MONITORING THE LONG-TERM PERFORMANCE OF URANIUM MILL TAILINGS COVERS

W.J. Waugh, Roy F. Weston, Inc.
Grand Junction Office, Grand Junction, CO 81503, U.S.A.

ABSTRACT

The effects of root intrusion on the performance of the uranium mill tailings disposal cell at Burrell, Pennsylvania, were evaluated. The intended design life of the disposal cell is 200 to 1,000 years. Within 3 years after construction, a diverse plant community established on the rock cover of the disposal cell. Within 10 years, Japanese knotweed, an exotic perennial, had rooted through the rock layer and an underlying 90-centimeter compacted clay layer. Air-entry permeameters were used to measure the in situ saturated hydraulic conductivity (K_{sat}) of the compacted clay. The K_{sat} averaged 3.0 ? 10^{5} centimeter per second (cm/s) at locations where Japanese knotweed roots penetrated the clay layer compared to 2.9 ? 10^{7} cm/s at locations where there were no plants. The weighted-average K_{sat} for the 6-acre cover, calculated using the leaf area index for Japanese knotweed, was 4.4 ? 10^{6} cm/s. At a nearby site with a subsoil consisting of the same type of clay, the K_{sat} of the subsoil averaged 1.3 ? 10^{4} cm/s. Earthworm holes, root channels, and structural planes all contributed to macropore flow of water in the subsoil. This nearby site was considered to be a reasonable analog of the long-term condition of the Burrell disposal cell cover. These results indicate that if the ecological consequences of a landfill cover design are not considered during the design process, the establishment of deep-rooted vegetation can degrade low-permeable barriers. At Burrell, because of low-radioactivity levels in the tailings, root intrusion is not expected to adversely influence human health or the environment.

INTRODUCTION

The Burrell, Pennsylvania, disposal cell is a covered landfill constructed by the U.S. Department of Energy (DOE), under the Uranium Mill Tailings Radiation Control Act (UMTRCA) of 1978, to isolate soil contaminated with uranium mill tailings. Observations of plants growing on the disposal cell cover, beginning in 1988, raised concerns about the effects of root intrusion on the long-term performance of the cell. The possibility that root intrusion can increase water infiltration in the cover, and as a consequence increase risks to human health and the environment at the Burrell site, was of particular concern.

This study evaluated possible consequences of root intrusion and long-term ecological change on the Burrell engineered cover as the basis for a vegetation management strategy. The premise for the study is that performance evaluations, and potentially costly maintenance decisions, should be based not only on design criteria and standards but also on risk management needs. Our objectives were to evaluate (1) effects of root intrusion on cover design criteria related to water infiltration and (2) effects of ecological change on long-term cover performance and risk. Our evaluation focused on collection of field data for parameters that sensitivity analyses suggest have the greatest influence on water infiltration (1). Waugh and Smith (2) address plant root intrusion effects on radon flux from the disposal.

This paper discusses regulatory drivers for water infiltration at UMTRCA sites, the role plant ecology should play in the process of designing and maintaining engineered covers, and methods and results of the plant root intrusion study at Burrell, including characterization of an area considered to be a natural analog of the long-term performance of the Burrell cover.

BACKGROUND INFORMATION

Applicable Statutes and Guidance

Our evaluation of the potential effects of root intrusion on the performance of the disposal cell cover at the Burrell site centered on regulatory standards concerning water resources protection and design life. In 1995, the U.S. Environmental Protection Agency (EPA) published 60 *Federal Register* (FR) 2854, the Final Rule for control of radioactive materials from inactive uranium processing sites. The Final Rule requires remediation action to ensure that amounts of radioactive and associated hazardous constituents in ground water meet certain concentration standards. Compliance with ground-water standards depends largely on an engineered cover that limits infiltration of water (3).

EPA established a standard for the design life of disposal cells of 1,000 years whenever reasonablyachievable, but, in any case, a minimum performance period of 200 years must be achieved (4). We assumed that the present plant community at Burrell is an early successional phase and that as the plant community changes the effects of root intrusion will likely surpass what has occurred thus far. Therefore, this study was designed to project possible ranges of ecological change that could occur tens to hundreds of years in the future.

