

Performance Assessment for the Idaho CERCLA Disposal Facility Landfill

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ABSTRACT

This performance assessment for the Idaho CERCLA Disposal Facility Landfill documents the projected radiological dose impacts associated with the disposal of low-level radioactive waste at the facility. The Idaho CERCLA Disposal Facility is part of the Idaho Cleanup Project on the Idaho National Laboratory Site, which is operated by the U.S. Department of Energy. This assessment evaluates compliance with the applicable radiological criteria of the U.S. Department of Energy, the U.S. Environmental Protection Agency, and the Idaho Department of Environmental Quality for protection of the public and the environment. The calculations involve modeling the transport of radionuclides from buried waste to surface soil and subsurface media and, eventually, to members of the public via air, groundwater, and food-chain pathways. Projections of doses are calculated for both off-Site receptors and individuals who inadvertently intrude into the waste after site closure. The results of the calculations are used to evaluate the future performance of the low-level radioactive waste disposal facility and to provide input for the establishment of waste acceptance criteria. The comparison of the performance assessment results to the applicable performance objectives provides reasonable expectation that the performance objectives will be met.

EXECUTIVE SUMMARY

This report documents the projected impacts associated with disposal of low-level radioactive waste (LLW) at the Idaho CERCLA Disposal Facility (ICDF) Landfill. The impacts were compared with applicable U.S. Department of Energy (DOE) and U.S. Environmental Protection Agency (EPA) standards. This performance assessment (PA) satisfies PA maintenance requirements identified in DOE M 435.1-1 Chg 1, Section IV.P.(4)(a).

This PA presents a comprehensive, systematic analysis of the long-term impacts of LLW disposal in an arid, near-surface environment. The assessment is conducted to comply with DOE requirements for post-closure PA as documented in DOE M 435.1-1 Chg 1. Occupational radiological doses and impacts of nonradioactive, hazardous constituents are beyond the scope of this radiological PA.

For the purpose of assessing the long-term performance of the ICDF Landfill, three time periods are of concern:

1. The institutional control period (100 years following closure of the landfill), which follows site closure and during which periodic maintenance and monitoring activities are conducted. The facility is assumed to be closed, stabilized, and maintained but is still part of the Idaho National Laboratory (INL) Site and is fenced and patrolled. For the purposes of this analysis, the assumed closure date for the ICDF Landfill is 2018. The basis for this assumption is the assumed 15-year operational period for the ICDF Landfill documented in the *INEEL CERCLA Disposal Facility Remedial Design/Construction Work Plan* (DOE-ID 2002) and supporting documents. ICDF Landfill operations began in 2003; therefore, 15 years of operations results in a closure date of 2018. Note that DOE will continue to evaluate the programmatic need to operate the facility longer than the initially intended 2018 closure date and an update to this PA will be made, as necessary.
2. The compliance period (from 100 to 1,000 years following closure), during which the landfill is assumed to be no longer maintained by DOE and may be accessible to the public. Radiological impacts are assessed for a period of 1,000 years, the maximum time of compliance for DOE LLW PAs.
3. The post-compliance period (beyond 1,000 years). Analyses were also carried out to the time of maximum potential impact to provide perspective on the magnitude of doses beyond the compliance timeframe.

Two receptor types were assessed consistent with requirements in DOE M 435.1-1 Chg 1. The first was a member of the public. During the operational and institutional control periods, this hypothetical individual is assumed to reside at the INL Site southern boundary approximately 12.7 km (8 mi) downgradient of the ICDF Landfill. During the compliance and post-compliance periods, the hypothetical member of the public (receptor) is assumed to reside 100 m from the downgradient edge of the landfill. The receptor is exposed to contaminants through the groundwater all-pathways scenario, which assumes the receptor consumes (1) contaminated groundwater, (2) leafy vegetables and produce that were irrigated with contaminated groundwater, and (3) milk and meat from animals that consume contaminated water and pasture grass irrigated with contaminated groundwater. Atmospheric and radon exposures are also considered in the assessment.

The second type of receptor evaluated was an inadvertent intruder. This hypothetical receptor was assumed to intrude inadvertently into the waste 100 years after closure of the landfill during the compliance period. Both acute and chronic inadvertent intruder well drilling scenarios were evaluated. The acute scenario included the doses from inhalation of contaminated air, external exposure, and soil

ingestion. The chronic scenario included doses from dust inhalation, external exposure, soil ingestion, and ingestion of contaminated food (i.e., beef, milk, and plants).

The modeling approach for the PA comprises conceptual models that link radionuclide inventory, release (or source term), environmental transfer, and impact assessment (see Figure ES-1) and culminate in radiological doses to receptors. The waste inventory used in the PA was obtained from the most current version of the Integrated Waste Tracking System maintained for the Idaho Cleanup Project and projected future disposals.

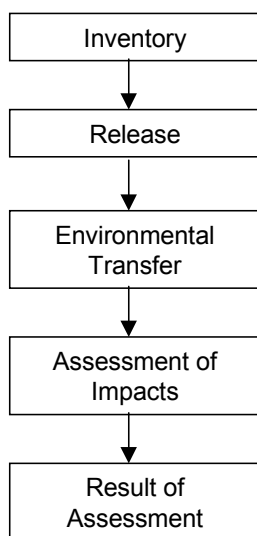


Figure ES-1. Model linkages for the performance assessment.

The PA focuses on two transport pathways to calculate exposure to off-Site members of the public: groundwater transport and atmospheric transport. The groundwater transport pathway describes the movement of radionuclides that leach from the landfill and move vertically down through the vadose zone to the aquifer. The atmospheric transport pathway considers radionuclides that diffuse to the landfill surface and are subsequently dispersed in the atmosphere.

The exposure pathways evaluated include ingestion of contaminated food and water, inhalation of radionuclides, and external exposure to radionuclides in the air and on the ground (or soil) surface. The agricultural products consumed by members of the public are contaminated via food-chain transport of radionuclides deposited from air onto soil or plant surfaces, from radionuclides deposited onto soil or plant surfaces by irrigation water, or from the direct ingestion of contaminated water.

The source of radionuclides for airborne transport during the institutional and compliance periods was diffusion of radioactive gases from the waste to the surface. The entire inventory of C-14, H-3, and I-129 was assumed to be present in a form that allows partitioning into the gas, liquid, and solid phases. Gas-phase diffusion to the surface was calculated using the EPA's one-dimensional multi-phase diffusion code EMSOFT (EPA 1997). Dispersion and subsequent doses from radionuclide fluxes at the soil surface were then modeled with the CAP88-PC computer code (EPA 2007) using INL Site-specific meteorological data and default input parameters. Radon diffusion from the waste through the cover was evaluated using the RESRAD code (Yu et al. 2001) for comparison with the 40 CFR 61, Subpart Q, standard for radon flux.

Impacts from the subsurface migration of radionuclides dissolved in groundwater were estimated using computer models that describe release of radionuclides from the waste disposed of within the landfill and subsequent transport through the vadose zone to aquifer compliance locations.

The source term for groundwater transport calculations was screened using a two-phase approach. In the first phase, radionuclides that had a half-life less than 5 years were removed from further consideration. This phase did not remove radionuclides that had half-lives less than 5 years and were part of a larger decay chain. The second phase used the GWSCREEN model (Rood 2003) coupled with conservative input parameters to compute drinking water doses for the remaining radionuclides. Radionuclides with a screening dose of less than 0.4 mrem/year were removed from further consideration. The remaining radionuclides retained for further evaluation and analysis were C-14, Cl-36, H-3, I-129, Np-237, Pu-239, Pu-240, Tc-99, U-233, U-234, U-235, and U-238.

The source term for the base case analysis considered two waste forms present in the landfill: miscellaneous waste and activated metals. Radionuclides in miscellaneous waste were assumed to be mixed homogeneously in the soil and readily leachable (soluble) in the presence of infiltrating water. Radionuclides in activated metal were released to waste soils via corrosion of the waste form. This was modeled using a first-order corrosion rate constant. The source term model considered reduced infiltration from the presence of an engineered cover over the ICDF Landfill. The cover will be installed upon closure of the landfill in 2018 and was assumed to remain intact and perform to design specifications of 0.01 cm/year for 500 years. After 500 years, the cover linearly fails, reaching a maximum infiltration rate of 1 cm/year 1,000 years after installation.

The vadose zone was modeled as a one-dimensional column consisting of 16.8 m of sedimentary interbeds and 128 m of fractured basalt. Initial moisture content in the vadose zone accounted for enhanced infiltration in the Idaho Nuclear Technology and Engineering Center area.

The near-field aquifer model consisted of a one-dimensional flow and three-dimensional transport model. Far-field modeling in the aquifer was not performed because radionuclide flux to the aquifer during the institutional control period was virtually zero for all radionuclides, and the near-field receptor would bound any far-field aquifer concentrations.

The mixing cell model (MCM, Rood 2005) was used to model the source and vadose zone, and the GWSCREEN model was used to model the aquifer. The MCM accounts for transient infiltration and differential transport of radionuclide decay products. Release of radionuclides from activated metals was calculated in a spreadsheet and then entered into the MCM source model via an external source.

Contaminant concentrations were estimated in the aquifer at a hypothetical receptor well located 100 m downgradient from the edge of the landfill during the compliance and post-compliance periods for comparison with the State of Idaho Rules for Public Drinking Water Systems (IDAPA 58.01.08). Contaminant concentrations were also estimated in the aquifer 100 m downgradient from the edge of the landfill during institutional control for comparison with the State of Idaho Ground Water Quality Rule (IDAPA 58.01.11).

The results of the all-pathways, atmospheric, inadvertent intruder, and groundwater protection analyses are shown in Table ES-1, based on a maximum time of compliance of 1,000 years. These results indicate that the atmospheric, all-pathways, inadvertent intruder, and groundwater protection performance objectives will be met.

Table ES-1. Comparison of the performance objectives and the ICDF Landfill performance assessment results for the institutional control and compliance period.

Performance Objective and/or Measure	Standard	Performance Assessment Results		
		Institutional Control Period (2018–2118)		Compliance Period (2119–3018)
		(100 m downgradient of ICDF Landfill)	(12.7 km downgradient at southern INL Site boundary)	(100 m downgradient of ICDF Landfill)
All pathways (DOE O 435.1 Chg 1)	25 mrem/yr EDE	NA	0 mrem/yr	8.1E-04 mrem/yr
Atmospheric (40 CFR 61, Subpart H)	10 mrem/yr EDE (entire INL Site)	NA	2.7E-05 mrem/yr	5.8E-03 mrem/yr
Atmospheric (40 CFR 61, Subpart Q)	20 pCi·m ⁻² ·s ⁻¹ radon flux (at surface of disposal facility)	NA	NA	0.6 pCi·m ⁻² ·s ⁻¹
Acute inadvertent intruder (DOE O 435.1 Chg 1)	500 mrem EDE	NA	NA	1.7 mrem @ ICDF Landfill
Chronic inadvertent intruder (DOE O 435.1 Chg 1)	100 mrem/yr EDE	NA	NA	0.7 mrem/yr @ ICDF Landfill
Groundwater protection (40 CFR 141) (IDAPA 58.01.11 and IDAPA 58.01.08)	Beta-gamma dose equivalent ≤4 mrem/yr (based on federal MCL)	1.7E-09 ^a mrem/yr	0 mrem/yr	7.4E-04 ^b mrem/yr
	Gross alpha activity concentration ≤15 pCi/L	<1E-10 ^c pCi/L	0 pCi/L	<1E-10 ^c pCi/L
	Ra-226/Ra-228 concentration ≤5 pCi/L	<1E-10 ^c pCi/L	0 pCi/L	<1E-10 ^c pCi/L
	Uranium concentration ≤30 µg/L	NA ^d	0 µg/L	<1E-10 ^c µg/L
	Sr-90 concentration ≤8 pCi/L ^e	NA	NA	NA
	H-3 concentration ≤20,000 pCi/L	1.4E-06 pCi/L	0 pCi/L	9.3E-07 pCi/L

a. Beta-gamma effective dose equivalent ≤4 mrem/yr (IDAPA 58.01.11, State of Idaho Ground Water Quality Rule).

b. Beta-gamma dose equivalent ≤4 mrem/yr (based on federal MCL) (IDAPA 58.01.08, State of Idaho Rules for Public Drinking Water Systems).

c. Concentrations less than 1E-10 are essentially zero.

d. Not applicable, uranium not evaluated for IDAPA 58.01.11 State of Idaho Ground Water Quality Rule.

e. Not applicable; Sr-90 was screened out during evaluation of the groundwater pathway due to its relatively short half-life and its low mobility in the subsurface.

EDE effective dose equivalent
ICDF Idaho CERCLA Disposal Facility
INL Idaho National Laboratory
MCL maximum contaminant level
NA not applicable

An uncertainty/sensitivity analysis was performed on the hydrological transport model to assess the influence of several key input parameters on the output variable (all-pathways effective dose equivalent [EDE] and radionuclide concentrations). The uncertainty analysis was conducted in two phases. In the first phase, model input parameters were varied one at a time. Model parameters and processes investigated included: infiltration rates through the cover, failure of the liner and leachate collection system at the end of active disposal operations, effects of the bentonite clay layer beneath the landfill, alternative conceptual models (missing interbed and liner remains intact allowing water to fill the landfill before failing or overflowing). In all cases, the all-pathways dose was never exceeded during either the compliance or post-compliance periods.

The second phase of the uncertainty analysis used Monte Carlo analysis to propagate uncertainty in the parameter to the concentration and dose end point. The output of the analysis was the distribution of all-pathways dose and individual radionuclide concentrations in the aquifer at selected output times during the compliance and post-compliance periods. Uncertainty was considered for cover infiltration, cover longevity, post-cover failure infiltration, radionuclide K_d values, radionuclide inventories, and transport parameters in the aquifer. The maximum of the distribution of all-pathways EDE never exceeded the all-pathways dose performance objective of 25 mrem/year both during and after the compliance period.

Rank correlation sensitivity analyses were also conducted to test the sensitivity of the results to changes in key parameter values and to identify the parameters that had the greatest influence on the results of the calculations. Results of the rank correlation sensitivity analysis indicate that the sensitivity of a given parameter is time-dependent. The most sensitive input parameters to the all-pathways EDE results are different depending on the timeframe of interest. During the compliance timeframe, the cap infiltration rate and the longevity of the cover were identified as important parameters. After the compliance timeframe (year 3018 and beyond), the carbon and iodine K_d values and infiltration through the cover after failure were identified as important parameters.

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ACRONYMS

ALARA	as low as reasonably achievable
BLM	U.S. Bureau of Land Management
CA	composite assessment
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act
CFA	Central Facilities Area
CWI	CH2M-WG Idaho
DD&D	deactivation, decontamination, and decommissioning
DOE	U.S. Department of Energy
DOE-ID	U.S. Department of Energy Idaho Operations Office
DSR	dose-to-source ratio
EBR	Experimental Breeder Reactor
EDE	effective dose equivalent
EMSOFT	Exposure Model for Soil-Organic Fate and Transport
EPA	U.S. Environmental Protection Agency
ESRP	Eastern Snake River Plain
GCL	geomembrane/geosynthetic clay liner
GSD	geometric standard deviation
HDPE	high-density polyethylene
ICDF	Idaho CERCLA Disposal Facility
ICP	Idaho Cleanup Project
ICRP	International Commission on Radiation Protection
IDAPA	Idaho Administrative Procedures Act
INL	Idaho National Laboratory
INTEC	Idaho Nuclear Technology and Engineering Center
IWTS	Integrated Waste Tracking System
LCRS	leachate collection recovery system
LFRG	Low-Level Federal Review Group
LLW	low-level waste
MCL	maximum contaminant level
MCM	mixing cell model

MCMT	mixing cell model (transport)
NCRP	National Council on Radiation Protection
NESHAP	National Emission Standards for Hazardous Air Pollutants
NRC	U.S. Nuclear Regulatory Commission
OFAT	one factor at a time
OU	operable unit
PA	performance assessment
PCB	polychlorinated biphenyl
PMP	probable maximum precipitation
RCRA	Resource Conservation and Recovery Act
RI/BRA	Remedial investigation/baseline risk assessment
RI/FS	remedial investigation/feasibility study
ROD	Record of Decision
RWMC	Radioactive Waste Management Complex
SBL	soil bentonite liner
SF	screening factor
SLDRS	secondary leak detection recovery system
SRPA	Snake River Plain Aquifer
STOMP	Subsurface Transport Over Multiple Phases
TAN	Test Area North
TSCA	Toxic Substances Control Act
USGS	U.S. Geological Survey
WAC	waste acceptance criteria
WAG	waste area group

Performance Assessment for the Idaho CERCLA Disposal Facility Landfill

1. INTRODUCTION

This report documents the performance assessment (PA) for the disposal of low-level radioactive waste (LLW) at the Idaho CERCLA Disposal Facility (ICDF) Landfill. The ICDF was authorized in the Operable Unit (OU) 3-13 Record of Decision (ROD) (DOE-ID 1999) for disposal of waste from the Idaho National Laboratory (INL) Site Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) environmental restoration activities. The ICDF has been operating since 2003 in compliance with the CERCLA requirements and the waste acceptance criteria (WAC) developed in the CERCLA process.

To obtain the Disposal Authorization Statement for facility operations, both a PA and a composite analysis (CA) were prepared (DOE-ID 2003a,b, respectively), a requirement under U.S. Department of Energy (DOE) O 435.1 Chg 1, "Radioactive Waste Management," demonstrating that the disposal facility is protective of human health and the environment. To demonstrate that the ICDF will be in compliance with DOE O 435.1 Chg 1 during operations, a compliance demonstration document was submitted (DOE-ID 2003c). This document cross-walked the process conducted under CERCLA for the ICDF Landfill to the requirements under DOE O 435.1 Chg 1. The Low-Level Waste Disposal Facility Federal Review Group reviewed the information submitted and found that the documentation submitted demonstrates compliance with DOE O 435.1 Chg 1 and recommended that disposal authorization be granted for the ICDF Landfill (Frei 2003).

Since that time, annual summaries and determinations (Bradford 2007; Koslow and Rood 2009) have documented that LLW operations at the ICDF have been conducted within the bounds of the PA (DOE-ID 2003a) and Disposal Authorization Statement (Frei 2003). However, the latest annual summary and determination indicated that, although the conclusions of the PA remain valid (i.e., there is still a reasonable expectation of meeting performance objectives), there is less conservatism in the results than previously believed because, for some contaminants of interest, the activity in the waste receipts to date are greater than the design inventory assessed in the original PA (DOE-ID 2003a). Additionally, some of the waste forms recently disposed of to the ICDF Landfill are different from the waste form (compacted soil) assessed in the original PA. Therefore, an update to the PA was recommended using the actual and projected inventory and using the new source release and vadose zone transport model, called the mixing cell model (MCM) (Rood 2005). This update does not address or modify the assumptions related to the cover design or the infiltration rate through the cover assessed in the original PA.

This PA includes compliance calculations for the 1,000-year period after closure to demonstrate that the regulatory performance objectives would be met. The calculations involve modeling the transport of radionuclides from buried waste to surface soil and subsurface media, and, eventually, to members of the public via air, groundwater, and food-chain pathways. Biotic pathways are briefly addressed but have been demonstrated to be insignificant dose contributors in previous versions of the PA, and the proposed design of the final cover is expected to minimize their significance. Projections of doses are made for both off-Site receptors and hypothetical individuals assumed to inadvertently intrude onto the site after closure. In addition, uncertainty and sensitivity analyses are performed to provide additional information about performance of the landfill. To provide perspective, calculations were also conducted to peak dose, for those radionuclides with peak doses that occur after 1,000 years.

This report follows the guidance and template provided in DOE G 435.1-1, “Format and Content Guide for U.S. Department of Energy Low-Level Waste Disposal Facility Performance Assessments and Composite Analyses.”^a The following introductory sections provide some discussion related to the overall approach taken for the PA, background information regarding the disposal site and facility, facility life-cycle, related documents that support the PA, performance criteria, and key assessment assumptions, respectively. The body of the report includes the following sections: Disposal Facility Characteristics (Section 2), Analysis of Performance (Section 3), Results of Analysis (Section 4), Inadvertent Intruder Analysis (Section 5), Interpretation of Results (Section 6), Performance Evaluation (Section 7), Preparers (Section 8), and References (Section 9).

1.1 General Approach

This PA revision was undertaken as part of the PA maintenance process described in DOE M 435.1-1 Chg 1 to update the PA based on actual and projected waste disposals rather than relying on the design inventory. This PA revision assumes the same final landfill cover design and infiltration rates through the final cover that were evaluated in the 2003 PA (DOE-ID 2003a) and does not further address or modify these assumptions. The following summarizes the review process that led to these assumptions.

A draft ICDF PA and Composite Analysis (CA) were submitted to the Low-Level Federal Review Group (LFRG) for review in November 2002. In February 2003, the LFRG Review Team came to Idaho, reviewed the drafts, and made recommendations for modifications. The ICDF PA and CA team prepared an information supplement report (March 2003) and a response letter (Hain 2003) to address the LFRG Review Team comments. The LFRG then published a final review document (DOE 2003). These documents provided additional information on the ICDF final landfill cover design, cover longevity, and expected infiltration rate through the cover. Appendix A contains the detailed landfill cover design and expected infiltration rates.

As a result of questions raised by the LFRG Review Team during the review process for the 2003 PA, a series of sensitivity runs (“cover integrity scenarios”) were presented in the 2003 PA (DOE-ID 2003a) that addressed the cover longevity and infiltration rate through the cover. This analysis developed final landfill cover longevity and cover infiltration rate assumptions that were assessed in the 2003 PA. These assumptions were not the impetus for this revision to the PA and therefore were not reevaluated. The following briefly summarizes the 2003 PA sensitivity analysis, and Sections 1.6 and 3.2.2.1 present the details of the related assumptions.

The 2003 PA (DOE-ID 2003a) evaluated seven cover integrity scenarios in the sensitivity analysis that examined several final landfill cover failure timeframe scenarios (design case, performance case, enhanced degradation, conservative case, rapid degradation, extreme degradation, and catastrophic failure). Each scenario is described by two time periods: (1) time from cover emplacement to start of cover degradation and (2) time over which cover degradation occurs. In all cases, the cover is installed in 2018. The cover restricts the water flux through the waste to 0.01 cm/year while the cover remains intact. The cover begins degrading at the time specified by the scenario. Infiltration is assumed to linearly increase from the design-base cover infiltration (0.01 cm/year) to background infiltration (1.0 cm/year) over the scenario-specific cover degradation time. The most robust design evaluated was the Design Case scenario with a cover lifetime of 1,000 years and 4,000 years of cover degradation. The least robust design evaluated was the Catastrophic Failure Case scenario with a cover life of 100 years and 20 years of cover degradation. The different potential cover lifetimes were evaluated and, in general, cover longevity

a. DOE G 435.1-1, “Format and Content Guide for U.S. Department of Energy Low-Level Waste Disposal Facility Performance Assessments and Composite Analyses,” U.S. Department of Energy (in preparation).

affects the time of maximum concentration in the aquifer and the time over which the cover degrades affects the peak concentration. The Conservative Case scenario with a cover life of 500 years and 500 years of cover degradation was agreed to be a reasonable assumption for the PA. The LFRG approved the 2003 PA (DOE-ID 2003a).

A PA is “an analysis of a radioactive waste disposal facility conducted to demonstrate there is a reasonable expectation that performance objectives established for the long-term protection of the public and the environment will not be exceeded following closure of the facility” (DOE O 435.1 Chg 1). The performance objectives are (1) dose to the public less than 25 mrem/year from all pathways, (2) dose to representative public via air pathways less than 10 mrem/year, and (3) radon less than average flux of 20 pCi/m²-s at the surface. The inadvertent intruder performance measures (both acute [500 mrem] and chronic [100 mrem/year]) are also evaluated in this PA. The results of the PA are used to demonstrate compliance with performance objectives for the LLW disposal facility and to support specification of design, construction, operation, and closure requirements for the facility.

The PA for the ICDF Landfill presents a comprehensive, systematic analysis of the long-term impacts of LLW disposal in a semiarid, near-surface environment. Related assessment activities (e.g., safety assessments, risk assessments, characterizations for siting or construction, engineering evaluations, and cost/design studies) have been evaluated in other documents related to the ICDF. Although occupational doses to workers are an important area of concern for facility operations, they are addressed by regulations and guidance different than those covering PAs. Additionally, this document excludes the potential impacts of chemical toxicity of radiological constituents and nonradiological hazardous constituents that may be in the waste.

1.2 General Facility Description

The INL Site is a DOE facility occupying approximately 2,305 km² (890 mi²) of mostly undeveloped, high desert terrain in southeastern Idaho (see Figure 1-1). The ICDF is an engineered CERCLA facility, located southwest of the Idaho Nuclear Technology and Engineering Center (INTEC) and on the INL Site, that meets the substantive requirements of Resource Conservation and Recovery Act (RCRA) Subtitle C (42 USC 6901), Toxic Substances Control Act (TSCA) polychlorinated biphenyl (PCB) landfill design and construction requirements (15 USC 2601 et seq.). The ICDF was constructed at INTEC to allow on-Site disposal of Waste Area Group (WAG) 3 and other CERCLA-generated wastes at the INL Site (see Figure 1-2). The purpose of the ICDF is to consolidate INL Site CERCLA wastes into one engineered facility to reduce the footprint of contamination across the INL Site.

The ICDF is situated at the southwest corner of the INTEC facility, outside the facility fence adjacent to Lincoln Boulevard (Figures 1-2 and 1-3). Fencing is maintained around the ICDF to provide security of the components and control of the waste handling practices. The location of the ICDF allows for easy access from Lincoln Boulevard, the main INL Site road between facilities. This allows for controlled yet straightforward access to the ICDF, as needed, for WAG waste management. The ICDF includes the necessary subsystems and support facilities to provide a complete waste disposal system.

The major components of the ICDF include the following: landfill, evaporation pond (consisting of two cells), administration trailer, scale, decontamination building with treatment area (not in use), contaminated equipment pad (not in use), and staging and storage areas. Together, the above components of the ICDF provide centralized waste acceptance; inspection; treatment, if necessary; and disposal of CERCLA-generated waste types resulting from remediation and deactivation, decontamination, and decommissioning (DD&D) sites at the INL Site.

