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Plant Encroachment on the Burrell, Pennsylvania, Disposal Cell: Evaluation of Long-Term Performance and Risk

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Executive Summary

The Burrell, Pennsylvania, disposal cell is a covered landfill constructed by the U.S. Department of Energy (DOE) to isolate soil contaminated with uranium mill tailings. The abundance of plants growing on the Burrell disposal cell has increased each year since closure of the cell in 1987. DOE's original plan for post-closure maintenance included regular herbicide spraying to suppress plant growth for the 200-to-1,000-year life of the disposal cell.

This report completes a two-part study of the effects of plant root intrusion and ecological development on the performance of the disposal cell cover and, as a consequence, on potential changes in risks to human health and the environment. The DOE Long-Term Surveillance and Maintenance (LTSM) Program plans to use the results of this study as the technical basis for choosing one of the following three management options for the Burrell disposal cell:

- Discontinue herbicide spraying if risks of root intrusion are acceptably low.
- Accept the cost and environmental consequences of continued herbicide spraying, or other long-term maintenance, if risks are sufficiently large.
- Modify the disposal cell cover design and, thereby, improve risk management over the long term.

In the first part of the study we evaluated the effects of root intrusion on radon flux and the saturated hydraulic conductivity of the cover. This work resulted in two findings. The first is that root intrusion and associated drying of the cover will not likely increase radon flux above the 20-picocurie-per-square-meter-per-second standard unless the western Pennsylvania climate changes from humid to semiarid. The second is that plant roots do increase the hydraulic conductivity of the radon barrier. We measured a 2-orders-of-magnitude increase in the saturated hydraulic conductivity where plant roots penetrated the radon barrier (or compacted soil layer). At a nearby analog site, the saturated hydraulic conductivity was 3 orders of magnitude above the design specification of 10^{-7} centimeter per second. The analog site represents a reasonable future condition of the cover after 200-to-1,000 years of ecological and pedogenic changes.

In the second part of the study, we evaluated possible consequences of increased water movement into the tailings that might result from root intrusion in the cover. The first phase of this screening-level risk assessment evaluated concentrations and mobility of contaminants in tailings pore fluid. Composite tailings samples were retrieved from locations within the disposal cell that had the highest radium levels at the time of construction. Column leach tests conducted using composite samples encompassed a range of current, possible future, and, less likely, extreme chemical conditions. The results suggest that manganese, molybdenum, selenium, uranium, and ^{226}Ra in pore fluid may exceed either the Uranium Mill Tailings Radiation Control Act (UMTRCA) maximum concentration limit (MCL) or a U.S. Environmental Protection Agency (EPA) risk-based screening level for one or more of the conditions tested. In other words, water extracted directly from the disposal cell, the worst-case exposure pathway, may be unsafe to drink.

The second phase of the risk assessment evaluated groundwater quality beneath the disposal cell for a range of conditions, reasonable and extreme, that could occur during the design life of the cover. We used a combination of historical monitoring data from seeps and wells, soil-water

balance modeling, and groundwater mixing calculations to estimate groundwater quality for a range of possible future conditions, including changes in the ecology of cover soils and changes in the tailings pore water chemistry. No contaminants of concern (COCs) in DOE's historical database for seeps and monitor wells came close to the UMTRCA MCLs or the EPA risk-based screening levels. Estimates of groundwater quality for existing conditions were comparable to the historical monitoring data. Even for extreme conditions, all model-predicted COCs, except ^{226}Ra, were well below MCLs and EPA risk-based screening levels.

The results suggest that ^{226}Ra in groundwater could exceed the MCL by at most 10 percent, but only for a highly unlikely combination of conditions: (1) pore water pH of 4.5 or less, (2) a 2-to-3-orders-of-magnitude increase in the saturated hydraulic conductivity of the radon barrier because of root intrusion, (3) 1,000 years of ^{226}Ra ingrowth, and (4) pore water contamination levels as high as that from the most contaminated tailings. Primarily because a pore water pH of 4.5 is highly unlikely, radium is expected to remain relatively immobile in the disposal cell. The results also suggest that, in the future, because of increased evapotranspiration, contaminant concentrations in groundwater would be substantially lower if native woodlands were allowed to establish. Conversely, regular denuding of the disposal cell with herbicides would reduce evapotranspiration and, in time, may actually increase drainage from the cover and leaching of contaminants into groundwater.

On the basis of the results of this study, we conclude that regular spraying of vegetation on the disposal cell is unwarranted and unjustified. DOE can safely eliminate this requirement from the Burrell long-term surveillance plan. Natural plant succession can be allowed to proceed with no increased risk to human health or the environment. In fact, continued spraying may interfere with the long-term performance of the disposal cell. Because of a much higher evapotranspiration rate, the development of a mature woodland plant community is expected to augment the performance of the disposal cell by limiting drainage through the cover and by reducing the likelihood of contaminant leaching into groundwater below the disposal cell.

1.0 Introduction

1.1 Purpose

This document presents methods, results, and recommendations of a screening-level risk assessment for the Burrell, Pennsylvania, disposal cell. The risk assessment was conducted to evaluate possible long-term changes in disposal cell performance, human health risks, and environmental risks associated with a documented increase in the permeability of the disposal cell cover caused by plant root intrusion. The U.S. Department of Energy (DOE) Long-Term Surveillance and Maintenance (LTSM) Program plans to use the results of this evaluation as the basis for vegetation management decisions at the site and, if warranted, for revision of the long-term surveillance plan for the Burrell disposal cell.

1.2 Current Vegetation Management Plan

The Burrell, Pennsylvania, disposal cell is a covered landfill constructed by DOE under the Uranium Mill Tailings Radiation Control Act (UMTRCA) of 1978 to isolate soil contaminated with uranium mill tailings. The disposal cell was constructed in 1987 (Morrison-Knudsen Engineers, Inc., 1994) and stewardship was transferred to the LTSM Program in 1994. Observations of plants growing on the disposal cell cover, beginning in 1988, raised concerns about effects of root intrusion on the long-term performance of the cell. Within 3 years after construction, a diverse plant community had established on the rock cover. Within 10 years, Japanese knotweed, an exotic perennial, had rooted through the rock layer and an underlying, 90-centimeter (cm)-thick, compacted soil layer (CSL). Of concern was the possibility that root intrusion would increase (1) radon flux from the surface of the disposal cell and (2) water movement through the cover and leaching of underlying tailings. Because of this concern, the long-term surveillance plan for Burrell recommended herbicide applications every 2 to 3 years to suppress plant growth for the design life of the disposal cell (DOE, 1993). Under UMTRCA, disposal cells are intended to last 200 to 1,000 years (EPA, 1983).

1.3 Summary of Root Intrusion Study

The LTSM Program recognizes that the costs and associated risks of committing to long-term spraying of herbicide are unjustified unless substantiated by sound technical reasons. Herbicide applications may actually increase human health and environmental risk at the site—the solution may be worse than the problem. Therefore, between 1995 and 1997, the LTSM Program conducted a field study of the consequences of root intrusion and long-term ecological change on the disposal cell cover as the basis for a reasonable vegetation management strategy (Waugh and Smith, 1997, 1998).

Waugh and Smith (1997, 1998) evaluated the effects of plant root intrusion on radon attenuation and water infiltration through the CSL, which is intended to serve as both a radon barrier and a water infiltration barrier. The results indicate that root intrusion will not increase radon flux above the 20-picocuries-per-square-meter-per-second ($pCi \cdot m^{-2} \cdot s^{-1}$) performance standard unless the CSL dries out because of unforeseen and unlikely climatic and ecological changes (see Section 3.0). However, LTSM Program personnel measured a significant increase in the saturated hydraulic conductivity (K_{sat}) where plant roots penetrated the CSL (see Section 4.0). The K_{sat} averaged 3.0×10^{-5} centimeter per second ($cm \cdot s^{-1}$) at locations where Japanese knotweed roots penetrated the clay layer compared with 2.9×10^{-7} $cm \cdot s^{-1}$ where there were no plants. The average K_{sat} for the cover, calculated using the leaf area index for Japanese knotweed as a weighting factor, was 4.4×10^{-6} $cm \cdot s^{-1}$. At nearby Hannastown Historical Park, a site with late-successional vegetation and a soil profile and clay subsoil similar to the Burrell cover, the K_{sat} of the clay subsoil averaged 1.3×10^{-4} $cm \cdot s^{-1}$. The Hannastown soil profile was teaming with life. Earthworm holes, root channels, and soil structural planes all contribute to macropore flow of water in the subsoil. The LTSM Program considers Hannastown to be a reasonable analog of the long-term ecology and soil hydrology of the Burrell disposal cell cover.

Burrell and Hannastown data indicate that during the 200- to 1,000-year life of the disposal cell, the hydraulic conductivity of the CSL will likely increase by 3 orders of magnitude in response to ecological and pedogenic changes. This greater capacity to move water through the disposal cell may cause unacceptable leaching of radioactive and other hazardous materials into nearby surface water and groundwater. Section 4.0 addresses the likelihood and risks of increased contaminant leaching.

1.4 Management Options

During 1998, the LTSM Program conducted two phases of a possible three-phase assessment of the added risks associated with increased permeability of the cover attributable to plant root intrusion. The goal of the risk assessment was to provide a technically based rationale that will allow DOE to choose among three management options for the Burrell disposal cell:

- Discontinue herbicide spraying if risks are acceptably low.
- Accept the cost and environmental consequences of continued herbicide spraying, or other long-term maintenance, if risks are sufficiently large.
- Modify the disposal cell cover design and, thereby, improve risk management over the long term.

2.0 Characterization Data

2.1 As-Built Contaminant Concentrations and Distributions

Evaluations of root intrusion effects on water infiltration, radon diffusion, plant uptake, and, ultimately, human health and ecological risks require data on the chemical species, concentrations, and distributions of contaminants in the Burrell disposal cell. Data on concentrations and distributions of radiological (^{226}Ra and ^{230}Th) and other contaminants are available in the *Burrell, Pennsylvania, Vicinity Property Completion Report* (Morrison-Knudsen Engineers, Inc., 1994). The estimated total ^{226}Ra activity in the 54,000 cubic yards of contaminated material placed in the cell is about 4 curies. The completion report did not contain an estimate of the ^{230}Th inventory. Table 2–1 provides a summary of as-built ^{226}Ra and ^{230}Th data in picocuries per gram (pCi/g) from a grid of 24 boreholes sampled in November 1986 after tailings were placed in the cell but before the cover was constructed.

Table 2–1. Summary Statistics for ^{226}Ra and ^{230}Th Concentrations in Burrell Disposal Cell

Depth	^{226}Ra (pCi/g)					^{230}Th (pCi/g)				
(cm)	Mean	S.E.(mean)[a]	Min.	Max.	*n*[b]	Mean	S.E.(mean)	Min.	Max.	*n*[b]
0 – 60	39.5	8.0	5.5	85.0	11	416.0	154.6	55.0	1910.0	11
60 – 120	26.5	5.3	8.0	83.0	12	204.1	32.1	77.0	410.0	12
120 – 300	79.8	18.8	28.0	280.0	13	878.5	171.9	350.0	2520.0	13
All	49.6	8.2	5.5	280.0	36	512.4	90.7	55.0	2520.0	36

[a]Standard error of tbe mean.
[b]Sample size.

Lateral and vertical heterogeneities of ^{226}Ra and ^{230}Th concentrations were high. Overall, concentrations were lower beneath the top slope and higher beneath the side slopes of the cell. Radon emanation fraction data, required for modeling radon flux, were also compiled from the completion report (Table 2–2).

Table 2–2. Radon Emanation Fraction Data for Burrell Disposal Cell

Depth (cm)	Mean	S.E.(mean)	Min.	Max.	*n*
0 – 60	0.14	0.011	0.04	0.23	22
60 – 120	0.13	0.014	0.01	0.27	23
120 – 180	0.15	0.013	0.00	0.23	23
180 – 240	0.17	0.015	0.00	0.31	24
240 – 300	0.16	0.016	0.02	0.29	22
All	0.15	0.006	0.00	0.31	114

Chemical analyses of soil samples from the Burrell site were performed in 1984. The analyses included pesticides (Methoxychlor, 2,4–D, and 2,4,5–T), metals (As, Ba, Cd, Pb, Hg, Se, and

Ag), sulfide, and cyanide. According to Morrison-Knudsen Engineers, Inc. (1988), no results for pesticides exceeded the U.S. Environmental Protection Agency (EPA) maximum allowable toxicity concentrations in Title 40 *Code of Federal Regulations* (CFR) Part 261.24. Except for one cadmium value, Morrison-Knudsen Engineers, Inc. (1988) also states that no metal results exceeded the maximum EPA toxicity limits for metals in 40 CFR 261.24.

2.2 As-Built Cover Design and Material Properties

As-built information on the soil, sand, and rock layer thicknesses; material properties (e.g., liquid limit, plasticity, texture, bulk density); and hydraulic properties (e.g., saturated conductivity and water retention characteristics) were compiled for use in radon flux and water infiltration evaluations.

From the tailings layer up, the Burrell cover consists of a 90-cm-thick radon barrier or CSL, a 30-cm-thick sand-and-gravel drainage layer, and a 30-cm-thick rock (riprap) layer (Figure 2–1). These three layers were designed to function together to meet the regulatory standards for radon releases and erosion for 200 to 1,000 years. A CSL thickness adequate to meet the radon flux standard was calculated using the U.S. Nuclear Regulatory Commission (NRC) RADON model (NRC, 1989). The target hydraulic conductivity for the CSL was 1×10^{-7} cm · s^{-1}.

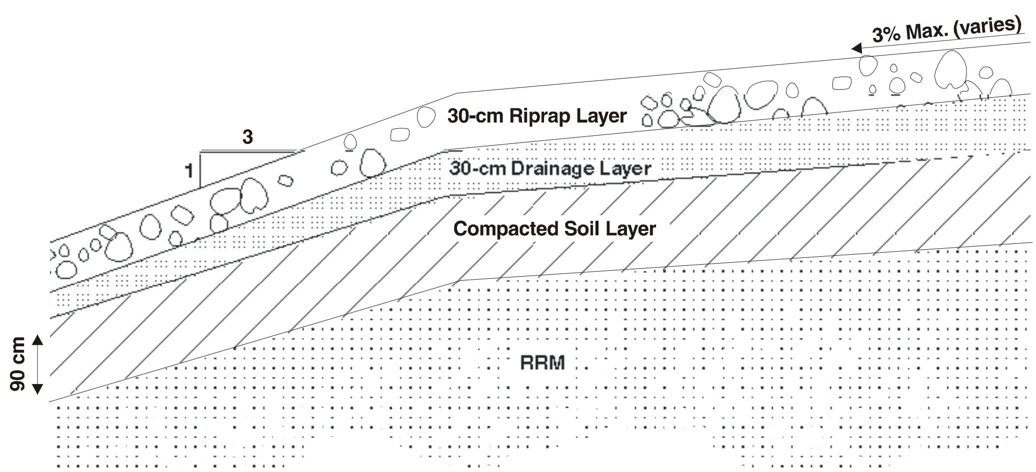

Figure 2–1. Surface Cover Design for Burrell Disposal Cell

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 (DOE, 1989).

Material property data for the CSL (Table 2–3) were compiled from the Burrell completion report (Morrison-Knudsen Engineers, Inc., 1994). Actual compaction of the radon barrier during construction averaged 96.6 percent of the maximum dry density. Actual average, maximum, and

Table 2–3. Summary of Engineering Test Results for CSL

								Proctor Compaction	
Soil Type	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	$1.73\ g \cdot cm^{-3}$

[a]Unified Soil Classification System.
[b]Silty clay with some coarse fragments.

minimum gravimetric moisture contents of the radon barrier during construction were 17.7 percent, 21.7 percent, and 14.7 percent, respectively. The bedding and rock materials are a greenish gray, calcareous, crossbedded sandstone. Grain-size curves for these materials are available in the Burrell completion report.

2.3 Natural Analog Site Selection

A goal of this study was to evaluate both current conditions and possible long-term effects of root intrusion on radon attenuation and water infiltration. Current influences of plants were evaluated by measuring the conditions 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 CSL.
- 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 (Taylor et al., 1992) were used to determine that the Burrell disposal cell CSL consisted of Gurnsey silt loam and Westmoreland silt loam series excavated from open pits at a nearby coal mine. Land parcels with Westmoreland silt loam and Gurnsey silt loam series and with mature vegetation were located using USDA soil survey maps. Hannastown Historical Park, an archaeological and historical site owned and managed by the Westmoreland County Historical Society, was selected as the natural analog site (Waugh and Smith, 1998).

A 0.5-hectare (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. This 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.

2.4 Soil Physical and Hydraulic Properties

A field measurement and sampling program was developed to acquire data that best capture near-term and possible long-term influences of ecological development on the performance of the cover. These data were used for analyses of radon flux and water infiltration. Three conditions were compared: (1) the Burrell cover without plant roots (as-built), (2) the Burrell cover with plant roots, and (3) the Hannastown analog of a possible future ecology of the Burrell cover.

2.4.1 Soil Water Content, Texture, Bulk Density, and Porosity

Soil samples were retrieved from the Burrell cover and from analog soil profiles at Hannastown to determine seasonal soil water content, texture (particle-size distribution), bulk density (compaction), and porosity. Soil pits were excavated in the Burrell cover at locations both with and without vegetation ($n = 5$). At locations with vegetation, pits were excavated through the root crowns of mature Japanese knotweed, sycamore, black locust, and tree-of-heaven. The surface layer of rock was moved to expose the gravel bedding layer. For water content and textural analyses, loose bedding-layer material was sampled at the contact with the CSL; a bucket auger was used to retrieve CSL samples. Samples were collected early in the growing season and again in midsummer to capture seasonal variation in soil water content. Plow layer and subsoil samples from random soil profiles ($n = 5$) at the Hannastown site were also retrieved with a bucket auger. Bulk density samples of the Burrell CSL and the Hannastown subsoil were retrieved with a double cylinder, hammer-driven core sampler. Table 2–4 presents methods used for analyses of gravimetric water content, soil particle size, dry-weight bulk density, and porosity. Tables 2–5 and 2–6 present the results of these analyses.

Table 2–4. Summary of Laboratory Methods for Soil Analyses

Soil Property and Method	Reference
Gravimetric Water Content	Klute (1986), Chapter 21, pp. 493–544
Dry-Weight Bulk Density	Klute (1986), Chapter 13, pp. 363–367
Soil Porosity	Klute (1986), Chapter 18, pp. 444–445
Saturated Hydraulic Conductivity	
Falling Head Method	Klute (1986), Chapter 28, pp. 700–703
Moisture-Retention Characteristics	
Hanging Column	Klute (1986), Chapter 26, pp. 637–639
Pressure Plate	ASTM D 2325-68 (81)
Thermocouple Psychrometer	Klute (1986), Chapter 24, pp. 597–618
Particle-Size Distribution	
Sieve	ASTM D 422-63 (90)
Hydrometer	ASTM D 422-63 (90)

Table 2–5. Particle Size and Bulk Density of Burrell CSL and Hannastown Analog Subsoil

Site	Particle Size[a]		Bulk Density (g · cm^{-3})		
	% Clay	% Sand	Mean	S.E.(mean)	*n*
Burrell Cover					
With Plants	27	39	1.76	0.02	5
Without Plants			1.77	0.02	5
Hannastown Analog Site	29	17	1.48	0.02	5

[a]USDA soil classification system.

Table 2–6. Gravimetric and Volumetric Soil Water Content in Burrell Cover and in Analog Soil Profiles at Hannastown

Site	Date	Material Type	Depth (cm)	Soil Water Content (% dry-wt)		Soil Water Content (% vol.)[1]		
				Mean	S.E.(mean)	Mean[2]	S.E.(mean)	n
Burrell Cover Without plants	May 10, 1995	Drainage Layer	15	4.3	0.6			5
		Drainage Layer	30–45	4.3	0.3			5
		Radon Barrier	15	20.3	1.0	35.9 a	1.0	5
		Radon Barrier	45–60	19.3	0.7	34.2 a	0.7	5
Burrell Cover Without Plants	July 28, 1995	Drainage Layer	30–45	4.7	0.2			5
		Radon Barrier	15	18.2	0.9	32.2 a	0.9	5
		Radon Barrier	30–60	19.2	0.5	34.1 a	0.5	5
Burrell Cover With Plants	July 28, 1995	Drainage Layer	30–45	4.8	0.2			5
		Radon Barrier	15	19.1	0.7	33.6 a	0.7	5
		Radon Barrier	30	18.8	0.3	33.2 a	0.3	5
		Radon Barrier	50–60	18.3	0.2	32.2 a	0.2	4
Hannastown Analog Site	July 27, 1995	A Horizon	15	17.8	0.9			5
		B Horizon	60	17.0	0.6	25.1 b	0.6	5
		B Horizon	110	16.5	0.7	24.4 b	0.7	5

[1]Calculated using bulk density values from Table 2–5.