Role of Plants on Disposal Cell Covers

Growth of vegetation on the Burrell cover should have been anticipated. Surface layers of rock reduce evaporation (5), increase soil water storage (6), and, consequently, create habitat for deep-rooted plants. Vegetation management decisions should rely on an understanding of the potential roles plants play, beneficial as well as detrimental, on the performance and longevity of the cover. The role of plant ecology in the process of designing and evaluating engineered covers has been addressed in detail elsewhere (7,8,9,10). A brief review follows.

A central issue is whether plants growing on a disposal cell cover will increase or decrease the likelihood of contaminant discharge from the disposal cell. This issue can be argued both ways. Decaying plant roots may create conduits through which water and gases readily pass, thus potentially increasing water infiltration and contaminant discharge. Conversely, extraction of soil water from the cover by plants (transpiration) may significantly decrease infiltration. Many disposal cell cover designs rely on a combination of plant transpiration and soil evaporation (evapotranspiration) to maintain infiltration at acceptable levels (11,12). Even in humid climates such as in western Pennsylvania, where precipitation exceeds potential evapotranspiration, water extraction by plants may account for more than half the soil water loss from disposal cell covers (13).

Vegetation also improves slope stability. Vegetation helps disperse raindrop energy, slow runoff flow velocity, filter sediment from runoff, bind soil particles, and deplete soil moisture, thereby delaying the onset of saturation and runoff (14). Woody vegetation has been shown to improve the stability of riprap-armored slopes (15). However, the complexity of vegetation and rock-slope interactions has hampered efforts to quantify their role in stability analyses (16,17).

On covers like the Burrell cover, problems with deep-rooted plants may counteract the benefits of vegetation. Plants can root through soil covers into underlying waste material, actively translocating and disseminating contaminants in aboveground tissues. Plants rooted in uranium mill tailings may contain elevated levels of U, Mo, Se, ^{226}Ra, ^{230}Th, and ^{210}Po (18,19,20,21,22). Plants rooted in uranium mill tailings may also increase releases of ^{222}Rn to the atmosphere. Radon can be transported into the atmosphere as plants extract water from tailings (23,24,25). Roots may also alter waste chemistry, potentially mobilizing contaminants (26,27).

Root intrusion may physically degrade the performance of the Burrell cover. Evidence has increased suggesting that covers with compacted soil layers are vulnerable to desiccation and cracking from wet-dry cycles, freeze-thaw cycles, and biointrusion (13,28,29,30). Macropores left by decomposing plant roots can act as channels for water and gases to rapidly bypass the soil mass in compacted soil layers (31). Plant roots also tend to concentrate in and extract water from compacted clay layers, causing desiccation and cracking (29). This dessication and cracking can occur even when overlying soils are nearly saturated (30), suggesting that the rate of water extraction by plants may exceed the rehydration rate of the compacted clay. In addition, roots may clog lateral drainage layers (32), potentially increasing rates of infiltration through the underlying compacted soil.

Long-Term Change and Natural Analogs

Changes in the plant ecology on the cover are inevitable. Plant community dynamics are manifested by shifts in vegetation abundance, species composition, and diversity and may be accompanied by changes in rates of nutrient cycling, energy exchange, and transpiration. Therefore, as the plant community changes, the performance of the cover may respond in ways that cannot be predicted by short-term field tests and numerical models.

Changes in the plant community will be accompanied by pedogenic (soil development) processes. Pedogenic processes may alter the physical and hydraulic properties of engineered soil layers in the cover. Pedogenesis includes processes such as soil structural development (dispersion or flocculation of fines and development of macropores), secondary mineralization and illuviation of materials that causes the formation of distinct layers or horizons, and pedoturbation (natural soil mixing). Although rates and magnitudes vary, pedogenesis takes place to some degree in all soils (33).

Rates of soil development are greatest in engineered soils. The evolution and architecture of macropores associated with root growth, animal holes, and soil structural development are highly relevant. Overall, soil structural development creates preferential flow paths under saturated conditions (34), causing fine-textured soil layers to behave more like a coarse, gravely soil with respect to water movement. Eluviation and illuviation (similar to emigration and immigration) of fine particles, colloids, soluble salts, and oxides in an engineered cover may create secondary layers or horizons with diverging physical and hydraulic characteristics (33).