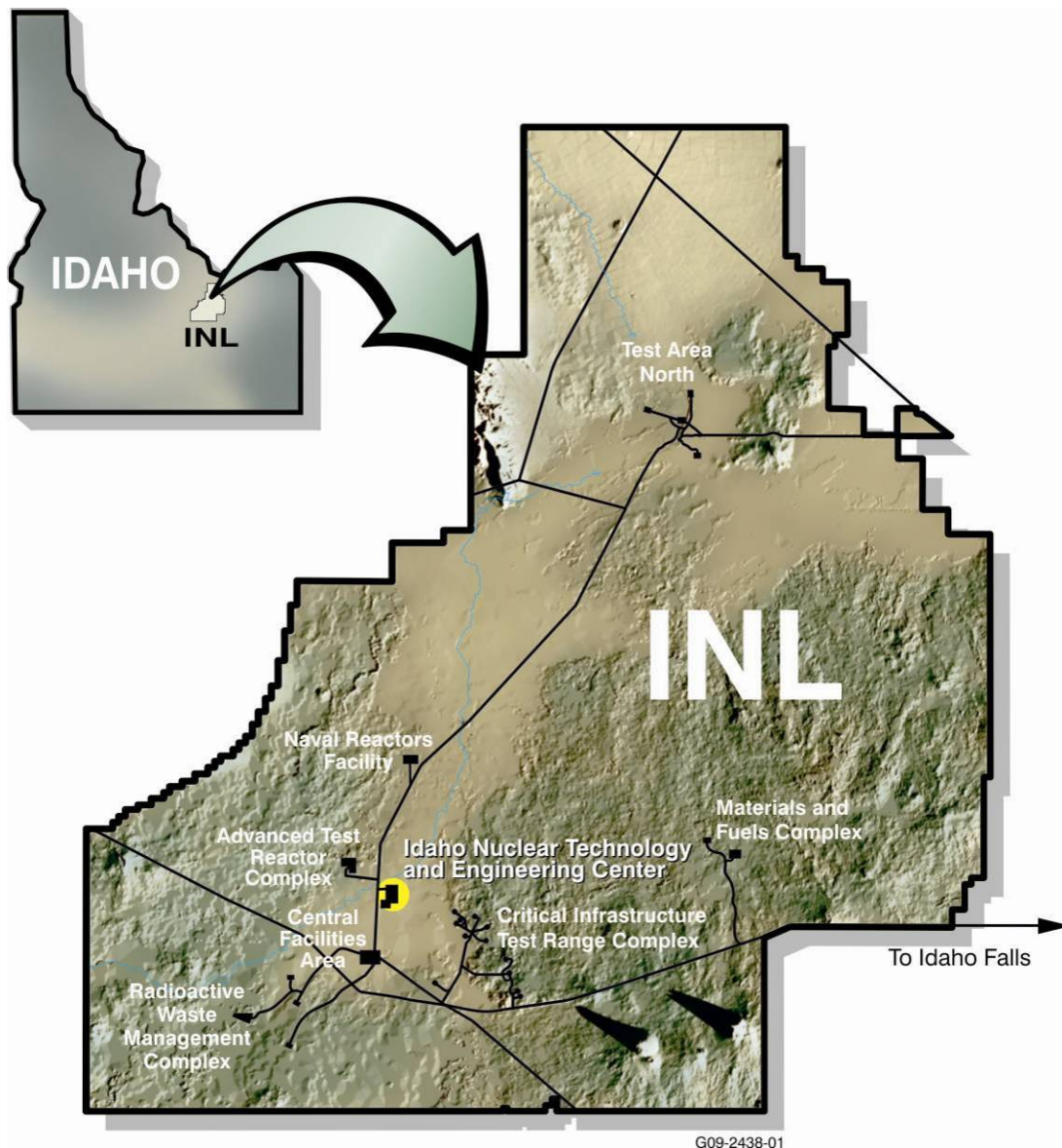


Figure 1-1. Map of the Idaho National Laboratory Site showing locations of the Idaho Nuclear Technology and Engineering Center and other Site facilities.

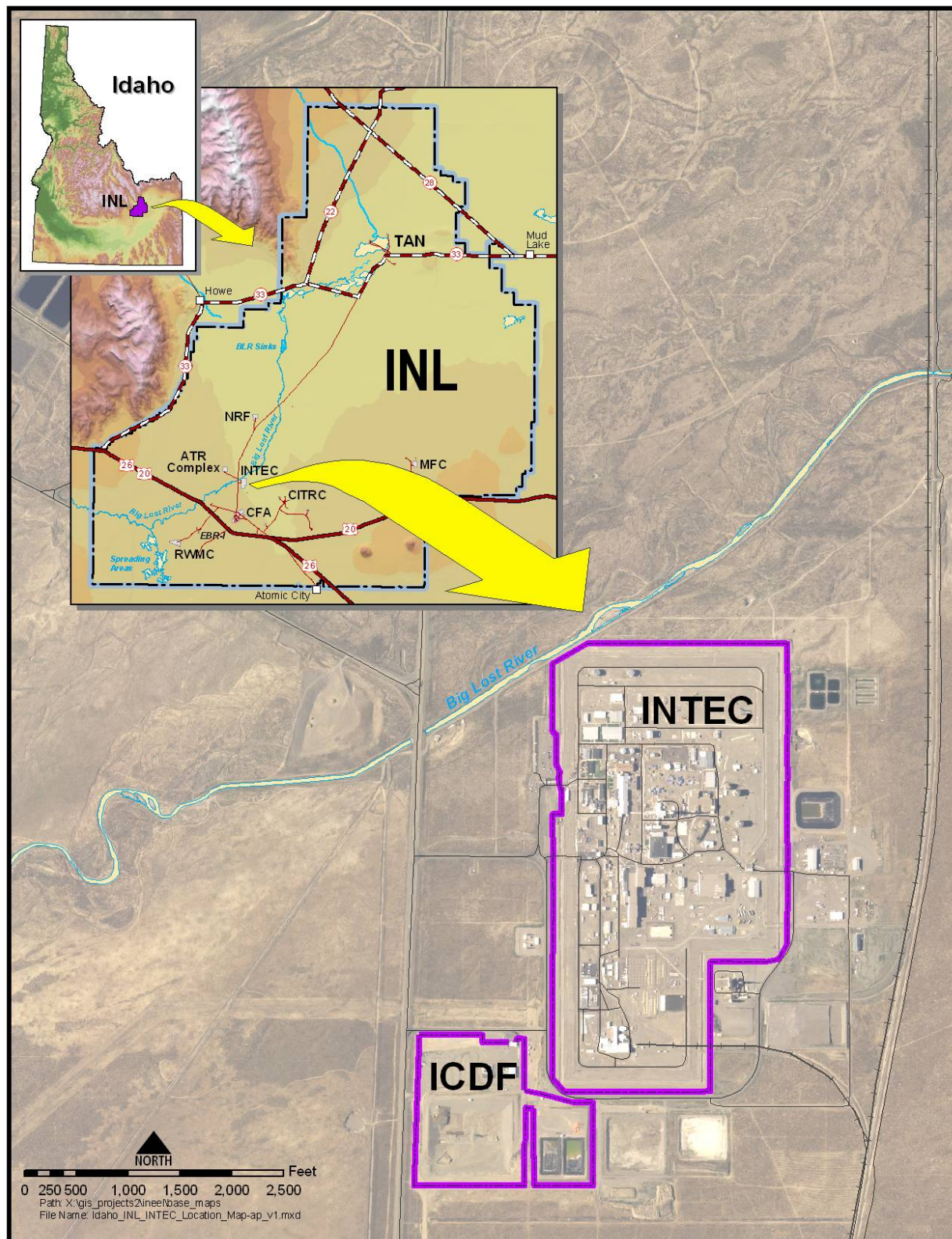


Figure 1-2. Map showing location of Idaho Nuclear Technology and Engineering Center and Idaho CERCLA Disposal Facility.

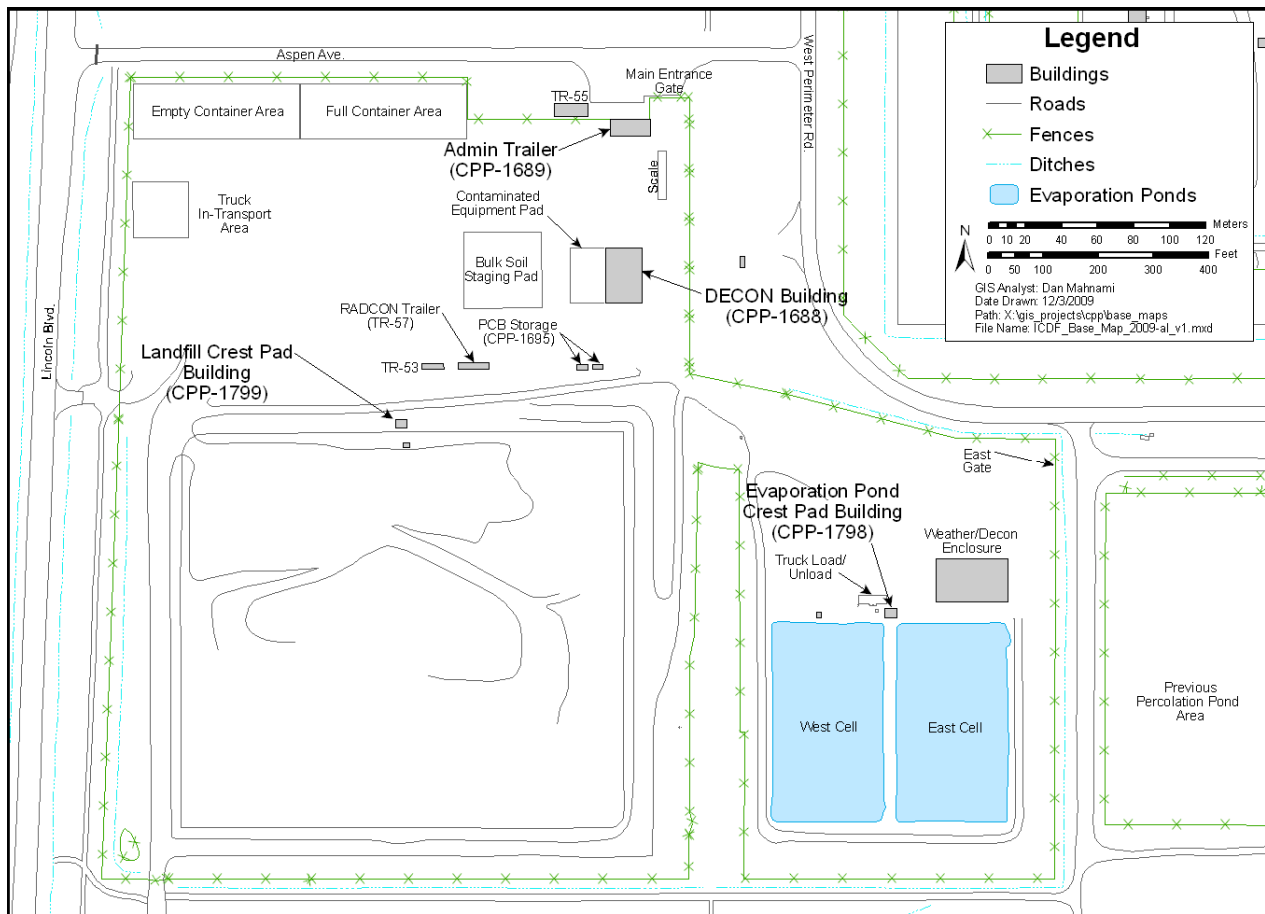


Figure 1-3. Location of the Idaho CERCLA Disposal Facility components.

The ICDF Landfill was designed as a two-cell facility with a common wall that separated the two cells during construction. Cell 1 was completed and disposal operations began in 2003. Cell 2 was completed in late 2005 and disposal operations began in 2006. With the completion of Cell 2, the landfill is one cell comprising the areas formerly referred to as Cell 1 and Cell 2. Both the liner and the leachate collection system of Cell 1 are extended in the new cell. The landfill design disposal capacity is roughly 389,293 m³ (510,000 yd³). After 6 years of operation, 56% of the available volume of the ICDF Landfill has been filled. The ICDF Landfill is scheduled to accept solid waste for a 15-year operations period with an anticipated closure date of 2018 (DOE-ID 2003c).

Remedial action objectives formulated under the CERCLA process required the landfill design to be protective of the Snake River Plain Aquifer (SRPA), such that groundwater contamination does not exceed a cumulative carcinogenic risk of 1E-04, a cumulative noncarcinogenic hazard index of one, or applicable State of Idaho groundwater quality standards. The landfill has been designed with an operational life of 15 years, a post-closure period of 30 years, and a landfill cover design life of 1,000 years. The landfill cover has been designed to minimize infiltration and run-on and maximize run-off by maintaining a sloped surface, storing water for later release to the atmosphere, utilizing lateral drainage, and providing a low-permeability composite liner barrier system. Design requirements include a multilayered liner and sump system to facilitate drainage and prevent leakage. The liner system is comprised of (1) a top liner designed and constructed of low-permeability materials (e.g., a membrane) to prevent the migration of hazardous constituents into such liner during the active and post-closure care period and (2) a composite bottom liner with the lower component constructed of at least 0.91 m (3 ft) of

compacted soil material with a hydraulic conductivity no greater than 1E-07 cm/second. The leachate collection recovery system (LCRS) is operated and maintained to collect and remove leachate from the landfill during the active operational and post-closure care periods or until leachate is no longer being accumulated. This includes the 15-year operational period, plus an additional 30 years of post-closure operation to handle any leachate that may be generated following placement of the final cover on the landfill. The information is automatically monitored and assessed on a weekly basis. All pumps, discharge piping, and control system components for the LCRS are accessible for maintenance, repair, or replacement. Standard operations include an annual pump inspection and level sensor calibration. For more complete details on the landfill design and operation, refer to the ICDF Remedial Design/Construction Work Plan (DOE-ID 2002) and the *ICDF Complex Operations Waste Management Plan* (DOE-ID 2006a).

Closure of the ICDF Landfill will be conducted in three stages. The first stage, interim closure, is conducted as waste is placed in the landfill. Waste placement is conducted in accordance with the “ICDF Waste Placement Plan.” Operational cover and soil fixatives are applied over contaminated material as waste is placed in the landfill. A 2-ft-thick clean soil fill cover will be placed over the final operational lift to provide clean access to the working face and to provide a final interim clean cover. The second stage, final closure, will be implemented through the CERCLA process as specified in the ROD (DOE-ID 1999). The anticipated date of final closure for the ICDF Landfill is 2018. The third stage, institutional control, will also be implemented through the CERCLA process as specified in the ROD (DOE-ID 1999) and the *INL Site-Wide Institutional Controls, and Operations and Maintenance Plan for CERCLA Response Actions* (DOE-ID 2010a). Closure and post-closure requirements for the ICDF as specified in the ROD (DOE-ID 1999) will (1) ensure that the final cover serves as an intrusion barrier for a period of 1,000 years; (2) place permanent land use restrictions, zoning restrictions, and deed restrictions on the ICDF and its adjacent buffer zone to permanently preclude industrial or residential development until unacceptable risks no longer exist at the site; and (3) provide access controls, monitoring, and maintenance for as long as the contents of the landfill remain a threat to human health or the environment if uncontrolled.

1.2.1 Waste Acceptance Criteria

Waste disposal constraints for the ICDF Landfill are outlined in *ICDF Complex Waste Acceptance Criteria* (DOE-ID 2010b). ICDF users are responsible for characterization of waste submitted for acceptance into the ICDF Complex. The process for characterizing waste by the generator and acceptance by ICDF is described in the *ICDF Complex Waste Profile and Verification Sample Guidance* (DOE-ID 2006b). Wastes that can be accepted at the ICDF Landfill include wastes generated from INL Site CERCLA remedial and investigative activities and other Agency-approved actions. These wastes typically include soils, drill cuttings, building demolition debris, boxed soils, and secondary CERCLA wastes such as personal protective equipment and secondary CERCLA wastes from waste processing and decontamination activities at the ICDF.

All waste received at the ICDF is tracked using the Integrated Waste Tracking System (IWTS). Before waste is accepted into the ICDF Complex, an IWTS Material Profile must be completed by the Waste Management Waste Generator Services organization and approved by the ICDF waste disposition specialist. As containers of waste are generated, container profiles are prepared by Waste Generator Services and approved by the ICDF waste disposition specialist. Once waste arrives at the ICDF, it goes through an acceptance process that includes weighing, verification, acceptance, quality assurance, and database management before the material proceeds to the ICDF Landfill or Evaporation Pond.

1.2.2 General Land Use Patterns

Land use at the INL Site is currently managed and operated by Battelle Energy Alliance, LLC, for DOE (CTR-274) for government-controlled industrial use. The primary use of INL Site land is to support facility and program operations dedicated to nuclear energy research, spent nuclear fuel management, hazardous and mixed waste management and minimization, cultural resources preservation, and environmental remediation. A security force is used to limit access to approved personnel and visitors. Restrictions limiting the use of groundwater beneath the INL Site by members of the public are in place. The distance from INTEC to the INL Site southern boundary is roughly 12.7 km (8 mi). The *INL Site-Wide Institutional Controls, and Operations and Maintenance Plan for CERCLA Response Actions* (DOE-ID 2010a), the INTEC ROD (DOE-ID 1999), and the *Idaho National Laboratory Comprehensive Land Use and Environmental Stewardship Report* (Kostelnik 2005) describe the land use for the INL Site and INTEC.

Approximately 77% of the land in the five counties surrounding the INL Site is considered open rangeland, forest, or barren. Roughly 21% of the land in these counties is used for farming. Somewhat less than 2% of the land in the surrounding counties is surface water or wetland, and only about 0.3% of the land in the counties is considered urban. The land outside the INL Site boundary closest to INTEC is primarily Bureau of Land Management (BLM) -controlled with small pockets of state-controlled or private, noncultivated land.

As part of the efforts related to the end state vision, planning assumptions for land use within and adjacent to the INL Site have moved towards the assumption that key areas of the INL Site, including INTEC, will remain under government control in perpetuity and no new major, private developments (residential or nonresidential) are expected in areas adjacent to the INL Site. Future land use during the 1,000-year compliance period most likely will remain essentially the same as the current use: a research facility within the INL Site boundaries and agriculture and open land surrounding the INL Site. Other potential, but less likely, land uses within the INL Site include agriculture and the return of the areas to their natural, undeveloped state.

1.3 Low-Level Waste Disposal Facility Life-Cycle

The assumed long-term life-cycle of the ICDF Landfill for the PA analysis consistent with DOE O 435.1 Chg 1 consists of:

- Waste Disposal Operations, 2003 through 2018, during which radioactive waste is actively disposed of at the facility. The waste inventory assessed in this PA includes the amount of waste accumulated from start of disposal operations in September 2003 through September 2009 plus the amount projected to accumulate through September 2018.
- Institutional Control, 2018 through 2118, which follows site closure and during which periodic maintenance and monitoring activities are conducted. The facility is assumed to be closed, stabilized, and maintained but is still part of the INL Site and is fenced and patrolled.
- Compliance Period, 2119 through 3018, which assumes that land use will remain nonresidential with passive institutional controls. Radiological impacts are presented for a period of 1,000 years, the maximum time of compliance for DOE LLW PAs. Analyses were also carried out to the time of maximum potential dose.

1.4 Related Documents

The following discussion describes the regulatory framework in which this PA was prepared. The U.S. Environmental Protection Agency (EPA) proposed listing the INL Site on the National Priorities List of the National Oil and Hazardous Substances Pollution Contingency Plan on July 14, 1989 (54 FR 19820). After considering the 60-day public comment period following the proposed INL Site listing, EPA issued a final ruling that listed the INL Site as a National Priorities List site in the Federal Register on November 21, 1989.

The Federal Facility Agreement and Consent Order between EPA Region 10, the State of Idaho Department of Environmental Quality, and the U.S. Department of Energy Idaho Operations Office (DOE-ID) established the procedural framework and schedule for developing, prioritizing, implementing, and monitoring response actions at the INL Site in accordance with CERCLA, RCRA, and the Idaho Hazardous Waste Management Act (DOE-ID 1991). The Federal Facility Agreement and Consent Order identified 10 WAGs to be addressed through the CERCLA process with the INTEC designated as WAG 3. A Comprehensive Remedial Investigation/Feasibility Study (RI/FS) (DOE-ID 1997) identified release sites at INTEC that pose a threat to human health and/or the environment requiring remedial action to mitigate these risks. In accordance with the signed OU 3-13 ROD (DOE-ID 1999), the ICDF was identified as a selected remedy for the OU 3-13 Group 3, "Other Surface Soils." As part of the selected remedy for Group 3, the ICDF was constructed at INTEC to allow disposal of WAG 3 and other CERCLA-generated wastes on the INL Site.

The ICDF was designed and constructed to meet Idaho Administrative Procedures Act (IDAPA) 58.01.05.008 [40 CFR 264.301] for hazardous waste, 40 CFR 761.75 for PCBs, and DOE O 435.1 Chg 1 for radioactive waste landfill design and operating substantive requirements. The ICDF Landfill will operate and close in accordance with the substantive requirements of IDAPA 58.01.05.008 (40 CFR 264 Subparts F, G, and N), and site access restrictions and institutional controls will be maintained throughout the CERCLA 30-year post-closure period.

Permanent land-use restrictions will be placed on the ICDF, which will be closed in place, for as long as land-use and access restrictions are required to be protective of human health and the environment. Maintenance will be performed on the final cover for the closed ICDF Landfill as necessary to prevent the release of leachate to underlying groundwater that would result in exceedance of groundwater quality standards (i.e., maximum contaminant levels [MCLs]) in the SRPA. The final landfill cover has been designed to protect against inadvertent intrusion for a period of at least 1,000 years.

Remedial actions taken under the ROD (DOE-ID 1999) will be reviewed under the CERCLA 5-year review process to ensure their protectiveness. Five-year reviews will also ensure that any changes in the physical configuration of the ICDF Landfill where there is suspicion of a release of hazardous or radioactive substances will be managed to achieve remediation goals established in the ROD (DOE-ID 1999). The 5-year reviews will continue as long as contaminants exist at levels that result in restricted or limited site usage.

The facility is operated and will be closed under CERCLA. DOE O 435.1 Chg 1 requirements apply and are being met. Major documents that have been prepared to comply with DOE O 435.1 Chg 1 include a PA (DOE-ID 2003a), CA (DOE-ID 2003b), and a cross-walk to demonstrate compliance with DOE O 435.1 Chg 1 (DOE-ID 2003c).

In accordance with DOE O 450.1A, a groundwater protection management plan has been instituted for the INL Site and is described in the following reports: *Idaho National Engineering and*

Environmental Laboratory Groundwater Protection Management Plan (DOE-ID 2004a) and *Idaho National Engineering and Environmental Laboratory Groundwater Monitoring Plan Update* (DOE-ID 2003d). Groundwater protection requirements applicable to operation, closure, and long-term performance of the landfill include prevention of the release of leachate to underlying groundwater, which could potentially result in exceeding applicable State of Idaho groundwater public drinking water systems (IDAPA 58.01.08) (i.e., MCLs) in the SRPA. The ICDF groundwater detection monitoring network consists of one monitoring well that is upgradient and five monitoring wells that are downgradient of the landfill and evaporation pond. The *ICDF Complex Groundwater Monitoring Plan* (DOE-ID 2007a) details the groundwater monitoring requirements associated with the ICDF, including monitoring wells, sample frequency, required analytes, laboratory analysis, fieldwork, and quality control. The *INEEL CERCLA Disposal Facility Groundwater Detection Monitoring Program: Data Analysis Plan* (DOE-ID 2003e) details the approach used to evaluate the groundwater data collected in support of the ICDF detection monitoring program.

INL Site activities must comply with two storm water pollution prevention plans: one for industrial activities (DOE-ID 2001), the other for construction activities (DOE-ID 2003f). The plans address storm water discharges associated with industrial activities to waters of the United States. EPA's goal in requiring these plans is to improve water quality by reducing pollutants in storm water discharges.

A hazard assessment document (HAD-136) serves as the ICDF Documented Safety Analysis.

The WAC for ICDF are outlined in *ICDF Complex Waste Acceptance Criteria* (DOE-ID 2010b). This document will be reevaluated based on the results of this PA. If a newly calculated threshold in the PA is more restrictive than the ICDF WAC, then the ICDF WAC (DOE-ID 2010b) will be modified accordingly. Likewise, any future updates to the ICDF WAC (DOE-ID 2010b) will be evaluated against the ICDF PA thresholds so that the ICDF WAC will be equal to or less than the PA thresholds. All WAC changes require review and approval by EPA Region 10, the State of Idaho Department of Health and Welfare, and DOE-ID. The *ICDF Complex Operations Waste Management Plan* (DOE-ID 2006a) contains the standard operating procedures and associated job safety analyses for all operations and maintenance activities to be conducted at the ICDF. The *ICDF Complex Remedial Action Work Plan* (DOE-ID 2006c) discusses operation and closure of the ICDF. The *ICDF Complex Waste Profile and Verification Sample Guidance* (DOE-ID 2006b) establishes the requirements for verification of waste destined for disposal at the ICDF Landfill and identifies the process to confirm that key parameters (those that limit waste acceptance in the landfill) in the waste do not exceed the limits on the Material Profile.

The ICDF Remedial Design/Construction Work Plan (DOE-ID 2002) provided the framework for the design and construction of the landfill and evaporation pond. Primary reference sources for the ICDF Landfill design criteria are

- DOE-ID, 1999, *Final Record of Decision, Idaho Nuclear Technology and Engineering Center, Operable Unit 3-13*, DOE/ID-10660, Rev. 0, U.S. Department of Energy Idaho Operations Office; U.S. Environmental Protection Agency, Region 10; State of Idaho Department of Health and Welfare, October 1999.
- DOE-ID, 2002, *INEEL CERCLA Disposal Facility Remedial Design/Construction Work Plan*, DOE/ID-10848, Rev. 1, U. S. Department of Energy Idaho Operations Office, May 2002.
- DOE-ID, 2006c, *ICDF Complex Remedial Action Work Plan*, DOE/ID-10984, Rev. 1, U.S. Department of Energy Idaho Operations Office, December 2006.

- TFR-71, 2004, “Technical and Functional Requirements INEEL CERCLA Disposal Facility and Evaporation Pond,” Rev. 3, Idaho Completion Project, Idaho National Engineering and Environmental Laboratory, August 2004. [Note: this document has been cancelled and should be used for reference purposes only.]
- TFR-2520, 2002, “Technical and Functional Requirements for the ICDF Complex Control System,” Rev. 0, Idaho National Engineering and Environmental Laboratory, May 2002. [Note: this document has been cancelled and should be used for reference purposes only.]
- 40 CFR 264.301, 2008, “Design and Operating Requirements,” *Code of Federal Regulations*, Office of the Federal Register, April 2008.
- 40 CFR 761.75, 2009, “Chemical Waste Landfills,” *Code of Federal Regulations*, Office of the Federal Register, June 2009.

Other documents used in the development of this performance assessment include

- DOE O 435.1 Chg 1, 2001, “Radioactive Waste Management Manual,” U.S. Department of Energy, August 28, 2001.

1.5 Performance Criteria

This PA estimates radiological exposure to future members of the public for a 1,000-year period after closure of the facility to demonstrate there is a reasonable expectation that performance criteria established for the long-term protection of the public and the environment will not be exceeded. Performance criteria consist of specific performance objectives and measures identified in DOE M 435.1-1 Chg 1. The following sections describe each performance objective and measure used to assess the long-term performance of the ICDF Landfill; each is summarized in Table 1-1.