[2]Means marked with the same letter are not significantly different (α = 0.05).

2.4.2 Soil Hydraulic Properties

Soil hydraulic properties of the Burrell CSL and the Hannastown subsoil were needed for radon flux and water infiltration analyses. These soil hydraulic-property data were also used as a measure of the value of Hannastown as an analog site. Saturated hydraulic conductivity and water-retention characteristics were determined with standard laboratory methods (see Table 2–4). For those tests, samples were recompacted at bulk densities consistent with field values (Table 2–5). The RETC code (van Genuchten et al., 1991) was used to quantify unsaturated soil-water retention characteristics and curve fitting. Table 2–7 presents a summary of the results. The soil-water retention curves are available in Waugh and Smith (1997).

Table 2–7. Initial Test Conditions, Laboratory Saturated Hydraulic Conductivity (K_{sat}), and Water-Retention Characteristics for Recompacted Burrell CSL and Hannastown Analog Subsoil

Material Type	Initial Test Conditions				K_{sat} (cm · s^{-1})	Water Retention Characteristics				
	θ_g [a]	θ_v [b]	ρ_b [c]	S_t [d]		θ_s [e]	θ_r [f]	n [g]	α [g]	r^2 [h]
Burrell CSL 1	19.0	33.9	1.78	32.7	2.6×10^{-8}	36.4	0.10	1.524	0.0001	0.963
Burrell CSL 2	18.5	33.2	1.79	32.5	3.3×10^{-8}	36.7	0.06	1.163	0.0014	0.966
Hannastown 1	16.2	24.1	1.48	44.0	1.4×10^{-7}	43.1	0.02	1.312	0.0022	0.993
Hannastown 2	16.0	23.8	1.49	44.0	5.1×10^{-7}	40.8	0.08	1.416	0.0008	0.999

[a]Gravimetric percent water content.
[b]Volumetric percent water content.
[c]Dry-weight bulk density (g · cm^{-3}).
[d]Total porosity calculated as $1 - \rho_b/\rho_p$ with an assumed particle density, ρ_p, of 2.65 g · cm^{-3}.
[e]Saturated water content as % volumetric; the maximum volumetric water content of the soil.
[f]Residual water content; the maximum amount of water in a soil that will not contribute to liquid flow.
[g]The symbols n and α are empirical curve-fitting constants that affect the shape of the water-retention curve using the equation of van Genuchten (1980).
[h]The coefficient of determination is a measure of how well the van Genuchten curve fits the observed data.

3.0 Root Intrusion Effects on Radon Flux

The Uranium Mill Tailings Remedial Action (UMTRA) Project designed the Burrell cover to conform to standards promulgated by EPA for the release rate of ^{222}Rn. The rules in 40 CFR Part 192 require assurance that the release rate will not exceed 20 pCi · m^{-2} · s^{-1} "for a period of 1000 years to the extent reasonably achievable and in any case for at least 200 years when averaged over the disposal area over at least a one-year period." The U.S. Nuclear Regulatory Commission (NRC) accepts cover designs for which radon attenuation is calculated with the computer program RADON (NRC, 1989) or its predecessor program, RAECOM, as a basis for compliance. We used RADON to test a range of possible current and future influences of root intrusion and ecological development on radon flux from the cover. Input data for the tests consisted of a combination of characterization data from the original investigation, field data depicting current conditions at Burrell, and data from the Hannastown site as an analog of possible future conditions (Waugh and Smith, 1998).

The mathematical model implemented in RADON describes one-dimensional, steady-state radon diffusion through a two-phase multilayer system. The model does not address preferential diffusion in soil macropore structure or active transport through the transpiration stream of plants. Therefore, although RADON is the accepted tool for designing UMTRA disposal cell covers, it may underestimate increases in flux rates attributable to root intrusion and soil development.

3.1 RADON Program Input Data

The RADON program requires input data on radiological and physical properties of tailings and cover layers. Original design values for parameters that are not expected to change appreciably or in response to root intrusion were held constant (Table 3–1).

Table 3–1. Constants Input to RADON Program for Calculating Radon Flux From Burrell Cover

Constant	Description	Source
Tailings Layer Thicknesses (from the bottom to top of the tailings)	Layer 1 = 180 cm Layer 2 = 60 cm Layer 3 = 60 cm	Burrell completion report (Morrison-Knudsen Engineers, Inc., 1994)
Tailings Dry Bulk Density	1.46 g · cm^{-3}	Burrell completion report (Morrison-Knudsen Engineers, Inc., 1994)
Tailings ^{222}Rn Emanation Coefficient (mean)	0.15	Table 2–2
Tailings Water Content	9.0	Burrell completion report (Morrison- Knudsen Engineers, Inc., 1994)
Cover ^{222}Rn Emanation Coefficient	0.00	NRC (1989) default
Cover ^{226}Ra Activity	0.00	NRC (1989) default

Radium-226 activity, soil water content, and dry-weight bulk density were selected as RADON test variables because (1) sensitivity analyses have shown them to be important (e.g., Smith et al., 1985), (2) they are expected to change in the long-term, and/or (3) field measurements (Section 2.4) show that they are influenced by root intrusion and long-term ecological change.

3.1.1 Radium-226 Activity

The radiological characterization data for Burrell tailings (Table 2–1) underestimate ^{226}Ra activity during the 200- to 1,000-year design life of the cover. Radium-226 activity is expected to increase over time as a consequence of ^{230}Th decay. Table 3–2 gives initial (t = 0) ^{226}Ra and ^{230}Th activity as measured during construction of the cell (from Table 2–1) and the serial decay of ^{226}Ra and ^{230}Th through the year t = 1,000.

Table 3–2. Serial Decay of ^{226}Ra and ^{230}Th (in picocuries per gram) at Three Depths Based on Average Activity From As-Built Characterization Data

Time (years)	Depth = 0–60 cm ^{226}Ra	Depth = 0–60 cm ^{230}Th	Depth = 60–120 cm ^{226}Ra	Depth = 60–120 cm ^{230}Th	Depth = 120–300 cm ^{226}Ra	Depth = 120–300 cm ^{230}Th
0	39.5	416.0	26.2	204.1	79.8	878.5
50	47.5	415.8	30.0	204.0	96.8	878.1
100	55.4	415.6	33.7	203.9	113.5	877.7
150	63.1	415.5	37.3	203.8	129.8	877.3
200	70.6	415.3	40.9	203.7	145.8	876.9
250	78.0	415.1	44.4	203.6	161.4	876.6
300	85.2	414.9	47.8	203.6	176.7	876.2
350	92.2	414.7	51.1	203.5	191.7	875.8
400	99.1	414.6	54.3	203.4	206.3	875.4
450	105.8	414.4	57.5	203.3	220.6	875.1
500	112.4	414.2	60.6	203.2	234.5	874.7
550	118.9	414.0	63.7	203.1	248.2	874.3
600	125.2	413.9	66.7	203.0	261.6	873.9
650	131.3	413.7	69.6	202.9	274.7	873.5
700	137.4	413.5	72.4	202.9	287.5	873.2
750	143.3	413.3	75.2	202.8	300.0	872.8
800	149.0	413.1	77.9	202.7	312.2	872.4
850	154.7	413.0	80.6	202.6	324.2	872.0
900	160.2	412.8	83.2	202.5	335.9	871.7
950	165.6	412.6	85.8	202.4	347.3	871.3
1,000	170.9	412.4	88.2	202.3	358.5	870.9

The total ^{226}Ra activity in picocuries per gram at any time (N_2) was calculated as

$$N_2 = \frac{\lambda_2 (N_1)_0}{\lambda_2 - \lambda_1}(e^{-\lambda_1 t} - e^{-\lambda_2 t}) + (N_2)_0 e^{-\lambda_2 t} \tag{1}$$

where

λ_2 = 8.63×10^{-6}, the decay constant for ^{226}Ra,
$(N_1)_0$ = the initial activity of ^{230}Th,
λ_1 = 4.32×10^{-4}, the decay constant for ^{230}Th, and
$(N_2)_0$ = the initial activity of ^{226}Ra.

3.1.2 Soil Water Content and Dry-Weight Bulk Density

Soil water content and dry-weight bulk density of the CSL are the two RADON input parameters most influenced by root intrusion and ecological development on the cover. Because radon diffusion in soil is elevated when interconnected pore spaces are filled with air, radon flux is most sensitive to the CSL water content and porosity (NRC, 1989). RADON calculates porosity as a function of the dry-weight bulk density, assuming a constant specific gravity ($2.65\ g \cdot cm^{-3}$) and the density of water as unity in grams per cubic centimeter.

NRC considers the long-term soil water content of the CSL to be the parameter that introduces the greatest uncertainty in radon attenuation calculations. In the absence of field data, NRC accepts the soil water content at which permanent wilting occurs as a reasonable value of the long-term soil water content. The permanent wilting point used by UMTRA for design calculations is –15 bars (DOE, 1989). Water retention characteristic curves (Waugh and Smith, 1997) indicated that the –15 bar-soil water equivalent is about 23 percent by volume for the Burrell CSL and about 15 percent by volume for the Hannastown subsoil. In situ dry-weight bulk densities were $1.76\ g \cdot cm^{-3}$ for the Burrell CSL and $1.48\ g \cdot cm^{-3}$ for the Hannastown subsoil (Table 2–5). Converting volumetric water content (θ_v) to gravimetric water content (θ_w) as

$$\theta_w = \theta_v(\rho_w / \rho_b) \tag{2}$$

where ρ_w, the density of water, is taken as unity in grams per cubic centimeter, gives –15 bar gravimetric water content equivalent values for Burrell and Hannastown of 13.1 percent and 10.1 percent, respectively. RADON requires gravimetric values.

The –15-bar soil water equivalent is a conservative annual average for the humid climate of western Pennsylvania. At the depth of the Burrell CSL, agricultural and woodland soils in western Pennsylvania only rarely dry to –15 bar (Rogowsky, 1995). NRC also accepts in situ measurements of soil water content if samples are obtained below depths influenced by high seasonal variability. Wet and dry season in situ gravimetric water contents of the Burrell CSL for 1995 (Table 2–6) were not significantly different and, therefore, provide a reasonable and still conservative annual average value of 19.0 percent. The 1995 dry-season water content of 17.1 percent for the Hannastown subsoil is a reasonable long-term value.

3.2 RADON Test Matrix

A suite of RADON tests were run encompassing a broad range of current and possible future conditions. Table 3–3 provides summaries of the factorial test structure.

Table 3–3. RADON Model Test Structure

Factor	Level		Description
Year	0		Current conditions
	200		Minimum cover design life
	1000		Target cover design life
^{226}Ra Activity (pCi · m^{-2} · s^{-1}) in Three Tailings Layers	Layer 1: (0–60 cm)	39.5 in year 0 70.6 in year 200 170.9 in year 100	^{226}Ra activity derived from serial decay calculations (Table 3–2) from sampling of three tailings layers during construction of the disposal cell
	Layer 2: (60–120 cm)	26.2 in year 0 40.9 in year 200 88.2 in year 1000	
	Layer 3: (120–300 cm)	79.8 in year 0 145.8 in year 200 358.5 in year 1000	
Soil Water Content (gravimetric)	Burrell CSL	13.1%	–15 bar equivalent (Waugh and Smith, 1997)
		19.0%	In situ mean value (Table 2–6)
	Hannastown	10.1%	–15 bar equivalent (Waugh and Smith, 1997)
		17.1%	In situ mean value (Table 2–6)
Dry-Weight Bulk Density (g · cm^{-3})	Burrell CSL	1.76	In situ mean value (Table 2–5)
	Hannastown	1.48	In situ mean value (Table 2–5)
CSL Layer Thickness (cm)	0.0		Rn flux calculated given no CSL
	90.0		Actual thickness of the Burrell CSL
	Optimum		RADON calculates the thickness required to maintain ^{222}Rn flux below the 20 pCi · m^{-2} · s^{-1} standard.

3.3 RADON Test Results and Discussion

Table 3–4 presents a summary of the RADON model test results. Given the constraints and assumptions of these tests, ^{222}Rn flux levels at the surface of the Burrell disposal cell should not exceed the standard within 1,000 years if the CSL remains intact and dries no more than the Hannastown analog subsoil.

Table 3–4. RADON Model Test Results; Shaded Results Are for Analog Site Conditions

	Test Conditions						Test Results[a]	
		^{226}Ra Activity (pCi/g) in Three Tailings Layers[b]			CSL			
Test No.	Time (0 + t)	0–60 cm	60–120 cm	120–300 cm	θ_w[c] (wt%)	ρ_b[d] (g · cm^{-3})	CSL (cm)	Rn Flux (pCi · m^{-2} · s^{-1})
1	0	39.5	26.2	79.8	–	–	0.0	23.6
2	0	39.5	26.2	79.8	19.0	1.76	< 10.0	20.0
3	0	39.5	26.2	79.8	19.0	1.76	90.0	< 0.1
4	0	39.5	26.2	79.8	13.1	1.76	< 10.0	20.0
5	0	39.5	26.2	79.8	13.1	1.76	90.0	0.8
6	200	70.6	40.9	145.8	–	–	0.0	42.0
7	200	70.6	40.9	145.8	19.0	1.76	< 10.0	20.0
8	200	70.6	40.9	145.8	19.0	1.76	90.0	15.7
9	200	70.6	40.9	145.8	13.1	1.76	25.1	20.0
10	200	70.6	40.9	145.8	13.1	1.76	90.0	1.3
11	200	70.6	40.9	145.8	17.1	1.48	26.5	20.0
12	200	70.6	40.9	145.8	17.1	1.48	90.0	6.3
13	200	70.6	40.9	145.8	10.1	1.48	72.3	20.0
14	200	70.6	40.9	145.8	10.1	1.48	90.0	16.8
15	1,000	170.9	88.2	358.5	–	–	0.0	101.0
16	1,000	170.9	88.2	358.5	19.0	1.76	< 10.0	20.0
17	1,000	170.9	88.2	358.5	19.0	1.76	90.0	< 0.1
18	1,000	170.9	88.2	358.5	13.1	1.76	74.7	20.0
19	1,000	170.9	88.2	358.5	13.1	1.76	90.0	3.2
20	1,000	170.9	88.2	358.5	17.1	1.48	73.2	20.0
21	1,000	170.9	88.2	358.5	17.1	1.48	90.0	15.2
22	1,000	170.9	88.2	358.5	10.1	1.48	163.3	20.0
23	1,000	170.9	88.2	358.5	10.1	1.48	90.0	40.5

[a] All test results are output of the RADON code (NRC, 1989).
[b] ^{226}Ra activity (picocuries per gram) for the years 0, 200, and 1,000 are based on characterization of ^{226}Ra and ^{230}Th activity in the cell during construction (Table 2–1) and calculation of their serial decay (Table 3–2).
[c] θ_w values: 13.1% was derived from the volumetric moisture retention curve for the Burrell CSL at –15 bar matric potential (Waugh and Smith, 1997), 19.0% was the dry-season mean for 1995 (Table 2–6), 17.1% was the dry-season mean for the Hannastown analog subsoil (Table 2–6), and 10.1% was derived from the volumetric moisture retention curve for the Hannastown analog subsoil at –15 bar matric potential (Waugh and Smith, 1997).
[d] ρ_b bulk density values: 1.76 and 1.48 g · cm^{-3} are in situ values for the Burrell CSL and Hannastown analog subsoil, respectively (Table 2–5).

Given current ^{226}Ra levels in the tailings, it appears there is little need for a CSL in the cover (Tests 1 through 5). Flux rates at the surface of the tailings in the year $t = 0$ barely exceed the standard (Test 1). A CSL less than 10 cm thick would be more than adequate for compliance with the standard (Tests 2 and 4). The 90-cm CSL maintains flux rates below

1.0 pCi · m^{-2} · s^{-1} regardless of root intrusion; present-day plant growth had no significant

effect on CSL water content (Test 3). Even for the unlikely scenario that plant transpiration dries the CSL water content to –15 bar, flux rates remain below 1.0 pCi · m^{-2} · s^{-1} (Test 5).

Tests 6 through 14 results are for ^{226}Ra activity levels in the year t = 200. Flux rates at the surface of the tailings (Test 6) are more than twice the standard (42.0 pCi · m^{-2} · s^{-1}). However, a CSL less than 10 cm thick would be adequate, given in situ soil water data (Test 7). A minimum 25-cm-thick CSL would be needed, assuming the –15 bar water content (Test 9). A 90-cm CSL remains more than adequate to meet the flux standard at the surface of the disposal cell (Tests 8 and 10), even if it degrades and dries to conditions equivalent to the Hannastown subsoil bulk density, porosity, or –15 bar moisture (Tests 11 through 14).

For the 1,000-year ^{226}Ra activity levels (Tests 15 through 23), ^{222}Rn flux rates at the top of the tailings exceed 100 pCi · m^{-2} · s^{-1} (Test 15). Given the unlikely assumption that in situ bulk density and porosity at Burrell will remain unchanged, a CSL less than 10 cm thick would be adequate if soil water also remains unchanged (Test 16); a minimum 75-cm CSL would be needed if soil water content dropped to the –15 bar equivalent (Test 18). For current Burrell conditions, the 90-cm CSL remains adequate (Tests 17 and 19). A 90-cm CSL on the disposal cell with dry-season field conditions equivalent to the Hannastown analog subsoil is also adequate to meet the standard (Test 21). However, if unforeseen ecological development and changes in climatic conditions caused the CSL to dry to –15 bar (Test 23), annual average radon flux rates, averaged over the surface of a 90-cm CSL, may double the standard (40.5 pCi · m^{-2} · s^{-1}). For this unlikely scenario, a minimum CSL thickness of 163 cm would be required (Test 22).

4.0 Contaminant-Leaching Risk Assessment

We developed a three-phase approach to evaluate possible consequences of increased water movement into the tailings that could result from root intrusion of the cover.

- **Phase I: Assessment of Tailings Contaminants**

  Phase I evaluated risks of water extracted directly from the disposal cell to human health and the environment. As a simple screening-level measure of risk, this evaluation required a comparison of reasonable estimates of pore-water concentrations of contaminants of concern (COCs) with drinking water standards. Estimates of existing and potential future COC concentrations were derived from a sequence of leaching and pore-fluid extraction tests using samples augered from the disposal cell. The tests were designed to capture a reasonable range of possible future changes in the chemistry of leach water.

  Phase I test results suggested that water extracted directly from the pile could pose unacceptable risk.

- **Phase II: Assessment of Groundwater Contamination**

  The purpose of Phase II was to model the effects of a higher CSL permeability on the leaching of pore-water COCs into groundwater beneath the disposal cell.

  Phase II required the following information:

  – Estimates of drainage from the cover for current and possible future ecological conditions. A simple soil-water balance model was used to estimate drainage for current Burrell conditions and for Hannastown analog site conditions.

  – Physical and hydraulic properties of disposal cell materials and underlying sediments. These properties were estimated from existing data in the Burrell completion report.

  – Existing water quality data for seeps and wells.

  The results of Phase II modeling indicated that a higher CSL permeability, attributable to root intrusion, would not likely cause concentrations of COCs in groundwater beneath the disposal cell to exceed drinking water standards.

- **Phase III: Exposure Assessment**

  If Phase II had reached the opposite conclusion, then the risk assessment would have proceeded with Phase III. Phase III would have followed EPA guidance for risk characterization and assessment, including identification of potential receptors, exposure analysis, effects assessment, and comparison of the risks of contaminant leaching with the risks of long-term herbicide spraying.

  Phase III would have consisted of the following tasks:

  – Compile information on residential and incidental use of surface water and groundwater in the area. Acquire any information on potential future land use. Clarify DOE property boundaries and the duration of DOE institutional controls at the site.

– Characterize aquatic and terrestrial habitats potentially affected by groundwater and surface water.
– Identify human and ecological pathways, potential receptors, and exposure points.
– Evaluate exposure pathways and estimate exposure point concentrations for a reasonable range of possible future site conditions.
– Calculate hazard quotients and indices.

Phase I and Phase II of the risk assessment were completed in 1998. This section provides summaries of the methods and the results of the Phase I and Phase II tasks listed in Table 4–1.