No unequivocal prediction can be made about the influences of long-term plant succession and soil development on the performance of the Burrell cover, but natural analogs can help. Natural analogs provide clues from present and past environments about possible long-term bounding conditions in engineered covers (10). Evidence from natural analogs is the only means to project emergent properties in the evolution of engineered covers, properties that cannot be captured with short-term monitoring of the cover or with numerical models. Ecological factors expected to have the greatest influence on the long-term performance of the cover can be evaluated by comparing soils and vegetation on the disposal cell with conditions at analog sites. Natural analogs may also have a role in communicating the results of a performance assessment to the public. Evidence from natural systems helps demonstrate that numerical predictions have real-world complements.

Burrell Cover Design and Vegetation Management

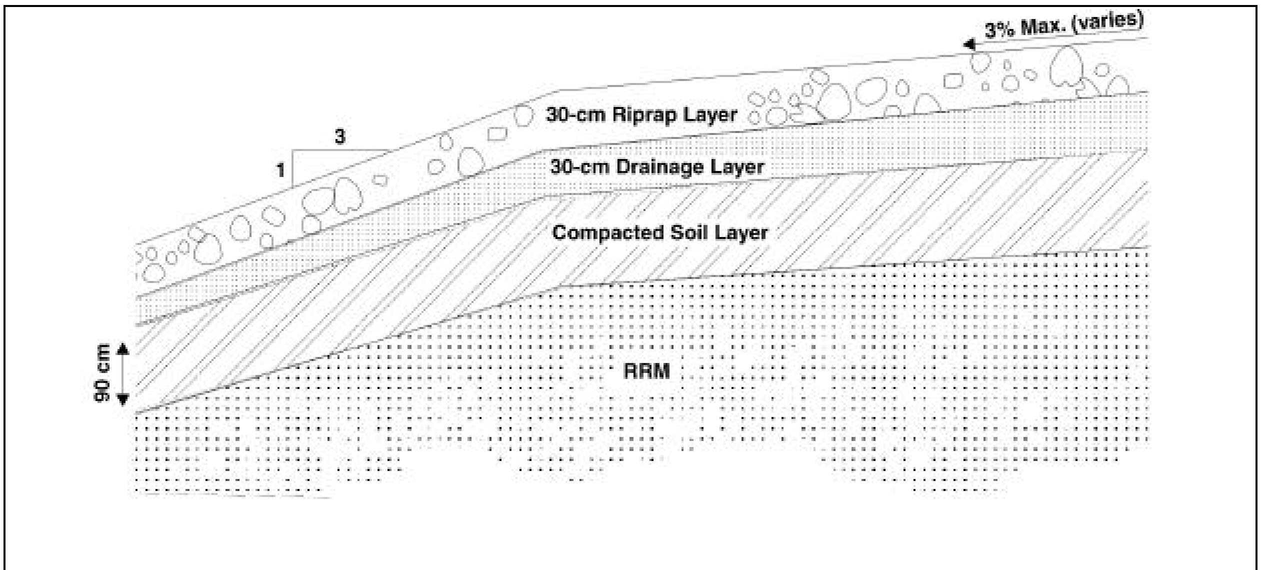
From the bottom up, the Burrell cover consists of a 90-cm-thick "radon barrier" or compacted soil layer (CSL) overlying the residual radioactive materials (RMM), a 30-cm-thick sand and gravel drainage layer, and a 30-cm-thick rock layer (Fig. 1). The target hydraulic conductivity for the CSL was 1 x 10^{7} centimeter per second (cm/s). The sand and gravel drainage or filter layer also serves as a bedding layer for the rock armor. The rock armor is sized to prevent erosion of underlying layers, given a probable maximum precipitation (PMP) event, the most severe combination of meteorological and hydrological conditions possible at a site (3).

Material property data for the CSL (Table I) were compiled from the completion report for Burrell. Actual compaction of the radon barrier during construction averaged 96.6 percent of the maximum dry density. Actual average, maximum, and minimum gravimetric moisture content of the radon barrier during construction were 17.7 percent, 21.7 percent, and 14.7 percent, respectively. The bedding and rock riprap materials are a greenish gray, calcareous, sandstone.