Table 1-1. Performance objectives and measures for the ICDF Landfill performance assessment.

Performance Objective/Measure	Dose or Concentration Limit	Receptor/Scenario
All-pathways (DOE O 435.1 Chg 1)	25 mrem/yr EDE	Hypothetical future member of the public exposed at maximum point of impact at INL Site boundary for first 100 yr then at least 100 m from ICDF at maximum dose location.
Atmospheric (40 CFR 61 Subpart H)	10 mrem/yr EDE (entire INL Site)	Representative member of the public exposed at maximum point of impact at INL Site boundary for first 100 yr then at least 100 m from ICDF at maximum dose location.
Atmospheric (40 CFR 61 Subpart Q)	20 pCi·m ⁻² ·s ⁻¹ radon flux (at surface of disposal facility)	Representative member of the public exposed at ICDF surface or boundary of facility.
Acute inadvertent intrusion (DOE O 435.1 Chg 1)	500 mrem EDE	Inadvertent intruder at the ICDF.
Chronic inadvertent intrusion (DOE O 435.1 Chg 1)	100 mrem/yr EDE	Inadvertent intruder at the ICDF.

Table 1-1. (continued).

Performance Objective/Measure	Dose or Concentration Limit	Receptor/Scenario
Groundwater Protection (40 CFR 141) (IDAPA 58.01.08)	Beta-gamma dose equivalent ≤ 4 mrem/yr (based on federal MCL)	Idaho Rules for Public Drinking Water Systems. Evaluated at INL Site boundary until 2118. After 2118, at least 100 m downgradient of ICDF.
	Gross alpha ^a activity concentration ≤ 15 pCi/L	
	Ra-226/Ra-228 concentration ≤ 5 pCi/L	
	Uranium concentration ≤ 30 μ g/L	
	Sr-90 concentration ≤ 8 pCi/L	
Groundwater Protection (IDAPA 58.01.11)	H-3 concentration $\leq 20,000$ pCi/L	Idaho Ground Water Quality Rule. During institutional control 100 m downgradient from ICDF Landfill.
	Beta-gamma EDE ≤ 4 mrem/yr	
	Gross alpha activity concentration ≤ 15 pCi/L	
	Ra-226/Ra-228 concentration ≤ 5 pCi/L	
	Sr-90 concentration ≤ 8 pCi/L ^b	
	H-3 concentration $\leq 20,000$ pCi/L	
a. Includes Ra-226, excludes radon and uranium.		
b. Not applicable; Sr-90 was screened out during evaluation of the groundwater pathway due to its relatively short half-life and its low mobility in the subsurface.		
EDE	effective dose equivalent	
ICDF	Idaho CERCLA Disposal Facility	
INL	Idaho National Laboratory	
MCL	maximum contaminant level	

1.5.1 Public Protection Performance Objectives

The first applicable performance objective from DOE M 435.1-1 Chg 1 IV P.(l)(a) states:

Dose to representative members of the public shall not exceed 25 mrem (0.25 mSv) in a year total effective dose equivalent from all exposure pathways, excluding the dose from radon and progeny in air.

This performance objective is interpreted as requiring the performance analysis to provide a reasonable expectation that the “all-pathways” dose to a hypothetical future member of the public will not exceed 25 mrem effective dose equivalent (EDE), which includes the 50-year committed EDE from ingestion and inhalation of radionuclides, plus the external EDE received during the exposure period (1 year) from all exposure pathways, excluding doses from inhalation of radon and its short-lived progeny. “All-pathways” include any and all modes by which a receptor at the point of public access could be exposed, including the air pathway. The analysis is to cover 1,000 years following closure of the disposal facility. Analysis beyond 1,000 years to calculate the maximum dose and the time of that dose shall be included as a means of increasing confidence in the outcome of the modeling. However, it should be noted that calculations for greater than 1,000 years have inherently large uncertainties due to extrapolating such calculations over longer timeframes. The point of compliance for this performance objective should normally be at the point of highest calculated dose beyond a 100-m buffer zone surrounding the waste.

The second performance objective (DOE M 435.1-1 Chg 1 IV.P.(l)(b)) states:

Dose to representative members of the public via the air pathway shall not exceed 10 mrem (0.10 mSv) in a year total effective dose equivalent, excluding the dose from radon and its progeny.

Consistent with the National Emission Standards for Hazardous Air Pollutants (NESHAP) (40 CFR 61), radon-220, radon-222, and their progeny need not be included in the air pathway analysis for comparison with the 10-mrem/year EDE performance objective; separate controls for the emission of radon are discussed below. For the air pathway dose analysis, the point of compliance should be the point of highest calculated dose beyond a 100-m buffer zone surrounding the waste. The 10-mrem/year limit should be recognized to refer to all sources, not just the ICDF Landfill. Therefore, if the PA assumes a point of compliance that corresponds to the future land-use boundary, a limit that is a fraction of the 10-mrem/year dose limit should be used in recognition of the potential presence of other sources. Estimates of dose from current INL Site facilities are added to the ICDF Landfill estimated dose and compared with the 10-mrem/year dose limit.

The third performance objective (DOE M 435.1-1 Chg 1 IV.P.(l)(c)) states:

Release of radon shall be less than an average flux of $20 \text{ pCi} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ ($0.74 \text{ Bq} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$) at the surface of the disposal facility. Alternately, a limit of 0.5 pCi/l (0.0185 Bq/l) of air may be applied.

The radon limit to be applied at the ICDF Landfill is an average ground-surface emanation rate of $20 \text{ pCi} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ directly over the disposal unit.

1.5.2 Water Resource Impact Assessment

DOE M 435.1-1 Chg 1 does not contain a specific performance objective (e.g., dose or concentration standard) for water resource impacts; instead,

DOE M 435.1-1 Chg 1, IV.P(2)(g) states:

For the purposes of establishing limits on radionuclides that may be disposed of near-surface, the performance assessment shall include an assessment of impacts to water resources.

For water resources protection, impacts were assessed on a site-specific basis in accordance with a hierarchical set of criteria. The hierarchical approach for establishing water resources protection is as follows:

- First, the ICDF Landfill must comply with any applicable state or local law, regulation, or other legally applicable requirement for water resource protection.
- Second, the ICDF Landfill must comply with any formal agreement applicable to water resource protection that is made with appropriate state or local officials.
- Third, if neither of the above conditions applies, the site should select assumptions for use in the PA based on criteria established in the site groundwater protection management program and any formal land-use plans.
- If none of the above conditions apply, the site may select assumptions for use in the PA for the protection of water resources that are consistent with the use of water as a drinking water source.

The hierarchical approach for water resources protection established for the ICDF Landfill is as follows:

- Groundwater protection during institutional control is evaluated by comparing predicted concentrations in groundwater 100 m downgradient from the ICDF to the Idaho Ground Water Quality Rule (IDAPA 58.01.11).
- The CERCLA OU 3-13 ROD requires that the SRPA meet the IDAPA MCLs (IDAPA 58.01.08) after the institutional control period. Groundwater protection is evaluated by comparing predicted concentrations in groundwater with Idaho Rules for Public Drinking Water Systems (IDAPA 58.01.08) (40 CFR 141) during the institutional control period at the INL Site boundary and during the compliance period 100 m downgradient of the ICDF Landfill.

1.5.3 Intruder Analysis

The intruder analysis is performed as one of the mechanisms for establishing concentration thresholds for waste considered acceptable for near-surface disposal. DOE intends to exercise control of the closure site until it can be safely released pursuant to DOE O 5400.5 Chg 2. Hence, intrusion is an accidental, temporary event. However, for purposes of conducting intruder analyses, the intrusion event is considered to occur because of a lapse in institutional controls that would be remedied within a few years. The focus of the intruder analysis is on the selection of reasonable scenarios and reasonably conservative parameters. Intrusion is assumed to occur no sooner than 100 years following facility closure and is not analyzed beyond 1,000 years post-closure.

Despite the fact that the land use at INTEC is nonresidential and institutional controls will be in place to prevent drilling into the landfill, both acute and chronic inadvertent intruder well drilling scenarios are assessed in this PA. No credit is taken for the final cover to be placed over the landfill at closure. The acute scenario involves intrusion into waste when drilling an irrigation well, with exposure to contaminated drill cuttings assumed to occur through inhalation, external exposure, and soil ingestion during the time the well is being drilled and completed. The chronic scenario involves intrusion into the waste while drilling a residential well and mixing of exhumed waste with garden soil. Exposure pathways include inhalation, external exposure, soil ingestion, and ingestion of contaminated food (i.e., beef, milk, and plants). The performance measures apply after hypothetical loss of active institutional control at 100 years following closure of the facility and allow a total EDE of 500 mrem from all exposure pathways for scenarios involving a single, acute exposure and a total EDE of 100 mrem/year from all exposure pathways for scenarios involving long-term or chronic exposure.

1.5.4 ALARA Analysis

DOE's approach to radiation protection for LLW disposal is based on two key components. One component is the performance objectives described in Section 1.5.1, which specify maximum doses for various pathways. The other component requires doses to be maintained "as low as reasonably achievable" (ALARA).

The goal of the ALARA process is attainment of the lowest practical dose level after taking into account social, technical, economic, and public policy considerations. Therefore, in addition to providing a reasonable expectation that the performance objectives described in Section 1.5.1 will not be exceeded, the PA also needs to show that LLW disposal is being conducted in a manner that maintains releases of radionuclides to the environment ALARA. In keeping with this philosophy, an ALARA analysis for the ICDF Landfill will be included in Section 7.2.3 of this PA.

1.6 Summary of Key Assessment Assumptions

To evaluate the performance of the ICDF Landfill, simplifying assumptions were made in the PA. The following text summarizes the key assumptions that are most critical to the analysis of performance:

- The performance scenario assumes there will not be a resident living on top of the ICDF Landfill, and a groundwater receptor will have to be at least 100 m downgradient of the ICDF (see Section 3.2.3).
- Waste form is assumed to be miscellaneous waste (treated as contaminated soils) and activated metal released by corrosion (see Section 3.2.1.2).
- The liner and leachate collection system collects all leachate from the waste during disposal operations. When disposal operations end, contaminants are allowed to migrate from the source zone (see Section 3.2.2.1).
- Initial moisture content in the vadose zone is based on the INTEC average infiltration rate of 18 cm/year for disturbed soils (see Section 3.2.2.1).
- The ICDF landfill cover has been designed to last for 1,000 years. However, as discussed in Section 1.1, General Approach, this PA assumes the same final landfill cover design and infiltration rates through the final cover that were evaluated in the 2003 PA (DOE-ID 2003a). The 2003 PA evaluated a Conservative Case (500-year final cover lifetime with a net infiltration rate of 0.01 cm/year through the cover and then 500 years of final cover degradation with a net infiltration rate increasing from 0.01 cm/year to the site background infiltration rate of 1 cm/year as a linear increasing rate) with respect to the 1,000-year design lifetime and net infiltration rate. Appendix A provides detailed information on the expected long-term performance of the landfill cover and expected infiltration rates. Section 3.2.2.1, Source and Unsaturated Zone, provides more details on the modeled infiltration rates.
- The cover restricts water flow through the ICDF Landfill and creates an infiltration shadow in the underlying vadose zone. While the cover is in place, most moisture is retained in the cover soil and released through evapotranspiration or runs off into the surrounding soil where it infiltrates. For the first 500 years, a small amount (0.01 cm/year) passes through the cover and into the waste. The enhanced infiltration around the cover travels vertically and does not affect water fluxes below the ICDF. From 500 to 1,000 years after the cover is in place, the cover gradually degrades until the infiltration rate is 1 cm/year (see Section 3.2.2.1).
- A sensitivity analysis is provided assuming the infiltration rate through the cover is equal to the undisturbed soils infiltration rate of 1 cm/year, and the uncertainty analysis considers a range of infiltration rates and cover lifetimes (see Section 4.6.2).
- Advection, dispersion, diffusion, sorption, and radioactive decay are the only processes that influence dissolved-phase contaminant movement in the subsurface beneath the ICDF. No gas-phase transport is accounted for (see Sections 3.3.1.2 and 3.3.1.3).
- A linear equilibrium reversible soil-to-water partition coefficient (K_d) is representative of all geochemical processes that occur between contaminants dissolved in water and sediments. All available site-specific information was used to determine appropriate contaminant partitioning coefficients. Radioactive decay and ingrowth are accounted for in the simulations (see Section 3.3.1.2.5 and Table 3-5).
- Sorption does not occur in fractured basalt portions of the vadose zone and the aquifer.
- The effective average depth of the SRPA is 76 m (250 ft) (Robertson, Schoen, and Barraclough 1974) (see Section 3.3.1.3.1 and Table 3-6).

- The aquifer comprises an equivalent homogeneous porous medium of infinite lateral extent and finite thickness (see Sections 3.2.1.5, 3.2.2.2, and 3.2.2.3).
- Water movement in the aquifer is treated as steady state (see Sections 3.2.2.2 and 3.3.1.2.1).
- The conceptual and numerical models for the vadose zone are assumed to be one-dimensional based on site characteristics, field studies, and numerical studies (see Section 2.1 and Appendix B).

1.7 Quality Assurance Measures

The Idaho Cleanup Project (ICP) Quality Assurance Program is a comprehensive program integrating all the essential elements for an effective and efficient quality assurance program. The individual elements are defined in the Quality Assurance Program requirements documents contained in Manual 13, *Quality Assurance Program*. The Quality Assurance Program requirements documents work in concert with each other for a total program to achieve and verify quality.

Software is managed in accordance with MCP-550, “Software Management.” Software quality assurance is tracked through the Enterprise Architecture database (LWP-1313). The calculations performed for the PA fall into the category of “commercial level” at Quality Level 3 (as per MCP-540, “Assigning Quality Levels”) in accordance with MCP-2059, “Commercial Analyses and Calculations,” which is used to support studies, designs, or operational requirements when the rigor of formal analyses and calculations^b are not required. MCP-2059 provides instructions to perform commercial analyses and calculations, including:

- Initiating
- Performing and documenting
- Technical checking
- Accepting and approving
- Revising.

For commercial-level calculations, a summary of the analyses and results is typically documented in an engineering design file (EDF), which is stored in the Electronic Data Management System (EDMS). The supplemental information (i.e., computer input and output files) is considered a record after the analyses are final (see MCP-557, “Records Management”). In the case of commercial calculations, the means of managing this information is left up to the analyst in accordance with MCP-557. Supplemental information for commercial-level calculations is not typically attached to the EDF in EDMS. However, in May 2010, an agreement was reached with CH2M-WG Idaho, LLC, (CWI) Records Management personnel to process the supplemental information (input and output files) as if it were a formal calculation (MCP-2374, “Formal Analyses and Calculations”). This agreement allows placement of all supplemental information for the PA and CA with the respective EDF records. All files pertaining to these PA calculations will be placed into EDMS as Supporting Information in accordance with the 2010 agreement.

b. “Formal analyses and calculations” are qualitative validations and quantitative computations that are performed to the highest level of rigor. Formal analyses and calculations are required for Quality Level 1, 2, and 3 Structures, Systems, and Components in Hazard Category 1, 2, or 3 facilities (see MCP-2374). Although PA and CA calculations fall into Quality Level 3, the Active LLW Disposal Facility is not a Structure, System, or Component.

The ICDF PA uses a variety of numerical codes to simulate source term releases, flow and transport in the subsurface, inadvertent intruder calculations, and air pathway transport in order to calculate doses resulting from the disposal of waste at the ICDF. All of the codes comply with companywide requirements as described above.

Code-specific descriptions and associated quality assurance documentation for each code used in the PA are provided in more detail below.

1.7.1 Mixing Cell Model

The Mixing Cell Model (MCM) computer code (Rood 2005) Version 110409f_110409t (Enterprise Architecture Application ID 198872), was selected to model the source-term release of surface sediments and the vadose zone water flow and contaminant transport. It is a one-dimensional model for water flow and contaminant transport through the vadose zone under steady-state or transient flow conditions based upon the principals of mixing cell model formulations (Whickler and Shultz 1982; Shanahan and Harleman 1984; Rao and Hathaway 1989). This code was selected because it can account for effects of transient infiltration and initial moisture content in the vadose zone, and it is a simple but robust code that incorporates important processes but keeps simulation time to a minimum.

The MCM includes two FORTRAN codes that are used to solve the water flow and solute transport equations: (1) the Mixing-Cell Model for Flow (MCMF) solves transient water flow problems and (2) the Mixing Cell Model for Transport (MCMT) solves the solute transport problem. The transient water flow problem is typically solved first by estimating the water flux through each cell in the model domain as a function of time using the MCMF code. These data are stored in either ASCII or binary files that are later read by the solute transport code (MCMT). Code output includes solute pore water concentrations, water and solute inventories in each cell and at each specified output time, and water and solute fluxes through each cell at each specified output time.

As documented in the user's manual (Rood 2005), the MCM was benchmarked against analytical solutions and finite-element approximations to the partial differential equations describing unsaturated flow and transport. Differences between the maximum solute flux estimated by the MCM and the partial differential equation models were typically less than 2%.

MCM was developed at the INL; thus, it is validated and controlled in accordance with Battelle Energy Alliance software development requirements. At CWI, the code is considered acquired software (MCP-550) controlled by a software management plan (PLN-2082) and a software test plan (PLN-2290). All files associated MCM analyses conducted for this PA are described in EDF-9916 and attached as Supporting Information in the CWI EDMS.

1.7.2 GWSCREEN

The GWSCREEN computer code (Rood 2003a) Version 2.5a (Enterprise Architecture Application ID 121200) was selected to perform screening calculations for the groundwater pathway and to model radionuclide transport in the saturated zone in more detailed base case calculations. For groundwater pathway screening calculations, the executable of Version 2.5a dated January 23, 2007, was used for transport through the source zone, vadose zone, and the aquifer (see Section 2.4.2). The executable version dated August 27, 2007, was used for the groundwater pathway base case and sensitivity/uncertainty analyses (see Sections 3.3 and 4.6). The code is a series of three primary models (source, unsaturated zone, and saturated zone) coupled together by the contaminant fluxes across the interface between the primary model boundaries.

The GWSCREEN computer code uses a mass balance approach that has its roots in the methodology presented by the Nuclear Regulatory Commission (Codell, Key, and Whelan 1982; Kozak, Chu, and Harlan 1990). Release from the source zone is modeled as a first-order leaching process that accounts for decay and sorption. Two choices exist for the vadose zone: either a one-dimensional plug flow model (i.e., one-dimensional advection-dominated system with no dispersion) or a solution with advection and dispersion. In both cases, GWSCREEN assumes one-dimensional transport in a homogeneous vadose zone with steady-state flow. For the saturated zone, GWSCREEN uses a semianalytical solution to solve the advective-dispersive equation for transient mass flux (Codell, Key, and Whelan 1982). GWSCREEN is written in FORTRAN-77 and compiled for operation on a personal computer.

The user's manual (Rood 2003a) includes calibration studies that were performed for tritium plumes emanating from the Idaho Chemical Processing Plant (now INTEC) injection well and the Test Reactor Area (now the Advanced Test Reactor Complex) percolation ponds at the INL Site (Codell, Key, and Whelan 1982; Rood, Arnett, and Barraclough 1989). The predicted concentrations matched measured data reasonably well, but were not as accurate as those made by a finite difference model.

GWSCREEN was developed at the INL; thus, it is validated and controlled in accordance with Battelle Energy Alliance software development requirements. At CWI, the GWSCREEN code meets quality assurance requirements for acquired software (MCP-550). Use of the code is controlled by a software management plan (PLN-2480). Installation and validation of the software are documented with a benchmark calculation to verify that the code executes properly on the CWI computer network in the software test plan (EDF-7372). All files associated with GWSCREEN analyses conducted for this PA are described in EDF-9453 (screening) and EDF-9916 (base case and sensitivity uncertainty analysis) and attached as Supporting Information in the CWI EDMS.

1.7.3 EMSOFT

The Exposure Model for Soil-Organic Fate and Transport (EMSOFT) Version 1.3 June 1996 computer code (EPA 1997a) was selected to calculate transport of volatile contaminants from the source zone to the land surface (Enterprise Architecture Application ID 236027). The code was developed by ENSR Consulting and Engineering for the EPA. It is used to assess the potential for atmospheric exposure to occur and quantify the mass flux of contaminants to the atmosphere over time. Mass fluxes can then be input to an atmospheric dispersion model to calculate exposure concentration (i.e., CAP-88, see Section 1.7.4).

The mathematical model of the code is derived from the differential equation and boundary conditions that describe vertical transport of a chemical in a uniform soil. Jury, Spencer, and Farmer (1983) and Jury et al. (1990) did fundamental theoretical development of the model. The model assumes pore water flux is steady state, soil properties are homogeneous, chemicals in dissolved form are present at low concentrations, and volatilization at the surface occurs through a stagnant air boundary layer of uniform thickness.

EMSOFT code verification and validation are documented in the user's manual (EPA 1997a). At CWI, the code is considered to be acquired software (MCP-550) controlled by a software management plan (PLN-2480). All files associated with EMSOFT analyses conducted for this PA are described in EDF-9917 and attached as Supporting Information in the CWI EDMS.

1.7.4 CAP-88

The Clean Air Act Assessment Package-1988 (CAP-88) PC Version 3 computer code (EPA 2007) was selected to model the atmospheric dispersion of volatile radionuclides from the surface of the landfill and dose to the receptor (Enterprise Architecture Application ID 202686). The CAP-88 computer model, a set of computer programs, databases, and associated utility programs, estimates dose and risk from radionuclide emission to air. CAP-88 uses a modified Gaussian plume equation to estimate the average dispersion of radionuclides released from up to six sources at the same release location with different release heights. A circular grid with a radius up to 50 miles can be assessed. The CAP-88 code was selected for this dose assessment because it has been used extensively at the INL Site as well as throughout the DOE system and is a mature code that EPA allows for demonstration of compliance with the applicable performance objective (40 CFR 61, Subpart H, “National Emission Standards for Emissions of Radionuclides Other Than Radon from Department of Energy Facilities”).

CAP-88 code verification and validation are documented in the user’s manual (EPA 2007). The Office of Radiation and Indoor Air compared predictions of annual average ground-level concentration to actual environmental measurements and found very good agreement (Beal et al. 1986). Environmental monitoring data at five DOE sites were compared to AIRDOS-EPA predictions. EPA concluded that, as often as not, AIRDOS-EPA predictions are within a factor of 2 of actual concentrations. At CWI, the code is considered to be acquired software (MCP-550) controlled by a software management plan (PLN-2480) and software test plan (EDF-6213), where installation and validation of the software are documented with a benchmark calculation to verify that the code executes properly on the CWI computer network. All files associated with CAP-88 analyses conducted for this PA are described in EDF-9917 and attached as Supporting Information in the CWI EDMS.

1.7.5 RESRAD

The RESidual RADioactivity (RESRAD) (Yu et al. 2001) computer code Version 6.4 (Enterprise Architecture Application ID 200634) was selected to calculate the radon flux at the surface of the landfill and to calculate the doses from inadvertent intrusion into the waste. RESRAD is a computer model designed to estimate radiation doses and risks from residual radioactive material. Version 6 provides a suite of tools to help users assess potential radiologic exposures. The code is sponsored by both DOE and NRC. RESRAD was developed at Argonne National Laboratory in 1989, and, since then, has been used extensively throughout the DOE complex, as well as by the EPA, NRC, industrial firms, universities, and foreign government agencies and institutions.

As described in the User’s Manual (Yu et al. 2001), RESRAD underwent extensive review, benchmarking, verification, and validation. Verification of the mathematical models was documented through hand calculations and spreadsheets. The code has been benchmarked against several models that can be used to conduct similar tasks: GENII-S Version 1.485 (Leigh et al. 1992), GENII (Napier et al. 1988), DECOM Version 2.2 (Till and Moore 1988), and others (Cheng, Yu, and Zielen 1991). Seitz et al. (1992, 1994) compare published RESRAD results published results for the GENII and PATHRAD-EPA codes. Validation tasks to test the mathematical model against accurately measured, independent sets of field or laboratory observations over the range of conditions for model applications were conducted for various sub-models: leaching model (Wang et al. 1990; Wang, Biwer, and Yu 1993; Wang, Orlandini, and Yu 1996), and against real world data collected after the Chernobyl accident (IAEA 1996).

RESRAD meets the software quality assurance requirements for acquired software at CWI. The code is controlled by a software management plan (PLN-2480). Installation and validation of the software are documented in the software test plan (EDF-7292). All files associated with RESRAD analyses conducted for this PA are described in EDF-9874 and attached as Supporting Information in the CWI EDMS.

2. DISPOSAL FACILITY CHARACTERISTICS

This section describes the INL Site, the environment, the ICDF Landfill, and LLW characteristics. This information provides the basis for the PA conceptual model and an understanding of the method of analysis.

2.1 Site Characteristics

The following sections discuss the location of the disposal facility, the general land surface features of the site, the population distribution in the area, and uses of adjacent lands.

2.1.1 Geography and Demography

The INL Site is located in southeastern Idaho, on the north-central part of the Eastern Snake River Plain (ESRP) (see Figure 1-1). Included in its 2,305-km² (890-mi²) area are portions of five Idaho counties (Bingham, Bonneville, Butte, Clark, and Jefferson) (Figure 2-1). The nearest INL Site boundaries are 51 km (32 mi) west of Idaho Falls, 37 km (23 mi) northwest of Blackfoot, 71 km (44 mi) northwest of Pocatello, and 11 km (7 mi) east of Arco, Idaho. There are no permanent residents within a 16-km (10-mi) radius of INTEC. The INL Site is approximately equidistant from the three larger metropolitan areas of Salt Lake City, UT, 339 km (211 mi); Boise, ID, 413 km (257 mi); and Butte, MT, 344 km (214 mi).

Approximately 95% of the INL Site has been withdrawn from the public domain. The remaining 5% includes public highways (U.S. 20 and 26 and Idaho 22, 28, and 33) and the Experimental Breeder Reactor I (EBR-I), which is a National Historic Landmark (Irving 1993). Neighboring lands are used primarily for farming or grazing or are in the public domain (e.g., national forests and state-owned land).

The surface of the INL Site is a relatively flat, semiarid, sagebrush desert. Predominant relief is manifested either as volcanic buttes jutting up from the desert floor or as unevenly surfaced basalt flows or flow vents and fissures. Elevations on the INL Site range from 1,460 m (4,790 ft) in the south to 1,802 m (5,913 ft) in the northeast, with an average elevation of 1,524 m (5,000 ft) above sea level (Irving 1993). Mountain ranges bordering the INL Site on the north and west are the Lost River Range, the Lemhi Range, and the Beaverhead Mountains of the Bitterroot Range (see Figure 1-1).