Table 4–1. Phase I and Phase II Tasks

Task	Description
Phase I: Assessment of Tailings Contaminants	
	• Complete project plans
	• Search and evaluate contaminant geochemistry literature
	• Sample and analyze disposal cell materials
	• Conduct leach studies of disposal cell materials
	• Compare leach study results with drinking water standards
Phase II: Assessment of Groundwater Contamination	
	• Evaluate existing water quality data
	• Compile soil physical and hydraulic property data
	• Model soil-water balance of cover
	• Model groundwater COC concentrations attributable to cover K_{sat} changes
	• Compare groundwater COC estimates with drinking water standards

4.1 Phase I: Assessment of Tailings Contaminants

4.1.1 Evaluation of Geochemistry Literature

The Burrell completion report (Morrison-Knudsen Engineers, Inc., 1994) and other project files contained no pore-water quality data for tailings materials. A search for literature on contaminant levels in similar geochemical environments did not provide reasonable or transferable estimates of pore-water quality. Therefore, geochemistry data that were needed to model pore-water quality based on solid-phase chemistry were lacking.

4.1.2 Sampling and Analysis of Disposal Cell Materials

Because of the lack of sufficient literature on mill tailings geochemistry similar to Burrell conditions, we chose to sample and analyze tailings materials from the Burrell disposal cell.

Drilling and sampling of tailings materials occurred during two trips to western Pennsylvania. A total of six boreholes were drilled on May 13 and 14, 1998. Figure 4–1 shows the borehole locations on the disposal cell. The holes were advanced using a Simco Model 4000 track-mounted drill equipped with 3.5-inch inside diameter hollow stem augers. Samples were collected with a 140-pound sliding hammer using a 30-inch drop. Borehole sites were prepared by removing the riprap and setting it aside for later replacement. Drill cuttings were placed on plastic sheeting to protect the ground from contamination. Radon barrier materials and tailings were segregated on the plastic sheets. Surface radiation levels were monitored continuously during the drilling operation.

Boreholes 1 and 2 (Figure 4–1) were advanced to the target depth of approximately 21.5 and 20 feet, respectively. However, when cuttings with elevated radioactivity were encountered, the on-site health and safety officer terminated drilling of boreholes 3 through 6 before the target depth was reached. Three new boreholes were drilled on July 8 and 9, 1998, at locations 4, 5, and 6 where the May drilling had encountered contaminated tailings (Figure 4–1). These holes were drilled to approximately 50 feet. Drive samples were collected at 5-foot intervals and lithologic logs of the cuttings were recorded (see Appendix A). Soil samples from an upgradient location were also collected to serve as a reference (background).

Boreholes 4, 5, and 6 were located on the west end of the Burrell disposal cell in an area that an earlier characterization study indicated has the highest radium concentrations in the disposal cell (Morrison-Knudsen Engineers, Inc., 1994).

After the samples were removed, all boreholes were backfilled with cuttings in approximately the same horizons from which they were taken, and the riprap layer was replaced. The auguring and sampling equipment was then cleaned with high-pressure washing equipment following completion of the last hole to prevent the potential spread of residual contamination.

4.1.3 Column Leach Study of Disposal Cell Materials

A column leach study was conducted by the Environmental Sciences Laboratory (ESL) at the DOE Grand Junction Office. The purpose of the study was to bound a range of possible future COC concentrations in tailings pore water. Precipitation (rainfall and snowfall) at the site was simulated and passed through samples of contaminated tailings materials that had been retrieved from the Burrell disposal cell. ESL personnel believed that small differences in the chemical composition of the simulated precipitation would have only minor effects on the results because the ionic composition will be dominated by interaction with the soils.

Soil chemical conditions may change over time because of plant growth, microbial activity, change in land use, and other factors. Thus, an acidic solution (pH = 4.5), the same as that used for the toxicity characteristic leaching procedure (TCLP) (51 FR 21648), was passed through the column to represent a worst-case scenario. Considering the chemical conditions currently existing in groundwater at the Burrell site (neutral pH, high sulfate, high calcium, and high alkalinity), groundwater chemistry would have to change drastically for TCLP conditions to occur; therefore, TCLP conditions are highly unlikely.

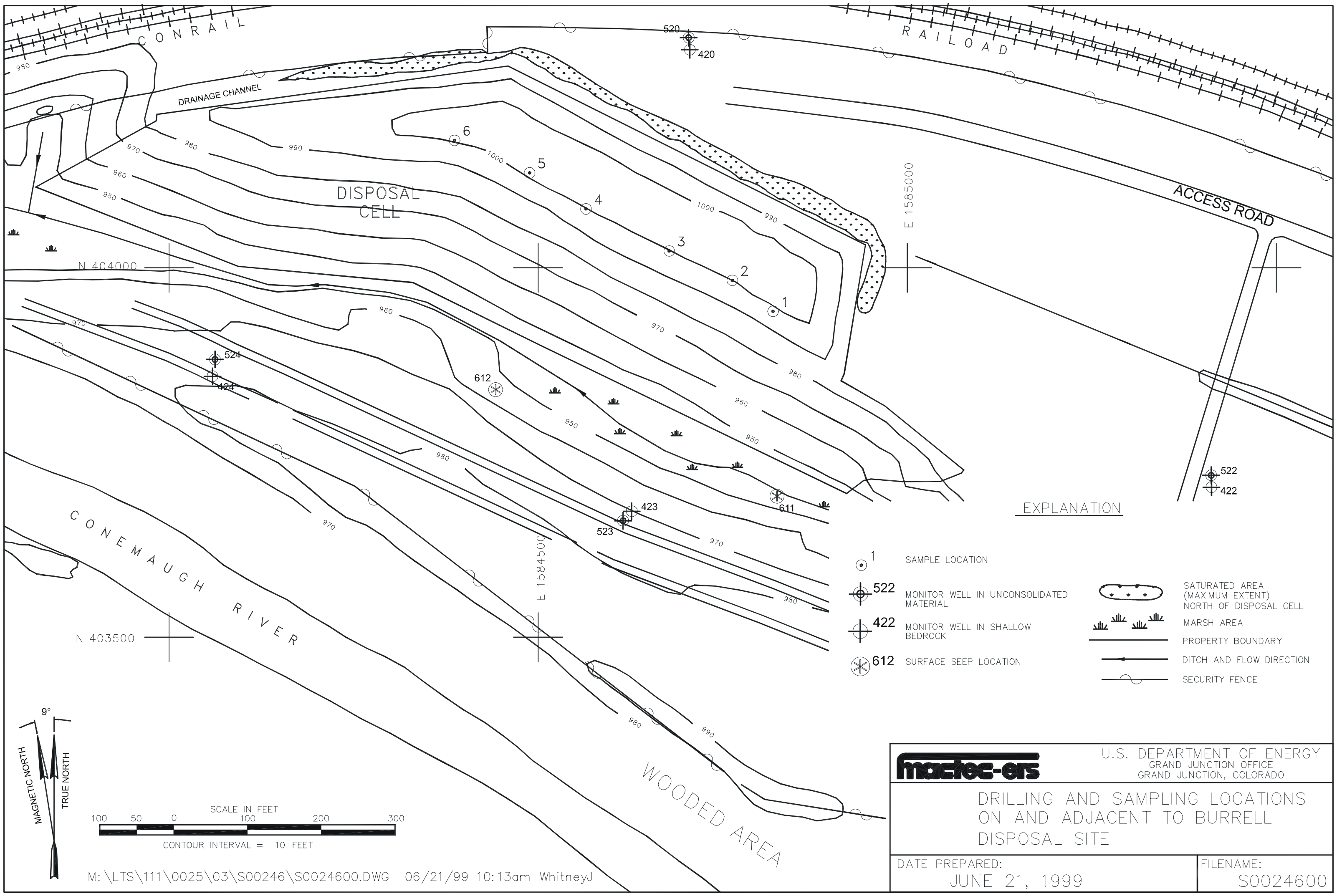

Figure 4–1. Drilling and Sampling Locations On and Adjacent to Burrell Disposal Site

A total of five leach tests were performed. Three of the tests used composite samples (a composite consists of material from the entire length of the borings) from each of three borings, boreholes 4, 5, and 6 (see Figure 4–1). Boreholes 4, 5, and 6 were located in an area with the highest radium concentrations in the disposal cell (Section 3.1). A fourth leach test used samples with the highest radioactivity levels. The fifth leach test used background or reference soils collected near, but not influenced by, the Burrell disposal cell. The purpose of the background test was to evaluate if contaminated soils in the disposal cell are likely to release COCs in concentrations above those released by "normal" soils in the area.

The column leach test procedure follows:

1. Borehole cuttings from the disposal cell and the background sample were air dried for 5 days.
2. Columns were constructed of clear acrylic tubing (4-inch inside diameter, 8-inch length). The columns were packed by lightly tamping the sample material. Column designations and sample weights follow:

Identifier	Sample Weight (g)	Description
A	2,099.60	Composite from borehole 4
B	2,267.20	Background sample
C	1,939.40	Composite from borehole 6
D	2,203.80	Composite from borehole 5
E	536.30 Boreholes 4 (15–16 feet) and 1,821.20 from borehole 6 (15–17 feet)	Hottest (radiological) material from boreholes 4 and 6

Composite samples were prepared by spooning nearly equivalent portions from throughout the boreholes. Again, composite samples from boreholes 4, 5, and 6, augered in the area of the disposal cell with highest ^{226}Ra levels, were selected to bias the tests at the high end of contaminant distribution.

3. Test fluids were passed through the columns from bottom to top with a peristaltic pump. Flow rates were about 1.5 milliliters per minute (mL/min). Samples were collected in a flask placed at the outlet. All fluids were filtered [0.45 micron (μm)] and submitted to the GJO Analytical Chemistry Laboratory for analyses. Each sample consisted of 1,625 mL divided into 5 separate aliquots for analyses.

Preservation techniques were as follows:

Container	Preservative	Analyses
1 L Nalge	HNO_3, pH<2	^{226}Ra, ^{228}Ra
250 mL Nalge	NaOH, pH>12	C, N
125 mL Nalge	HNO_3, pH<2	Pb, Mn, Mo, Se, U, V
125 mL Nalge	None	SO_4
125 mL Nalge	H_2SO_4, pH<2	NO_3, NH_4

4. Deionized water was passed through the columns initially. The first four samples were collected using deionized water as the influent. Then the TCLP fluid was used as the influent. The last two samples were collected using TCLP fluid as the influent. The TCLP fluid was prepared in the GJO Analytical Chemistry Laboratory by combining 5.7 mL of glacial acetic acid, 64.3 mL of 1N NaOH, and diluting the solution to 1L with deionized water. The pH of the TCLP solution is 4.5.

Table 4–2 presents results of the leach study. Appendix B contains several figures that display leachate concentrations for selected constituents.

Table 4–2. Comparison of the Burrell Site Leach Study Results With Risk-Based Screening Levels and UMTRA Maximum Concentration Limits (MCLs)

Constituent (units)	Risk-Based Screening Level[a]	UMTRA MCL	Maximum Deionized Water Concentration	Exceeds Risk Level or MCL?	Maximum TCLP Concentration	Exceeds Risk Level or MCL?
Lead (µg/L)	N/A[b]	50	1	No	38.7	No
Manganese (µg/L)	840	N/A	1,120	Yes	28,300	Yes
Molybdenum (µg/L)	180	100	793	Yes	125	Yes
Selenium (µg/L)	180	10	5.8	No	24.6	Yes
Uranium (µg/L)	110	44	210	Yes	583	Yes
Vanadium (µg/L)	260	N/A	7	No	7	No
Cyanide (µg/L)	N/A	N/A	3.9	N/A	3.9	N/A
Ammonia (µg/L)	1000	N/A	233	No	419	No
Nitrate (µg/L)	58,000	44,000	2,400	No	96	No
^{226}Ra (pCi/L)	N/A	5[c]	3.8	No	128	Yes
^{228}Ra (pCi/L)	N/A	5	<1.4	No	6.9	Yes
Sulfate (mg/L)	N/A[d]	N/A	418	N/A	85.5	N/A

[a]These are screening-level risks developed by EPA Region III using standard default values. Site concentrations below these levels are generally considered to be protective of human health. Reference "Updated Risk-Based Concentration Table" by Roy L. Smith, Ph.D., Toxicologist, March 17, 1997.
[b]N/A = not available.
[c]Combined ^{226}Ra and ^{228}Ra level is 5 pCi/L.
[d]Although an official risk-based level has not been developed, proposed levels range from 250 to 2,000 mg/L, depending on site-specific conditions.

4.1.4 Comparison of Leach Study Results with Drinking Water Standards

Table 4–2 also presents a comparison of the Phase I leach study results with risk-based screening levels and UMTRA maximum concentration limits (MCLs). The highest leachate concentrations for manganese, molybdenum, and uranium concentrations, using deionized water, exceeded the respective screening threshold and/or the MCL. When leached with the TCLP solution, the COCs manganese, molybdenum, selenium, uranium, ^{226}Ra, and ^{228}Ra all exceeded the respective screening threshold and/or the MCL. Risk-based screening threshold values and UMTRA MCLs are shown on the leach study figures in Appendix B.

These Phase I results indicate that water extracted directly from the Burrell disposal cell may pose unacceptable risk to human health and the environment. Therefore, we chose to proceed with Phase II of the risk assessment, Assessment of Groundwater Contamination.

4.2 Phase II: Assessment of Groundwater Contamination

The purpose of Phase II was to review existing groundwater quality data and then to model the effects of a higher CSL permeability on the leaching of COCs into groundwater beneath the disposal cell.

4.2.1 Summary of Existing Water Quality Data

Groundwater monitor wells and seeps are sampled annually in the fall at the Burrell site (DOE, 1999). The groundwater monitor network consists of two pairs of wells at five locations: two hydraulically downgradient point-of-compliance locations, one hydraulically crossgradient point-of-compliance location, and two hydraulically upgradient point-of-compliance locations. Each well pair consists of a shallow well completed in unconsolidated fill or alluvium and a deeper well completed in shallow bedrock. Seeps along the base of the south side slope of the disposal cell are also sampled. The following 18 constituents are analyzed in the water samples:

ammonium	magnesium	selenium
calcium	manganese	sodium
chloride	molybdenum	sulfate
gross alpha	nitrate	total dissolved solids
iron	potassium	uranium
lead	^{226}Ra and ^{228}Ra	vanadium

Of the 18 analytes, 7 have exceeded minimum laboratory detection limits since sampling began in 1987, but none exceeded the MCLs in October 1998:

- Gross alpha has occasionally reached detection limits but remains well below the MCL.
- Lead concentrations in samples were anonymously high in 1987, as high as 0.15 mg/L. The MCL is 0.05 mg/L. Lead concentrations have not reached detection limits since then.

- Values for molybdenum (0.06 to 0.08 mg/L) in samples from downgradient locations were also highest in 1987 but below the MCL (0.10 mg/L). Since then, values have dropped by more half but remain higher than samples from upgradient and crossgradient locations.
- Low values for nitrate in samples from downgradient and background locations, barely above detection limits, have persisted.
- Radium-226 and -228 levels in samples from downgradient and background locations have also remained barely above detection limits.
- Selenium concentrations in samples have been at or below laboratory detection limits at all locations since sampling began in 1987.
- Uranium concentrations in samples from downgradient alluvial wells is higher than in background wells. Uranium values increased slightly between 1996 and 1998 but remain below MCLs.

Table 4–3 and Table 4–4 present the analytical results of alluvial and bedrock groundwater samples for October 1998**.**

Table 4–3. Summary of Alluvial Groundwater Sample Analytical Results[a]

Analyte	UMTRA MCL	Alluvial Groundwater Sample Location				
		MW-420 (upgradient)	MW-421 (upgradient)	MW-422 (crossgradient)	MW-423 (downgradient)	MW-424 (downgradient)
Gross alpha	15[b]	9.23 U[c]	17.14 U	7.92 U	24.93 U	14.57 U
Lead	0.05	0.001 U	0.001 U	0.001 U	0.001 U	0.001 U
Molybdenum	0.10	0.001 U	0.001 U	0.001 U	0.0153	0.021
Nitrate as NO_3	44	0.0294	0.011 U	0.0245	0.0208	0.0188
^{226}Ra	5, combined	0.15 U	0.13 U	0.14 U	0.51	0.13 U
^{228}Ra		0.93	0.62 U	0.66 U	0.67 U	0.64 U
Selenium	0.01	0.001 U	0.001 U	0.001 U	0.001 U	0.001 U
Uranium	0.044	0.001 U	0.001 U	0.001 U	0.022	0.0019

[a]All results in milligrams per liter, except ^{226}Ra, ^{228}Ra, and gross alpha are in picocuries per liter.
[b]Excludes contributions from uranium and ^{222}Rn decay. Groundwater sample results include uranium and ^{222}Rn decay.
[c]U = undetected at respective laboratory reporting limit.

Table 4–4. Summary of Bedrock Groundwater Sample Analytical Results[a]

Analyte	MCL	Bedrock Groundwater Sample Location				
		MW-520 (upgradient)	MW-521 (upgradient)	MW-522 (crossgradient)	MW-523 (downgradient)	MW-524 (downgradient)
Gross alpha	15[b]	5.93 U[c]	10.73 U	7.37 U	14.22 U	9.23 U
Lead	0.05	0.001 U	0.001 U	0.001 U	0.001 U	0.001 U
Molybdenum	0.10	0.0014	0.0143	0.001 U	0.0138	0.0012
Nitrate as NO_3	44	0.0361	0.0113	0.0194	0.0224	0.011 U
^{226}Ra	5, combined	0.15 U	0.19 U	0.14 U	0.14 U	0.14 U
^{228}Ra		1.27	1.05	0.68 U	0.69 U	0.66 U
Selenium	0.01	0.001 U	0.001 U	0.001 U	0.001 U	0.001 U
Uranium	0.044	0.001 U	0.001 U	0.001 U	0.001 U	0.001 U

[a]All results in milligrams per liter, except ^{226}Ra, ^{228}Ra, and gross alpha are in picocuries per liter.
[b]Excludes contributions from uranium and ^{222}Rn decay. Groundwater sample results include uranium and ^{222}Rn decay.
[c]U = undetected at respective laboratory reporting limit.

4.2.2 Soil Physical and Hydraulic Property Data for Modeling

Modeling of water movement and drainage from the cover and tailings requires input data on the design, physical properties, and hydraulic properties of cover materials and vegetation.

Cover Design

From the tailings layer up, the Burrell cover consists of a 90-cm-thick CSL, a 30-cm-thick sand and gravel drainage layer, and a 30-cm-thick rock layer (Figure 2–1). The specified hydraulic conductivity for the CSL was 1×10^{-7} cm · s^{-1}. The sand-and-gravel drainage or filter layer in the cover also serves as a bedding layer for the rock armor. The rock armor is sized to prevent erosion of underlying layers given a PMP event, the most severe combination of meteorological and hydrological conditions possible at a site.

Soil Physical Properties

Material property data for the CSL were compiled from the completion report for Burrell (Table 2–3). Section 2.4.1 presents soil water content, texture (particle-size distribution), bulk density (compaction), and porosity of samples retrieved from the Burrell cover and from analog soil profiles at Hannastown.

Soil Hydraulic Properties

Water retention characteristic data for the Burrell CSL and the Hannastown subsoil, needed to model water movement through the cover, were presented in Section 2.4.2. These data were also used as a measure of the value of Hannastown as an analog site.

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 (Meyer et al., 1996). Root channels and eventually earthworms, burrowing animals, soil structural changes, and other heterogeneities can all combine to promote preferred pathways for flow of water.

At Burrell, given high precipitation and a CSL that is often saturated, the passage of water through the cover is most sensitive to changes in the saturated hydraulic conductivity. Under these conditions, the hydraulic gradient is approximately 1 and water flux through the CSL (Q^{CSL}) can be calculated using Darcy's law (Meyer et al., 1996) as

$$Q^{CSL} = K_{sat} \cdot I \qquad (3)$$

where

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

Under saturated conditions, when H is small with respect to T, water flux through the CSL is approximated by saturated hydraulic conductivity (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. The AEPs were designed and manufactured by Daniel B. Stephens and Associates, Inc., for use on engineered clay layers and other low-permeability clay soils (Stephens et al., 1988; Havlena and Stephens, 1992).

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 or analog subsoil 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 and three dominant tree species (sycamore, black locust, and staghorn sumac).

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

- Bouwer (1966) method, which assumes initially unsaturated soil, was used for the analog soils;

- Young et al. (1995) method, which assumes initially saturated or nearly saturated soil and deep seepage, was used for most of the cover tests with plants; and

- Young et al. (1995) method that assumes initially saturated or nearly saturated soil and *no* deep seepage. This method was used for cover tests without plants and one test with plants where water moved to the surface after a period of monitoring.