Table I. Summary of Engineering Test Results for Compacted Soil Layer

								Proctor Compaction	
Soil Type[a]	Specific Gravity	Liquid Limit (%)	Plasticity Index (%)	% Passing 200 Sieve	Silt (%)	Clay (%)	Moisture Content (%)	Optimum % Moisture	Max. Dry Density
Cl[b]	2.66	35.8	16.0	62	38	24	16.7	16.9	1.73 g/cm^3

[a]Unified Soil Classification System.



[b]Silty clay with some coarse fragments.

Vegetation was first observed growing out of the rock riprap layer of the cover in 1988 (35). By 1991, four tree species (sycamore, box elder, black locust, and tree-of-heaven) had rooted as deep as 33 cm into the compacted soil layer (36). An exotic perennial forb, Japanese knotweed, had rooted 46 cm into the compacted soil layer. All Japanese knotweed and woody plants on the disposal cell were sprayed with herbicides in August 1992, excluding a 0.5-hectare (ha) study plot that was established in June 1992 to monitor the effects of plant encroachment. In 1993, herbaceous species and some trees as tall as 1 meter were observed in areas on the disposal cell that had been treated with herbicides the previous year (37), indicating that annual herbicide applications may be required if the vegetation management goal is to eliminate trees from the cover. In 1994, robust growth of herbaceous and woody vegetation was observed over nearly all the disposal cell (38). The number, density, cover, and size of plant species were visibly greater between 1993 and 1994. By 1996, plants were as abundant in areas sprayed during 1992 as in the 0.5-ha plot that has not been sprayed since closure of the cell in 1987.

METHODS

Natural Analog Site Selection

A goal of this study was to evaluate both current conditions and possible long-term effects of root intrusion on water infiltration. Current influences of plants were evaluated by measuring the hydraulic properties of the disposal cell cover at locations both with and without plants. We inferred a potential long-term condition of the cover with data from a natural analog site.

Three criteria were used to search for an appropriate natural analog of possible future ecological conditions on the Burrell cover:

- The same soil type as the CSL.
- A soil depth equal to or greater than the radon barrier.
- A chronosequence of plant community development with the oldest sere (successional stage) at least 50 years old.

Construction records, a series of aerial photographs, and a copy of the U.S. Department of Agriculture (USDA) Soil Survey for Westmoreland County (39) were used to determine that the CSL consisted of Gurnsey silt loam and Westmoreland silt loam series excavated from open pits at a nearby coal mine. Land parcels with mature vegetation within the Westmoreland silt loam and Gurnsey silt loam series were located using the USDA soil survey maps. Hannastown Historical Park, an archaeological and historical site owned and managed by the Westmoreland County Historical Society, was selected.
A 0.5-ha rectangular area near the northeast corner of Hannastown Historical Park was chosen for study. The second-growth, closed-canopy woodland consists primarily of sugar maple with scattered beech and yellow birch and virtually no understory vegetation. The northeast-facing stand has a slope of approximately 5 percent. The soil series, Westmoreland silt loam, formed in residuum derived from interbedded gray calcareous shale, sandstone, and limestone. The soil profile at the study site consisted of a 15- to 20-cm brown, silt loam plow layer over a 80+ cm yellowish-brown silty clay loam subsoil.

In Situ Measurement of Saturated Hydraulic Conductivity

Engineered covers on disposal cells are designed to limit the amount of water that passes into underlying waste. Passage of water can be controlled by lateral drainage layers, by CSLs, and by evapotranspiration. Plant growth and root intrusion can greatly influence all three processes. At humid sites like Burrell where CSLs have been constructed as the primary barrier to water infiltration, macropore structure in the CSL created by root intrusion and soil development is of greatest concern (1). Root channels and eventually earthworms, burrowing animals, soil structural changes, and other heterogeneities can combine to promote preferred pathways for flow of water.

At Burrell, given high precipitation and a CSL that is often saturated (2), the passage of water through the cover would be sensitive to changes in the saturated hydraulic conductivity (K_{sat}). Under these conditions, the hydraulic gradient is approximately 1 and water flux through the CSL (Q^{CSL}) can be calculated with Darcy's law (1) as

$$Q^{CSL} = K_{sat} \bullet I \tag{1}$$

ere

K_{sat} = vertical saturated conductivity of the CSL,
I = vertical gradient across the CSL, calculated as $(H + T)/T$,
H = head of water above the CSL, and
T = thickness of the CSL.