The location of the INL Site relative to the SRPA is illustrated in the map on Figure 2-2. The SRPA, which consists of saturated basalt and sediments, is one of the largest aquifers in the United States (Irving 1993) and was classified as a sole-source aquifer by the EPA in 1991 (56 FR 50634). Generally, groundwater flows in the aquifer from the northeast to the southwest.

2.1.1.1 Disposal Site Location. INTEC occupies approximately 80 ha (200 acres) in the south-central portion of the INL Site and consists of more than 100 buildings, trailers, and support facilities. Primary facilities at INTEC include storage and treatment for spent nuclear fuel, mixed HLW, and mixed transuranic waste. Located outside the INTEC perimeter fence are parking areas, a helicopter landing pad, the wastewater treatment lagoon, various pits, and percolation ponds. These areas occupy approximately 22 ha (55 acres). The ICDF (Figure 1-2) is adjacent to Lincoln Boulevard and is situated at the southwest corner of the INTEC facility, outside the facility fence.

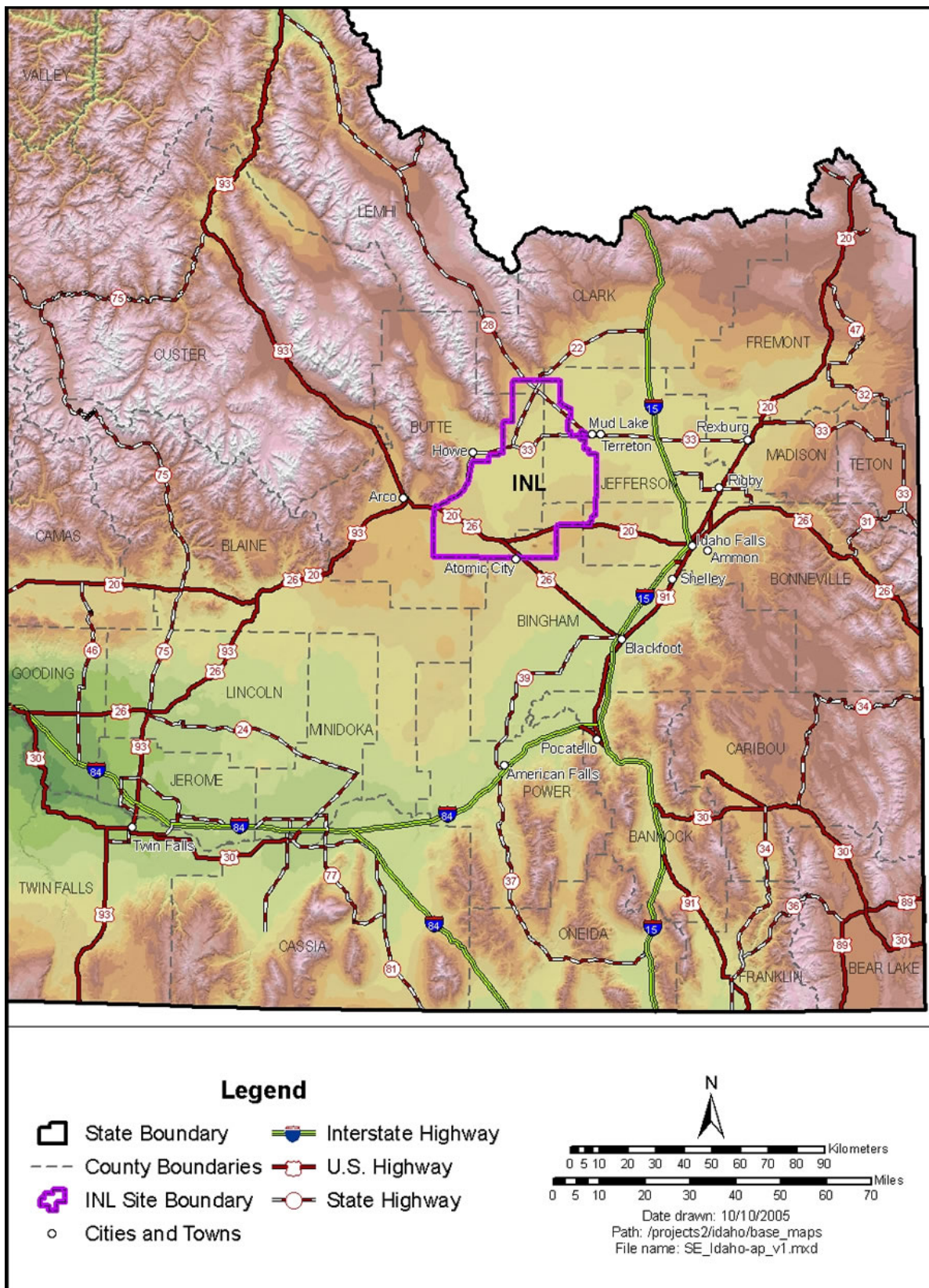


Figure 2-1. Counties adjacent to the Idaho National Laboratory Site.

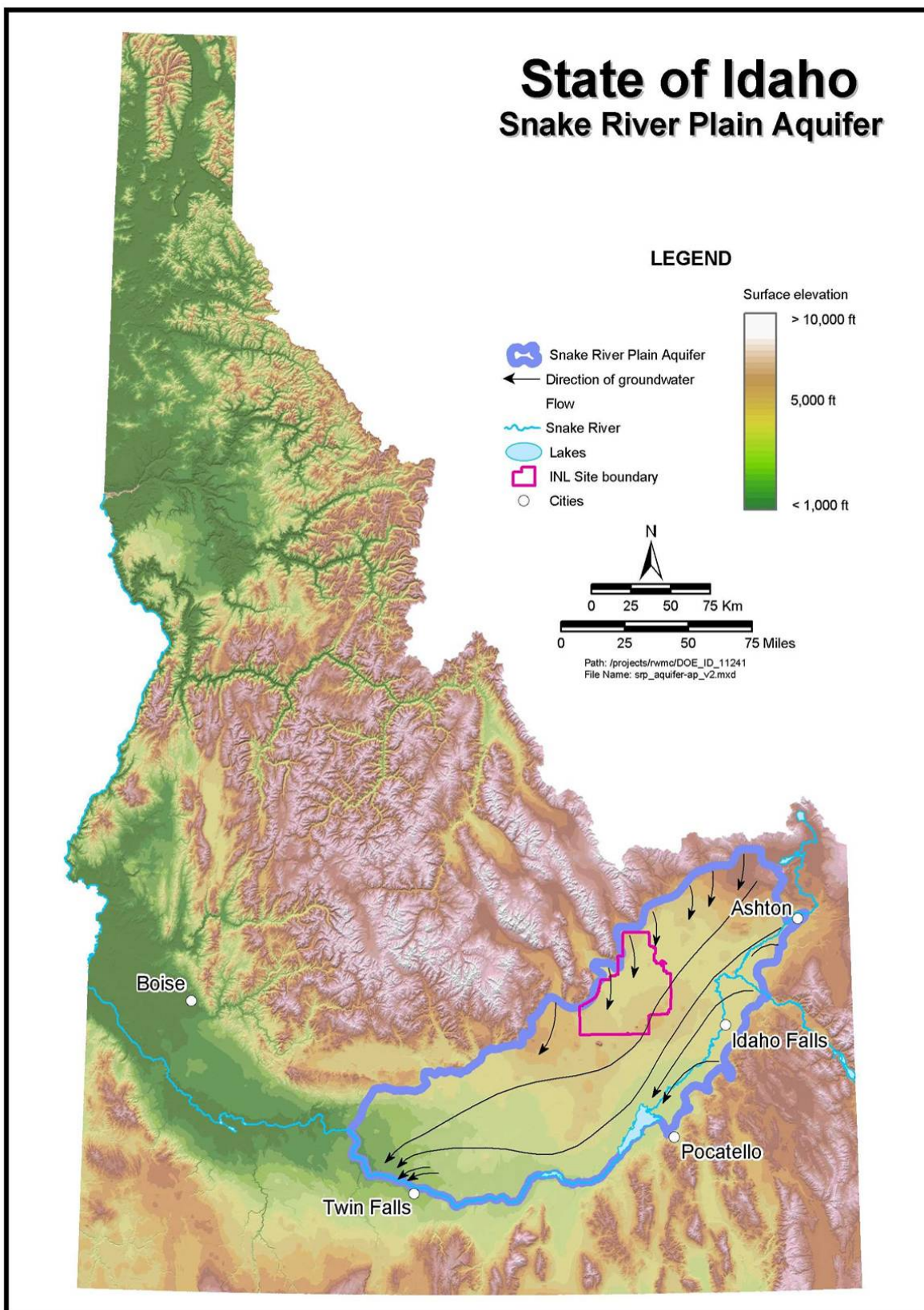


Figure 2-2. Location of the Idaho National Laboratory Site on the Snake River Plain Aquifer in Idaho.

Fencing is maintained around the ICDF to provide security of the components and control of the waste handling practices that take place. The location of the ICDF allows for easy access from Lincoln Boulevard, the main INL Site road between facilities. This allows controlled yet straightforward access to the ICDF components, as needed, for ICP CERCLA waste management. The ICDF consists of a landfill, two evaporation ponds, staging and storage areas, a decontamination facility, a treatment facility, utilities required to operate, and an administrative facility. A photo of the landfill taken during a recent flyover on September 11, 2009, is shown in Figure 2-3.



Figure 2-3. View of ICDF Landfill and Evaporation Ponds looking east (photo taken September 11, 2009).

INTEC is 16 km (10 mi) north of public highway U.S. 20 that bisects the southern portion of the INL Site. The nearest towns are Arco 29 km (18 mi) to the northwest with a population of 977 and Atomic City 18 km (11 mi) to the southeast with a population of 25. The largest city nearby is Idaho Falls 97 km (60 mi) to the east of INTEC with a population of 57,133. The INL Site boundary is over 24 km (13 mi) to the south of INTEC. There are no plans to change the existing boundaries of the INL Site DOE-controlled land and there are no plans for expansion of the ICDF Landfill at this time.

2.1.1.2 Disposal Site Description. INTEC is located on an alluvial plain at an average elevation of 1,498 m (4,914 ft). Gravelly, medium-to-coarse-textured soils derived from alluvial deposits occur in the vicinity of INTEC. The underlying basalt is covered with as much as 15.2 m (50 ft) of these soils and

the land surface is flat. The natural plant life is limited by soil type, meager rainfall, and extended drought periods and consists mainly of sagebrush and various grasses.

The Big Lost River is 0.8 km (0.5 mi) west of INTEC. The Big Lost River is an intermittent stream on the INL Site that flows to the northeast to its termination in the playas at the north end of the INL Site. The INL Site diversion dam, a small earthen dam on the Big Lost River, 18 km (10 mi) southwest of INTEC, diverts water from the Big Lost River into a series of four natural depressions, called spreading areas.

2.1.1.3 Population Distribution. Populations potentially affected by INL Site activities include INL Site employees, ranchers who graze livestock in areas on or near the INL Site, hunters on or near the Site, residential populations in neighboring communities, travelers along U.S. Highway 20/26, and visitors at EBR-I.

2.1.1.3.1 On-Site Populations—Nine separate facilities at the INL Site include a total of more than 550 buildings and trailers and more than 500 other support facilities. The INL and ICP employed 7,814 contractor and government personnel as of October 2009. Approximately 41% of the total workforce is located in Idaho Falls, Idaho, and 59% are employed at the INL Site location about 80 km (50 mi) west in the Arco Desert. As of October 2009, the total INL/ICP workforce included 5,546 employees at Site locations (1,436 employees at the Naval Reactors Facility, 1,147 at INTEC, 603 at the Central Facilities Area [CFA], 881 at the Materials and Fuels Complex, 638 at the Advanced Test Reactor Complex, 268 at the Test Area North [TAN], 528 at the Radioactive Waste Management Complex [RWMC], 11 at the Critical Infrastructure Test Range Complex, 2 at EBR-I, and 32 at unspecified areas); 2,243 employees in Idaho Falls occupying numerous offices, research laboratories, and support facilities; and 25 employees at off-Site locations. Authorized groups and visitors occasionally are escorted at the INL Site. Subcontracted employees and personnel from Idaho Department of Environmental Quality and EPA oversight programs also visit the area.

2.1.1.3.2 Off-Site Populations—The INL Site is bordered by five Idaho counties: Bingham, Bonneville, Butte, Clark, and Jefferson (see Figure 2-1). Major communities include Blackfoot and Shelley in Bingham County, Idaho Falls and Ammon in Bonneville County, Arco in Butte County, and Rigby in Jefferson County. Population estimates for the counties surrounding the INL Site and the largest population centers in these counties are shown in Table 2-1 (U.S. Census 2008). There are no residents within 17 km (10 mi) of INTEC in the general southern direction of groundwater flow. The community nearest to the INL Site is Atomic City, Idaho, located south of the Site boundary on U.S. Highway 20/26. Other population centers near the INL Site include Arco, 11 km (7 mi) west of the Site; Howe, west of the Site on U.S. Highway 22/33; and Mud Lake and Terreton on the northeast border of the Site. The INL Site supports no permanent residents.

2.1.1.3.3 Shoshone-Bannock Tribal Interests—The Shoshone-Bannock Tribes of the Fort Hall Indian Reservation are a federally recognized Indian tribe and a sovereign government. The Fort Bridger Treaty of July 3, 1868, Stat. 673, secured the Fort Hall Reservation as the permanent homeland of the Shoshone-Bannock peoples [15 Stat. 673]. The 1868 Treaty also reserved aboriginal rights to these peoples that extend to areas of unoccupied land in Idaho and surrounding states, allowing access for cultural, political, and economic activities essential to the Tribes' survival. Though the INL Site is occupied land, DOE-ID protects cultural resources and allows tribal members access to areas of cultural and religious significance at the INL Site. In 1994, DOE-ID entered into a Memorandum of Agreement that provides the Tribes free access to the Middle Butte area of the INL Site. Other INL Site areas may be identified for access in the future for cultural, religious, and educational activities. The Agreement-In-Principle (DOE 2007a) with the Tribes ensures that activities being conducted at the INL Site protect health, safety, environment and cultural resources of the Tribes and address tribal interests in

Table 2-1. Population estimates for counties and selected communities surrounding the Idaho National Laboratory (U.S. Census 2008).

Location	Population Estimate
Bingham County	43,903
Blackfoot	11,012
Shelley	4,257
Clark County	910
Bonneville County	99,135
Ammon	13,646
Idaho Falls	57,133
Butte County	2,751
Arco	977
Jefferson County	23,860
Rigby	3,394

DOE-administered programs. From its inception, the Agreement-In-Principle has been updated periodically to reflect the working relationship between the Tribes and DOE-ID. Therefore, it is likely that future INL Site activities will include tribal support to avoid endangering the Tribes' environment or impairing their ability to protect health, welfare, and safety of tribal members, others within the Tribes' jurisdiction, and the environment and cultural resources of the Tribes.

2.1.1.4 Uses of Adjacent Lands. Livestock produced on land surrounding the INL Site includes sheep, beef cattle and dairy cattle, hogs, and poultry. The major crops produced on the surrounding lands include wheat, alfalfa, barley, potatoes, oats, corn, and sugar beets (see Table 2-2). Land ownership around the INL Site is illustrated in Figure 2-4. Most of the land immediately adjacent to the INL Site is owned by the U.S. Government. About 75% of the land immediately adjacent to the INL Site is owned by the federal government and administered by BLM. Land uses on this land consist of grazing, wildlife management, mineral and energy production, and recreation. The State of Idaho owns approximately 1% of the adjacent land. State-owned lands are also used for grazing, wildlife management, and recreation. Private lands near the INL Site are used primarily for grazing and farming. Irrigated farmlands make up about 24% of the land bordering the INL Site.

INL Site operations are performed within the Site's primary facility areas (TAN, the Advanced Test Reactor Complex, INTEC, CFA, the Materials and Fuels Complex, the Naval Reactors Facility, the Critical Infrastructure Test Range Complex, and RWMC). A 140,000-ha (340,000-acre) security and safety buffer zone, consisting of grazing land administered by BLM, is located around the core development area, which also accommodates environmental research and ecological and socio-cultural preservation (see Figure 2-4). Grazing areas at the INL Site support cattle and sheep, especially during dry conditions. However, grazing of livestock is prohibited within 1/2 mi of any primary facility boundary and within 3.2 km (2 mi) of any nuclear facility. Depredation hunts of game animals managed by the Idaho Department of Fish and Game are permitted on the Site within the buffer zone during selected years. Hunters are allowed access to an area that extends 0.8 km (0.5 mi) inside the INL Site boundary on portions of the northeastern and western borders of the Site.

Table 2-2. Acreage by county of major crops harvested on land surrounding INL Site (USDA 2007).

County	Wheat	Alfalfa ^a	Barley	Potatoes	Sugar Beets	Oats	Silage Corn
Bingham	118,896	64,500	13,980	74,371	20,022	282	1,560
Bonneville	51,322	37,400	64,111	27,162	—	210	1,905
Butte	2,288	32,000	9,238	—	—	—	—
Clark	5,382	21,700	2,163	—	—	—	—
Jefferson	36,831	98,000	40,641	28,911	—	900	4,439

a. Data are for 2004.

Note: The dash indicates little or no production.

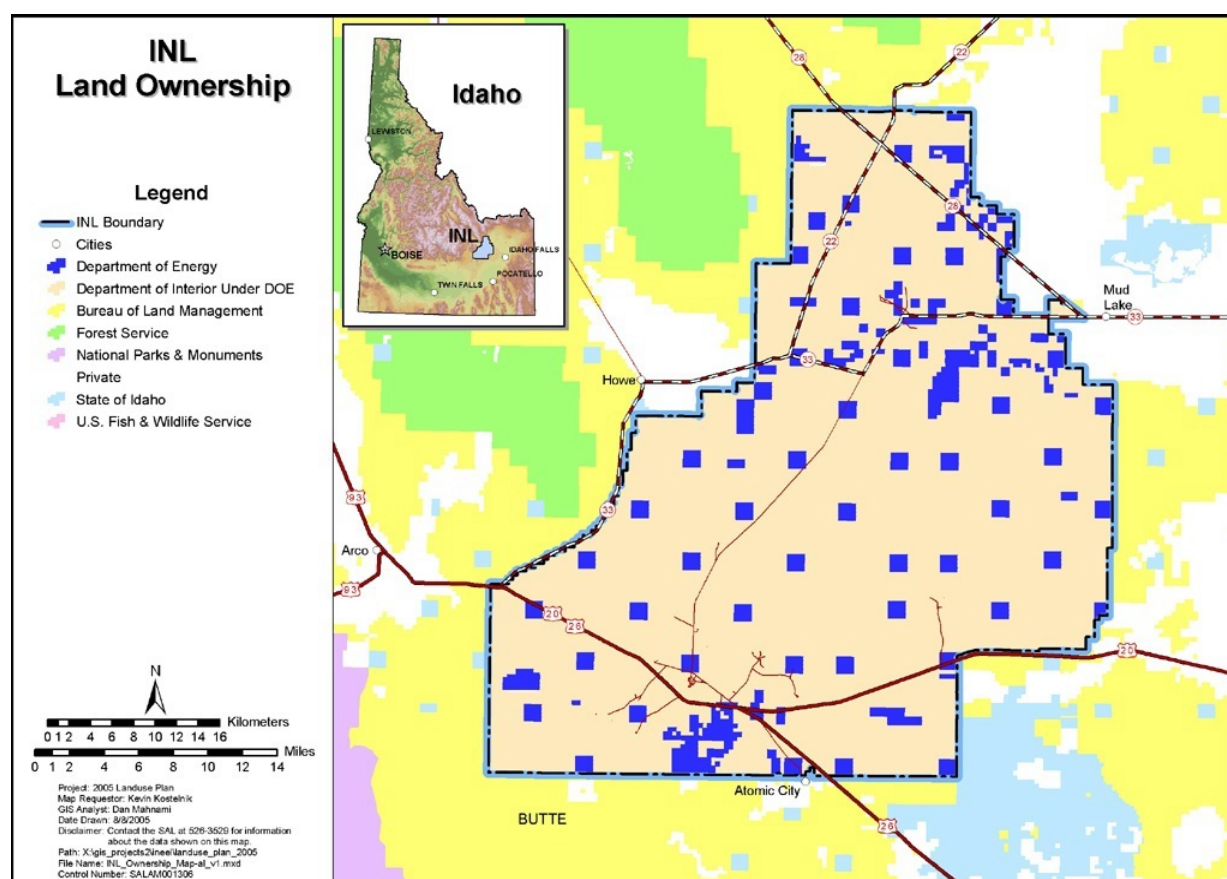


Figure 2-4. Land ownership distribution in the vicinity of the Idaho National Laboratory Site.

EBR-I, the first reactor in the world to generate electricity, now a National Historic Landmark, is located 15 km (8 mi) southwest of INTEC and is open to the public during the summer months for tours.

The INL Site is designated as a National Environmental Research Park, functioning as a field laboratory set aside for ecological research and evaluation of the environmental impacts from nuclear energy development.

The SRPA underlies about 10,000 mi² of the ESRP. Irrigated agriculture provides the economic base for the people of southern Idaho, and the SRPA makes possible a significant percentage of that base. It is a remarkable water resource to the area, and pumping for irrigation during a typical year averages 1.6 million acre-ft. Springs from the aquifer provide clean, safe water at just the right temperature for raising more than 25 million lb of rainbow trout, about 75% of the entire United States annual production. It is estimated that over 127,000 people depend on the aquifer for domestic and municipal water needs (Hackett, Pelton, and Brockway 1986).

Because the INL Site is remotely located from most developed areas, INL Site lands and adjacent areas are not likely to experience residential and commercial development. No residential development will be allowed to occur within the INL Site boundaries while the land is under DOE control.

2.1.2 Meteorology and Climatology

Meteorological data have been collected periodically at over 45 locations on and near the INL Site since 1949. The longest and most complete record of air temperature and precipitation observations (over 35 years) at the INL Site was collected from the weather station at CFA. The CFA station is located approximately 5 km (3 mi) south of INTEC. INTEC and CFA are at approximately the same terrain elevation and have the same exposure to wind, snow, and cloud cover. Differences in climate between the CFA monitoring station and INTEC are minimal.

The National Oceanic and Atmospheric Administration Air Resources Laboratories conduct most of the meteorological monitoring within 80 km (50 mi) of the INL Site. An overview of climatological data is available from data summaries collected from the CFA monitoring station. A summary of the climatology of the INL Site is available in *Climatology of the Idaho National Engineering Laboratory* (Clawson, Start, and Ricks 1989).

2.1.2.1 Temperature. Temperatures at the INL Site vary widely over the course of the year. Records for CFA indicate that the highest and lowest daily temperatures range from 41°C (105°F) to -44°C (-47°F), respectively. The average annual temperature at the INL Site exhibits a gradual 7-month increase, beginning with the first week in January and continuing through the third week in July. During the months of April through October, the average monthly temperature varies from 5 to 20°C (41 to 68°F). The temperature then decreases over the course of 5 months until the minimum average temperature is again reached in January. During the months of November through March, the average monthly temperature varies from -9 to -1°C (15 to 30°F). On average, 42% of the days in a year contain a freeze/thaw cycle, in which the maximum air temperature exceeds 0°C (32°F) and the minimum air temperature is at or below 0°C (32°F). Inversion conditions (warmer air temperature with increasing altitude) and lapse conditions (cooler air temperature with increasing altitude) occur approximately 46% and 54% of the time, respectively.

2.1.2.2 Wind. The prevailing wind direction at INTEC and at most locations on the INL Site is southwesterly. In summer, a very sharp reversal in wind direction occurs daily; winds from the southwest predominate during daylight hours, and northeasterly winds predominate at night. The reversals normally occur shortly after sunrise and sunset. The average wind speed at the 6-m (20-ft) level at CFA ranges from 8.2 km/hr (5.1 mph) in December to 15 km/hr (9.3 mph) in March and April. The highest hourly average wind speed at the 6-m (20-ft) level was 108 km/hr (67 mph), and the maximum instantaneous gust at the same level was 125.5 km/hr (78 mph). Strong wind gusts can occur in the immediate vicinity of thunderstorms. On the average, these gusts occur 2 or 3 days per month during June, July, and August. Calm conditions prevail 11% of the time.

2.1.2.3 Precipitation. The average annual precipitation at CFA is 21.4 cm (8.4 in.). The highest recorded annual amount of precipitation was 36.6 cm (14.4 in.) in 1963, and the lowest amount was 11.4 cm (4.5 in.) in 1966. The majority of precipitation occurs in May and June, with an average precipitation of 3 cm (1.2 in.) for each of these months. Precipitation amounts in excess of 2.54 cm (1 in.) per day have been recorded eight times at CFA, with the maximum being 4 cm (1.64 in.). The maximum hourly precipitation observed at CFA is 1.37 cm (0.54 in.). Snowfall is a substantial contributor to total annual precipitation and ranges from 17 to 152 cm/year (6.7 to 60 in./year), with an annual average of 70 cm (28 in.). The maximum average monthly snowfall is 16.3 cm (6.4 in.), occurring in December.

2.1.2.4 Evaporation. The potential annual evaporation from a saturated ground surface at the INL Site is approximately 109 cm (43 in.), with 80% of the evaporation occurring between May and October. During July, the warmest month of the year, the daily potential evaporation rate is approximately 0.63 cm (0.25 in.). Evaporation occurring during the remainder of the year is small. Actual evaporation rates are much lower than potential rates because the ground surface is rarely saturated. Transpiration by the native vegetation of the Snake River Plain is estimated at 15 to 23 cm/year (6 to 9 in./year). From late winter to spring, precipitation is most likely to infiltrate into the ground because of the low evapotranspiration rates, except when frozen conditions preclude infiltration (Mundorff, Crosthwaite, and Kilbum 1964). For evaporation from surface water bodies (ponds), a pan evaporation rate of approximately 109 cm/year (43 in./year) has been estimated (Clawson, Start, and Ricks 1989).

2.1.2.5 Relative Humidity. The highest relative humidity is observed in the winter, with the average midday relative humidity at about 55%. The lowest is observed in the summer, when the midday average is approximately 18%. An absolute maximum relative humidity value of 100% was observed in every month of the year except July, and the lowest observed was 4% in July and August. This is indicative of the very dry summers experienced at the INL Site.

2.1.2.6 Special Phenomena. Several other types of meteorological phenomena, such as thunderstorms, hail, and tornadoes, occur at the INL Site. The INL Site may experience an average of two to three thunderstorm days during each of the summer months from June through August with considerable year-to-year variation. Thunderstorms over the INL Site are usually much less severe than what is normally experienced in the mountains surrounding the ESRP or areas of the Rocky Mountains. Precipitation from many thunderstorms evaporates before reaching the ground (virga). The frequent result is little or no measurable precipitation. Occasionally, however, rain amounts exceeding the long-term average may result from a single thunderstorm. Small hail has been observed to occasionally occur in conjunction with thunderstorms. The size of the hail is usually smaller than 1/4 in. in diameter. The diameter may range up to 3/4 in. on very rare occasions. No hail damage has ever been reported at the INL Site.