Table 4–5 presents in situ K_{sat} test results. Results for four conditions are presented: (1) the Burrell CSL without plants, (2) the Burrell CSL with Japanese knotweed, (3) the Burrell CSL with trees, and (4) the Hannastown analog subsoil. For all Burrell cover tests, field soil-water content values were at saturation and water was observed ponding in AEP test pits.

- At locations on the disposal cell where plants have *not* rooted (Table 4–5), the in situ K_{sat} of 2.9×10^{-7} cm · s^{-1} was about 3 times the CSL design standard (1×10^{-7} cm · s^{-1}) (DOE, 1989) and about an order of magnitude higher than laboratory falling-head results for the same soil (2.6×10^{-8} cm · s^{-1}).

- Japanese knotweed increased the Burrell CSL K_{sat}, within their root zone, by 2 orders of magnitude (3.0×10^{-5} cm · s^{-1}). Japanese knotweed taproots grew vertically through the drainage layer of sand and gravel, were diverted laterally at the surface of the CSL, but often turned again deep into the CSL with many secondary laterals and fibrous roots.

- The CSL K_{sat} for the three tree species (4.8×10^{-7} cm · s^{-1}; Q^{CSL} = 0.41 millimeter per day) was not significantly different than the control (no plants; Table 4–5). The test trees were taller than Japanese knotweed but had significantly lower foliage density. Tree roots clogged the drainage layer, but only a small percentage of the root biomass was observed in the CSL.

Table 4–5. Air-Entry Permeameter Tests of In Situ K_{sat} *in Burrell CSL and Hannastown Analog Subsoil*

Conditions Tested	K_{sat} (cm · s^{-1})	K_{sat} (mean)[a]	Calculation Method
Burrell CSL Without Plants			
Replicate 1	1.8×10^{-7}	2.9×10^{-7} a	Young et al. (1995)[c]
Replicate 2	6.0×10^{-7}		Young et al. (1995)[c]
Replicate 2	1.0×10^{-7}		Young et al. (1995)[c]
Burrell CSL With Plants			
Japanese knotweed	1.6×10^{-6}	3.0×10^{-5} b	Young et al. (1995)
Japanese knotweed	5.8×10^{-5}		Young et al. (1995)
Japanese knotweed	6.1×10^{-4} [b]		Young et al. (1995)[c]
Trees			
Sycamore	4.0×10^{-7}	4.8×10^{-7} a	Young et al. (1995)
Staghorn sumac	7.4×10^{-7}		Young et al. (1995)
Black locust	3.1×10^{-7}		Young et al. (1995)
Hannastown Analog Subsoil			
Replicate 1	1.2×10^{-4}	1.2×10^{-4} c	Bouwer (1966)
Replicate 2	1.2×10^{-4}		Bouwer (1966)
Replicate 3	1.2×10^{-4}		Bouwer (1966)

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

- Measurements of K_{sat} at the Hannastown analog site are considered a reasonable upper range for future conditions on the Burrell cover (Waugh and Smith, 1997). The Hannastown K_{sat} (1.3×10^{-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.

4.2.3 Ecological Data for Modeling

Plant canopy structure plays a fundamental role in processes involving the interaction of plant communities and their environment such as evapotranspiration (McNaughton and Jarvis, 1983), biomass productivity (deWit,1965), and radiation interception (Ross, 1981) and, therefore, is needed to model these processes. Plant community leaf area index (LAI) was measured at Burrell and Hannastown vegetation with an LAI–2000 Plant Canopy Analyzer (LI-COR, Inc., 1992). The LAI–2000 provides an indirect but accurate estimate of LAI using "fish-eye" lens measurements of canopy gap fractions (the fraction of the sky visible through the canopy) at various angles (Welles and Norman, 1991). Table 4–6 presents a summary of LAI results.

Table 4–6. Leaf Area Index on Burrell Cover and at Hannastown Site

Site	Date	Start Time	Finish Time	LAI[a] Mean	LAI[a] S.E.(mean)	Visible Sky (%)[b]	n[c]
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]Leaf area index (LAI) is a dimensionless measure of "How much foliage?" LAI can be thought of as square meter of foliage area divided by square meter of ground area. It is also an index of leaf-evaporation surface area.
[b]"Visible sky" is an indicator of canopy light absorption.
[c]The number of sample points (n) were located using random points along transects originating at random locations along a baseline.

LAI data for Burrell and Hannastown plant communities provide 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, a 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, resulting in higher evapotranspiration rates that may help dry the soil and reduce the probability of saturated flow events. Lower standard error values for LAI at Hannastown 1 than at Hannastown 2 is an indication of increased uniformity in the canopy over time.

4.2.4 Model Soil Water Balance of Cover

Soil moisture data (Table 2–6) suggest that under present-day conditions the Burrell CSL is often saturated. So for present-day conditions, the passage of water through the cover is most sensitive to changes in the saturated hydraulic conductivity of the CSL. Therefore, for the purpose of modeling present-day groundwater contamination, given saturated conditions, the hydraulic gradient is approximately 1 and water flux through the CSL can be approximated by the saturated hydraulic conductivity.

Hundreds of years from now, assuming Hannastown is a reasonable analog of long-term conditions, the CSL will be significantly drier (Table 2–6). Prediction of water flux through a drier CSL must take into account many factors in the soil water balance and, thus, is more complex. We used a computer model called HELP (Hydrologic Evaluation of Landfill Performance) to predict the water flux or leakage for Hannastown as an analog of a future condition of the Burrell cover.

HELP Version 3.07 (Schroeder et al., 1996) is a quasi two-dimensional hydrologic model of water movement across, into, through, and out of landfills. The model accepts weather, soil, and design data and uses solution techniques that account for surface storage, snowmelt, runoff, infiltration, vegetative growth, evapotranspiration, soil moisture storage, lateral subsurface drainage, leachate recirculation, unsaturated vertical drainage, and leakage through soil, geomembrane, or composite liners. Landfill systems, including combinations of vegetation, cover soils, waste cells, lateral drain layers, barrier soils, and synthetic geomembrane liners, can be modeled. The program was developed to conduct water balance analyses of landfills, cover systems, and solid-waste disposal facilities. The model facilitates rapid estimation of the amounts of runoff, evapotranspiration, drainage, leachate collection, and liner leakage that may be expected to result from the operation of a wide variety of landfill designs.

Tables 4–7, 4–8, and 4–9 present summaries of input parameters, input values, and the source of input values. Table 4–10 presents a summary of average annual water-balance results, averaged for a 10-year simulation.

For Hannastown analog conditions, the HELP simulation indicates that drainage from the Burrell disposal cell cover should not be approximated by the saturated hydraulic conductivity. Water balance changes were most sensitive to LAI. The simulation calculated greater than 60 percent of precipitation lost by evapotranspiration. Approximately 25 percent of the precipitation was lost as leakage from the cover, and the balance was lost as runoff from the disposal cell. Appendix C contains the HELP 3.07 output file for the simulation.

4.2.5 Model Groundwater Contaminants of Concern Concentrations

The purpose of this task is to model the effects of the projected increase in the permeability of the CSL on COC concentrations in groundwater beneath the Burrell disposal cell. A range of possible future site conditions are defined based on the root intrusion study (Waugh and Smith, 1998), the column leach study (Section 4.1.3), and cover water-balance modeling (Section 4.2.4).

The following mixing equation from the Summers model (EPA, 1989) was used:

$$Cgw = [QpCp + QaCa] / Qp + Qa \qquad (4)$$

where

Cgw = concentration of contaminant in groundwater after source mixing,

Qp = volumetric flux of source water to aquifer,

Cp = contaminant concentration in source water,

Qa = volumetric flux in aquifer beneath source area, and

Ca = initial contaminant concentration in aquifer.

Table 4–7. Cover Layer Input Values for HELP Model of Cover Water Balance

Parameter	Rock Layer	Drainage Layer	Compacted Soil Layer	Tailings Layer	Data Source
Layer Type[a]	Lateral drainage	Lateral drainage	Barrier soil	Vertical percolation	HELP user's manual
Soil Texture Classification[b]	Sand	Sand	Clay loam	Silty clay loam	Waugh and Smith (1997)
Thickness (cm)	30.0	30.0	90.0	600.0	Morrison-Knudsen Engineers, Inc. (1994)
Porosity (vol/vol)	0.437	0.437	0.464	0.398	HELP default value
Field Capacity (vol/vol)	0.062	0.062	0.310	0.244	HELP default Value
Wilting Point (vol/vol)	0.024	0.024	0.187	0.136	HELP default value
Initial SWC[c] (vol/vol)	0.188	0.127	0.464	0.274	HELP calculation
Effective K_{sat}[d] ($cm \cdot s^{-1}$)	5.8×10^{-3}	5.8×10^{-3}	6.4×10^{-5}	1.2×10^{-4}	Waugh and Smith (1997)
Slope (%)	—	17.0	—	—	Morrison-Knudsen Engineers, Inc. (1994)
Slope Length (meters)	—	60.0	—	—	Morrison-Knudsen Engineers, Inc. (1994)

[a]Selected from options in HELP.
[b]USDA soil texture classification.
[c]SWC = soil water content.
[d]HELP calculated the *effective* K_{sat} for the compacted soil layer from input of Hannastown AEP data. The other K_{sat} values were HELP default values specified for the textural classes selected.

Table 4–8. Cover Design and Evaporative Zone Data for HELP Model of Water Balance

Parameter	Value	Data Source
Soil Conservation Service runoff curve number	74.7	Computed by HELP model based on slope percent, slope length, soil texture, and vegetation
Fraction of area allowing runoff	100.0%	Specified by user
Area of landfill surface	2.5 ha	Morrison-Knudsen, Inc. (1994)
Evaporative zone depth	60.0 cm	HELP override of user input of 150 cm
Initial water in evaporative zone	9.44 cm	Computed by HELP based on weather data
Upper limit of evaporative storage	26.22 cm	Computed by HELP based on soil input data
Lower limit of evaporative storage	1.44 cm	Computed by HELP based on soil input data
Initial snow water	0.0 cm	Computed by HELP based on weather data
Initial water in layer materials	215.41 cm	Computed by HELP based on soil input data
Total initial water	215.41 cm	Computed by HELP based on soil input data
Total subsurface inflow	0.0 cm	Specified by user

Table 4–9. Evapotranspiration and Weather Data for HELP Model of Cover Water Balance

Parameter	Value	Data Source
Station latitude	40.50°	HELP input data for Pittsburgh, Pennsylvania
Maximum LAI	5.37	Hannastown analog data (Table 4–7)
Start of growing season (Julian date)	114	HELP weather input data for Pittsburgh
End of growing season (Julian date)	288	HELP weather input data for Pittsburgh
Average annual wind speed	14 $km \cdot h^{-1}$ [a]	HELP weather input data for Pittsburgh
Average first quarter relative humidity	67%	HELP weather input data for Pittsburgh
Average second quarter relative humidity	63%	HELP weather input data for Pittsburgh
Average third quarter relative humidity	71%	HELP weather input data for Pittsburgh
Average fourth quarter relative humidity	70%	HELP weather input data for Pittsburgh

[a] $km \cdot h^{-1}$ = kilometers per hour.

Table 4–10. Output Summary of HELP Simulation of Burrell Cover Water Balance for Hannastown Analog Conditions

Water Balance Parameter	Water (cm)		
	Mean	Std. Dev.	Percent
Precipitation	93.3	8.3	100.0
Runoff	9.6	7.0	10.3
Evapotranspiration	58.6	5.4	62.9
Lateral drainage from layer 2 (sand drainage layer)	1.0	0.5	1.1
Vertical drainage/leakage through layer 3 (CSL)	24.1	6.1	25.8
Average head on top of layer 3 (CSL)	0.08	0.03	—
Vertical drainage/leakage through layer 4 (tailings)	24.8	6.6	26.7
Overall change in water storage	–0.8	0.2	–0.1

We computed a suite of groundwater COC calculations encompassing a broad range of present-day and possible future conditions. Descriptions of the test conditions follow:

Factor Descriptions	Level Descriptions
1. **Leach Test.** A range of COC concentrations from results of the column leach tests (Section 4.1).	a. Maximum levels from deionized water tests. b. Maximum levels from TCLP tests. c. Mean levels from TCLP tests.
2. **CSL K_{sat}.** Range of K_{sat} values from air-entry permeameter measurements on the Burrell cover and at the Hannastown analog site.	a. Current CSL K_{sat} with no plants. b. Current CSL K_{sat} with Japanese knotweed. c. Analog site K_{sat} and vegetation.
3. **Percent of Maximum Q_c.** Percent of the annual precipitation through the CSL; 25% level is based on a HELP simulation (Section 4.0); 100% and 50% levels were sensitivity tests.	a. 100% of precipitation. b. 50% of precipitation. c. 25% of precipitation.
4. **Percent Aquifer K_{sat}.** Percent of measured aquifer saturated conductivity. The 10% level was a sensitivity test.	a. 100% aquifer K_{sat}. b. 10% aquifer K_{sat}.
5. **^{226}Ra Ingrowth Time.** A range of ^{226}Ra concentrations spanning current levels to 1,000 years of ingrowth.	a. Current Ra-226 levels. b. ^{226}Ra levels after 200 years of ingrowth. c. ^{226}Ra after 1,000 years of ingrowth.

4.2.6 Results and Discussion of Groundwater Contamination Assessment

The assessment of root intrusion effects on current and possible long-term groundwater quality was based on historical water-quality data and on model simulations of water quality for a range of possible future conditions of the disposal cell cover. Tables 4–11, 4–12, 4–13, and 4–14 present summaries of test conditions and results. Appendix D contains the input and assumptions for the full calculation.

Since monitoring of wells and seeps began in 1987, no COC values have exceeded either the UMTRA MCLs or EPA risk-based drinking water standards (see Table 4–2 and Table 4–3 for MCLs and EPA standards). The maximum historical ^{226}Ra value (0.5 pCi/L) is an order of magnitude below the MCL (Table 4–11). Concentrations of only 7 of 18 analytes from historical data exceeded minimum laboratory detection limits.

The modeling results suggest that ^{226}Ra concentrations may slightly exceed MCLs, but only for combinations of the following test conditions (Table 4–11):

- Leaching from the most contaminated areas of the disposal cell.
- pH of 4.5 or less (the TCLP test condition).
- K_{sat} where knotweed rooted through the CSL and at the analog site.
- 100 percent of precipitation percolating through the CSL for current ^{226}Ra levels or 25 percent of precipitation passing through the CSL for ^{226}Ra after 1,000 years of ingrowth.
- 100 percent of the measured aquifer K_{sat}.

Table 4–11. UMTRA MCL for ^{226}Ra, Maximum Value From Historical Monitoring, and Modeling Conditions for Which ^{226}Ra Exceeded UMTRA MCL

Test Condition					Test Result
Leach Test	CSL K_{sat}	Percent of Max Q_c	Percent Aquifer K_{sat}	^{226}Ra Ingrowth Time (years)	^{226}Ra (pCi/L)
UMTRA MCL					5.0
Maximum Value From Historical Monitoring Data					0.5
Max TCLP	Knotweed	100	100	0	5.3
Max TCLP	Analog	100	100	0	5.3
Max TCLP	Analog	25	100	1,000	5.5

Table 4–12. Groundwater Modeling Test Conditions and Results for Maximum Deionized Water Leaching

Test No.	Test Condition					Test Result				
	Leach Test	CSL K_{sat}	Percent of Max Q_c	Percent Aquifer K_{sat}	^{226}Ra Ingrowth Time (years)	Mn (mg/L)	Mo (mg/L)	U (mg/L)	Se (mg/L)	^{226}Ra (pCi/L)
1	Risk screening level	—	100	100	—	840	180	110	180	—
2	Max DI[a]	No Plants	100	100	0	9,155	3.5	1.7	1.1	0.3
3	Max DI	Knotweed	100	100	0	8,874	31.0	8.9	1.3	0.4
4	Max DI	Analog	100	100	0	8,874	31.0	8.9	1.3	0.4
5	Max DI	No Plants	100	100	200					0.3
6	Max DI	No Plants	50	100	200					0.3
7	Max DI	No Plants	25	100	200					0.3
8	Max DI	Knotweed	100	100	200					0.5
9	Max DI	Knotweed	50	100	200					0.4
10	Max DI	Knotweed	25	100	200					0.3
11	Max DI	Analog	100	100	200					0.5
12	Max DI	Analog	50	100	200					0.4
13	Max DI	Analog	25	100	200					0.4
14	Max DI	No Plants	100	100	1,000					0.3
15	Max DI	No Plants	50	100	1,000					0.3
16	Max DI	No Plants	25	100	1,000					0.3
17	Max DI	Knotweed	100	100	1,000					0.8
18	Max DI	Knotweed	50	100	1,000					0.6
19	Max DI	Knotweed	25	100	1,000					0.4
20	Max DI	Analog	100	100	1,000					0.8
21	Max DI	Analog	50	100	1,000					0.6
22	Max DI	Analog	25	100	1,000					0.4

[a]Max DI = maximum deionized water.

Table 4–13. Groundwater Modeling Test Conditions and Results for Maximum TCLP Water Leach Tests

Test No.	Test Condition					Test Result				
	Leach Test	CSL K_{sat}	Percent of Max Q_c	Percent Aquifer K_{sat}	^{226}Ra Ingrowth Time (years)	Mn (mg/L)	Mo (mg/L)	U (mg/L)	Se (mg/L)	^{226}Ra (pCi/L)
23	Max TCLP	No Plants	100	100	0	9,241	1.6	2.8	1.2	0.7
24	Max TCLP	Knotweed	100	100	0	9,905	8.5	22.1	2.0	5.3
25	Max TCLP	Analog	100	100	0	9,905	8.5	22.1	2.0	5.3
26	Max TCLP	No Plants	100	100	200					1.1
27	Max TCLP	No Plants	50	100	200					1.1
28	Max TCLP	No Plants	25	100	200					1.1
29	Max TCLP	Knotweed	100	100	200					10.4
30	Max TCLP	Knotweed	50	100	200					5.4
31	Max TCLP	Knotweed	25	100	200					2.9
32	Max TCLP	Analog	100	100	200					10.4
33	Max TCLP	Analog	50	100	200					5.4
34	Max TCLP	Analog	25	100	200					2.9
35	Max TCLP	No Plants	100	100	1,000					1.9
36	Max TCLP	No Plants	50	100	1,000					1.9
37	Max TCLP	No Plants	25	100	1,000					1.9
38	Max TCLP	Knotweed	100	100	1,000					20.6
39	Max TCLP	Knotweed	50	100	1,000					10.6
40	Max TCLP	Knotweed	25	100	1,000					5.5
41	Max TCLP	Analog	100	100	1,000					20.6
42	Max TCLP	Analog	50	100	1,000					10.6
43	Max TCLP	Analog	25	100	1,000					5.5

Table 4–14. Groundwater Modeling Test Conditions and Results for Mean TCLP Water Leach Tests

Test No.	Test Condition					Test Result				
	Leach Test	CSL K_{sat}	Percent of Max Q_c	Percent Aquifer K_{sat}	^{226}Ra Ingrowth Time (years)	Mn (mg/L)	Mo (mg/L)	U (mg/L)	Se (mg/L)	^{226}Ra pCi/L)
44	Mean TCLP	No Plants	100	100	0	9,216	1.4	1.9	1.1	0.5
45	Mean TCLP	No Plants	100	10	0	9,535	5.1	9.5	1.4	2.9
46	Mean TCLP	No Plants	50	10	0	9,535	5.1	9.5	1.4	2.9
47	Mean TCLP	Knotweed	100	100	0	9,617	6.0	11.4	1.5	3.5
48	Mean TCLP	Knotweed	100	10	0	12,438	38.3	78.8	4.1	24.6
49	Mean TCLP	Knotweed	50	10	0	11,077	22.7	46.3	2.8	14.4
50	Mean TCLP	Analog	100	100	0	9,617	6.0	1104	1.5	3.5
51	Mean TCLP	Analog	100	10	0	12,438	38.3	78.8	4.1	24.6
52	Mean TCLP	Analog	50	10	0	11,077	22.7	46.3	2.8	14.4
53	Mean TCLP	No Plants	100	100	200					0.8
54	Mean TCLP	No Plants	50	100	200					0.8
55	Mean TCLP	No Plants	25	100	200					0.8
56	Mean TCLP	Knotweed	100	100	200					6.8
57	Mean TCLP	Knotweed	50	100	200					3.6
58	Mean TCLP	Knotweed	25	100	200					1.9
59	Mean TCLP	Analog	100	100	200					6.8
60	Mean TCLP	Analog	50	100	200					3.6
61	Mean TCLP	Analog	25	100	200					1.9
62	Mean TCLP	No Plants	100	100	1,000					1.3
63	Mean TCLP	No Plants	50	100	1,000					1.3
64	Mean TCLP	No Plants	25	100	1,000					1.3
65	Mean TCLP	Knotweed	100	100	1,000					13.3
66	Mean TCLP	Knotweed	50	100	1,000					6.9
67	Mean TCLP	Knotweed	25	100	1,000					3.6
68	Mean TCLP	Analog	100	100	1,000					13.3
69	Mean TCLP	Analog	50	100	1,000					6.9
70	Mean TCLP	Analog	25	100	1,000					3.6

The sensitivity tests indicated that ^{226}Ra levels would exceed the MCL only for TCLP test conditions and if one of the following conditions was met:

- The cover K_{sat} reached 1.2×10^{-4} cm · s^{-1} (equivalent to analog site conditions).
- The cover drainage rate was 2 to 4 times greater than that predicted by the HELP model.
- The aquifer K_{sat} dropped to 10 percent of that measured by pump tests.