Under saturated conditions, when H is small with respect to T, water flux through the CSL is approximated by K_{sat}. Therefore, the objective of this phase of the study was to obtain in situ measurements of the effects of root intrusion and soil development on K_{sat}.

Air-entry permeameters (AEPs) (ASTM D5126) were used to estimate in situ changes in K_{sat} and preferential flow attributable to root intrusion and soil development. Our AEPs were designed and manufactured by Daniel B. Stephens and Associates, Inc., for use on engineered clay layers and other low-permeability clay soils (40,41). Each AEP, based on a design by Bouwer (42), consists of a round, 30-cm-deep permeameter ring, air-tight cover, standpipe, graduated water reservoir, and vacuum gauge.

The AEP tests were designed to capture a reasonable range of current and possible future conditions on the cover. Replicate AEP tests were conducted on the cover in areas without plants (n = 3), on the cover where woody plants have rooted into the CSL (n = 6), and at the Hannastown analog site (n = 3). Permeameter rings were driven into the cover CSL and analog subsoils after removing overlying materials (rock and bedding layers on the cover and plow-layer soil at Hannastown). The CSL-with-plants tests included three Japanese knotweed plants and three dominant tree species (sycamore, black locust, and staghorn sumac). After installing a permeameter ring, we sealed polycarbonate plates to the ring top, attached standpipes and water reservoirs, and filled the reservoirs. Reservoir water was dyed to trace wetting fronts and preferred 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 used to calculate the air-entry or bubbling pressure of the soil (ASTM D5126).

Three different methods corresponding to three different conditions encountered during the tests were used to calculate K_{sat} :

1. The Bouwer method (42), which assumes initially unsaturated soil, was used for the analog soils.

2. The Young et al. method (43), which assumes initially saturated or nearly saturated soil and deep seepage, was used for most of the cover tests with plants.
3. The Young et al. method (43), which assumes initially saturated or nearly saturated soil and ***no*** deep seepage, was used for cover tests without plants and one test with plants where water moved to the surface after a period of monitoring.

Saturated conductivity (K_{sat} in centimeters per second) for condition (1) was calculated as

$$K_{sat} = [2 \cdot dH/dT \cdot L \cdot (R_{ws}/R_{sr})2]/[H_f + L + (0.5 \cdot P_a)] \qquad (2)$$

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.

K_{sat} for conditions (2) and (3) was determined using Eq. (3):

$$[K_{sat} \cdot R_{sr} \cdot (t_2 \quad t_1)]/(pr^2 \cdot N) = \ln(S_1 \cdot H_1) \quad \ln(S_2 \cdot H_2) \qquad (3)$$

where H_1 and H_2 are the heads at times t_1 and t_2, respectively; S_1 and S_2 are shape factors presented in Table 1 of Young et al. (43) for flow into saturated soil; r is the radius of the standpipe; and N, a shape factor dependent on the depth of penetration of the permeameter ring, d, and area of the ring, a, is calculated as

$$N = 0.316 \cdot (d/a) + 0.184. \qquad (4)$$

Plant Canopy Measurements

Measurements of the plant canopy structure were used to compare attributes of plant communities that are indicative of the functional performance of the Burrell cover and the Hannastown analog site. Canopy structure plays a fundamental role in processes such as evapotranspiration (44), biomass productivity (45), and radiation interception (46). The structure or architecture of individual plant canopies can also be used as a weighting factor to project, over the greater community, other attributes of individual plants, such as rooting influences on soil water (47).

The canopy structure of individual Japanese knotweed plants that had been selected for in situ K_{sat} tests was evaluated. Measurements of leaf area index (LAI, leaf area per unit ground area) and foliage density (foliage area per unit canopy volume) of plants used for K_{sat} tests were made before excavation of plants and installation of permeameter rings. The canopy volume of each plant was estimated from a sufficient number of x,y coordinate dimensions to describe the shape of the canopy. The foliage density of these plants was measured with an LAI 2000 Plant Canopy Analyzer (48). The LAI 2000 provides an indirect but accurate estimate of foliage density and LAI using "fish-eye" lens measurements of canopy gap fractions (the fraction of the sky visible through the canopy) at various angles (49). A 90° view cap was placed over the lens and readings were taken with the LAI-2000 in four quadrants at the base of each plant. Using 2000 90 software from LI-COR, Inc. (48), LAI within the drip line, or drip-line LAI (DLLAI), was calculated as

$$\text{DLLAI} = \text{Foliage Area Density} \cdot (\text{Canopy Volume/Drip-Line Area}) \quad (5)$$