Most tornado activity in the United States occurs east of the Rocky Mountains. In Idaho, tornadoes have been reported only in the spring and summer seasons (April through August). Records from 1950 through 1989 indicate a total of five funnel clouds and no tornadoes sighted within the boundaries of the INL Site.

Dust devils can entrain dust and pebbles and transport them over short distances. Common in the region, dust devils usually occur on warm sunny days with little or no wind. The dust cloud may be several hundred yards in diameter and extend several thousand feet into the air (Clawson, Start, and Ricks 1989).

2.1.3 Ecology

The following sections discuss the plant and animal species and communities that may be found on the INL Site, including threatened, endangered, and sensitive species.

2.1.3.1 Flora. The INL Site represents the largest remnant of undeveloped, ungrazed sagebrush steppe ecosystem in the Intermountain West. This ecosystem has been listed as critically endangered with less than 2% of its original coverage remaining (Noss, LaRoe, and Scott 1995; Saab and Rich 1997).

In 1975, the INL Site was dedicated as one of five DOE National Environmental Research Parks. It is an outdoor laboratory used to study ecological relationships and the effects of human activities on natural systems. In addition, it provides a unique setting for scientific investigation because the public has been excluded from much of the area for the past 25 years. Ecological data collected from the Idaho National Environmental Research Park provide a basis for analyzing environmental changes over time and assessing the effect of human influence on the environment.

Research on the flora and fauna of the INL Site has largely been conducted by or in conjunction with the DOE Radiological and Environmental Sciences Laboratory. The physical aspects of the INL Site and its flora and fauna are typical of cold, high-altitude, sagebrush ecosystems found in the western United States.

Much of the following discussion of the flora and fauna at the INL Site is from the *Environmental Resource Document for the Idaho National Engineering Laboratory* (Irving 1993). This report contains additional detailed information and references to specific ecological studies.

Extensive surveys of INL Site vegetation were carried out in 1952, 1958, and 1967 using 150 permanent transects established and maintained for this purpose (Harniss and West 1973). McBride et al. (1978) and Jeppson and Holte (1978) also have described vegetation.

More recently, Anderson and Ruppel et al. (1996) broadly described 10 vegetation classes and plant communities that occur on the INL Site (Figure 2-5). These communities do not represent homogeneous community types, but integrated communities that share dominant species and are more similar to each other than to communities represented by other vegetation classes. Sagebrush steppe is the dominant community on the INL Site. Other community types include juniper woodlands, grasslands, low shrubs on lava, sagebrush-rabbitbrush, sagebrush-winterfat, salt desert shrub, wetlands, playas, bare ground or disturbed areas, and lava. Figure 2-5 depicts the distribution of vegetation on the INL Site.

Several studies have been conducted at the INL Site on plant rooting depths. Studies of plant uptake of radionuclides at the INL Site have focused primarily on (a) determining if deep-rooted plants are a mechanism for waste pit intrusion and subsequent uptake of radionuclides and (b) analyzing inventories of radionuclides in aerial portions of plants. Aerial portions of plants are important because they can potentially transport subsurface contaminants through dispersal of leaves, consumption by herbivores, use by birds as nesting materials, and wildfire.

One study comparing radionuclide uptake by crested wheat grass (rooting depth 1 to 1.5 m [3 to 4.9 ft]) with that by Russian thistle (rooting depth 1 to 5 m [3 to 16 ft]) showed higher radionuclide concentrations in the deeper-rooted species (Arthur 1982). Examples of other deep-rooting species are rabbitbrush and sagebrush. General examples of shallow-rooting plant types are grasses and annual forbs.

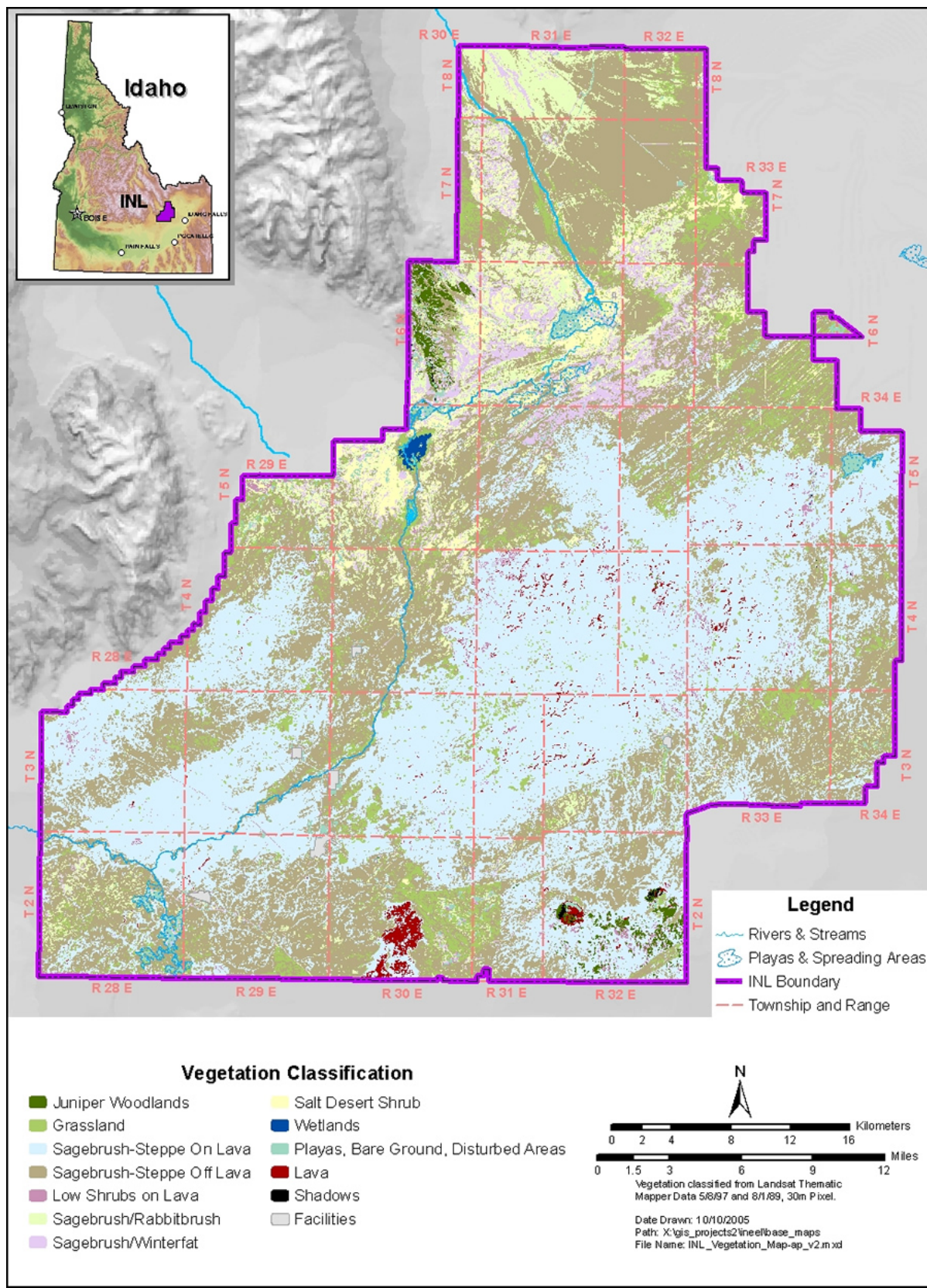


Figure 2-5. Approximate distribution of vegetation at the Idaho National Laboratory Site.

Reynolds and Fraley (1989) found that the roots of big sagebrush extended to a depth of 2.25 m (7.3 ft), green rabbitbrush to a depth of 1.9 m (6.2 ft), and Great Basin wild rye to a depth up to 2 m (6.5 ft). Maximum lateral spread of the roots of both big sagebrush and Great Basin wild rye was 90 cm (35.5 in.) and occurred at a depth of 40 cm (15.8 in.). In addition, studies indicate root penetration of up to 1.6 m (5.2 ft) for sodar and crested wheat grass at the INL Site (Markham 1987).

2.1.3.2 Fauna. The INL Site supports a variety of wildlife including small mammals, birds, reptiles, and a few large mammals. Aquatic life on the INL Site is limited and depends mainly upon the flow of the Big Lost River. During several months of the year, and even during some entire years, the river does not flow. However, during spring runoff and periods of high rainfall, the diversion system (at the southern boundary of the INL Site) and the Big Lost River sinks (at the northern boundary of the INL Site) support water flow during periods of water accumulation. This normally occurs for less than 2 or 3 months in the spring. Fish species observed in the Big Lost River on the INL Site include rainbow trout, mountain whitefish, eastern brook trout, Dolly Varden char, Kokanee salmon, and the shorthead sculpin (Overton et al. 1976).

A total of 219 vertebrate species have been recorded on the INL Site. Vertebrate species include six species of fish, one amphibian, nine reptiles, 164 birds, and 39 mammals (Reynolds et al. 1986). Several vertebrate species present on the INL Site are considered sagebrush-obligate species, meaning that they rely upon sagebrush for survival. Among others, these species include sage sparrow (*Amphispiza belli*), Brewer's sparrow (*Spizella breweri*), northern sagebrush lizard (*Sceloporus graciosus*), sage grouse (*Centrocercus urophasianus*), and pygmy rabbit (*Brachylagus idahoensis*).

A total of 740 insect species have been recorded at the INL Site; 226 of these species have not yet been identified beyond the family level. The majority of the abundant species belong to the orders Hymenoptera (wasps and ants) and Diptera (flies).

Studies have been performed on burrowing characteristics of small mammals such as ground squirrels, deer mice, and voles (Arthur, Grant, and Markham 1983; Markham 1987; Reynolds and Laundre 1988). Results of the studies indicate burrows no deeper than 1.4 m (4.6 ft) at the INL Site.

2.1.3.3 Threatened, Endangered, and Sensitive Species. A list of threatened or endangered and sensitive species that may occur on the INL Site is given in Table 2-3. Originally compiled from the U.S. Fish and Wildlife Service periodic updates for the INL Site (USFWS 1996, 1997, 2001); the Idaho Fish and Game Conservation Data Center threatened, endangered, and sensitive species for the State of Idaho (CDC 1994); and general documentation for the INL Site (Reynolds 1994; Reynolds et al. 1986), this list was most recently updated in September 2005.^c Numerous changes to the status and ranking protocols for threatened or endangered and sensitive species (e.g., U.S. Fish and Wildlife Service and BLM designations) have been made in recent years. The species contained on Table 2-3 have been evaluated in previous INL Site documentation. Although some taxa no longer have status within individual wildlife management agencies, and additional species have been addressed (e.g., species such as the sage sparrow, Brewer's sparrow, and sage thrasher are now listed as having special status in Idaho), the original suite of species is retained here to maintain continuity with ICP CERCLA documentation. The most current threatened or endangered and sensitive species designations, definitions, and information can be accessed through the Idaho Conservation Data Center (IDFG 2008).

c. Updated by N. L. Hampton, Idaho National Laboratory, September 8, 2005.

Table 2-3. Threatened or endangered species, sensitive species, and species of concern that may be found on the INL Site.

Common Name ^a	Scientific Name	Federal Status ^{b,c}	State Status ^c	BLM Status ^c	USFS ^d Status ^c
Plants					
Lemhi milkvetch	<i>Astragalus aquilonius</i>	—	GP3	TY2	S
Painted milkvetch ^c	<i>Astragalus ceramicus</i> var. <i>apus</i>	SC	R	—	—
Plains milkvetch	<i>Astragalus gilviflorus</i>	—	1	TY3	R
Winged-seed evening primrose	<i>Camissonia pterosperma</i>	—	S	TY4	—
Nipple cactus ^e	<i>Coryphantha missouriensis</i>	—	R	—	—
Spreading gilia	<i>Ipomopsis</i> (= <i>Gilia</i>) <i>polycladon</i>	—	2	TY3	—
King's bladderpod	<i>Lesquerella kingii</i> var. <i>cobrensis</i>	—	M	—	—
Tree-like oxytheca ^c	<i>Oxytheca dendroidea</i>	—	R	R	—
Inconspicuous phacelia ^f	<i>Phacelia inconspicua</i>	C	GP1	TY2	R
Ute ladies' tresses ^f	<i>Spiranthes diluvialis</i>	LT	GP2	TY1	—
Puzzling halimolobos	<i>Halimolobos perplexa</i> var. <i>perplexa</i>	—	M	TY5	S
Earth lichen					
Birds					
Peregrine falcon	<i>Falco peregrinus</i>	R	T	—	S
Merlin	<i>Falco columbarius</i>	—	P	TY3	—
Gyr falcon	<i>Falco rusticolus</i>	—	R	R	—
Bald eagle	<i>Haliaeetus leucocephalus</i>	LT	T	TY1	—
Ferruginous hawk	<i>Buteo regalis</i>	SC	P	TY3	—
Black tern	<i>Chlidonias niger</i>	—	P	TY3	—
Northern pygmy owl ^f	<i>Glaucidium gnoma</i>	—	P	TY5	—
Burrowing owl	<i>Athene</i> (= <i>Speotyto</i>) <i>cunicularia</i>	—	P	TY5	—
Common loon	<i>Gavia immer</i>	—	P	—	S
American white pelican	<i>Pelicanus erythrorhynchos</i>	—	P	TY2	—
Great egret	<i>Casmerodius albus</i>	—	P	—	—
White-faced ibis	<i>Plegadis chihi</i>	—	P	TY4	—
Long-billed curlew	<i>Numenius americanus</i>	SC	P	TY5	—
Loggerhead shrike	<i>Lanius ludovicianus</i>	—	P	TY3	—
Northern goshawk	<i>Accipiter gentiles</i>	—	P	TY3	S
Swainson's hawk	<i>Buteo swainsoni</i>	—	—	R	—
Trumpeter swan	<i>Cygnus buccinator</i>	—	G	TY3	S
Sharptailed grouse	<i>Tympanuchus phasianellus</i>	—	G	TY3	S
Boreal owl	<i>Aegolius funereus</i>	—	P	TY5	S
Flammulated owl	<i>Otus flammeolus</i>	—	P	TY3	S
Yellow-billed cuckoo ^f	<i>Coccyzus americanus</i>	C	P	TY1	—
Greater sage grouse	<i>Centrocercus urophasianus</i>	C	—	TY2	—
Mammals					
Gray wolf ^g	<i>Canis lupus</i>	LE/XN	E	TY1	—
Pygmy rabbit	<i>Brachylagus</i> (= <i>Sylvilagus</i>) <i>idahoensis</i>	SC	G	TY2	S
Townsend's Western big-eared bat	<i>Corynorhinus</i> (= <i>Plecotus</i>) <i>townsendii</i>	SC	P	TY3	S
Merriam's shrew	<i>Sorex merriami</i>	SC	P	—	—
Long-eared myotis	<i>Myotis evotis</i>	SC	P	TY5	—
Small-footed myotis	<i>Myotis ciliolabrum</i> (= <i>subulatus</i>)	SC	P	TY5	—

Table 2-3. (continued).

Common Name ^a	Scientific Name	Federal Status ^{b,c}	State Status ^c	BLM Status ^c	USFS ^d Status ^c
Western pipistrelle ^f	<i>Pipistrellus hesperus</i>	—	P	TY5	—
Fringed myotis ^f	<i>Myotis thysanodes</i>	—	P	TY3	—
California myotis ^f	<i>Myotis californicus</i>	—	P	TY4	—
Reptiles and amphibians					
Northern sagebrush lizard ^h	<i>Sceloporus graciosus</i>	SC	—	—	—
Ringneck snake ^f	<i>Diadophis punctatus</i>	C	P	TY5	—
Night snake ^e	<i>Hypsiglena torquata</i>	—	—	R	—
Insects					
Idaho pointheaded grasshopper ^f	<i>Acrolophitus punchellus</i>	—	—	TY2	—
Fish					
Shorthead sculpin ^{f,e}	<i>Cottus confusus</i>	—	R	—	—

- a. This list was compiled by N. Hampton from letters from the U.S. Fish and Wildlife Service (USFWS) (USFWS 1996, 1997, 2001, 2005) for threatened or endangered, and sensitive species listed by the Idaho Fish and Game Conservation Data Center (IDFG 1994 and IDFG 2008) and other species information for the Idaho National Laboratory Site (Reynolds et al. 1986).
- b. The U.S. Fish and Wildlife Service no longer maintains a candidate (C2) species listing but addresses former listed species as “species of concern” (USFWS 1996). The C designation replaces C2 (defined in CDC 1994).
- c. Status codes: BLM = Bureau of Land Management; INPS = Idaho Native Plant Society; 1 = State Priority 1 (INPS); 2 = State Priority 2 (INPS); C = candidate for listing - see item b; E = endangered; G = game species; GP1 to 3 = global rarity index; LE = listed endangered; LT = listed threatened; M = State of Idaho monitor species (INPS); P = protected nongame species; S = sensitive species; SC = species of concern designated in Idaho National Laboratory species update (USFWS 2005); T = threatened; U = undetermined; XN = experimental population, nonessential; TY1 through TY5 = rank from threatened or endangered to species of special concern; and R = removed or no longer appears on sensitive list (this nonagency code is included for clarification).
- d. U.S. Forest Service Region 4.
- e. Removed from the list as a result of updates to threatened or endangered and sensitive species lists (Bureau of Land Management, U.S. Fish and Wildlife Service, Idaho Native Plant Society, and U.S. Forest Service) (IDFG 2008).
- f. No documented sightings at the Idaho National Laboratory Site; however, the ranges of these species overlap the Idaho National Laboratory Site and are included as possibilities to be considered for field surveys.
- g. Anecdotal evidence indicates that isolated wolves may occur on the Idaho National Laboratory Site. However, no information exists to substantiate hunting or breeding on-site (Morris 2001).
- h. The sagebrush lizard was placed on the list as a result of a miscommunication; however, it remains on the official U.S. Fish and Wildlife Service update periodically issued for the Idaho National Laboratory Site (N. Hampton, BBWI, lecture at IDFG by Dr. Charles Peterson, Idaho State University, January 10, 2002, Idaho Falls, ID).

BBWI Bechtel BWXT Idaho, LLC
 BLM Bureau of Land Management
 IDFG Idaho Department of Fish and Game
 USFS U.S. Forest Service

The only species documented at the INL Site and currently recognized as threatened or endangered under the Endangered Species Act is the bald eagle, which was recently down-listed to threatened. The peregrine falcon, recently removed from the federal list, remains on the threatened list for the State of Idaho.

A number of species recorded at the INL Site no longer have status under the Endangered Species Act, but remain on the U.S. Fish and Wildlife Service list of species of concern for the INL Site (USFWS 2005). These species include the ferruginous hawk (*Buteo regalis*), long-billed curlew (*Numenius americanus*), greater sage grouse (*Centrocercus urophasianus*), pygmy rabbit (*Brachylagus idahoensis*), Merriam’s shrew (*Sorex merriami*), Townsend’s big-eared bat (*Corynorhinus townsendii*), long-eared myotis (*Myotis evotis*), and small-footed myotis (*Myotis ciliolabrum*). Painted milk-vetch (*Astragalus ceramicus* var. *apus*) also remains on the U.S. Fish and Wildlife Service periodic update for the INL Site (USFWS 2005) but has been removed from the list for the State of Idaho. The sagebrush

lizard (*Sceloporous graciosus*) was designated as a candidate for listing through a miscommunication^d but remains as a species of concern on the periodic threatened or endangered update for the INL Site (USFWS 2005).

2.1.4 Geology, Seismology, and Volcanology

The following sections discuss the regional and site-specific geology, seismology, and volcanology.

2.1.4.1 Regional and Site-Specific Geology/Topography. The INL Site is located on the west-central part of the ESRP, a northeast-trending structural basin about 322 km (200 mi) long and 80 to 112 km (50 to 70 mi) wide (Figure 2-6). The INL Site is underlain by a sequence of Tertiary and Quaternary volcanic rocks and sedimentary interbeds that are more than 3,048 m (10,000 ft) thick (Whitehead 1992). The volcanic rocks consist mainly of basalt flows in the upper part of the sequence and rhyolitic ash-flow tuffs in the lower part. Basalt and interbeds generally range in age from about 200,000 to 4 million years before present (Anderson, Liszewski, and Cecil 1997), and underlie the plain to depths ranging from about 670 m to 1,158 m (2,200 to 3,800 ft) below land surface.

Hundreds of basalt flows, basalt-flow groups, and sedimentary interbeds underlie the INL Site. Basalt makes up about 85% of the volume of deposits in most areas. A basalt flow is a solidified body of rock formed by the surficial outpouring of molten lava from a vent or fissure (Bates and Jackson 1980). A basalt-flow group consists of one or more distinct basalt flows deposited during a single, brief eruptive event. All basalt flows of a group erupted from the same vent or several nearby vents; represent the accumulation of one or more lava flows from the same magma; and have similar geologic ages, paleomagnetic properties, potassium contents, and natural-gamma emissions (Anderson and Bartholomay 1995). The basalt flows consist mainly of medium- to dark-gray vesicular to dense olivine basalt. Individual flows generally range from 3 to 15 m (10 to 50 ft) thick and are locally interbedded with scoria and thin layers of sediment. Sedimentary interbeds are as thick as 15 m (50 ft) and consist of well-sorted to poorly sorted deposits of clay, silt, sand, and gravel. In places, the interbeds contain or consist mainly of scoria and basalt rubble. Sedimentary interbeds accumulated on the ancestral land surface for hundreds to hundreds of thousands of years during periods of volcanic quiescence and are thickest between basalt-flow groups.

At least 178 basalt-flow groups and 103 sedimentary interbeds underlie the INL Site above the effective base of the aquifer (Anderson and Ackerman et al. 1996; Anderson, Liszewski, and Cecil 1997). Basalt-flow groups and sedimentary interbeds are informally referred to as A through S5. Basalt-flow groups A through L and related sediment range in age from about 200,000 to 800,000 years and make up the unsaturated zone and the uppermost part of the aquifer in most areas of the INL Site. Most wells in the southern and western parts of the INL Site are completed in basalt-flow groups AB through I, and the related sediments. Flow groups AB through I and related sediments range in age from about 200,000 to 640,000 years and make up a stratigraphic section characterized by horizontal to slightly inclined layers. Anderson, Liszewski, and Cecil (1997) estimated the geologic ages of basalts and sediments in the unsaturated zone and the SRPA from about 200,000 to 1.8 million years; average accumulation rates are reflective of a subsidence rate of 50 m (164 ft)/100,000 years.

d. N. L. Hampton, Bechtel BWXT Idaho, LLC, lecture at Idaho Fish and Game by Dr. Charles Peterson, Idaho State University, January 10, 2002, Idaho Falls, ID.

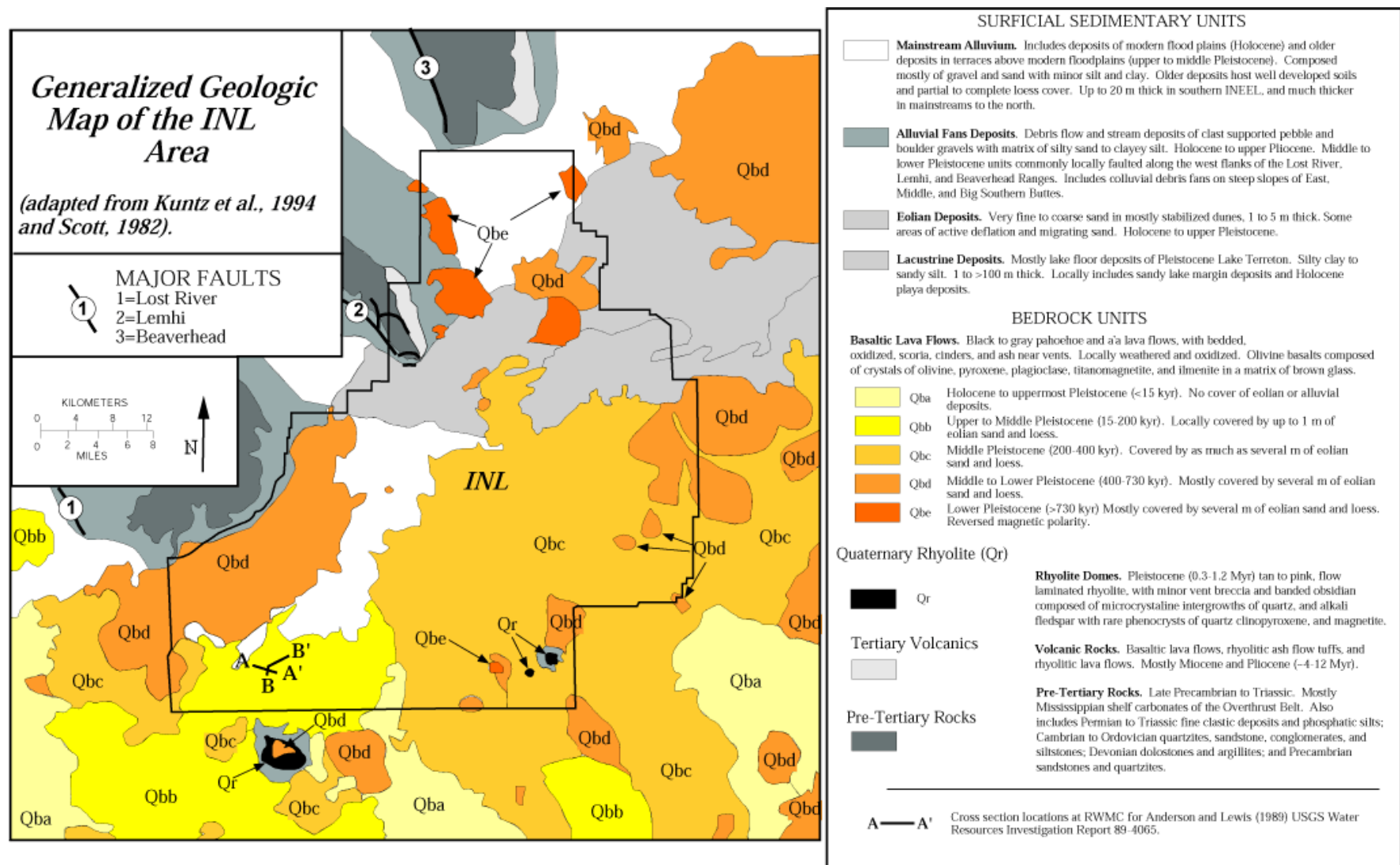


Figure 2-6. Generalized geological map of the Idaho National Laboratory Site area.