Model estimates of ^{226}Ra levels in groundwater at the edge of the disposal cell are considered to be conservative. Radium-226 levels are expected to be much less than the MCL, even after 1,000 years of ingrowth, primarily because radium is relatively immobile in the natural environment. The immobility is due to its strong tendency to substitute with alkaline cations (particularly Ba, Sr, and Ca) in minerals. Radium also adsorbs to mineral surfaces. While ^{226}Ra is the predominant radioactive component at 22 UMTRA sites, it has not migrated any significant distance in the groundwater at these sites.

Because the TCLP leach solution used in the Burrell tests has a low pH (4.5), it is capable of dissolving some of the alkaline cation-bearing mineral phases that would otherwise be stable. Once these minerals are in solution, the radium is released and can migrate. If the conditions changed back to higher pH, the minerals would reprecipitate and the radium would again become immobile. However, it is not likely that the low pH conditions used in the TCLP leach tests will occur in the Burrell tailings. This TCLP leach test was used to represent a worst-case scenario. The chemical conditions of neutral pH, high sulfate, high calcium, and high alkalinity currently existing in groundwater at the Burrell site favor the stability of the radium-bearing minerals. Groundwater chemistry would have to change drastically for these phases to dissolve and mobilize radium.

The results also indicate that high drainage rates from the disposal cell, between 50 and 100 percent of precipitation, would be high enough to leach radium at levels that would exceed the groundwater MCL if TCLP conditions existed. However, such high drainage rates are very unlikely if plant succession progresses unimpeded. Water-balance modeling with the HELP code supports the premise that a combination of runoff and evapotranspiration from native woodland vegetation would limit drainage from the cover to about 25 percent of the precipitation. Therefore, denuding the disposal cell with regular herbicide applications would reduce evapotranspiration and may, in time, actually increase both drainage from the cover and contaminant leaching.

In summary, Phase II modeling results show that a higher CSL permeability attributable to root intrusion would not likely cause concentrations of COCs in groundwater beneath the disposal cell to exceed UMTRA MCLs. Therefore, Phase III, Exposure Assessment, was considered unnecessary.

5.0 Summary and Recommendations

This report completes the second part of a two-part investigation of plant root intrusion on the Burrell, Pennsylvania, disposal cell. The first part was a field study of the consequences of plant root intrusion and long-term ecological change on the performance of the disposal cell cover. The second part was a screening assessment of changes in human health and environmental risks associated with existing and potential future changes in cover performance. The LTSM Program planned to use the results of this investigation as the technical basis for choosing one of the following three management options for the Burrell disposal cell and, if warranted, for revision of the long-term surveillance plan for the cell:

- Discontinue herbicide spraying if risks of root intrusion are acceptably low.
- Accept the cost and environmental consequences of continued herbicide spraying, or other long-term maintenance, if risks are sufficiently large.
- Modify the disposal cell cover design and thereby improve risk management over the long term.

5.1 Summary

In the first part of the study we evaluated the effects of root intrusion on radon flux and the saturated hydraulic conductivity of the cover. This work resulted in two findings. The first is that root intrusion and associated drying of the cover is not likely to increase radon flux above the 20-pCi $m^{-2} \cdot s^{-1}$ standard unless the western Pennsylvania climate changes from humid to semiarid. The second is that plant roots do increase the hydraulic conductivity of the radon barrier. We measured a 2-orders-of-magnitude increase in the K_{sat} where plant roots penetrated the compacted soil layer (CSL or radon barrier). At a nearby analog site, the K_{sat} was 3 orders of magnitude above the design specification. The analog site represents a reasonable future condition of the cover after 200 to 1,000 years of ecological and pedogenic changes.

The second part of the investigation, the screening-level risk assessment, evaluated possible consequences of increased water movement into the tailings that might result from root intrusion in the cover. Phase I of the risk assessment evaluated concentrations and mobility of contaminants in tailings pore fluid. Composite tailings samples were retrieved from locations within the disposal cell that had the highest radium levels at the time of construction. Column leach tests conducted with the composite samples encompassed a range of current, possible future, and less likely extreme chemical conditions. The results show that manganese, molybdenum, selenium, uranium, and ^{226}Ra in pore fluid may exceed either the UMTRCA MCL or an EPA risk-based screening level for one or more of the conditions tested. These results prompted the LTSM Program to proceed with Phase II of the risk assessment.

Phase II estimated groundwater quality beneath the disposal cell for a range of conditions, reasonable and extreme, that could occur during its design life. Phase II combined historical monitoring data from seeps and wells, soil water-balance modeling, and groundwater mixing calculations to estimate groundwater quality for a range of possible future conditions of the cover soils, plant ecology, and tailings pore water chemistry. No COCs in the DOE historical database for seeps and monitor wells came close to the UMTRCA MCLs or the EPA risk-based screening levels. Modeled groundwater quality estimates for existing conditions were comparable to the historical monitoring data. Even for extreme conditions, all model-predicted COCs, except ^{226}Ra, were well below the UMTRA MCL and the EPA risk-based screening levels.

The Phase II modeling suggests that ^{226}Ra in groundwater would exceed the MCL by, at most, 10 percent, but only for the following unlikely combination of conditions:

- Pore water pH of 4.5 or less,
- A 2 to 3 orders of magnitude increase in the K_{sat} of the CSL because of root intrusion,
- One thousand years of ^{226}Ra ingrowth from ^{230}Th decay, and
- All pore water leaching from the disposal cell would have contamination levels equal to the most contaminated tailings.

Because a pore water pH of 4.5 is highly unlikely, radium is expected to remain relatively immobile at the Burrell disposal cell. Historical information in the DOE seeps and monitor wells database, and the modeling runs with a pH close to current conditions, support this reasoning. For modeling runs with pH held constant at existing levels, changes in the K_{sat} of the CSL had little effect on ^{226}Ra concentrations. Furthermore, contaminant concentrations in groundwater were substantially lower for modeling runs with plant data from the native woodlands at the analog site. LTSM Program personnel concluded that regular denuding of the disposal cell with herbicides would reduce evapotranspiration and, in time, may actually increase drainage from the cover. This increase in drainage could lead to an increase in contaminants leaching into groundwater.

5.2 Recommendations

On the basis of the results of this study, we conclude that regular spraying of vegetation on the disposal cell is unwarranted and unjustified. DOE can safely eliminate this requirement from the Burrell long-term surveillance plan. Natural plant succession can be allowed to proceed with no increased risk to human health or the environment. In fact, continued spraying may interfere with the long-term performance of the disposal cell. Because of a much higher evapotranspiration rate, the development of a mature woodland plant community is expected to augment the performance of the disposal cell by limiting drainage through the cover and by reducing the likelihood of contaminant leaching into groundwater below the disposal cell.

6.0 References

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Appendix A
Burrell Disposal Cell Borehole Logs
May 13 and May 14 and July 8 and 9, 1998

MACTEC-ERS
2597 B 3/4 Road
Grand Junction, Colorado 81502

Borehole Summary

Page 1 of 2

Facility: USDOE GJO LTSM Site: Burrell, PA Project: LTSM

Boring/~~Well~~ No.: 1 Location (N): 403900 (E): 1584835

Ground Elev. (Ft.): ____ Bit/Auger Size: 6 1/4 OD 3 1/4 ID Hole Depth (Ft): 21.5

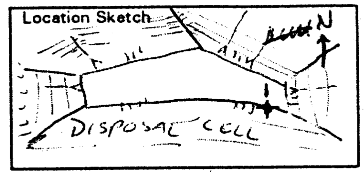
Diameter (inch I. D.) No. of Completions: ____

Stick-Up Height (Ft): ____

Slot Size: ____

	TYPE	Vol. (cf. gal)	Interval (Ft.)
Blank Casing			to
Screen			to
Sump/End Cap			to
Sand Pack			to
Sealant			to
Grout			to

Location Sketch



Locking Cover Installed Y / N Padlock No. ____

Drilling Method: HSA Track Mounted (Simco 4000) Sampling Method: ____

Date Drilled: 5-13-98 Date Developed: ____ Fluid Level/Date: ____

Sampler(s): M. Kautsky Remarks: Sunny, Dry ~70°F

Depth* (FT)	Blows/ 6"	PID ppm	Sample No.; Interval	WELL CONSTRUCTION	GRAPHIC LOG	DESCRIPTION
						Required Information: Typical name; Munsell color; percentage sand and gravel; sorting (poor to well); grain angularity; induration or plasticity; moisture content (moist to saturated).
0–2						MED GY RIP RAP to 12-inch DIAM w/ D-50 ≈ 8-inches. ~~DK~~ Grading finer/gravelly @ 1ft - 2ft. ~~DK YEL BWN SILT (ML), MOIST, DENSE (10YR 4/4)~~
2–4						DK YEL BWN SILT (ML) 10YR 4/4 MOIST DENSE
4–6						Turns BLACK & SANDY @ 6ft depth
6–8	12, 35, 48					BLACK (2.5YR N 2.5/0) SANDY SILT MOIST, DENSE. V. LITTLE SAMPLE RECOVERED. AT 7 ft hit apparent RR. tie lots of wood frags recovered while drilling out sample interval. Apparently drilled through it at 8 ft will sample again.
8–10	11, 68, 71, 100/3					BLACK SANDY SILT (ML) (CARBONACEOUS) MOIST, DENSE w/ WOOD FRAGS (FILL)

a - All depths measured from ground level.

Completed By: M. Kautsky Verified By: ____

MACTEC-ERS
2597 B 3/4 Road
Grand Junction, Colorado 81502

Borehole No. 1

Date 5-13-98

Borehole Summary
Page 2 of 2

Depth (FT)	Blows/ 6"	PID ppm	Sample No.: Interval	Well Construction	Graphic Log	DESCRIPTION
	20 25					BLACK SANDY SILT (ML) (2.5 YR N 2.5/0) MOIST, DENSE CARBONACEOUS CONTAINS WOOD FRAGS (FILL)
11	24					
12						
13						
14						
15	17 33					BLACK SANDY CARBONACEOUS SILT (ML) MOIST, DENSE (2.5 YR N 2.5/0) W/ WOOD FRAGS, BOTTLE CAP, RAGS. (FILL)
16	40					
17						
18						
19						
20	75 48 44					BLACK SANDY CARBONACEOUS SILT (ML) MOIST DENSE (2.5 YR N 2.5/0) W/ WOOD FRAGS (FILL)
						No Water Encountered.

All depths measured from ground level.

Completed By Mark Kautsky

Verified By

MACTEC-ERS
2597 B 3/4 Road
Grand Junction, Colorado 81502

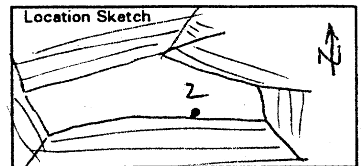
Borehole Summary
Page 1 of 2

Facility: US DOE LTSM
Site: Burrell, PA
Project: Root Intrusion Study

Boring/Well No.: 2
Location (N): 403580 ~~403580~~ (E): 1584780

Ground Elev. (Ft.): ____
Bit/Auger Size: 6 3/4 OD 3 1/4 - ID
Diameter (inch I. D.)
Hole Depth (Ft): ____
No. of Completions: ____
Stick-Up Height (Ft): ____
Slot Size: ____

	TYPE	Vol. (cf. gal)	Interval (Ft.)
Blank Casing			to
Screen			to
Sump/End Cap			to
Sand Pack			to
Sealant			to
Grout			to



Locking Cover Installed Y / N
Padlock No. ____
Drilling Method: Track-Mounted HSA (Simco 4000)
Sampling Method: Hollow Stem Auger 140# hammer 30"
Date Drilled: 5-13-98
Date Developed: ____
Fluid Level/Date: None
Sampler(s): M. Kautsky
Remarks: ____

Depth[a] (FT)	Blows/ 6"	PID ppm	Sample No.; Interval	WELL CONSTRUCTION	GRAPHIC LOG	DESCRIPTION
						Required Information: Typical name; Munsell color; percentage sand and gravel; sorting (poor to well); grain angularity; induration or plasticity; moisture content (moist to saturated).
0						MED GY Riprap to 12-inch diam w/ d-50 ≈ 8 inches. (Fill)
1						Finer more gravelly riprap ~2-inch d-50 med-gy
2						DK yel-brn (2.5YR N2.5/0) silt (ML) dense, moist radon-barrier cover material
3						
4						
5						Black
6						
7						
8						hard drilling @ 8 ft. – 9 1/2 ft.

a - All depths measured from ground level.

Completed By: Mark Kautsky
Verified By: ____

MACTEC-ERS
2597 B 3/4 Road
Grand Junction, Colorado 81502

Borehole No. 2 Date 5-13-98

Borehole Summary
Page 2 of 2

Depth (FT)	Blows/ 6"	PID ppm	Sample No.; Interval	Well Construction	Graphic Log	DESCRIPTION
	21					BLACK GRAVELLY SILT (ML), CARBONACEOS (FILL) (2.5 YR N2.5/0) dense, moist.
11	26 76/4					
12						
13						
14						
15	140/4"					Refusal to sampling (140 blows/4") Black Gravelly Silt (ML) carbonaceous w/ abundant wood frags. (Fill) dense, slightly moist
16						
17						Grabbed bulk sample of cuttings
18	13	nm				
19	75 67	nm nm	13 75 67			No recovery (collected bulk cuttings sample)
20						No Water Encountered.

All depths measured from ground level.

Completed By Mark Kautzky Verified By ______

MACTEC-ERS
2597 B 3/4 Road
Grand Junction, Colorado 81502

Borehole Summary

Facility US Dept Energy LTSM Site Burrell Project Weed Intrusion Study

Boring/Well No. 3 Location (N) 404020 (E) 1584680

Ground Elev. (Ft.) ______ Bit/Auger Size 6 1/4" OD ; 3 1/4" ID Hole Depth (Ft) 17.5

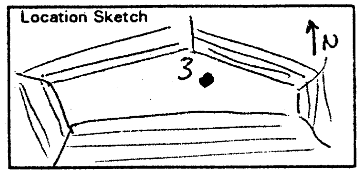
Diameter (inch I. D.) No. of Completions ______

Stick-Up Height (Ft) ______

Slot Size ______

	TYPE	Vol. (cf. gal)	Interval (Ft.)
Blank Casing			to
Screen			to
Sump/End Cap			to
Sand Pack			to
Sealant			to
Grout			to

Location Sketch



Locking Cover Installed Y / N Padlock No. ______

Drilling Method Track Mounted HSA (Simco 4000) Sampling Method 140# hammer 30 inch drop

Date Drilled 5-13-98 Date Developed ______ Fluid Level/Date No water encountered

Sampler(s) Mark Kautsky Remarks ______

Depth[a] (FT)	Blows/ 6"	PID ppm	Sample No.; Interval	WELL CONSTRUCTION	GRAPHIC LOG	DESCRIPTION
						Required Information: Typical name; Munsell color; percentage sand and gravel; sorting (poor to well); grain angularity; induration or plasticity; moisture content (moist to saturated).
0						Dk Gy rip rap loose (fill) dry
1						Gray finer gravelly sand (GP) loose, dry (fill)
2						Dk yel-brn (10YR 4/4) silt (ML) moist, dense fill radon barrier cover material
3						
4						
5						Black silt (ML) dense, moist w/ gravel & wood frags.
6						Rough drilling @ 7 ft
7						
8						
9	80 60 50					Gray silty Gravel (GP) dense, moist (fill)

a - All depths measured from ground level.

Completed By Mark Kautsky Verified By ______

MACTEC-ERS
2597 B 3/4 Road
Grand Junction, Colorado 81502

Borehole No. 3

Date 5-13-98

Borehole Summary
Page 2 of 2

Depth (FT)	Blows/ 6"	PID ppm	Sample No.: Interval	Well Construction	Graphic Log	DESCRIPTION
11						
12						
13						(2.5 YR N 2.5/0) BLACK Gravelly carbonaceous silt (ML) dense, moist w/ wood frags. (Fill)
14	29 25 31					
15						
16						Cuttings are contaminated @ >5000 dpm ( )
17						terminated drilling @ 17.5 ft. collected bag/grab sample off lead auger
18						
19						
20						

All depths measured from ground level.

Completed By Mark Kautsky

Verified By

MACTEC-ERS
2597 B 3/4 Road
Grand Junction, Colorado 81502

Borehole Summary

Facility DOE GJO LTSM Site Burrel Site Project Root Intrusion study

Boring/Well No. 4 Location (N) 404,100 (E) 1584560

Ground Elev. (Ft.) ______ Bit/Auger Size 6¼ OD 3¼-inch ID Hole Depth (Ft) 11.5 ft.

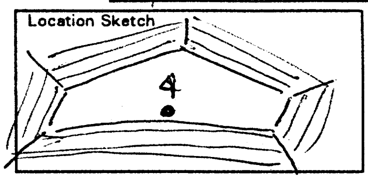
No. of Completions Ø

Stick-Up Height (Ft) Ø

Slot Size Ø

	TYPE	Diameter (inch I. D.) Vol. (cf. gal)	Interval (Ft.)
Blank Casing			to
Screen			to
Sump/End Cap			to
Sand Pack			to
Sealant			to
Grout			to

Location Sketch



Locking Cover Installed Y / N Padlock No. ______

Drilling Method HSA track-mounted (Simco 4000) Sampling Method ______

Date Drilled 5-14-98 Date Developed Ø Fluid Level/Date 54 ft BGL 7-9-98

Sampler(s) Mark Kautsky Remarks ______

Depth* (FT)	Blows/ 6"	PID ppm	Sample No.; Interval	WELL CONSTRUCTION	GRAPHIC LOG	DESCRIPTION
						Required Information: Typical name; Munsell color; percentage sand and gravel; sorting (poor to well); grain angularity; induration or plasticity; moisture content (moist to saturated).
0						Gray Riprap to 12-inch diam, loose, dry, (fill)
1						Dk yel-brwn (10YR 4/4) silt (ML) moist, dense (radon cover material)
2						
3						
4						
5						Drilling is harder @ 5½ ft. & black cuttings appearing
6						
7						
8	55					
	26					Black carbonaceous silt (ML) w/ wood chips, dense, moist.
	64					

* - All depths measured from ground level.

Completed By Mark Kautsky Verified By ______

MACTEC-ERS
2597 B 3/4 Road
Grand Junction, Colorado 81502

Borehole No. 4 Date 7-8-98

Depth (FT)	Blows/ 6"	PID ppm	Sample No.; Interval	Well Construction	Graphic Log	DESCRIPTION
11						Cuttings are running about 8000 – 9000 dpm through this interval of 10 – 15 ft.
12						
13						Drilling is quite rough at 13 – 15 ft. depth
14						
15	30 100		☒			Black Carbonaceous SILT (ML) w/ SLAG, WOOD FRAG, METAL FRAGS Dense, moist
16						Sample material running 600 – 1000 dpm above background.
17						
18	200		☐			No Recovery will offset to continue boring. Drilling very rough at 18.5 – will try sampling it since we can't drill through it. Ringing blows w/ 140# hammer
19						
20	58 53/3		☒			OFFSET BORING 5 ft east BLACK GRAVELLY SILT, ORGANIC, (ML) w/ wood chips & frags of brick, wire steel. ~~etc~~. dense, moist.
21						
22						
23						
24						
25	54 23 35		☐			No Recovery.
26						
27						
28						

All depths measured from ground level.