We also used the LAI 2000 to measure plant-community LAI on the Burrell cover and at the Hannastown analog site. A hundred pre-dawn readings were taken at random locations within the patchy Japanese knotweed-dominated stand on the Burrell cover. At Hannastown, two stands were measured: (1) a relatively open, mixed deciduous canopy with abundant understory growth (Hannastown 1) and (2) the closed-canopy sugar maple stand where we measured in situ K_{sat} (Hannastown 2). In both stands, 25 random readings provided satisfactory statistics. Hannastown 1 was a pasture when the soil survey photographs were taken in 1967; the woodland, therefore, is less than 30 years old. The sugar maple stand at Hannastown 2 may be more than 100 years old, the oldest sere on Westmoreland soil in the park.

RESULTS AND DISCUSSION

Table II presents the in situ saturated hydraulic conductivity (K_{sat}) test results; Table III presents plant canopy structure results. Results for four conditions are presented:

- Burrell CSL without plants.
- Burrell CSL with Japanese knotweed.
- Burrell CSL with trees.
- Hannastown analog subsoil.

Table II. Air-Entry Permeameter Tests of In Situ Saturated Hydraulic Conductivity (K_{sat}) *in the Burrell CSL and the Hannastown Analog Subsoil*

Conditions Tested	K_{sat} (cm/s)	K_{sat} (mean) [a]	Calculation Method
Burrell CSL/No Plants			

Replicate 1	1.8×10^{7}	2.9×10^{7} (a)	Eq. (3)[b]
Replicate 2	6.0×10^{7}		Eq. (3)[b]
Replicate 3	1.0×10^{7}		Eq. (3)[b]
Burrell CSL/ Japanese Knotweed			
Replicate 1	1.6×10^{6}	3.0×10^{5} (b)	Eq. (3)
Replicate 2	5.8×10^{5}		Eq. (3)
Replicate 3	6.1×10^{4} [c]		Eq. (3)[b]
Burrell CSL/Trees			
Sycamore	4.0×10^{7}	4.8×10^{7} (a)	Eq. (3)
Staghorn sumac	7.4×10^{7}		Eq. (3)
Black locust	3.1×10^{7}		Eq. (3)
Hannastown Analog Subsoil			
Replicate 1	1.2×10^{4}	1.3×10^{4} (c)	Eq. (2)
Replicate 2	1.2×10^{4}		Eq. (2)
Replicate 3	1.2×10^{4}		Eq. (2)

[a]Mean values followed by the same letter were not significantly different at ? = 0.05.
[b]Shape factors used for calculation were based on the assumption of no deep seepage.
[c]This value was excluded from the mean because water may have seeped along the permeameter wall, resulting in an inflated K_{sat} value.

For all Burrell cover tests, field soil-water content values were at saturation (1), and water was observed ponding in AEP test pits. Therefore, for the purposes of this study, water flux through the Burrell CSL (Q^{CSL}) can be approximated by K_{sat}.

At locations on the disposal cell where plants have ***not*** rooted, the in situ K_{sat} of 2.9×10^{7} cm/s (Table II), or a Q^{CSL} of 0.25 millimeter per day (mm/d), was about 3 times greater than the design standard for a CSL (1×10^{7} cm/s) required by both UMTRA (3) and RCRA subtitle C (50).
In situ measurements were as much as an order of magnitude greater than laboratory falling-head results for the same soil (2.6×10^{8} cm/s) (2). This discrepancy appears to be in agreement with Rogowsky (51), who conducted field-scale tests in Pennsylvania comparing the variation in hydraulic conductivity of an engineered compacted clay, similar to the Burrell CSL, with laboratory values. Unlike the fairly homogenous recompacted clay used in laboratory column tests, water and solutes may move in the CSL through only a small portion of the total porosity. Elsbury et al. (52) suggest that the persistence of clods and the failure of soil lifts to bond can lead to macropore flow between clods and lifts.