The nomenclature for the stratigraphy underlying the INTEC facility and the surrounding area is based on work presented by Anderson (1991) and Anderson and Ackerman et al. (1996). A north-south geologic cross section, illustrated in Figures 2-7 and 2-8, show the complexity of the subsurface at INTEC.

The stratigraphy of the aquifer at and near INTEC is dominated by thick, massive basalt flows of flow group I and thin, overlying flows of flow groups B through H. Significant changes in the flow thickness are often related to changes in the lithology of the flow or are caused by the flow margins in which the flow appears as a lobe of basalt. The lithologic changes that may cause a change in the flow thickness are the existence of pyroclastic deposits on or within a flow, or a flow being very vesicular, and, thus, more susceptible to the effects of erosion.

Based on the Anderson (1991) geologic cross section, the unsaturated zone and upper regional aquifer underlying INTEC are comprised of 19 basalt-flow groups, 11 sedimentary interbeds, and surficial alluvium. The sediments, as interpreted, appear to be primarily made up of sands and silts with some small clay lenses. The majority of the sediments are thin 0.3- to 1.5-m (1- to 5-ft) layers of silt between the major basalt flows. Sediments were most likely deposited in eolian or fluvial-type environments. Two major sediment sequences are shown on the cross sections: the upper sequence associated with the “CD,” thick “D,” and “DE2” sands and silts; and the lower sediments associated with the “DE6,” “DE7,” and “DE8” stratigraphic units.

The cross sections show a very thick sequence of sediments, particularly in the northern end of the south-north section, which are stratigraphically shown as the “CD,” “D,” and “DE2” units. These sediments appear to be a thick sequence of sands over silts and clays. The sediments associated with the “DE6,” “DE7,” and “DE8” stratigraphic units appear to be made up of gravels, silts, and clays. These sediments were most likely deposited in a fluvial environment and may indicate a braided stream deposit.

The geology beneath the ICDF has been characterized from information gathered from logs (lithologic, geophysical, and video) as well as tests (geotechnical and hydrologic) from the drilling of numerous SRPA and perched water wells and coreholes located in the vicinity of the ICDF and INTEC. The locations of wells closest to the ICDF are shown in Figure 2-9. East-west geologic cross sections through the ICDF (A-A' and B-B' in Figure 2-9) are shown in Figures 2-10 and 2-11. North-south geologic cross sections through the ICDF (C-C', D-D', and E-E') are shown in Figures 2-12 through 2-14.

The subsurface beneath the ICDF, as shown in Figure 2-9, is characterized by approximately 9 to 16.8 m (30 to 55 ft) of alluvial materials underlain by a series of basalt flows and discontinuous sedimentary interbeds. An intermittent layer of fine sand, silt, and clay known as “old alluvium” in the literature (designation SM to CL) ranges in thickness from 0 to 4 m (0 to 13 ft) and occurs at the top of basalt. The thickness correlates to low spots and depressions and tends to increase to the south and west of the ICDF. It is less prevalent in the northwest area. Sand lenses were periodically found within this layer. The sediments overlie vesicular dark gray, olivine basalt bedrock that may be weathered and fractured in the first several feet near the interface (DOE-ID 2000).

As can be seen in Figure 2-10, two very distinctive massive basalt flows can be used as marker beds and traced between most boreholes underneath the ICDF. The depth at which these distinctive flows occur varies between boreholes. The CD basalt flow occurs at a depth between approximately 41 to 53 m (135 and 175 ft), and the DE5 basalt occurs at a depth between approximately 98 and 120 m (320 and 395 ft) in USGS-57. The CD basalt flow is characterized by a higher-than-average natural-gamma count. Above the CD basalt flow is a fairly continuous series of thin interbeds interspersed with thin basalt

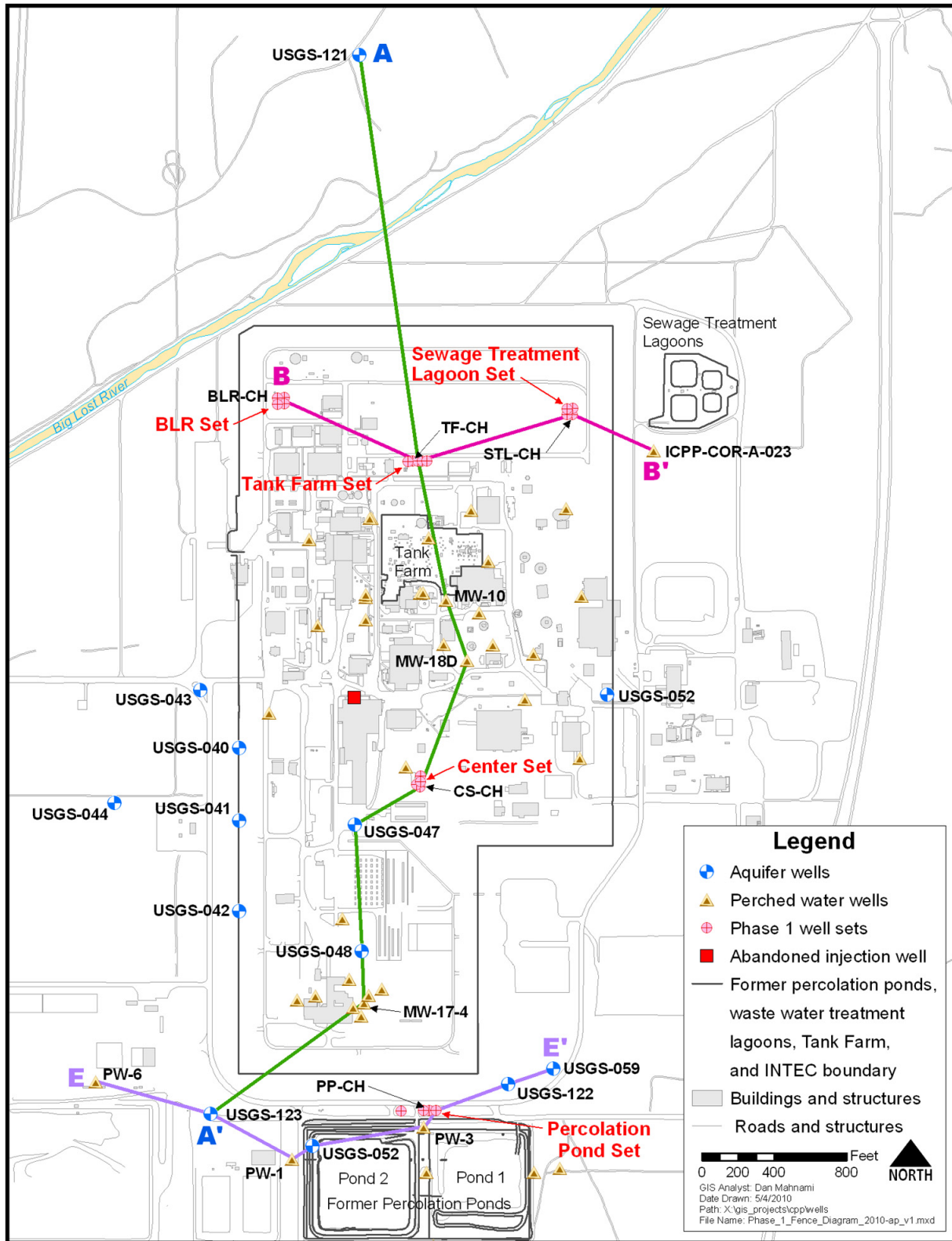


Figure 2-7. Plan view of cross section shown in Figure 2-8.

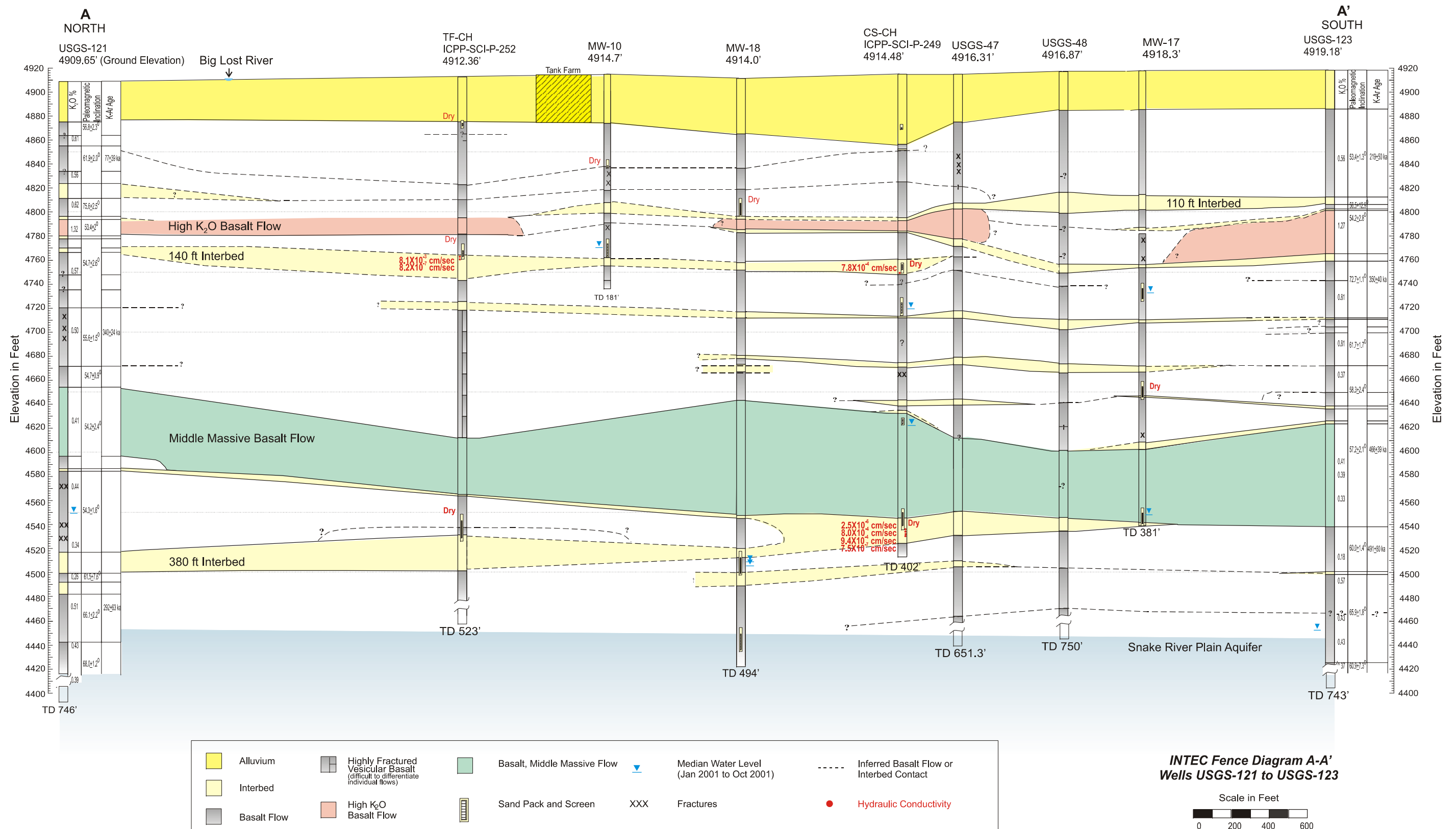


Figure 2-8. North-south geological cross section at INTEC.

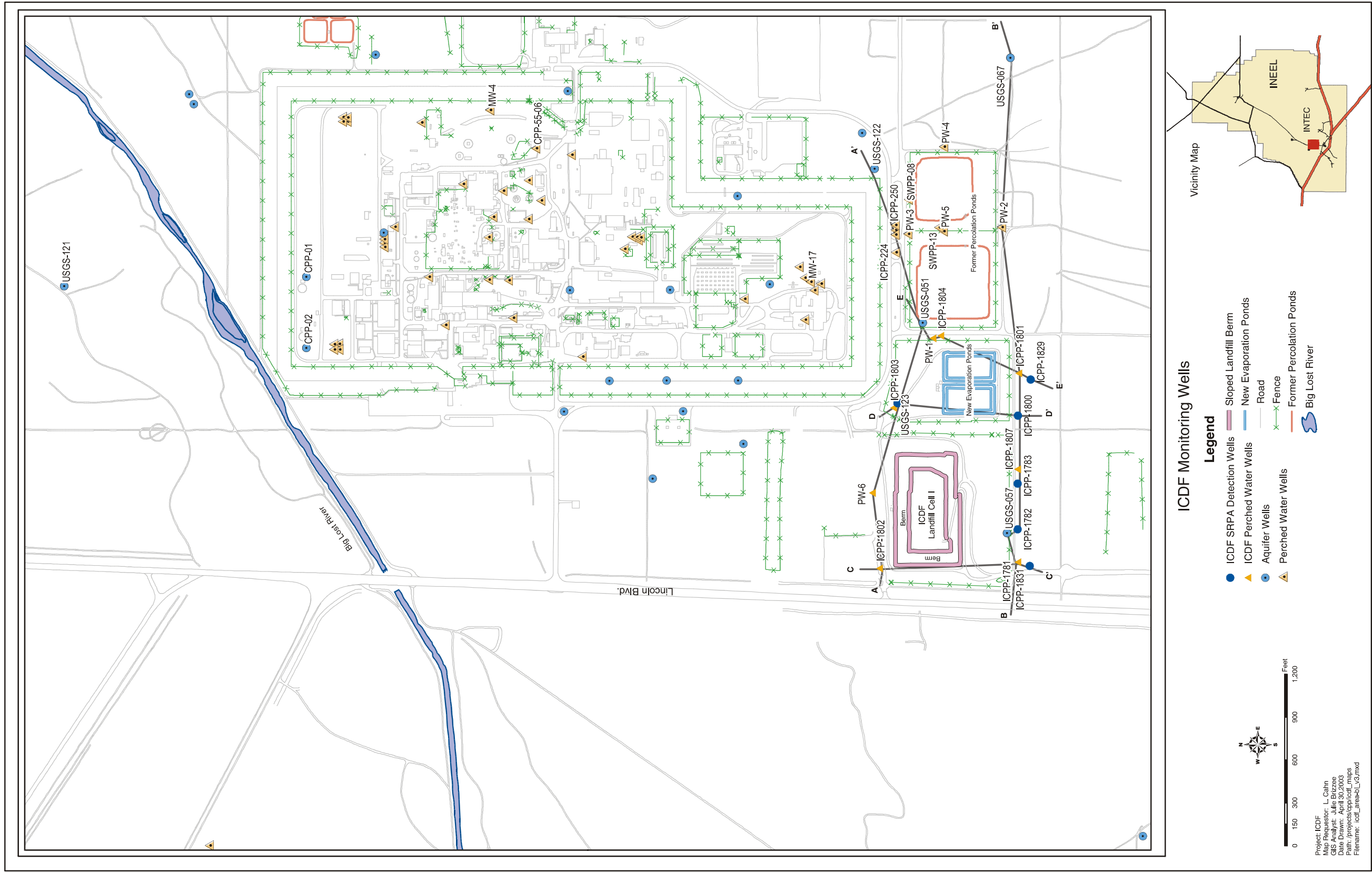


Figure 2-9. Locations of geologic cross sections and existing wells.

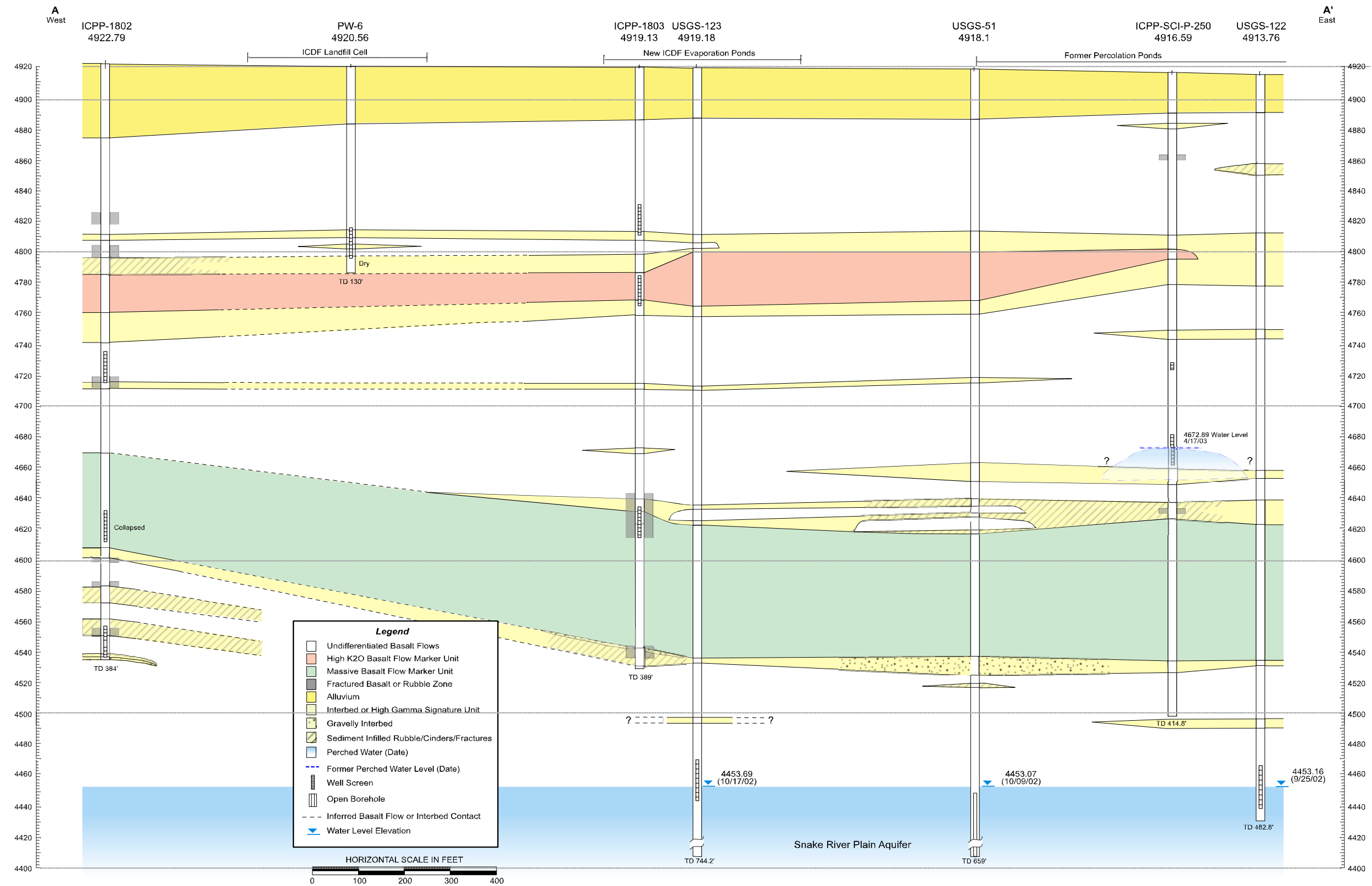


Figure 2-10. East-west geologic cross section A-A' through the ICDF.

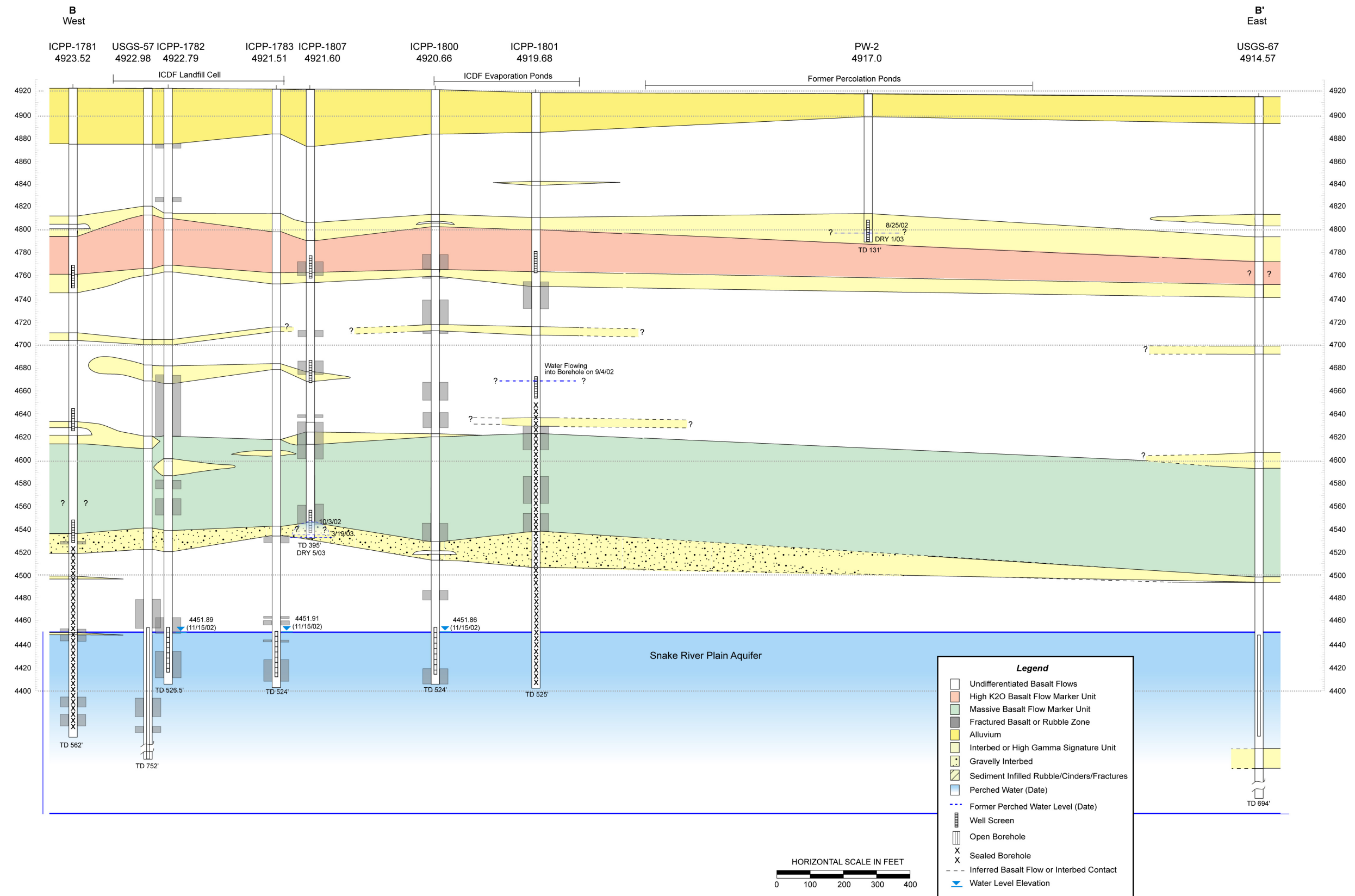


Figure 2-11. East-west geologic cross sections B-B' through wells south of the ICDF.

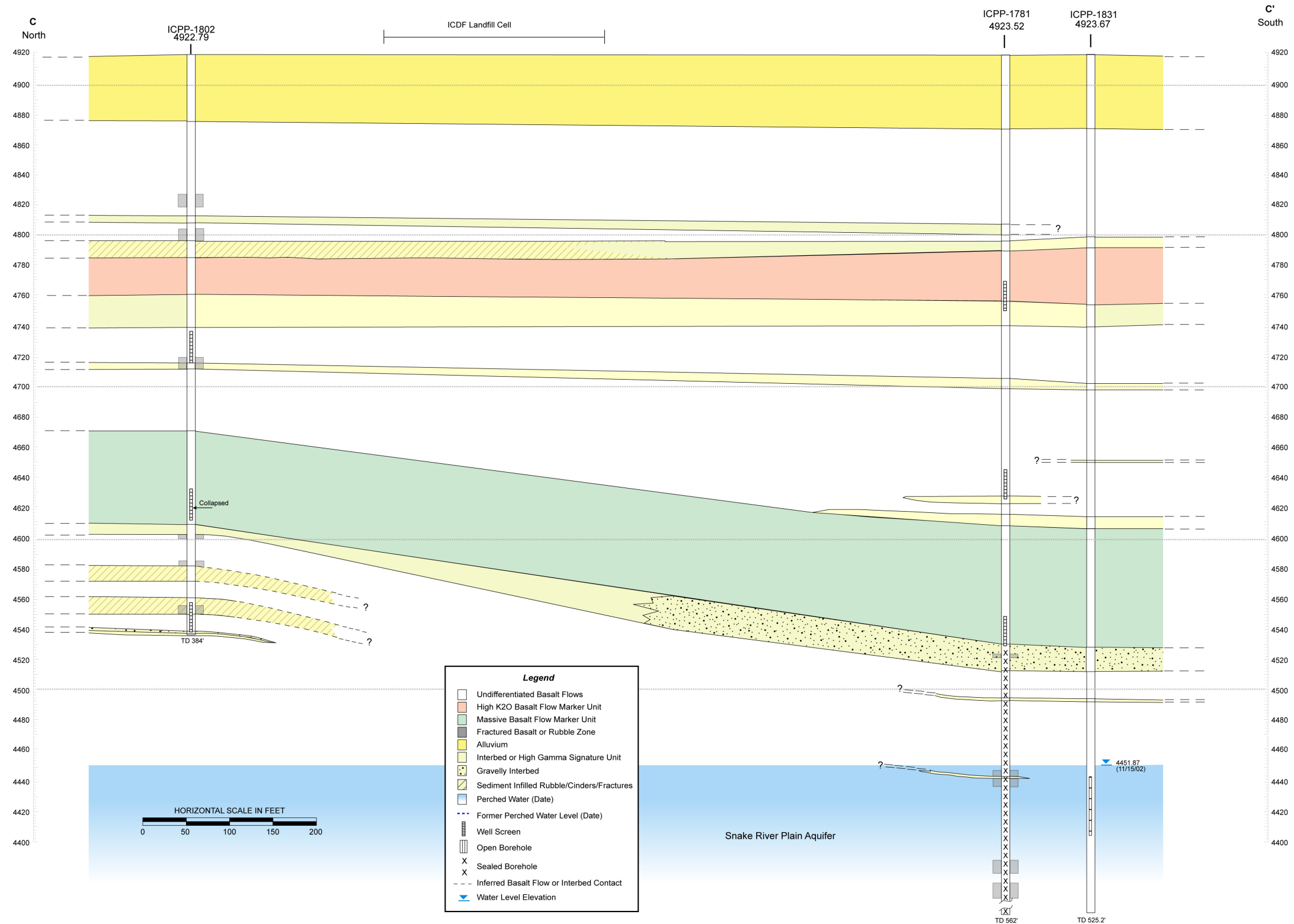


Figure 2-12. North-south cross section C-C' through wells west of the ICDF.