Completed By Mark Kautzky Verified By ______

MACTEC-ERS
2597 B 3/4 Road
Grand Junction, Colorado 81502

Borehole No. 4 | Date 7-8-98 | Borehole Summary Page 3 of 4

Depth (FT)	Blows/ 6"	PID ppm	Sample No.; Interval	Well Construction	Graphic Log	DESCRIPTION
28						
29						
30	10		☐			Black Carbonaceous Gravelly SILT (ML); med dense, Moist. (FILL) Radioactivity is at background levels.
31	23 38		☒			
32						
33						
34						
35	18 12		☐			
36	14		☒			WOOD FRAGS IN SAMPLE BARREL CREOSOTE ODOR, RADIATION LEVELS AT BACKGROUND.
37						
38						
39						Drilled to 40ft by COB 7-8-98
40	9		☒			WOOD CHIPS & FRAGS IN SAMPLE BARREL BLACK, CREOSOTE ODOR. Rad at background.
41	66 37/1		☐			
42						
43						
44						
45	15 14		☒			BLACK CARBONACEOUS SILT (ML) with wood fragments. Loose, Moist. (Fill) Rad @ Background
46						

All depths measured from ground level.

Completed By Mark Kautsky   Verified By ____________

MACTEC-ERS
2597 B 3/4 Road
Grand Junction, Colorado 81502

Borehole No. 4   Date 7-9-98

Borehole Summary
Page 4 of 4

Depth (FT)	Blows/ 6"	PID ppm	Sample No.; Interval	Well Construction	Graphic Log	DESCRIPTION
46	15					
47						Grading Sandier below 46 feet
48						
49						
50	8					BLACK SILTY SAND (SM) loose, moist with wood frags (FILL)
51	10 20					Radiation at background levels
52						
53						
54						
55	11					water level 54 ft measured.
56	11 13					No Recovery, Sampler Saturated Borehole 7-9-98 @ 08:35
57						
58						
59						
60						
61						
62						
63						
64						

All depths measured from ground level.

Completed By Mark Kautz   Verified By ________

MACTEC-ERS
2597 B 3/4 Road
Grand Junction, Colorado 81502

Borehole Summary

Facility DOE GJO LTSM   Site Burrell LTSM Site   Project Root Intrusion Study

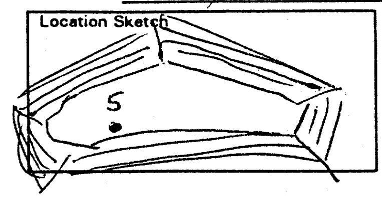
Boring/Well No. 5   Location (N) 404150   (E) 1584480

Ground Elev. (Ft.) ______   Bit/Auger Size 6¼ OD & 3¼ ID   Hole Depth (Ft) 14.5 ft.

No. of Completions Ø
Stick-Up Height (Ft) Ø
Slot Size Ø

	TYPE	Diameter (inch I. D.) Vol. (cf. gal)	Interval (Ft.)
Blank Casing			to
Screen			to
Sump/End Cap			to
Sand Pack			to
Sealant			to
Grout			to

Location Sketch



Locking Cover Installed Y / N   Padlock No. ______
Drilling Method Hollow Stem Auger (truck mounted) (Simco 4000)   Sampling Method ______
Date Drilled 5-14-98   Date Developed Ø   Fluid Level/Date 60.4 ft. BGL 7-8-98
Sampler(s) Mark Kautsky   Remarks ______

Depth^a (FT)	Blows/ 6"	PID ppm	Sample No.; Interval	WELL CONSTRUCTION	GRAPHIC LOG	DESCRIPTION
						Required Information: Typical name; Munsell color; percentage sand and gravel; sorting (poor to well); grain angularity; induration or plasticity; moisture content (moist to saturated).
0–1						Gray Riprap to 12-inch diam (fill)
1–2						Fine Gravelly (sand) Filter layer (GP) fill ~~DK YEL BWN 10YR 4/4~~
2–4						DK YEL BWN (10YR 4/4) SILT (ML) Radon Barrier moist, dense.
4–6						
6–8						(2.5YR N2.5/0)
8–10	40 47 30		☒			Black carbonaceous silt (ML) w/ wood & metal frags (fill) dense, moist.

a - All depths measured from ground level.

Completed By Mark Kautsky   Verified By ______

MACTEC-ERS
2597 B 3/4 Road
Grand Junction, Colorado 81502

Borehole No. 5 Date 7-7-98

Depth (FT)	Blows/ 6"	PID ppm	Sample No.; Interval	Well Construction	Graphic Log	DESCRIPTION
11						
12						
13	40					Black (2.5 YR N 2.5/0) Carbonaceous silt (ML) w/ wood frags (fill); dense, moist
14	75 35/3					Radiation levels @~7,500 - 8,000 dpm in cuttings
15	4 6					
16	30 100/5					sample @ 15.5 - 16.9 ft Rad levels back down to ~50 counts > bkg
17						
18						Cuttings are running ~ 5000 - 6000 dpm Rad.
19						
20	8					Sample Rad is ~ 60 counts > bkg.
21	27 58					Black silt (ML) with brick & RR tie frags dense, moist. (FILL).
22						
23						
24						Drilled to 25 ft depth by COB 7-7-98
25	35					Black organic silt (ML) w/ creosote odor and brick fragments and wood chips; moist, dense (FILL)
26	73					Rad levels @~ 600 dpm.
27						
28						

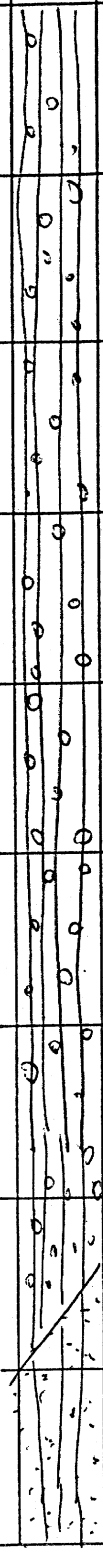
All depths measured from ground level.

Completed By Mark Kautsky Verified By ______

MACTEC-ERS
2597 B 3/4 Road
Grand Junction, Colorado 81502

Borehole No. 5 Date 7-7-98

Depth (FT)	Blows/ 6"	PID ppm	Sample No.; Interval	Well Construction	Graphic Log	DESCRIPTION
29						
30	4		[sample]			Black Gravelly Carbonaceous Silt (ML) w/ wood frags dense, moist (FILL); Rad Levels at Background.
31	28 43					
32						
33						
34						
35	30 100		[sample]			Contains white powdery material in sample barrel Background Radiation Levels
36						
37						
38						
39						
40	7		[sample]			Black Gravelly Silt, Carbonaceous (ML) FILL Radiation levels at Background
41	21 21					
42						
43						
44						
45	8 8		[sample]			has become Black silty sand (SM) w/ gravel fragments



All depths measured from ground level.

Completed By ____________________ Verified By ____________________

MACTEC-ERS
2597 B 3/4 Road
Grand Junction, Colorado 81502

Borehole No. 5 Date 7-8-98

Depth (FT)	Blows/ 6"	PID ppm	Sample No.: Interval	Well Construction	Graphic Log	DESCRIPTION
46	~~8~~8, 8, 14					Radiation levels at 20 counts above background or ~ 600 dpm > Background.
47						
48						
49						
50	14, 26					Black gravelly ~~sandy~~ silty sand (ML) w/
51	14					Wood frags (Fill) loose, moist Radiation levels at 600 dpm > Bkg.
52						
53						
54						
55	180					RR ties, Black, wet, Dense. (Fill) Radiation Levels are at Background.
56						
57						
58						
59						
60	21, 25				▽	R.R. Ties Black, saturated, Radiation at Background levels
61	26					Creosote odor
62						Groundwater level at 60.4 ft BG

All depths measured from ground level.

Completed By Mark Kantsky Verified By

MACTEC-ERS
2597 B 3/4 Road
Grand Junction, Colorado 81502

Borehole Summary
Page 1 of 2

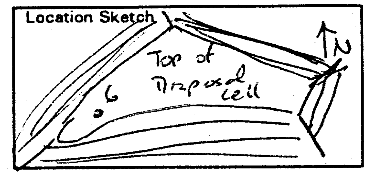
Facility DOE GJO LTSM Site Burrell Project Root Intrusion Study

Boring/Well No. 6 Location (N) 404200 (E) 1584400

Ground Elev. (Ft.) ____ Bit/Auger Size Diameter (inch I. D.) 6¼" OD x 3¼" ID HSA Hole Depth (Ft) 12.5 feet

No. of Completions ____
Stick-Up Height (Ft) ____
Slot Size ____

	TYPE	Vol. (cf. gal)	Interval (Ft.)
Blank Casing			to
Screen			to
Sump/End Cap			to
Sand Pack			to
Sealant			to
Grout			to



Locking Cover Installed Y / N Padlock No. ____
Drilling Method Track Mounted Hollow Stem Auger (Simco 4000) Sampling Method ____
Date Drilled 5-14-98 Date Developed ____ Fluid Level/Date ____
Sampler(s) Mark Kautsky Remarks Auger Refusal @ 39.5 ft BGL 7-7-98

Depth* (FT)	Blows/ 6"	PID ppm	Sample No.; Interval	WELL CONSTRUCTION	GRAPHIC LOG	DESCRIPTION
						Required Information: Typical name; Munsell color; percentage sand and gravel; sorting (poor to well); grain angularity; induration or plasticity; moisture content (moist to saturated).
0						Riprap, Gray to 12-inch diam. (GP)
1						Fine Gravel / coarse sand filter blanket (GP)
2						Dk yel-bwn (2.5 YR 4/4) SILT (ML) dense moist, (radon barrier)
3						
4						
5						(2.5 YR N 2.5/0)
6						Black to organic silt (ML) w/ Abundant wood frags moist, dense
7						
8						
9	60					
10	85					No Recovery

ε - All depths measured from ground level.

Completed By Mark Kautsky Verified By ____

MACTEC-ERS
2597 B 3/4 Road
Grand Junction, Colorado 81502

Borehole No. 6 Date 7-7-98

Depth (FT)	Blows/ 6"	PID ppm	Sample No.; Interval	Well Construction	Graphic Log	DESCRIPTION
	40/4					No Recovery; Sampled again @ 11-12.3 ft
11	30					
	50					Black (2.5 YRN 2.5/0) organic silt (ML), dense, moist
12	25/3					
13						
14						
15	11				sluff	Light Yel Brn SANDY CLAY (CL) @ top of Sample tube is probable slough from cover material
16	19					Black gravelly silt (ML) organic, dense, moist. ~~Counts~~ Rad ≈ 9000 dpm
	29					
17	29					
18						
19						
20	9					Black gravelly organic silt (ML) med dense, moist. Rad ≈ Background
	17					
21	26					
22						
23						
24						
25	16					Black organic silt w/ wood frags & creosote odor (ML) med dense, moist. (fill) Rad ≈ 2X > Bgd.
26	17					
	18					
27						

All depths measured from ground level.

Completed By ______ Verified By ______

MACTEC-ERS
2597 B 3/4 Road
Grand Junction, Colorado 81502

Borehole No. 6 Date 7-7-98

Depth (FT)	Blows/ 6"	PID ppm	Sample No.: Interval	Well Construction	Graphic Log	DESCRIPTION
28						
29						
30	8					
31	10 12					WOOD FRAGS, BLACK ORGANIC SILT (ML) FILL, loose, moist. Rad ~ 60-100 DPM
32						
33						
34						
35	14					
36	14 12					WOOD DEBRIS & BRICK (FILL)
37						
38	180/5"					WOOD DEBRIS (RR Ties) Hard drilling @ ~~38 ft~~ 37.5 ft Driller says v. hard material; we'll ~~try~~ sample to see. Rad levels @ Background
39						TD @ 37.5 ft due to auger refusal.
40						
41						
42						
43						
44						

All depths measured from ground level.

Completed By ______________________ Verified By ______________________

Appendix B
Leach Study Results for
Burrell Phase I Screening-Level Risk Assessment

