plants. All other species were seeded.

criteria had not been met. Three primary concerns existed: (1) cheatgrass and jointed goatgrass, two annual weedy species, continued to increase on the cover; (2) the density of shrubs remained less than 10 percent of the success criterion, and (3) the relative cover of forbs did not meet success criteria and did not appear to be increasing over time. In response, the disposal cell cover was seeded again, but with a single, native, perennial grass species—bottlebrush squirreltail (*Elymus elymoides)*, which is known to compete with cheatgrass—and several shrub species.

Table III. Revegetation criteria and monitoring results for percent cover, LAI, and shrub density on the Monticello cover.

Year	Percent Cover[a]	LAI[b]	Shrub Density[c]
Criteria	*40*	*NA*	*1000*
2001	5.5	0.14	28
2002	12.2	0.23	139
2003	23.5	0.27	88
2004	31.3	0.47	96
2005	37.7	0.61	142
2006	45.3	0.83	125
2007	45.8		90

[a] Percent canopy cover for desirable species (excludes cover of noxious and other weeds) for the entire cover.
[b] LAI (leaf area index) ratio = total leaf surface area of canopy / ground surface area below canopy.
[c] Number of plants per acre.

By September 2006, abundance of perennial grass species from both seedings had increased, the percentage of cheatgrass and jointed goatgrass cover was sharply reduced, and the criterion for percent cover of desirable plant species was met for the first time. Shrub density, however, remained below the acceptance criterion.

Likely causes of poor shrub establishment on the disposal cell were evaluated in 2006 [58]. Vegetation, soil, and wildlife parameters on the cover and in nearby analog areas were compared. Results of this study indicated that the likely contributors to poor shrub establishment include undeveloped soil structure, factors affecting germination of rabbitbrush and sagebrush seed, and predation by voles. Rabbitbrush seedlings were planted in 2007 in an effort to increase shrub density.

CONCLUSIONS

Results after seven years of monitoring the ET cover at the Monticello, Utah Disposal Site will help guide (1) long-term surveillance and maintenance decisions, and (2) the design and management of future waste disposal cells. Some conclusions and lessons learned follow:

- The Monticello ET cover, designed to mimic the water storage capacity and evapotranspiration of surrounding native soils and vegetation, successfully limited percolation through the cover, satisfying an EPA percolation objective of less than 3 mm per year.
- Percolation, a key cover performance monitoring parameter, was less by a factor of 100-1000 times in the Monticello ET cover than in conventional low-conductivity covers constructed at other DOE uranium mill tailings disposal cells.
- Continuous monitoring over several years is necessary to understand how covers are influenced by fluctuations in climate and other environmental factors. Almost all percolation from the Monticello ET cover occurred during one exceptionally wet year.
- Water storage capacity measured in lysimeters during a period of percolation, a key design and performance parameter for ET covers, was 80-90% of the storage capacity computed on the basis of soil water characteristic curves. Performance evaluations should use field measurements when possible.
- Successful design, performance monitoring, and maintenance of ET covers require measurement of soil edaphic properties (properties that influence vegetation establishment and growth), as well as measurement of soil hydraulic properties.
- Successful design, performance monitoring, and maintenance of ET covers also require an understanding of plant ecology and ecophysiology. For example, poor establishment of deep-rooted shrubs on the Monticello cover likely caused water accumulation lower in the profile after an exceptionally wet year and hence, a subsequent decrease in the available water storage capacity.

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