Root intrusion effects on K_{sat} were tested for four species: Japanese knotweed and sycamore, staghorn sumac, and black locust trees. Japanese knotweed roots increased the Burrell CSL K_{sat} by two orders of magnitude (3.0×10^{5} cm/s); a daily Q^{CSL} of 26.0 mm. Japanese knotweed taproots grew vertically through the drainage layer of sand and gravel, then diverted laterally at the surface of the CSL. Many secondary and fibrous roots branched vertically into the CSL. The height of Japanese knotweed test plants varied little (mean = 2.0 m); however, canopy volume and drip-line area were highly variable (Table III). In contrast, the CSL K_{sat} in the rooting zone of the three tree species (4.8 x 10^7 cm/s; Q^{CSL} = 0.41 mm/d) and the CSL K_{sat} with no plants were not significantly different (Table II). The test trees were taller than Japanese knotweed but had significantly lower foliage density (Table III). Tree roots clogged the drainage layer, but only a small percentage of their root biomass was observed in the CSL.

Table III. Canopy Dimensions, Foliage Density, and Drip-Line LAI for Plants on the Burrell Cover Used for K_{sat} Tests

Plant	Height (m)	Mean Diameter (m)	Foliage Density[a]	Mean[b]	Canopy Vol. (m^3)	Drip-Line Area (m^2)	DLLAI[c]	Mean
Japanese knotweed								
Replicate 1	1.85	2.81	4.2	4.2(a)	6.7	5.3	5.4	4.7(a)
Replicate 2	2.4	4.25	3.7		15.2	16.9	3.3	
Replicate 3	1.8	3.68	4.7		8.1	7.1	5.4	
Trees								
Sycamore	3.39	1.72	2.6	2.3(b)	3.3	2.3	3.7	3.4(a)
Staghorn sumac	2.71	2.92	1.9		13.6	9.6	2.7	
Black locust	3.87	2.34	2.3		28.5	17.2	3.8	

[a]Foliage area per unit canopy volume.
[b]Mean values followed by the same letter were not significantly different at a = 0.05.
[c]Drip-line leaf area index.

The LAI of individual Japanese knotweed test plants on the Burrell cover (Table III) and the plant-community LAI for the Burrell cover (Table IV) were used to estimate a weighted-average K_{sat} for the entire disposal cell cover (4.4 x $10^{?6}$ cm/s; Q^{CSL} = 3.8 mm/d). The calculation was based on the following assumptions: (1) the LAI of the Burrell plant community is dominated by Japanese knotweed, (2) the test plants were representative of the stand, and (3) test-plant K_{sat} measurements were representative of conditions within the drip line. Given these caveats, we conclude that root intrusion may already have increased the Burrell CSL K_{sat} more than tenfold.

Table IV. LAIs on the Burrell Cover and at the Hannastown Site

Site	**Date**	**Start Time**	**Finish Time**	**LAI[a]**		**Visible Sky (%)[c]**	***n*[d]**
				Mean (mean)[b]	**SE**		
Burrell Cover	July 28, 1995	19:47	20:45	0.65	0.07	57.9	100
Hannastown 1	July 27, 1995	19:38	19:56	4.86	0.19	1.4	25
Hannastown 2	July 27, 1995	18:59	19:37	5.37	0.04	1.0	25

[a]LAI is a dimensionless measure of How much foliage? LAI can be thought of as m^2 foliage area/m^2
ground area. It is also an index of leaf evaporation surface area.

[b]Standard error of the mean.

[c] Visible sky is an indicator of canopy light absorption.

[d]The number of sample points (*n*) were located using random points along transects originating at random locations along a baseline.

Measurements of K_{sat} and LAI at the Hannastown analog site are considered a reasonable upper range for future conditions on the Burrell cover. A comparison of the Burrell CSL and Hannastown subsoil shows that

? The Burrell CSL consists of recompacted Westmoreland series soil (27 percent clay); the Hannastown subsoil is also Westmoreland series (29 percent clay).

? The Burrell CSL underlies a gravely sand drainage layer. Where mature plants were uprooted for AEP tests, the upper 10 to 15 cm of the drainage layer was filled with organic matter derived from plant litter. The Hannastown subsoil underlies a silt loam plow layer high in organic matter. The drainage layer may become more like the plow layer with time.