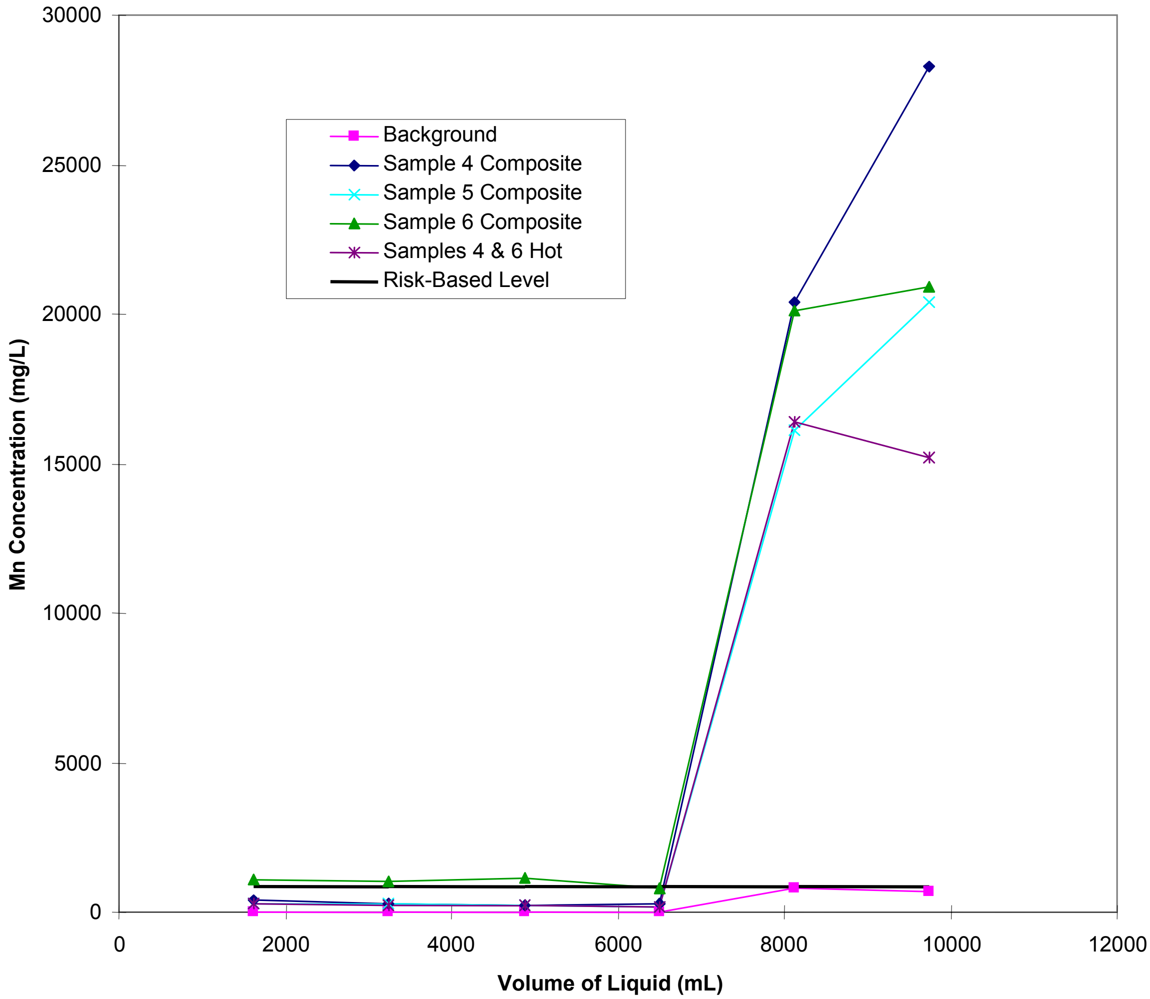


Figure B–1. Manganese Concentration Results of Leach Study

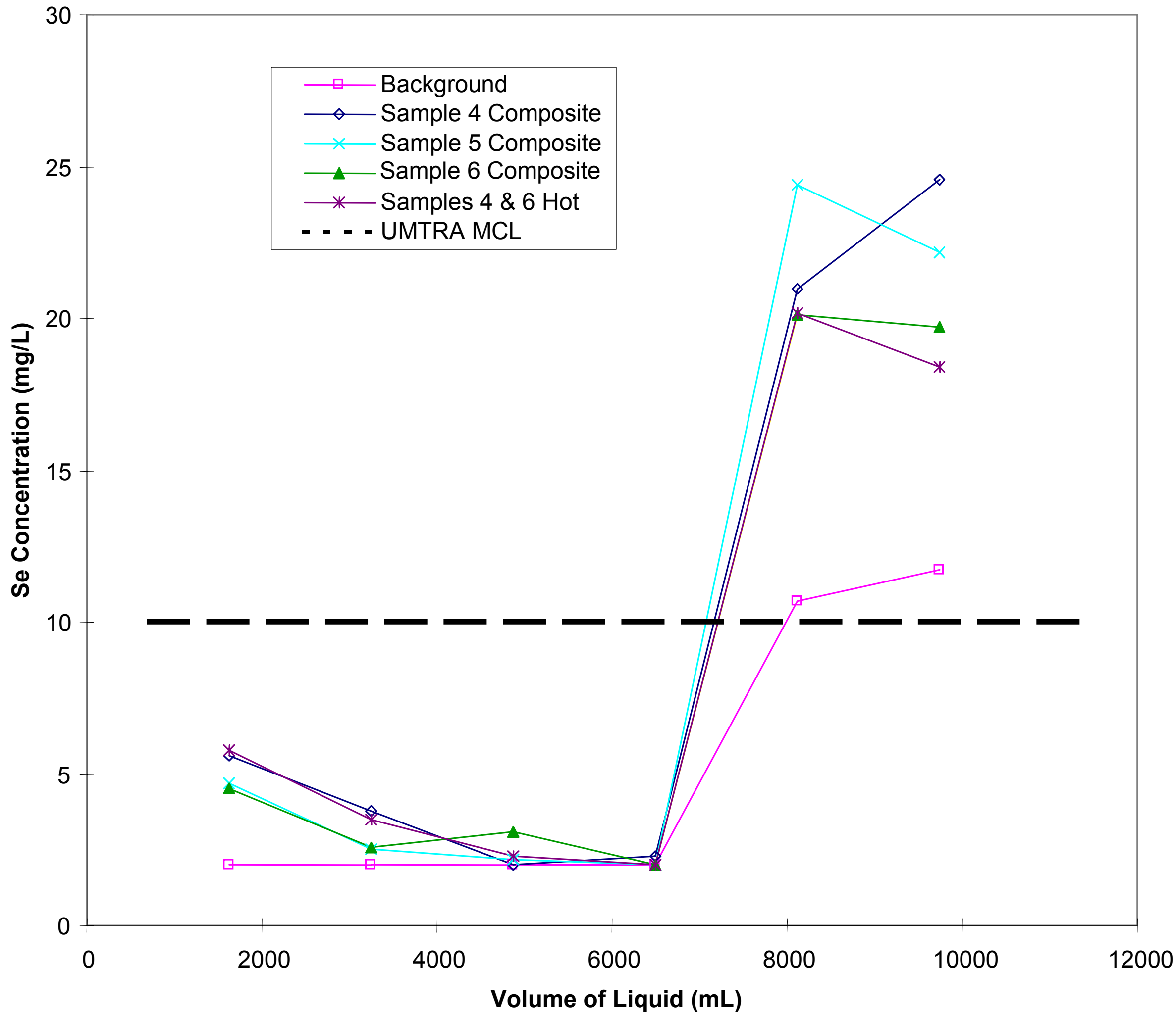


Figure B–2. Selenium Concentration Results of Leach Study

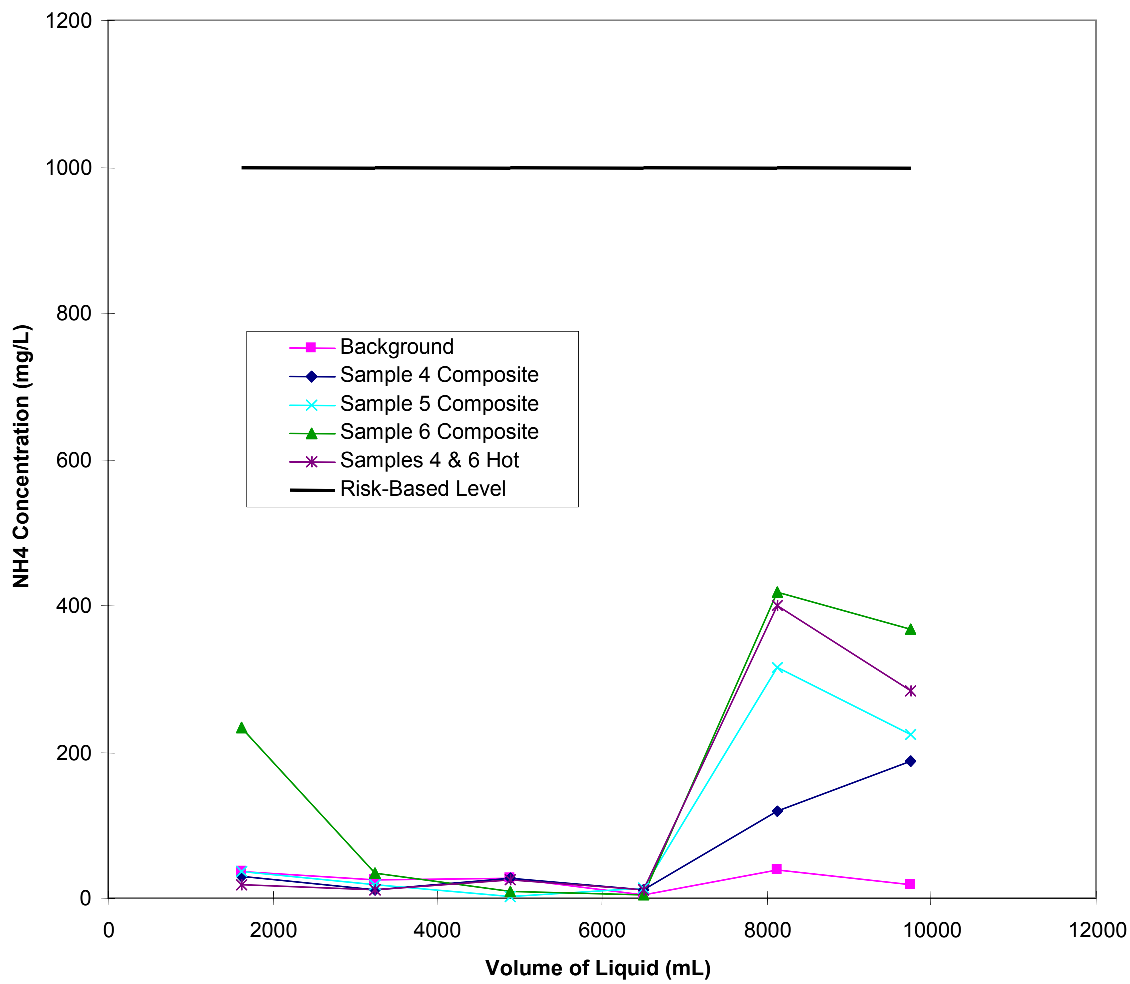


Figure B–3. Ammonium Concentration Results of Leach Study

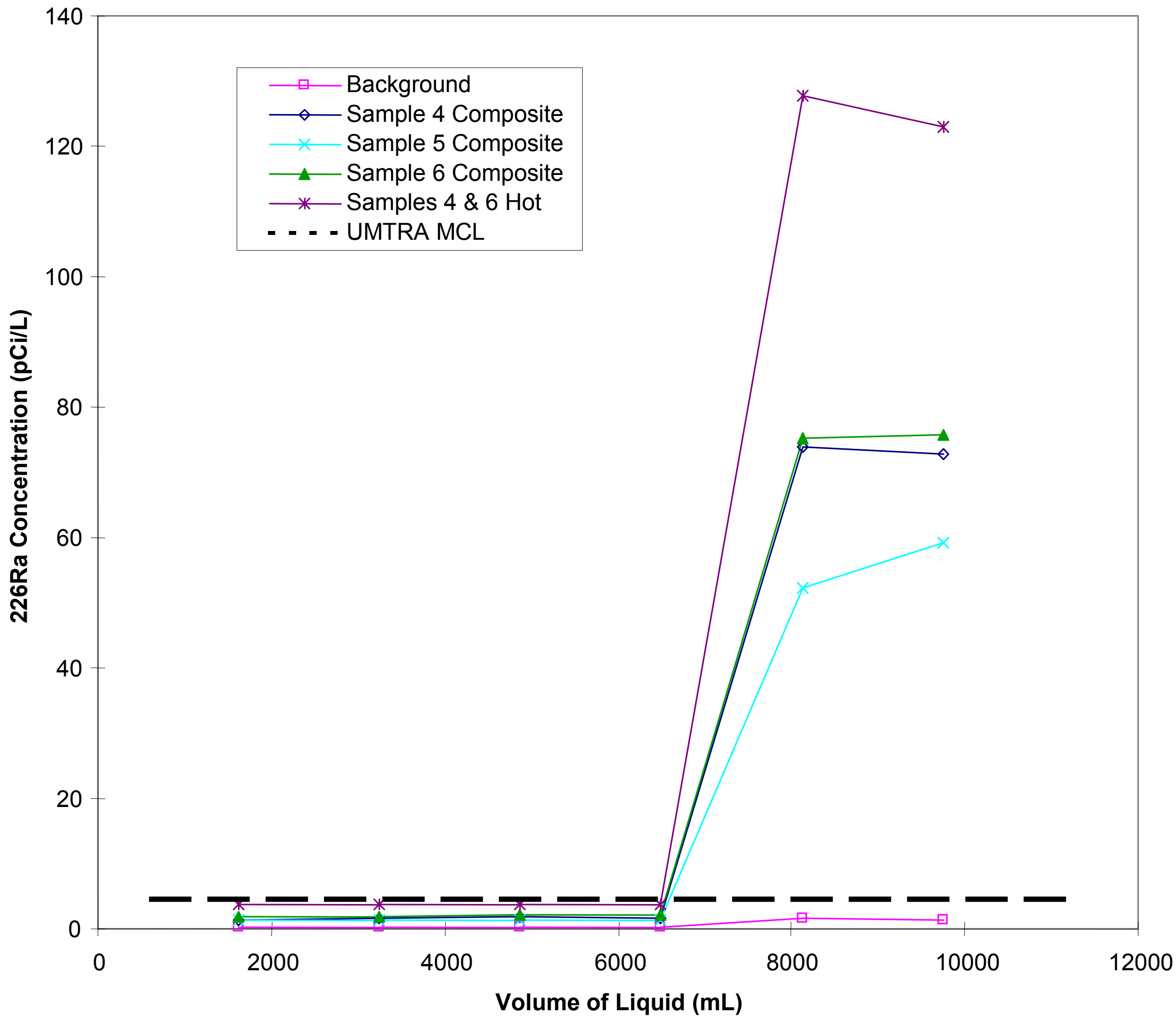


Figure B–4. Radium-226 Concentration Results of Leach Study

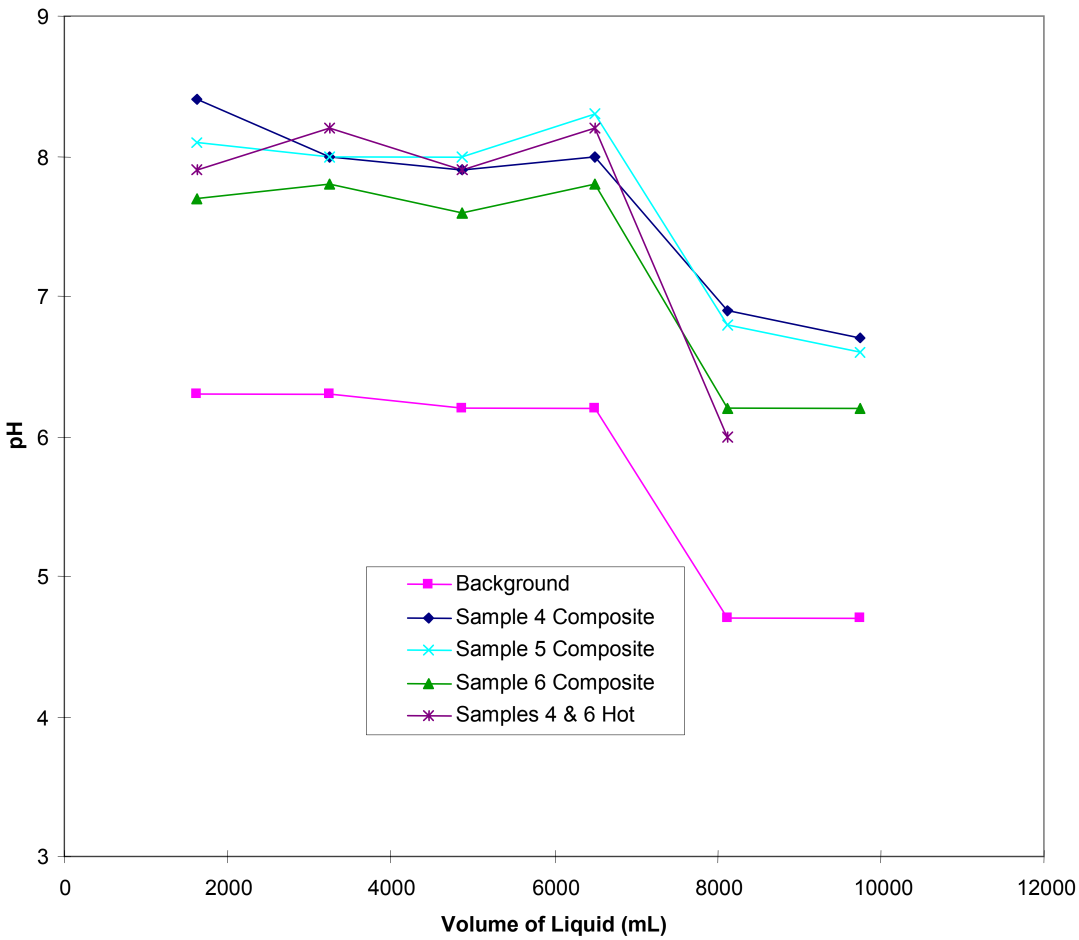


Figure B–5. pH Concentration Results of Leach Study

Appendix C
HELP Version 3.07 Output File

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******************************************************************************
******************************************************************************
**                                                                          **
**                                                                          **
**              HYDROLOGIC EVALUATION OF LANDFILL PERFORMANCE               **
**                HELP MODEL VERSION 3.07  (1 NOVEMBER 1997)                **
**                 DEVELOPED BY ENVIRONMENTAL LABORATORY                    **
**                   USAE WATERWAYS EXPERIMENT STATION                      **
**             FOR USEPA RISK REDUCTION ENGINEERING LABORATORY              **
**                                                                          **
**                                                                          **
******************************************************************************
******************************************************************************


PRECIPITATION DATA FILE:      C:\HELP\HELP3\BURRELL\DATA4.D4
TEMPERATURE DATA FILE:        C:\HELP\HELP3\BURRELL\DATA7.D7
SOLAR RADIATION DATA FILE:    C:\HELP\HELP3\BURRELL\DATA13.D13
EVAPOTRANSPIRATION DATA:      C:\HELP\HELP3\BURRELL\DATA11.D11
SOIL AND DESIGN DATA FILE:    C:\HELP\HELP3\BURRELL\DATA10.D10
OUTPUT DATA FILE:             C:\HELP\HELP3\BURRELL\Hannas.OUT


TIME:  15:22     DATE:   1/ 6/1999


******************************************************************************

    TITLE:  Burrell LTP Analog

******************************************************************************


    NOTE:  INITIAL MOISTURE CONTENT OF THE LAYERS AND SNOW WATER WERE
             COMPUTED AS NEARLY STEADY-STATE VALUES BY THE PROGRAM.