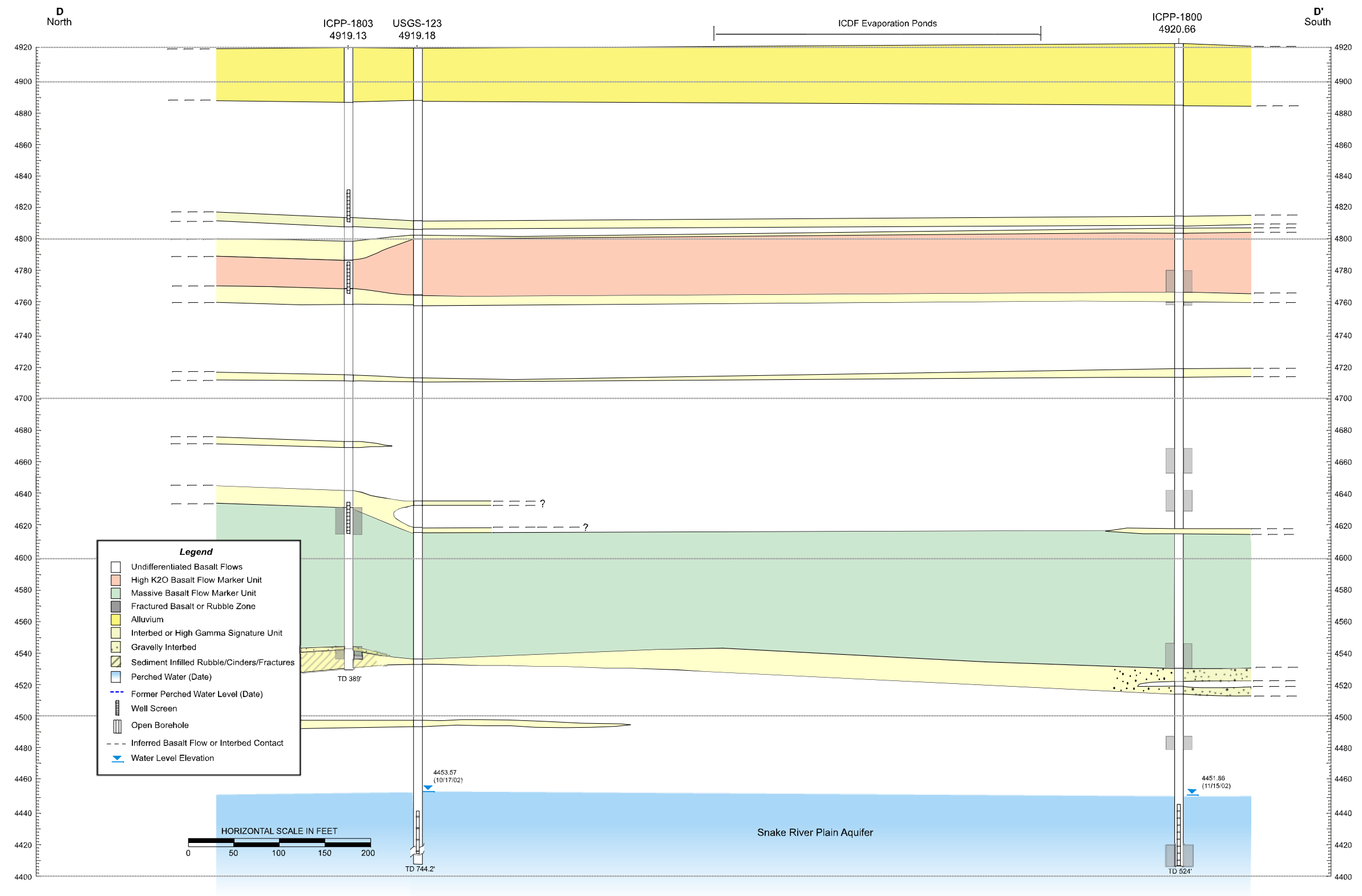


Figure 2-13. North-south cross section D-D' through the center of the ICDF Complex.

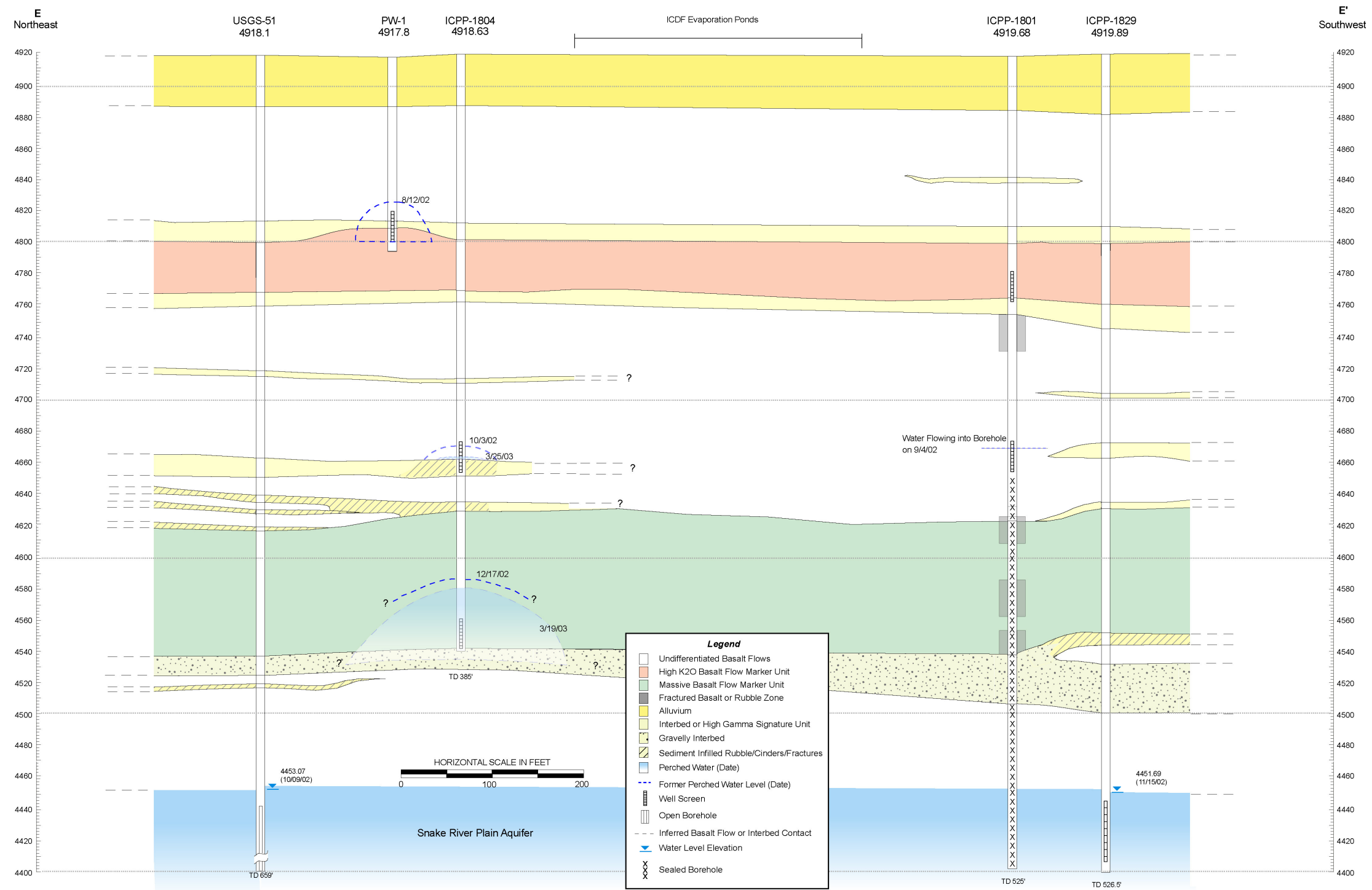


Figure 2-14. North-south cross section E-E' through wells east of the ICDF.

flows. This is the most continuous interbed underlying the ICDF and is the location of perched water that formed intermittently in response to wastewater discharges to the former percolation ponds. As can be seen in Figure 2-10, the other interbeds are discontinuous, are less massive, and cannot be traced horizontally between boreholes. The DE5 basalt is among the thickest and most massive of the basalt flows found in the subsurface underlying the ICDF and has a typical thickness of nearly 30 m (100 ft).

Well USGS-51 is completed in the SRPA and is just east of the ICDF, between the ICDF and the former west percolation pond. In this well, there are at least six sedimentary interbeds and 13 basalt flow groups. Narrow interbeds ranging from 1.2 to 4.5 m (4 to 15 ft) thick are interspersed with basalt flow groups ranging from 2.4 to 29 m (8 to 96 ft) thick (Anderson 1991).

Holocene surficial geology and archaeology suggest that fluvial and eolian deposition and tectonic subsidence in the INL Site area have been in approximate net balance for at least the past 10,000 years. A reversal of the long-term, regional pattern of ESRP subsidence, sedimentation, and volcanism into an erosional rather than a depositional regime would require major changes from the Holocene tectonic or climatic configuration of the ESRP. Worldwide geologic evidence indicates that the Quaternary epoch (approximately the past 2 million years) has been a time of major climatic fluctuations. During colder and wetter periods, glaciers occupied high-elevation areas. Lowland areas such as the ESRP received thick, widespread loess blankets. If the future ESRP climate were to become warmer and more arid, the probable consequences would be decreased vegetation and increased eolian transport of fine-grained sediment, mainly as longitudinal dunes of fine sand.

Future climate fluctuations on the ESRP, to either colder/wetter or warmer/drier conditions, are not expected to erode the INTEC land surface. Quaternary geologic and Holocene archaeological data suggest the INL Site area will probably continue its long-term history of regional subsidence and net accumulation of sedimentary and volcanic materials, although sedimentation patterns on the ESRP will change in response to future climate fluctuations.

Surface soil erosion at INTEC could occur as a consequence of faulting and uplift, but this erosion would involve a major change in the Quaternary tectonic configuration of the ESRP. Therefore, this scenario is improbable within the next 10,000 years, considering;

- The regional seismicity and tectonic history of the INL Site area
- The absence of Quaternary tectonic faults on the ESRP in the vicinity of the INTEC
- The long response time for significant erosion to occur as a result of protracted faulting and uplift.

In summary, the following impacts from volcanic and tectonic activity are relevant to INTEC radiological PA:

- During the past 4 million years, the ESRP and the INTEC area have undergone regional subsidence, basaltic volcanism, and fluvial and eolian sedimentation. Erosion has not been a significant process on the ESRP.
- Surficial and subsurface geologic data indicate that the INTEC area has both subsided and accumulated basalt lava flows and sediments at an average rate of 0.03 cm (0.01 in.)/year. Significant uplift or erosion has not interrupted this long-term trend.
- Lava inundation or magma intrusion associated with volcanism from the nearby Arco Volcanic Rift Zone is improbable considering the volcanic history of the area. Lava inundation or magma intrusion would not likely result in the release of radionuclides to the environment.

2.1.4.2 Seismology. The seismically active Intermountain seismic belt and Centennial Tectonic seismic belts surround the ESRP. Seismic activity in eastern Idaho is concentrated along the Intermountain seismic belt, which extends more than 1,287 km (800 mi) from southern Arizona through eastern Idaho to western Montana. INTEC is subject to the same seismic conditions. The Centennial seismic belt extends from central Idaho into southwestern Montana.

A historical catalog has been compiled from regional seismic networks for earthquakes within a 322-km (200-mi) radius of the INL Site that have magnitudes 2.5 and greater and occurred from 1872 to 2004 (Figure 2-15). This distribution of epicenters indicates that the Snake River Plain is devoid of earthquakes relative to the active areas surrounding it, with the possible exception of the 1905 earthquake located at Shoshone, Idaho (WCFS 1996). Historical records suggest that the epicenter for the 1905 earthquake is not located within the Snake River Plain but, rather, near the Idaho/Utah border.

The INL Site has maintained a seismic network for monitoring earthquake activity on and around the ESRP since December 1971. Currently, the seismic network consists of 27 seismic stations and 25 strong-motion accelerographs. The seismic stations continually record seismic data that are used to calculate the locations and magnitudes of earthquakes that occur locally. When triggered, the strong-motion accelerographs record earthquake ground motions within INL Site buildings or free-field sites that may be generated by local moderate to large earthquakes.

The INL Site seismic network has compiled earthquake epicenters for all magnitudes within a 161-km (100-mi) radius of the INL Site occurring from 1973 to 2004 (Figure 2-16). During this period, approximately 30 microearthquakes have been located within the ESRP, indicating that infrequently occurring, small-magnitude earthquakes ($M < 1.5$) are characteristic of ESRP seismicity (Jackson et al. 1993; Pelton, Vincent, and Anderson 1990). These data are in agreement with the historical earthquake data compiled for the surrounding region (Figure 2-15).

A large earthquake, in the vicinity of the INL Site, but outside the Snake River Plain, occurred in the Centennial seismic belt on October 28, 1983, with a surface-wave magnitude of 7.3 (Figure 2-15). The earthquake resulted from slippage along the Lost River fault—a northwest rupture along a normal fault with relative vertical movement downward to the west. The epicenter for this event was located in the Thousand Springs Valley near the western flank of Borah Peak, approximately 89 to 97 km (55 to 60 mi) from INL Site facilities. There was substantial damage to masonry structures in the local communities of Mackay and Challis near the epicentral area. Although the earthquake ground motions were felt at the INL Site, only minor damage occurred in the form of hairline cracks and settlement to nonnuclear buildings (Gorman and Guenzler 1983). INTEC did not experience structural failures or waste spills as a result of the earthquake, and waste storage facilities did not show evidence of permanent movement or resulting damage. Peak ground accelerations ranging from 0.022 to 0.078 g were recorded at several INL Site facility areas. The INL Site was located in Modified Mercalli Intensity Zone VI during the earthquake (Jackson 1985).

The largest historic earthquake in the region occurred on August 17, 1959, at Hebgen Lake, Montana, located approximately 193 km (120 mi) northeast of the INL Site (Figure 2-15). The event had a surface-wave magnitude of 7.5 and was felt at the INL Site, but it caused no damage at the Site.

Because the seismically active Intermountain and Centennial seismic belts surround the ESRP and several Quaternary faults are located near the western boundary of the INL Site, seismic hazard assessments were completed for all facility areas at the INL Site (WCFS 1996; INEEL 2000; Payne et al. 2002; SAR-II-8.4). Seismic hazard evaluations were conducted using a probabilistic methodology that incorporates the most up-to-date region- and site-specific geologic, seismologic, and geotechnical information for the INL Site. These assessments quantitatively estimated peak ground motions that

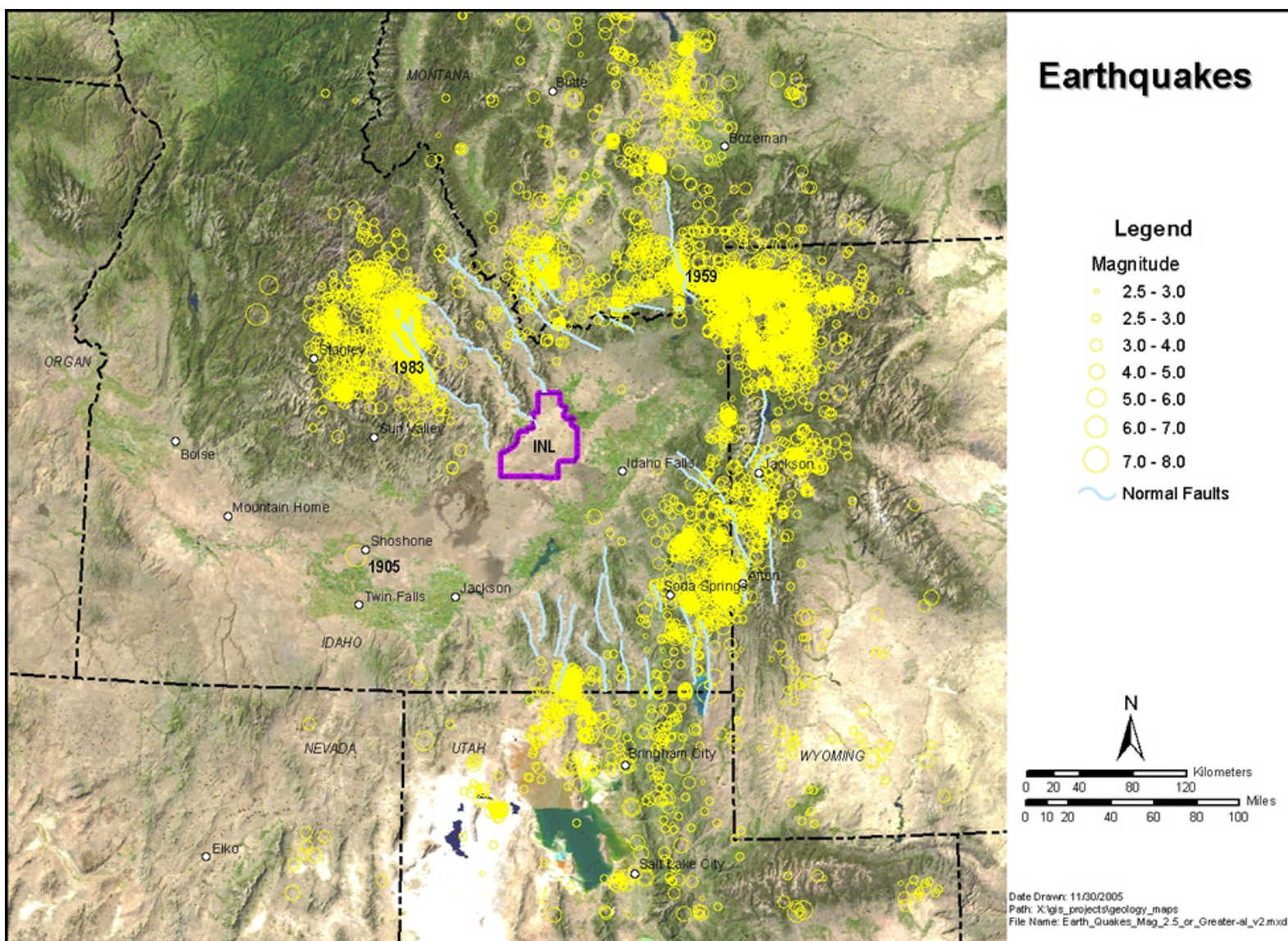


Figure 2-15. Map shows earthquake epicenters compiled from regional seismic networks for magnitudes greater than 2.5 occurring from 1872 to 2004.

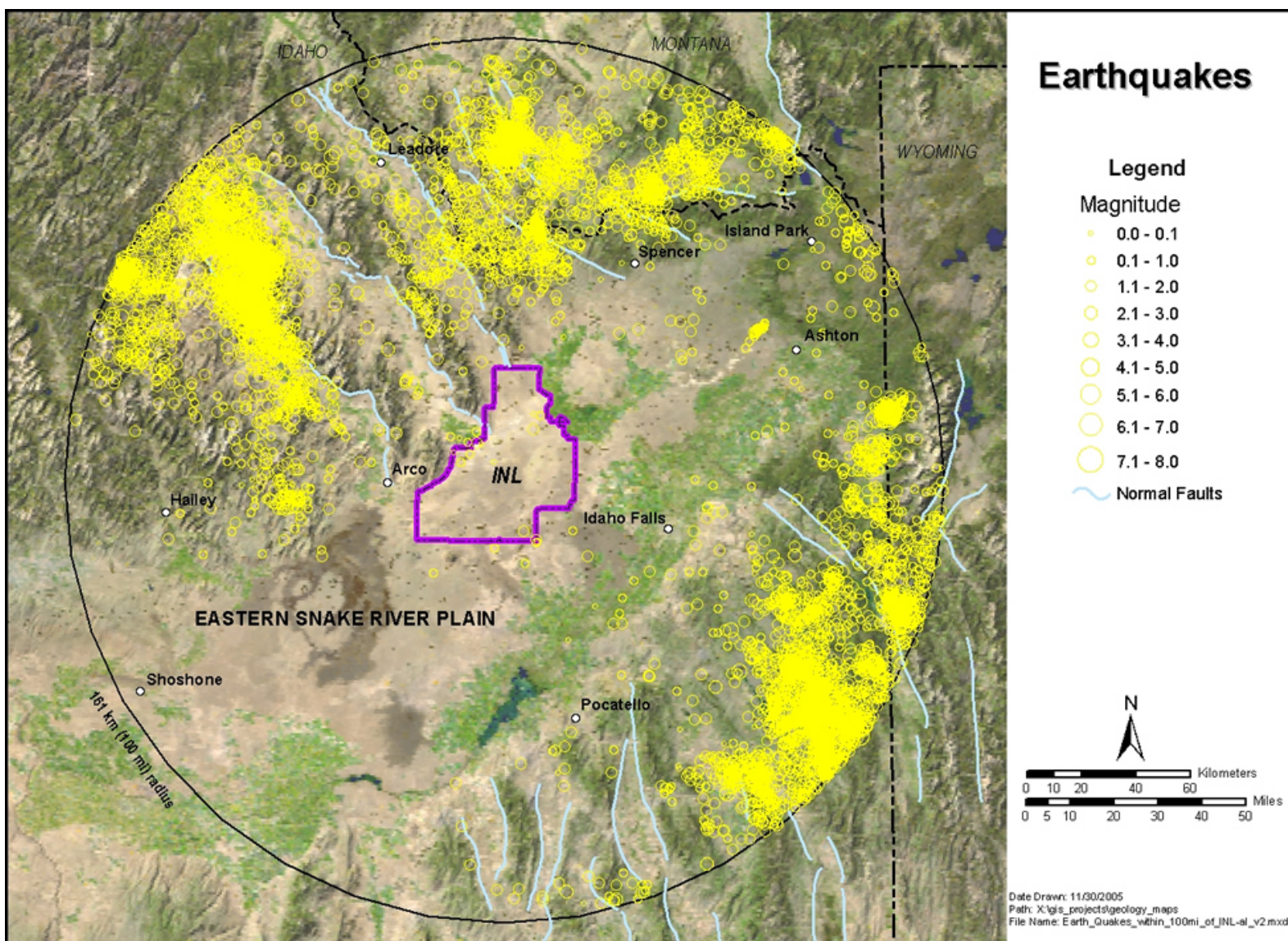


Figure 2-16. Map shows earthquake epicenters compiled by Idaho National Laboratory Site seismic monitoring occurring from 1973 to 2004.

INL Site facilities may experience from nearby large-magnitude earthquakes. The site-specific geological, seismological, and geotechnical data used in INL Site ground motion evaluations were provided to the U.S. Geological Survey (USGS), who also used these data to develop the national seismic hazard maps. The seismic design levels in the form of peak ground accelerations are obtained from the USGS seismic hazard maps (USGS 2005) for the International Building Code (ICC 2000), which is currently used for nonnuclear facilities at INTEC. Seismic stability evaluations have been conducted for the landfill and they indicate the factor of safety requirements have been met (EDF-ER-282). It was concluded the ICDF Landfill and final cover design are stable under seismic loading conditions.

2.1.4.3 Volcanology. The INL Site is located in a region of Pleistocene and Holocene volcanic activity typically characterized by nonviolent, effusive basalt lava flows (Hackett and Smith 1992). Explosive rhyolite volcanism occurred beneath the INL Site 4 to 7 million years ago, forming calderas now buried beneath basalt lava flows. In the region immediately surrounding the INL Site, the youngest lava flow erupted about 4,100 years ago from Hell's Half Acre Lava Flow southeast of the INL Site. Within INL Site boundaries, the most recent lava flow—the Cerro Grande flow—occurred 13,000 years ago, near the southern boundary (Hackett, Pelton, and Brockway 1986).

Renewed explosive rhyolite volcanism at the INL Site is very unlikely. Geological and geochronological data indicate an eastward progression of silicic volcanism. The mantle plume or hotspot assumed responsible for the volcanism now lies beneath Yellowstone National Park. Past patterns of volcanism suggest that future volcanism at the INL Site within the next 1,000 to 10,000 years is very improbable (INEL 1990), and the two most likely sources of future basalt flows on the INL Site are the Arco-Big Southern Butte and Lava Ridge-Hell's Half Acre rift zones (see Figure 2-17).

Most of the INL Site is underlain by a 0 to 1-km (0 to 0.6-mi) -thick sequence of Tertiary and Quaternary basalt lava flows and interbedded sediments. Based on drill-hole information, regional mapping along the margins of the ESRP, and geophysical information, the basalt and sediment sequence is underlain by an older section (up to several kilometers thick) of late Tertiary rhyolitic volcanic rock. These two volcanic sequences are a consequence of the passage of the Yellowstone mantle plume (hotspot) through the INL Site area of the ESRP in late Tertiary. The Tertiary rhyolitic volcanic rocks were erupted 6.5 to 4.3 million years ago when the hotspot resided beneath the INL Site area (Pierce and Morgan 1992). These volcanic rocks are composed mostly of ash-flow tuffs erupted during large, violent explosive episodes and large rhyolitic lava flows. These rocks are analogous to the ash flow tuffs and lava flows that erupted from calderas in the Yellowstone Plateau from 2.0 to 0.6 million years ago.

These types of large-scale explosive eruptions can occur only directly over the position of the mantle hotspot because large inputs of heat into the lower and middle crust are required to generate such large volumes of rhyolitic magma. Because the hotspot is now situated beneath Yellowstone National Park, there is no possibility for recurrence of this type of volcanic activity in the INL Site area. Regional extension of the crust and residual heat in the upper mantle after passage of the hotspot has resulted in basaltic magmas that have risen to the surface and erupted onto the subsiding ESRP. Basaltic eruptions in the INL Site area began at about 4 Ma, soon after passage of the hotspot, and have occurred as recently as 2,100 years ago along the Great Rift.

Basalt vents on the ESRP include broad, low-relief shield volcanoes, small spatter cones, and spatter ramparts along eruptive fissures. Lava fields related to single vents range in surface area from 2 to 400 km² (0.7 to 154 mi²) and in volume from 0.05 to 7 km³ (0.01 to 1.7 mi³) (Kuntz, Covington, and Schorr 1992). Volcanic vents are not randomly distributed on the ESRP; they are concentrated in northwest-trending linear zones known as volcanic rift zones (Figure 2-17).