? The Burrell CSL bulk density (1.73 gram per cubic centimeter [g/cm^3]) was much higher than the Hannastown subsoil bulk density (1.48 g/cm^3). It could be argued that the lower Hannastown bulk density, higher porosity, and higher K_{sat} will not occur in the engineered Burrell CSL and, therefore, Hannastown is a poor analog. Conversely, the Hannastown subsoil is residuum derived from interbedded calcareous shale, sandstone, and limestone and, therefore, originally had a much higher bulk density than the Burrell CSL. We can expect the porosity of the engineered CSL to increase in response to soil development processes. The Hannastown soil is a reasonable analog of the long-term condition.

? Hannastown has a higher laboratory K_{sat} and saturated water content as expected, given the higher porosity.

The Hannastown subsoil was literally teaming with life (e.g., roots, earthworms, insects) all contributing to preferred pathways for flow of water. The Hannastown K_{sat} (1.3 x 10^{4}) was nearly 3 orders of magnitude higher than the Burrell CSL K_{sat} without plants. Dye was used to trace water movement patterns during AEP tests. Excavation of soil profiles following AEP measurements revealed dye on coarse and fine root surfaces, in earthworm holes, and along planes of weakness between soil peds.

In situ measurements of hydraulic conductivity in analog soils, like the Hannastown subsoil, may provide the most defensible predictions of future effects of ecological succession and soil development on the performance of CSLs, particularly in humid regions. In contrast, methods for characterizing sizes, configurations, and distributions of macropores in humid soils has only recently been evaluated; no reliable methods exist for numerically predicting water infiltration and recharge rates through these preferred pathways (1).

The LAI chronosequence for Burrell and Hannastown plant communities (Table IV) provides clues for possible future changes in the plant canopy structure on the engineered cover. Hannastown 1 is a 30-year-old mixed deciduous open woodland sere in an abandoned pasture. Hannastown 2, the second-growth closed-canopy sugar maple woodland, is perhaps more than 100 years old. A comparison of stands suggests that the Burrell LAI, presently 0.65, may increase sevenfold within 30 years as the community begins to resemble Hannastown 1. Greater LAI will most likely result in higher evapotranspiration rates and, on average, a dryer CSL. The lower standard deviation for LAI at Hannastown 1 than at Hannastown 2 reflects increased uniformity in the canopy over time.

CONCLUSIONS

Plant succession and soil development are inevitable on the Burrell disposal cell. Within a few years after construction, a plant community dominated by Japanese knotweed established on the cover, several species rooted in the CSL, and an organic soil began to develop in the drainage layer. Current UMTRA guidance advocates chemical control of plant growth for the design life of the disposal cell (200 to 1,000 years). The Long-Term Surveillance and Monitoring Program evaluated current and possible long-term consequences of root intrusion and ecological change on cover design standards as a basis for a reasonable vegetation management strategy. The study emphasized field measurements of plant effects on radon attenuation and water infiltration in the CSL and in a natural (analog) system that represents a reasonable condition of the cover following unabated ecological and soil development.

At Burrell, the most detrimental effect of root intrusion and ecological change, now and in the future, is the development of soil macropores in the CSL, which is the primary barrier to water infiltration. Water flux through the CSL can be approximated by the saturated hydraulic conductivity (K_{sat}) given the saturated and nearly saturated conditions. In situ measurements of K_{sat} within the root zone of Japanese knotweed show that the potential for water flux through the CSL is already 2 orders of magnitude above the design standard. Normalized for LAI, the K_{sat} value is an average of more than 10 times the standard over the entire disposal cell.

Measurements at the analog site indicate that the plant canopy will increase sevenfold within 30 years and the K_{sat} value will continue to increase as root channels, earthworm holes, and structural planes create preferred flow paths through the CSL. In 200 to 1,000 years, the K_{sat} value may exceed the design standard by more than 3 orders of magnitude (1.3 x $10^{?4}$ cm/s). Although the greater plant canopy will raise evapotranspiration rates and may reduce the frequency of saturated flow events, higher K_{sat} values would most likely lead to significant recharge through underlying residual radioactive material. Periodic control of plant growth on the cover may slow down soil development, changes in soil hydraulic properties, and consequent increases in water infiltration. However, physical soil development processes, such as freeze-thaw cycles, secondary mineralization, and aggregation of fines, will continue.

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