                                    LAYER  1
                                    --------

                         TYPE 2 - LATERAL DRAINAGE LAYER
                          MATERIAL TEXTURE NUMBER   2
         THICKNESS                    =     30.00    CM
         POROSITY                     =      0.4370 VOL/VOL
         FIELD CAPACITY               =      0.0620 VOL/VOL
         WILTING POINT                =      0.0240 VOL/VOL
         INITIAL SOIL WATER CONTENT   =      0.1875 VOL/VOL
         EFFECTIVE SAT. HYD. COND.    =  0.579999993000E-02 CM/SEC
       NOTE:  SATURATED HYDRAULIC CONDUCTIVITY IS MULTIPLIED BY   5.00
                FOR ROOT CHANNELS IN TOP HALF OF EVAPORATIVE ZONE.
```

SCS RUNOFF CURVE NUMBER	=	74.70	
FRACTION OF AREA ALLOWING RUNOFF	=	100.0	PERCENT
AREA PROJECTED ON HORIZONTAL PLANE	=	2.5000	HECTARES
EVAPORATIVE ZONE DEPTH	=	60.0	CM
INITIAL WATER IN EVAPORATIVE ZONE	=	9.444	CM
UPPER LIMIT OF EVAPORATIVE STORAGE	=	26.220	CM
LOWER LIMIT OF EVAPORATIVE STORAGE	=	1.440	CM
INITIAL SNOW WATER	=	0.000	CM
INITIAL WATER IN LAYER MATERIALS	=	215.409	CM
TOTAL INITIAL WATER	=	215.409	CM
TOTAL SUBSURFACE INFLOW	=	0.00	MM/YR

EVAPOTRANSPIRATION AND WEATHER DATA

NOTE: EVAPOTRANSPIRATION DATA WAS OBTAINED FROM
PITTSBURGH PENNSYLVANIA

STATION LATITUDE	=	40.50	DEGREES
MAXIMUM LEAF AREA INDEX	=	5.40	
START OF GROWING SEASON (JULIAN DATE)	=	114	
END OF GROWING SEASON (JULIAN DATE)	=	288	
EVAPORATIVE ZONE DEPTH	=	60.0	CM
AVERAGE ANNUAL WIND SPEED	=	14.00	KPH
AVERAGE 1ST QUARTER RELATIVE HUMIDITY	=	67.00	%
AVERAGE 2ND QUARTER RELATIVE HUMIDITY	=	63.00	%
AVERAGE 3RD QUARTER RELATIVE HUMIDITY	=	71.00	%
AVERAGE 4TH QUARTER RELATIVE HUMIDITY	=	70.00	%

NOTE: PRECIPITATION DATA WAS SYNTHETICALLY GENERATED USING
COEFFICIENTS FOR PITTSBURGH PENNSYLVANIA

NORMAL MEAN MONTHLY PRECIPITATION (MM)

JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
72.6	61.0	90.9	83.3	89.9	83.8
97.3	84.1	71.1	63.2	59.4	65.3

NOTE: TEMPERATURE DATA WAS SYNTHETICALLY GENERATED USING
COEFFICIENTS FOR PITTSBURGH PENNSYLVANIA

NORMAL MEAN MONTHLY TEMPERATURE (DEGREES CELSIUS)

JAN/JUL	FEB/AUG	MAR/SEP	APR/OCT	MAY/NOV	JUN/DEC
-2.9	-1.8	3.6	10.1	15.4	20.1
22.2	21.5	17.8	11.4	5.3	-0.3

NOTE: SOLAR RADIATION DATA WAS SYNTHETICALLY GENERATED USING
COEFFICIENTS FOR PITTSBURGH PENNSYLVANIA
AND STATION LATITUDE = 40.50 DEGREES

****

ANNUAL TOTALS FOR YEAR 1

	MM	CU. METERS	PERCENT
PRECIPITATION	979.10	24477.496	100.00
RUNOFF	48.960	1224.002	5.00
EVAPOTRANSPIRATION	611.612	15290.303	62.47
DRAINAGE COLLECTED FROM LAYER 2	6.9924	174.809	0.71
PERC./LEAKAGE THROUGH LAYER 3	311.337738	7783.443	31.80
AVG. HEAD ON TOP OF LAYER 3	0.8431		
PERC./LEAKAGE THROUGH LAYER 4	293.131042	7328.276	29.94
CHANGE IN WATER STORAGE	18.404	460.103	1.88
SOIL WATER AT START OF YEAR	2154.090	53852.254	
SOIL WATER AT END OF YEAR	2172.494	54312.359	
SNOW WATER AT START OF YEAR	0.000	0.000	0.00
SNOW WATER AT END OF YEAR	0.000	0.000	0.00
ANNUAL WATER BUDGET BALANCE	0.0001	0.002	0.00

****

****

ANNUAL TOTALS FOR YEAR 2

	MM	CU. METERS	PERCENT
PRECIPITATION	949.50	23737.506	100.00
RUNOFF	175.239	4380.977	18.46
EVAPOTRANSPIRATION	505.172	12629.296	53.20
DRAINAGE COLLECTED FROM LAYER 2	12.9647	324.117	1.37
PERC./LEAKAGE THROUGH LAYER 3	276.708069	6917.702	29.14
AVG. HEAD ON TOP OF LAYER 3	1.0357		
PERC./LEAKAGE THROUGH LAYER 4	258.220673	6455.517	27.20
CHANGE IN WATER STORAGE	-2.096	-52.405	-0.22
SOIL WATER AT START OF YEAR	2172.494	54312.359	
SOIL WATER AT END OF YEAR	2170.398	54259.953	
SNOW WATER AT START OF YEAR	0.000	0.000	0.00
SNOW WATER AT END OF YEAR	0.000	0.000	0.00
ANNUAL WATER BUDGET BALANCE	0.0002	0.005	0.00

****

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ANNUAL TOTALS FOR YEAR 3

	MM	CU. METERS	PERCENT
PRECIPITATION	941.20	23530.002	100.00
RUNOFF	200.294	5007.351	21.28
EVAPOTRANSPIRATION	538.866	13471.652	57.25
DRAINAGE COLLECTED FROM LAYER 2	17.5808	439.519	1.87
PERC./LEAKAGE THROUGH LAYER 3	165.019241	4125.481	17.53
AVG. HEAD ON TOP OF LAYER 3	1.1729		
PERC./LEAKAGE THROUGH LAYER 4	268.563354	6714.084	28.53
CHANGE IN WATER STORAGE	-84.104	-2102.598	-8.94
SOIL WATER AT START OF YEAR	2170.398	54259.953	
SOIL WATER AT END OF YEAR	2082.600	52065.004	
SNOW WATER AT START OF YEAR	0.000	0.000	0.00
SNOW WATER AT END OF YEAR	3.694	92.350	0.39
ANNUAL WATER BUDGET BALANCE	-0.0002	-0.005	0.00

****

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ANNUAL TOTALS FOR YEAR 4

	MM	CU. METERS	PERCENT
PRECIPITATION	957.00	23925.006	100.00
RUNOFF	128.703	3217.580	13.45
EVAPOTRANSPIRATION	590.142	14753.546	61.67
DRAINAGE COLLECTED FROM LAYER 2	13.2144	330.359	1.38
PERC./LEAKAGE THROUGH LAYER 3	202.929260	5073.231	21.20
AVG. HEAD ON TOP OF LAYER 3	0.9980		
PERC./LEAKAGE THROUGH LAYER 4	163.453217	4086.331	17.08
CHANGE IN WATER STORAGE	61.488	1537.190	6.43
SOIL WATER AT START OF YEAR	2082.600	52065.004	
SOIL WATER AT END OF YEAR	2140.796	53519.910	
SNOW WATER AT START OF YEAR	3.694	92.350	0.39
SNOW WATER AT END OF YEAR	6.985	174.633	0.73
ANNUAL WATER BUDGET BALANCE	0.0000	0.001	0.00

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ANNUAL TOTALS FOR YEAR 5

	MM	CU. METERS	PERCENT
PRECIPITATION	962.20	24055.006	100.00
RUNOFF	152.428	3810.693	15.84
EVAPOTRANSPIRATION	616.114	15402.859	64.03
DRAINAGE COLLECTED FROM LAYER 2	13.3424	333.560	1.39
PERC./LEAKAGE THROUGH LAYER 3	212.949890	5323.747	22.13
AVG. HEAD ON TOP OF LAYER 3	0.9850		
PERC./LEAKAGE THROUGH LAYER 4	198.382782	4959.569	20.62
CHANGE IN WATER STORAGE	-18.067	-451.685	-1.88
SOIL WATER AT START OF YEAR	2140.796	53519.910	
SOIL WATER AT END OF YEAR	2129.714	53242.859	
SNOW WATER AT START OF YEAR	6.985	174.633	0.73
SNOW WATER AT END OF YEAR	0.000	0.000	0.00
ANNUAL WATER BUDGET BALANCE	0.0004	0.009	0.00

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ANNUAL TOTALS FOR YEAR 6

	MM	CU. METERS	PERCENT
PRECIPITATION	792.00	19800.002	100.00
RUNOFF	12.794	319.859	1.62
EVAPOTRANSPIRATION	565.461	14136.536	71.40
DRAINAGE COLLECTED FROM LAYER 2	1.5919	39.797	0.20
PERC./LEAKAGE THROUGH LAYER 3	154.971283	3874.282	19.57
AVG. HEAD ON TOP OF LAYER 3	0.2365		
PERC./LEAKAGE THROUGH LAYER 4	188.292969	4707.324	23.77
CHANGE IN WATER STORAGE	23.860	596.490	3.01
SOIL WATER AT START OF YEAR	2129.714	53242.859	
SOIL WATER AT END OF YEAR	2091.350	52283.742	
SNOW WATER AT START OF YEAR	0.000	0.000	0.00
SNOW WATER AT END OF YEAR	62.224	1555.608	7.86
ANNUAL WATER BUDGET BALANCE	-0.0002	-0.005	0.00

****

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ANNUAL TOTALS FOR YEAR 7

	MM	CU. METERS	PERCENT
PRECIPITATION	958.80	23969.998	100.00
RUNOFF	131.269	3281.722	13.69
EVAPOTRANSPIRATION	570.604	14265.103	59.51
DRAINAGE COLLECTED FROM LAYER 2	12.6456	316.140	1.32
PERC./LEAKAGE THROUGH LAYER 3	304.658539	7616.463	31.77
AVG. HEAD ON TOP OF LAYER 3	1.0521		
PERC./LEAKAGE THROUGH LAYER 4	200.663025	5016.576	20.93
CHANGE IN WATER STORAGE	43.618	1090.455	4.55
SOIL WATER AT START OF YEAR	2091.350	52283.742	
SOIL WATER AT END OF YEAR	2196.486	54912.141	
SNOW WATER AT START OF YEAR	62.224	1555.608	6.49
SNOW WATER AT END OF YEAR	0.706	17.662	0.07
ANNUAL WATER BUDGET BALANCE	0.0001	0.002	0.00

****

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ANNUAL TOTALS FOR YEAR 8

	MM	CU. METERS	PERCENT
PRECIPITATION	1049.30	26232.498	100.00
RUNOFF	8.389	209.731	0.80
EVAPOTRANSPIRATION	698.205	17455.135	66.54
DRAINAGE COLLECTED FROM LAYER 2	1.9622	49.054	0.19
PERC./LEAKAGE THROUGH LAYER 3	306.695312	7667.383	29.23
AVG. HEAD ON TOP OF LAYER 3	0.3481		
PERC./LEAKAGE THROUGH LAYER 4	393.382294	9834.558	37.49
CHANGE IN WATER STORAGE	-52.639	-1315.976	-5.02
SOIL WATER AT START OF YEAR	2196.486	54912.141	
SOIL WATER AT END OF YEAR	2125.097	53127.426	
SNOW WATER AT START OF YEAR	0.706	17.662	0.07
SNOW WATER AT END OF YEAR	19.456	486.403	1.85
ANNUAL WATER BUDGET BALANCE	-0.0001	-0.004	0.00

****

****

ANNUAL TOTALS FOR YEAR 9

	MM	CU. METERS	PERCENT
PRECIPITATION	959.40	23985.014	100.00
RUNOFF	75.986	1899.650	7.92
EVAPOTRANSPIRATION	623.452	15586.295	64.98
DRAINAGE COLLECTED FROM LAYER 2	13.6253	340.632	1.42
PERC./LEAKAGE THROUGH LAYER 3	276.018829	6900.471	28.77
AVG. HEAD ON TOP OF LAYER 3	1.0329		
PERC./LEAKAGE THROUGH LAYER 4	270.685883	6767.147	28.21
CHANGE IN WATER STORAGE	-24.349	-608.716	-2.54
SOIL WATER AT START OF YEAR	2125.097	53127.426	
SOIL WATER AT END OF YEAR	2110.373	52759.332	
SNOW WATER AT START OF YEAR	19.456	486.403	2.03
SNOW WATER AT END OF YEAR	9.831	245.780	1.02
ANNUAL WATER BUDGET BALANCE	0.0002	0.005	0.00

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ANNUAL TOTALS FOR YEAR 10

	MM	CU. METERS	PERCENT
PRECIPITATION	781.30	19532.502	100.00
RUNOFF	27.259	681.463	3.49
EVAPOTRANSPIRATION	544.285	13607.131	69.66
DRAINAGE COLLECTED FROM LAYER 2	6.4340	160.851	0.82
PERC./LEAKAGE THROUGH LAYER 3	193.920670	4848.017	24.82
AVG. HEAD ON TOP OF LAYER 3	0.7036		
PERC./LEAKAGE THROUGH LAYER 4	254.105759	6352.644	32.52
CHANGE IN WATER STORAGE	-50.783	-1269.586	-6.50
SOIL WATER AT START OF YEAR	2110.373	52759.332	
SOIL WATER AT END OF YEAR	2038.710	50967.762	
SNOW WATER AT START OF YEAR	9.831	245.780	1.26
SNOW WATER AT END OF YEAR	30.711	767.765	3.93
ANNUAL WATER BUDGET BALANCE	0.0000	0.000	0.00

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AVERAGES OF MONTHLY AVERAGED DAILY HEADS (CM)

DAILY AVERAGE HEAD ON TOP OF LAYER 3

AVERAGES	0.0056	0.0731	0.5222	0.3199	0.0112	0.0006
	0.0000	0.0063	0.0123	0.0102	0.0255	0.0220
STD. DEVIATIONS	0.0124	0.2304	0.4718	0.5014	0.0106	0.0018
	0.0000	0.0084	0.0250	0.0175	0.0227	0.0213

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AVERAGE ANNUAL TOTALS & (STD. DEVIATIONS) FOR YEARS 1 THROUGH 10

	MM		CU. METERS	PERCENT
PRECIPITATION	932.98	(82.781)	23324.5	100.00
RUNOFF	96.132	(70.3886)	2403.30	10.304
EVAPOTRANSPIRATION	586.391	(54.4921)	14659.79	62.851
LATERAL DRAINAGE COLLECTED FROM LAYER 2	10.03535	(5.42582)	250.884	1.07562
PERCOLATION/LEAKAGE THROUGH LAYER 3	240.52086	(60.95679)	6013.021	25.77985
AVERAGE HEAD ON TOP OF LAYER 3	0.841 (	0.317)		
PERCOLATION/LEAKAGE THROUGH LAYER 4	248.88809	(66.38271)	6222.202	26.67668
CHANGE IN WATER STORAGE	-8.467	(1.8194)	-211.67	-0.908

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FINAL WATER STORAGE AT END OF YEAR 10

LAYER	(CM)	(VOL/VOL)
1	3.8725	0.1291
2	2.4004	0.0800
3	41.7600	0.4640
4	155.8383	0.2597
SNOW WATER	3.071	

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Appendix D
Calculation of Groundwater Contamination Resulting From Tailings Leaching

Problem Statement: Estimate groundwater concentration resulting from leaching residual radioactive material [RRM] in the Burrell disposal cell. Three scenarios of disposal cell cover integrity are evaluated:
Scenario 1 - Undegraded compacted soil layer [CSL] on cell controls infiltration through underlying RRM [CSL w/o plants scenario]
Scenario 2 - Hydraulic conductivity of the CSL is increased by Japanese knotweed root intrusion [CSL w/knotweed scenario]
Scenario 3 - Hydraulic conductivity of the CSL is increased by mature plant/biotic community intrusion [mature analog site scenario]
Analytes of concern are manganese, molybdenum, selenium, radium, and uranium.

Method of Solution: Analytical mixing model [Summers Model, in EPA 1989].

Summers Model Mixing Equation:
Cgw = [QpCp + QaCa] / Qp + Qa; where:

Cgw = concentration of contaminant in groundwater after source mixing [M/L3],
Qp = volumetric flux of source water to aquifer [L3/T],
Cp = contaminant concentration in source water [M/L3],
Qa = volumetric flux in aquifer beneath source area [L3/T].
Ca = initial contaminant concentration in aquifer [M/L3],

Burrell Site Parameters

		Data Source:
Area of source:		
Cell footprint area	2.5 hectare = 2.5E+08 cm2	Waugh & Smith 1997
Cell length perpendicular to groundwater flow direction = 1300 ft [39,624 cm]		DOE 1993, site map

Average annual precipitation: 112cm — Data Source: Waugh & Smith, 1997

Saturated hydraulic conductivity [Ksat]:		Data Source:
CSL w/o plants	Ksat 1 = 2.9E-07 cm/sec	Waugh & Smith 1997, field measurement
CSL w/knotweed	Ksat 2 = 3.0E-05 cm/sec	Waugh & Smith 1997, field measurement
Mature analog site	Ksat 3 = 1.3E-04 cm/sec	Waugh & Smith 1997, field measurement
Aquifer/fill beneath cell	Ksat aq = 8.6E-02 cm/sec	DOE 1982, documented pump test result
Hydraulic gradient:	0.011 to 0.023 cm/cm	DOE 1994 and 1988, GJO 1998; 9/87, 7/93 data
Aquifer saturated thickness:	25 ft [762 cm]	DOE 1985, thickness estimated from geologic cross-sections
	20 ft [610 cm]	DOE 1982, derived from pump test result

Analyte Concentrations in Source Water

	Max conc in DI water leach	Max conc in TCLP leach	Mean of Max concs in 4 TCLP leach tests, minus background
manganese	1,120 ug/L	28,300 ug/L	20,700 ug/L
molybdenum	793 ug/L	200 ug/L	133 ug/L
uranium	210 ug/L	583 ug/L	276 ug/L
selenium	5.8 ug/L	24.6 ug/L	11.6 ug/L
radium 226+228	4 pCi/L	134.3 pCi/L	86.3 pCi/L

Data Source: Waugh 1997, column leach test results, composite RRM samples

Analyte Concentrations in Groundwater

	Maximum observed concentration in groundwater, background wells; 11/97		Maximum observed concentration in groundwater, downgradient wells; 11/97	
manganese	9180 ug/L		9980 ug/L	
molybdenum	<1 ug/L	not detected	26.5 ug/L	
uranium	<1 ug/L	not detected	8.2 ug/L	
selenium	<1.1 ug/L	not detected	<1.1 ug/L	not detected
radium 226+228	0.25 pCi/L		0.16 pCi/L	

Data Source: GJO 1998, November 1997 groundwater sample results.

Infiltration Water Budget

[1] Estimate maximum volume of water [Qmax] available to infiltrate RRM, where
Qmax = infiltration rate [L/T] x infiltration area [L2]
Assume 100% infiltration of average annual precipitation on disposal cell; therefore,
Qmax = 112cm/yr x 2.5E+08 cm2 = 2.8E+10 cm3/yr [or 0.9 L/sec]

[2] Calculate infiltration [Qc] at variable Ksat for 3 site scenarios
Assume gravity drainage under saturated conditions, and K RRM >= Ksat 1, 2, and 3; therefore,
Qc = Ksat x hydraulic gradient x infiltration area, where

Ksat 1 =	2.9E-07 cm/sec	CSL w/o plants
Ksat 2 =	3.0E-05 cm/sec	CSL w/knotweed
Ksat 3 =	1.3E-04 cm/sec	mature analog site,

hydraulic gradient = 1, and
infiltration area = 2.5E+08 cm2

Results: Qc 1 = 0.0725 L/sec
Qc 2 = 7.5 L/sec
Qc 3 = 32.5 L/sec

[3] Compare calculated infiltration [Qc] with maximum available infiltration [Qmax = 0.9 L/sec]

Qc 1 < Qmax	Qc 1 is valid; use Qc 1 in mixing calculation for CSL w/o plants scenario
Qc 2 > Qmax	Qc 2 is not valid; use Qmax in mixing calculation for CSL w/knotweed scenario
Qc 3 >> Qmax	Qc 3 is not valid; use Qmax in mixing calculation for mature analog site scenario

Mixing Calculation Inputs

Scenario	Ksat CSL [cm/sec]	Source area [cm2]	Qp [L/sec]	Ksat aquifer [cm/sec]	Hydraulic gradient	Sat thick [cm]	Flow tube width [cm]	Qa [L/sec]
CSL w/o plants	2.90E-07	2.50E+08	0.0725	8.60E-02	0.011	609	39624	22.8
CSL w/knotweed	Not Applicable	2.50E+08	0.9000	8.60E-02	0.011	609	39624	22.8
Mature analog site	Not Applicable	2.50E+08	0.9000	8.60E-02	0.011	609	39624	22.8

Mixing calculation assumptions:

[1] Qa = Ksat aquifer x gradient x saturated thickness x width of cell perpendicular to flow.
[2] Instantaneous homogenous source/groundwater mixing.
[3] No retardation of contaminants in subcell vadose zone or in aquifer.
[4] Initial groundwater concentration [Ca] = max concentration in background wells, 11/97 results.
[5] Ca = detection limit for undetected analytes.
[6] Source concentration [Cp] is constant through time except Calculations 4 and 5. See assumption 9.
[7] Aquifer and source flow rates are constant through time.
[8] Calculated groundwater concentrations [Cgw] are in aquifer beneath disposal cell and donwgradient of the site to Conemaugh River.
[9] For Calculation 4 & 5 only, Cp Ra-266 will increase in proportion to Ra-226 ingrowth predicted in Waugh 1997. Therefore, at times = 200 yr and 1,000 yr from present, Cp Ra-226 = 2x and 4x values measured in leach tests, respectively.
[10] For Calculation 5 with Ra-226 ingrowth, Qp = 0.5 x Qmax for plant scenarios, i.e., 50% of mean annual precipitation infiltrates RRM.
[11] For Calculation 6, Ksat aquifer = 0.1 x pump test result, all else same as Calculation 3.
[12] For Calculation 7, Ksat aquifer = 0.1 x pump test result, and Qp = 0.5 x Qmax [plant scenarios only], all else same as Calculation 6.
[13] For Calculation 8 with Ra-226 ingrowth, Qp = 0.25 x Qmax for plant scenarios, i.e., 25% of mean annual precipitation infiltrates RRM.

Mixing Calculation 1: Cp = Max conc in DI leach

	Calculated groundwater concentration [Cgw] CSL w/o plants	CSL w/knotweed	Mature Analog	RSL [ug/L]	MCL
Mn [ug/L]	9154.5	8874.3	8874.3	840	N/A ug/L
Mo [ug/L]	3.5	31.0	31.0	180	100 ug/L
U [ug/L]	1.7	8.9	8.9	110	44 ug/L
Se [ug/L]	1.1	1.3	1.3	180	10 ug/L
Ra [pCi/L]	0.3	0.4	0.4	N/A	5 pCi/L

Mixing Calculation 2: Cp = Max conc in TCLP leach

	Calculated groundwater concentration [Cgw] CSL w/o plants	CSL w/knotweed	Mature Analog	RSL [ug/L]	MCL
Mn [ug/L]	9240.5	9905.2	9905.2	840	N/A ug/L
Mo [ug/L]	1.6	8.5	8.5	180	100 ug/L
U [ug/L]	2.8	22.1	22.1	110	44 ug/L
Se [ug/L]	1.2	2.0	2.0	180	10 ug/L
Ra [pCi/L]	0.7	5.3	5.3	N/A	5 pCi/L

Mixing Calculation 3: Cp = Mean of max concs in 4 TCLP leach tests

	Calculated groundwater concentration [Cgw] CSL w/o plants	CSL w/knotweed	Mature Analog	RSL [ug/L]	MCL
Mn [ug/L]	9216.5	9617.0	9617.0	840	N/A ug/L
Mo [ug/L]	1.4	6.0	6.0	180	100 ug/L
U [ug/L]	1.9	11.4	11.4	110	44 ug/L
Se [ug/L]	1.1	1.5	1.5	180	10 ug/L
Ra [pCi/L]	0.5	3.5	3.5	N/A	5 pCi/L

Mixing Calculation 4: Cp Ra-226 = estimate based on Ra-226 ingrowth at 200 yr and 1,000 yr

			Calculated Ra-226 concentration in groundwater [pCi/L]		
Ra-226 source	Cp [pCi/L]	Time yr	CSL w/o plants	CSL w/knotweed	Mature analog site
Max DI water leach x 2	8	200	0.3	0.5	0.5
Max DI water leach x 4	16	1000	0.3	0.8	0.8
Max TCLP leach x 2	268	200	1.1	10.4	10.4
Max TCLP leach x 4	536	1000	1.9	20.6	20.6
Mean of max TCLP leach x 2	172	200	0.8	6.8	6.8
Mean of max TCLP leach x 4	344	1000	1.3	13.3	13.3

Mixing Calculation 5: Cp Ra-226 = estimate based on Ra-226 ingrowth at 200 yr and 1,000 yr Qp = 0.5 x Qmax

			Calculated Ra-226 concentration in groundwater [pCi/L]		
Ra-226 source	Cp [pCi/L]	Time yr	CSL w/o plants	CSL w/knotweed	Mature analog site
Max DI water leach x 2	8	200	0.3	0.4	0.4
Max DI water leach x 4	16	1000	0.3	0.6	0.6
Max TCLP leach x 2	268	200	1.1	5.4	5.4
Max TCLP leach x 4	536	1000	1.9	10.6	10.6
Mean of max TCLP leach x 2	172	200	0.8	3.6	3.6
Mean of max TCLP leach x 4	344	1000	1.3	6.9	6.9

Mixing Calculation 6: All conditions same as Calculation 3 but Ksat aquifer = 0.1 x pump test result

	Calculated groundwater concentration [Cgw]				
	CSL w/o plants	CSL w/knotweed	Mature Analog	RSL [ug/L]	MCL
Mn [ug/L]	9534.6	12437.5	12437.5	840	N/A ug/L
Mo [ug/L]	5.1	38.3	38.3	180	100 ug/L
U [ug/L]	9.5	78.8	78.8	110	44 ug/L
Se [ug/L]	1.4	4.1	4.1	180	10 ug/L
Ra [pCi/L]	2.9	24.6	24.6	N/A	5 pCi/L

Mixing Calculation 7: All conditions same as Calculation 6 but Qp = 0.5 x Qmax for root intrusion scenarios

	Calculated groundwater concentration [Cgw]				
	CSL w/o plants	CSL w/knotweed	Mature Analog	RSL [ug/L]	MCL
Mn [ug/L]	9534.6	11077.0	11077.0	840	N/A ug/L
Mo [ug/L]	5.1	22.7	22.7	180	100 ug/L
U [ug/L]	9.5	46.3	46.3	110	44 ug/L
Se [ug/L]	1.4	2.8	2.8	180	10 ug/L
Ra [pCi/L]	2.9	14.4	14.4	N/A	5 pCi/L

Mixing Calculation 8: Cp Ra-226 = estimate based on Ra-226 ingrowth at 200 yr and 1,000 yr Qp = 0.25 x Qmax

			Calculated Ra-226 concentration in groundwater [pCi/L]		
Ra-226 source	Cp [pCi/L]	Time yr	CSL w/o plants	CSL w/knotweed	Mature analog site
Max DI water leach x 2	8	200	0.3	0.3	0.3
Max DI water leach x 4	16	1000	0.3	0.4	0.4
Max TCLP leach x 2	268	200	1.1	2.9	2.9
Max TCLP leach x 4	536	1000	1.9	5.5	5.5
Mean of max TCLP leach x 2	172	200	0.8	1.9	1.9
Mean of max TCLP leach x 4	344	1000	1.3	3.6	3.6

RSL = Risk Screening Level, RSLs per Waugh 1997.
MCL = UMTRA Maximum Contaminant Limits.

Summary

[1] Presently, no contaminant concentration in groundwater, except manganese, exceeds an MCL or RSL.
[2] Manganese concentrations in background groundwater presently exceed the RSL.
[3] The RRM source is not presently causing MCLs or RSLs to be exceeded.
[4] MCLs or RSLs will not be exceeded by contributions from the RRM under the scenarios evaluated in Calculation 1, 2, and 3.
[5] As a result of Ra-226 ingrowth from Th-230 decay [Calculation 4], the MCL for Ra-226 may be exceeded at approximately 200 yr through 1,000 yr under the root intrusion scenarios [w/knotweed and mature analog site], assuming aggressive leaching [TCLP leach conditions]. However, the predicted future Ra-226 concentrations are not mass conservative with respect to source depletion from Th-230 and Ra-226 leaching.
[6] Predicted Ra-226 concentrations only marginally exceed the MCL at 1,000 yr if infiltration is reduced by 50% [evapotranspirative losses and runoff] and are at or below the standard when infiltration is 25% of mean annual precipitation (Calculations 5 and 8).
[7] Calculation 6 [aquifer Ksat sensitivity analysis] indicates that the MCL for Ra-226 will be exceeded under the root intrusion scenarios assuming aggressive leaching [TCLP leach conditions] and aquifer Ksat = 0.1 x pump test result. However, because the Ra-226 concentration predicted in Calculation 6 no-plant scenario is approximately 18 times greater than presently in groundwater immediately downgradient of the disposal cell [0.16 pCi/L], the aggressive leach conditions or lower Ksat are overly conservative, or Ra-226 is immobile in the aquifer [see assumption 3].

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