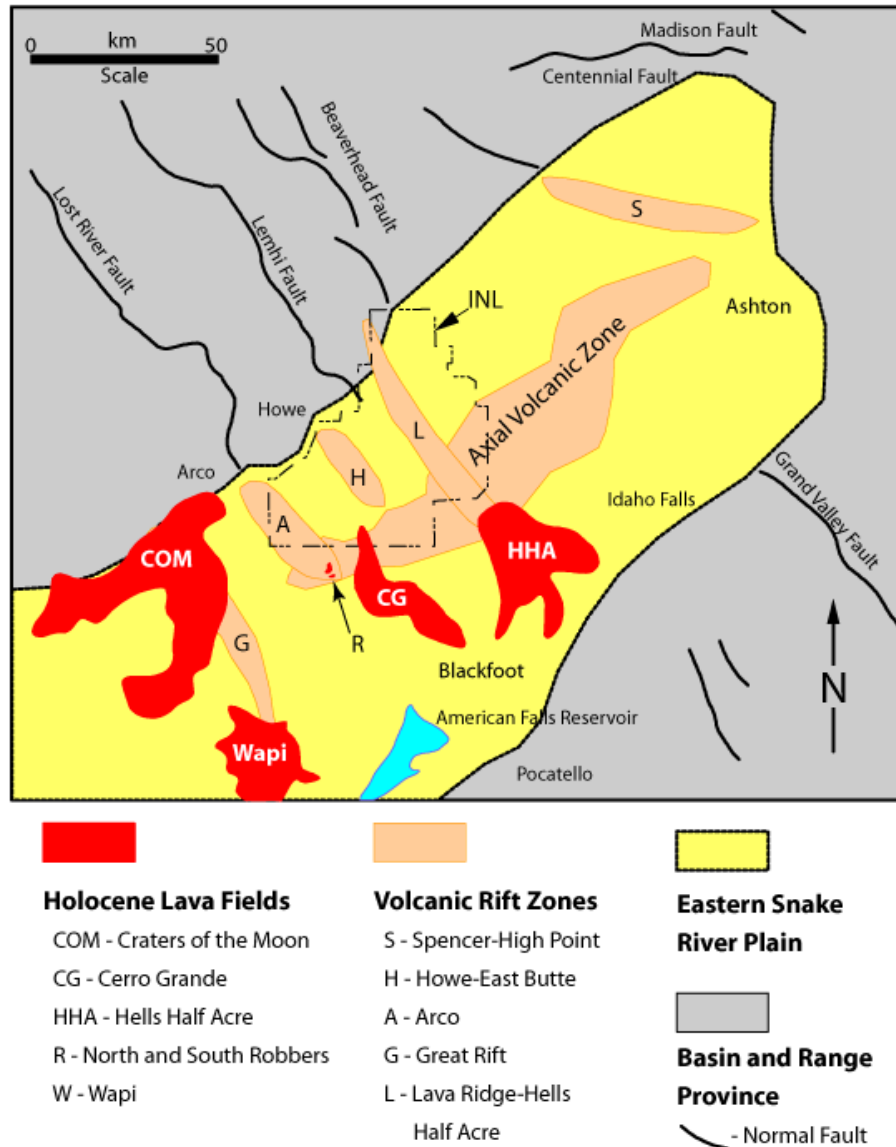


Figure 2-17. Map showing the locations of volcanic rift zones and Holocene basalt lava fields.

In addition, vents are concentrated in a northeast-trending zone, known as the Axial Volcanic Zone, along the central axis of the ESRP. The Axial Volcanic Zone is a constructional highland caused by more voluminous magma output along the axis of the ESRP.

Based on radiometric age determinations of basalt lava flows, the Arco Volcanic Rift Zone north of Big Southern Butte was active between 600,000 and 100,000 annum (ka) (Kuntz, Covington, and Schorr 1992). The Cerro Grande and North and South Robbers flows (10,500 to 12,000 ka) near Big Southern Butte occur at the intersection of the Arco Volcanic Rift Zone and the Axial Volcanic Zone. Except for volcanism along the Great Rift, all of the Holocene volcanic fields of the ESRP occur along the Axial Volcanic Zone (Figure 2-17). Recurrence of volcanism in the ESRP has a greater likelihood of occurring along the Great Rift or the Axial Volcanic Zone. The estimated volcanic-recurrence interval near the INTEC is 45 ka and the corresponding annual eruption probability is $6E-05$ per year (Hackett, Smith, and Khericha 2002).

Available geologic map data and geochronometry of basalt lava flows at the INL Site suggest minimum (i.e., most conservative) volcanic-recurrence intervals of E-04 to E-05/year for the Axial Volcanic Zone and the Arco and Lava Ridge-Hell's Half Acre volcanic rift zones. Therefore, probabilistic risk of basalt lava inundation or intrusion-related ground disturbance is estimated to be less than E-05/year (i.e., 1 chance in 100,000/year) for the southern INL Site. The probability of significant impact from volcanic phenomena (e.g., growth of new rhyolite domes on the ESRP or tephra falls thicker than 8 cm [3 in.] from non-Snake River Plain vents) is estimated to be less than E-05/year because of the combined effects of great distance, infrequency, low volume, and topographic or atmospheric barriers to dispersal of tephra on the INL Site.

INTEC is unlikely to be impacted by tephra-, gas-, or dike-induced ground deformation, since it is not within a mapped volcanic rift zone. The chief volcanic hazard at INTEC is inundation by lava flows from source vents outside INTEC boundaries as suggested by Hackett, Smith, and Khericha (2002). The Volcanism Working Group (INEL 1990) estimated the probability of inundation of INTEC by basalt flows to be E-06 (i.e., 1 chance in 1,000,000) per year.

2.1.5 Hydrology

The following sections discuss the surface water and groundwater at the ICDF Landfill site and vicinity.

2.1.5.1 Surface Water. Surface water sources at INTEC and near ICDF have included (1) the Big Lost River (when flowing), (2) infiltration of rain and snowmelt, (3) the former percolation ponds (taken out of service August 2002), and (4) the former Sewage Treatment Plant infiltration trenches (taken out of service December 2004).

The Big Lost River is the major surface water feature on the INL Site. At its closest point, the channel of the Big Lost River lies within 30 m (100 ft) of the northwest corner of the INTEC facility, and about 1 km (0.6 mi) from the ICDF Landfill location. The Big Lost River is an intermittent stream that flows north through the INL Site to its terminus at the Big Lost River sinks, where all of the water either infiltrates into the ground or evaporates. The stretch of the Big Lost River on the INL Site is ephemeral with no recreational or consumptive uses (e.g., irrigation, manufacturing, or drinking) of the water. In addition, there are no identified future uses of surface water that may enter onto the INL Site.

Big Lost River flows are regulated at Mackay Reservoir, which is located approximately 40 miles to the northwest of the INL Site. Flows that reach the INL Site may be diverted at the INL Site diversion dam to flow to the flood control "spreading areas" located southwest of RWMC. Water that is not diverted to the spreading areas continues to flow northward across the INL Site in a shallow channel to its terminus at the Big Lost River sinks. Flow that reaches the Big Lost River sinks is lost to a combination of evaporation and infiltration.

When it is flowing, the Big Lost River constitutes a source of recharge to perched water and the aquifer. However, this recharge is limited to the immediate vicinity of the Big Lost River, and with the ICDF 1 km (0.6 mi) away from the river, it is not a significant source of recharge near the landfill. Flow in the Big Lost River depends on winter snowpack conditions and whether controlled releases are occurring from Mackay Reservoir. Figure 2-18 shows the mean daily discharge (flow rate) for the Big Lost River at the Lincoln Boulevard gaging station at INTEC during the period 1984 to 2008. The river flowed for extended periods during the wet years of 1984 to 1987 and again during 1995 to 2000. During periods of below-normal precipitation/snowpack, the Big Lost River near ICDF may remain dry for several years in a row. Most recently, the Big Lost River was dry from May 2000 through May 2005 as the result of a 5-year drought. However, due to above-normal snowpack during 2004–2006, brief periods

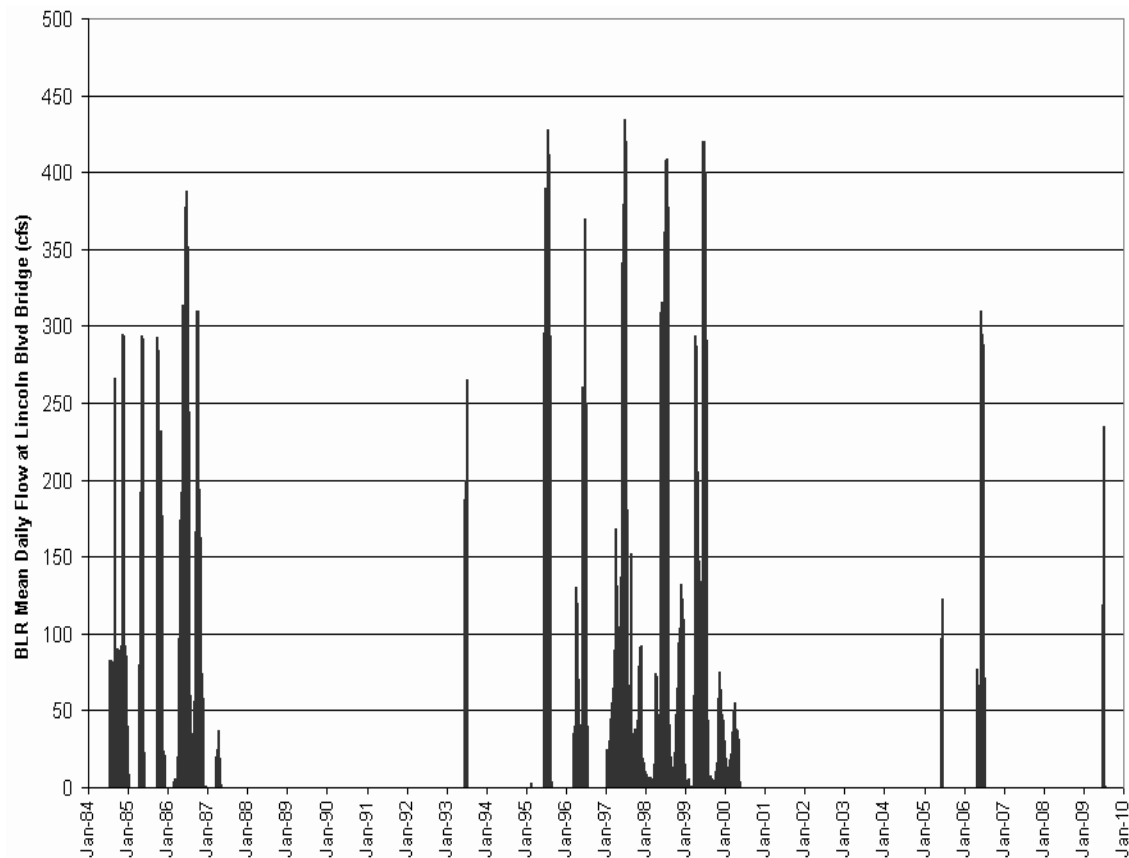


Figure 2-18. Big Lost River hydrograph 1984–2009.

of river flow occurred at INTEC during the spring and early summer months of 2005, 2006, and 2009. When flow does occur, peak flows are typically in June and July due to snowmelt, and there is often no flow in the river during the winter months.

Perched water levels are monitored in the INTEC area and the approximate lateral extent of the northern shallow perched water from the Big Lost River is also evaluated each year (DOE-ID 2010c). Consistent with the hydrograph depicted in Figure 2-18, during 2008 and 2009, shallow perched water wells were essentially dry (<0.5 ft of water). The Big Lost River flowed past INTEC between June 18 and July 4, 2009. However, only one monitoring well (Well BLR-CH located closest to the river and 500 ft from the river channel) showed a significant water-level response to the river flow event. After a 4-day time lag following the onset of flow in the river, the perched water level in Well BLR-CH rose 22 ft over 16 days. No other wells showed any response to flow changes in the river (see DOE-ID 2010c). The ICDF landfill is located about 1 km (0.6 mi) away from the Big Lost River channel, and these data support the assumption neglecting any influence of recharge from the Big Lost River on vadose zone flow at the ICDF landfill.

The ICDF Landfill is located outside the 100-year flood plain of the Big Lost River (Ostenaa and O’Connell 2005). This conservative flood plain study estimates a 100-year peak flow of 3,072 cfs onto the INL Site and indicates a potential for flooding in the north end of INTEC. The ICDF Landfill site location at an average elevation of 1,500 m (4,922 ft) and about 1 km (0.6 mi) south of the Big Lost River is located outside of the Big Lost River 100-year flood plain. Flood inundation maps (Ostenaa and O’Connell 2005, Appendix E) showing water depths near the ICDF Landfill indicate the landfill is

outside the inundation area through the 2,000-year flood plain, beyond the 1,000-year period of compliance defined by DOE O 435.1 Chg 1. An evaluation of the INTEC geomorphic setting (based on soil profiles taken along the Big Lost River and used to develop a late Quaternary soil chronosequence) indicates that INTEC is sited on geomorphic surfaces that are well in excess of 10,000 years in age. This evaluation suggests that the hazard of significant flooding of this area by the Big Lost River is low under natural channel conditions (Ostenaar et al. 1999). Flood water containment will be maintained beyond the institutional control period because of (a) a final cover that will be designed to prevent surface water erosion (see Section 2.2.2.1) and (b) the very low probability ($<5E-04$) of natural unregulated flows of the Big Lost River flooding the ICDF Landfill (Ostenaar and O'Connell 2005).

Existing surface conditions at the ICDF site consist of relatively flat terrain overlain with native sagebrush. The land slopes downward at approximately 0.3% in the northeast direction. Soil conditions are porous with a relatively low percentage of clay material. Natural depressions are present throughout the drainage basin. There are no natural channels or drainage-ways on or near the ICDF. The basin area, including the ICDF, is approximately 22.3 ha (55 acres). The existing paved roadway located west of the ICDF serves as a barrier to any additional flows west of the roadway. An investigation was performed to determine water surface elevations in the channels surrounding the ICDF under severe site conditions. Such conditions include accumulation of ice within the channel cross section, a frozen land surface resulting in decreased infiltration, and accumulation of snow on the drainage area prior to the rainfall event. Under these conditions, the drain channels surrounding the ICDF have been shown to adequately transport the increased flows without overtopping. In the event that the channels should overtop, the embankment surrounding the ICDF would prevent run-on/run-off from entering into the cells. The perimeter ditch channels are located approximately 36.6 m (120 ft) away from the ICDF cell, which would preclude any subsurface infiltration into the cell due to the limited hydraulic gradient between the ditch and the ICDF cell locations.

The facility storm water drainage system is designed to (1) direct storm water and snowmelt run-off around the ICDF and (2) minimize soil erosion on and around the facility (EDF-ER-270). Erosion control measures include silt fences, planted vegetation, and temporary straw bale check structures. Run-off is directed with the use of ditches. The ditches are sized to accept run-off from offsite areas in addition to drainage produced from the landfill. The ICDF Landfill has been designed to accommodate the run-on/run-off from a 25-year, 24-hour storm event (DOE-ID 2001; EDF-ER-270).

2.1.5.2 Precipitation Infiltration. Rain and snowmelt periodically infiltrate into the gravelly alluvium in and around ICDF and the INTEC facility. Even though average annual precipitation (22.1 cm/year) is much less than the pan evaporation rate (109 cm/year), water from snowmelt or heavy rains can and does infiltrate into the ground to depths where it cannot evaporate. This water then continues to move downward until it recharges perched water and the aquifer.

The combination of coarse surficial sediments and lack of vegetation permits infiltration of a large fraction of the natural precipitation. Furthermore, many areas at INTEC are occupied by buildings or are paved with asphalt or concrete. Precipitation falling on building roofs is routed to downspouts. Water falling on paved surfaces tends to flow laterally to the pavement edge, where it may then flow into drainage ditches. The ditches are mostly unlined, and a significant fraction of infiltration is likely to occur along the ditches. Therefore, infiltration may actually be greater due to the impervious areas, which act to focus much of the surface run-off into gravelly areas or unlined drainage ditches.

The OU 3-14 Remedial Investigation/Baseline Risk Assessment (RI/BRA) (Cahn et al. 2006) concluded that the recharge rate inside the INTEC security fence may be approximately 18 cm/year, which constitutes 85% of the average annual precipitation (22 cm/year). Additional details regarding precipitation infiltration and recharge rates can be found in that report.

2.1.5.3 Anthropogenic Water Infiltration. Anthropogenic water includes intentional clean water discharges to the ground and accidental water leaks from underground water pipelines. It has been demonstrated that anthropogenic water infiltration at INTEC can be more important than precipitation infiltration with respect to perched water recharge (DOE-ID 2007b).

Over the past 5 years, several remedial actions have been performed to reduce anthropogenic recharge rates at and near INTEC. These actions include:

- Old percolation ponds taken out of service (2002)
- Concrete-lined ditches installed around tank farm (2003–2004)
- Lined evaporation pond installed (2003)
- Sewage effluent re-directed to new percolation ponds (2004)
- Lawn irrigation eliminated (2005)
- Subsurface injection of steam condensate eliminated (2008)
- Plastic liner installed in North Ditch (2009)
- Underground water line leaks located/repared (ongoing).

Of the actions listed above, the elimination of the former percolation ponds in 2002 was the most significant in reducing anthropogenic recharge near ICDF and the southern portion of INTEC. ICDF has little or no anthropogenic recharge and none is expected in the future.

2.1.5.4 Perched Water. Perched water zones have been observed at various depths within the 460-ft-thick vadose zone beneath INTEC as early as 1956 (Robertson, Schoen, and Barraclough 1974). Perched water has been observed at depths that coincide with the presence of low-permeability sedimentary interbeds within the thick sequence of basalt flows. Water moves downward through the alluvium, into fractures in the basalt, and continues vertically downward with minor lateral spreading until it encounters sedimentary interbeds, where vertical flow is impeded. Perched water has been observed in two distinct geographic areas: northern and southern INTEC. Based on the distribution and geochemistry of the perched water, it has been determined that the northern and southern shallow perched water systems were discontinuous, with separate recharge sources (Cahn et al. 2006).

Perched water was present in the southern portion of INTEC as early as 1963 (Robertson, Schoen, and Barraclough 1974), but larger volumes of perched water began to accumulate in this area starting in 1984 when the former percolation ponds began receiving service wastewater. Prior to 2002 when the former percolation ponds were taken out of service, the principal zones of southern perched water observed were (1) intermittent perched water in the alluvium at the top of basalt at 30 ft bgs, (2) shallow perched water at the 110-ft interbed, (3) intermediate perched water at a low-permeability basalt or interbed at 250 ft bgs, and (4) deep perched water at the 380-ft sedimentary interbed.

The relocation of the INTEC percolation ponds in August 2002 to their present location 2 miles west of INTEC caused a large reduction in anthropogenic recharge, resulting in rapid drain out of perched water beneath the ICDF and the southern part of INTEC. By 2004, nearly all of the perched water monitoring wells near ICDF and the former percolation ponds had gone dry (Figure 2-19). Well locations are shown in Figure 2-9. More details regarding the accumulation and subsequent dissipation of perched water beneath the former percolation ponds can be found in Cahn and Ansley (2004) and Cahn et al. (2006).

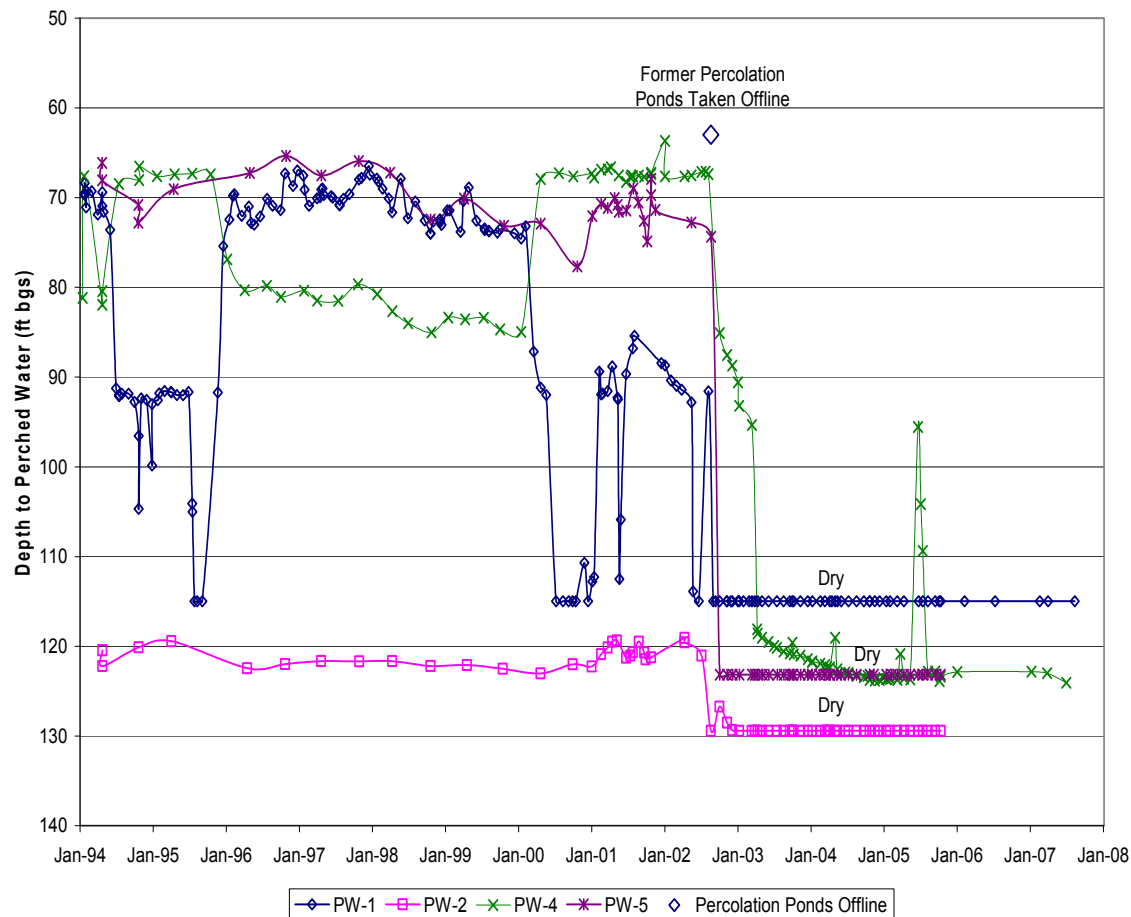


Figure 2-19. Hydrographs for selected perched water monitoring wells near ICDF.

2.1.5.5 Snake River Plain Aquifer. The SRPA, one of the largest and most productive groundwater resources in the United States, underlies the INL Site. The aquifer is listed as a Class I aquifer. It is the primary source of water for domestic, municipal, and industrial use in southeastern Idaho and also provides large quantities of water for agricultural irrigation (along with surface water from the Snake River). The SRPA consists of a series of saturated basalt flows and interlayered pyroclastic and sedimentary materials that underlie the ESRP. The SRPA is approximately 322 km (200 mi) long, 64 to 97 km (40 to 60 mi) wide, and covers an area of 24,853 km² (9,600 mi²). It extends from Bliss, Idaho, on the southwest to near Ashton, Idaho, northeast of the INL Site. Aquifer boundaries are formed by contacts with less permeable rocks at the margins of the plain (Mundorff, Crosthwaite, and Kilburn 1964).

Groundwater flow in the SRPA occurs predominantly through fractures (joints) in the basalt and along rubble zones at flow contacts (bedding planes). In the eastern SRPA, regional groundwater flow is to the southwest. Recharge occurs primarily in mountain-front areas near the Yellowstone Plateau and Lost River Ranges. Lesser recharge sources include seepage into the bed of the Big Lost River (when flowing) and infiltration of irrigation water applied to agricultural lands near Howe and Mud Lake to the north and northeast of the INL Site, respectively. The groundwater then flows southwest toward discharge areas at Thousand Springs near Hagerman. On a local scale, groundwater flow directions may differ from regional flow paths as a result of fracture orientations.

The USGS has maintained a groundwater-monitoring network at the INL Site to characterize the occurrence, movement, and quality of water and to delineate the movement of facility-related wastes in the SRPA since 1949. This network consists of a series of wells from which periodic water level and water quality data are obtained. In addition to the independent USGS groundwater monitoring, a groundwater monitoring program was implemented at INTEC in October 1991 to satisfy RCRA and DOE O 231.1A Chg 1 groundwater monitoring requirements.

Hydraulic conductivities in the SRPA near INTEC commonly exceed 1,000 ft/day (0.35 cm/s), with a maximum value of 8,800 ft/day (3.1 cm/s) at the former INTEC injection well (Anderson, Kuntz, and Davis 1999). Hydraulic conductivities beneath INTEC are among the highest anywhere in the INL Site. The very large hydraulic conductivities and fractured nature of the basalt aquifer matrix result in very rapid groundwater flow velocities, typically 5 ft/day near INTEC.

Depths to SRPA groundwater near INTEC range from 460 to 510 ft below ground surface. Figure 2-20 shows a groundwater elevation contour map for the area surrounding INTEC and ICDF. The general direction of groundwater flow was south to southwest. The groundwater hydraulic gradient varies considerably across the map area but is relatively flat between INTEC and CFA, with less than 4 ft of head difference over this 2-mile distance because this is an area of very high hydraulic conductivity.

Groundwater levels declined during 2000–2005 as a result of drought during this time period. Figure 2-21 shows groundwater hydrographs for several SRPA wells. The hydrographs show that groundwater levels declined more than 10 ft in many aquifer wells across the southern INL Site during the most recent drought cycle (2000 through 2005). However, as a result of above-normal precipitation during 2005 and 2006 and corresponding periods of flow of the Big Lost River during those 2 years, the hydrographs show a slight rise in groundwater levels during 2006–2007.

The water quality in the SRPA at and downgradient from the INTEC has been adversely impacted due to past facility operations, beginning in 1952. The most significant water quality impacts resulted from the former INTEC injection well. The injection well (CPP-03) was routinely used to discharge INTEC service wastewater to the aquifer from 1952 to February 1984, when it was taken out of service as the percolation ponds became operational. During its operation, the injection well constituted a source of low-level radioactivity to the aquifer. The principal radionuclides of environmental significance discharged to the injection well were tritium (H-3), strontium-90 (Sr-90), iodine-129 (I-129), cesium-137 (Cs-137), and technetium-99 (Tc-99).

Since it was taken out of service in 1984, the former INTEC injection well no longer constitutes a continuing source of contaminants to the aquifer. However, drain out of service waste from the deep vadose zone continues to contribute a slow flux of tritium, Sr-90, I-129, and other radionuclides to the SRPA. By 2003, tritium and I-129 activities (derived from the injection well) had declined below their respective MCLs in all SRPA monitor wells downgradient of INTEC. As of 2009, Sr-90 and Tc-99 were the only radionuclides whose concentrations in groundwater still exceeded MCLs at and downgradient of INTEC. However, concentrations of these contaminants are slowly declining as a result of radioactive decay and/or dilution and dispersion. Current trends indicate that concentrations of Sr-90 and Tc-99 from the former injection well will decline below the MCL before the year 2095 (Cahn et al. 2006). However, other sources of Sr-90 in perched water pose a potential threat to the SRPA that are being remediated under OU 3-14.

Detection groundwater monitoring is currently being conducted at the ICDF at six monitoring wells completed in the uppermost portion of the SRPA (Figure 2-22). The ICDF detection monitoring program has established methods to determine whether there is statistically significant evidence of contamination for any monitoring parameter at the ICDF SRPA wells (DOE-ID 2008a). Groundwater

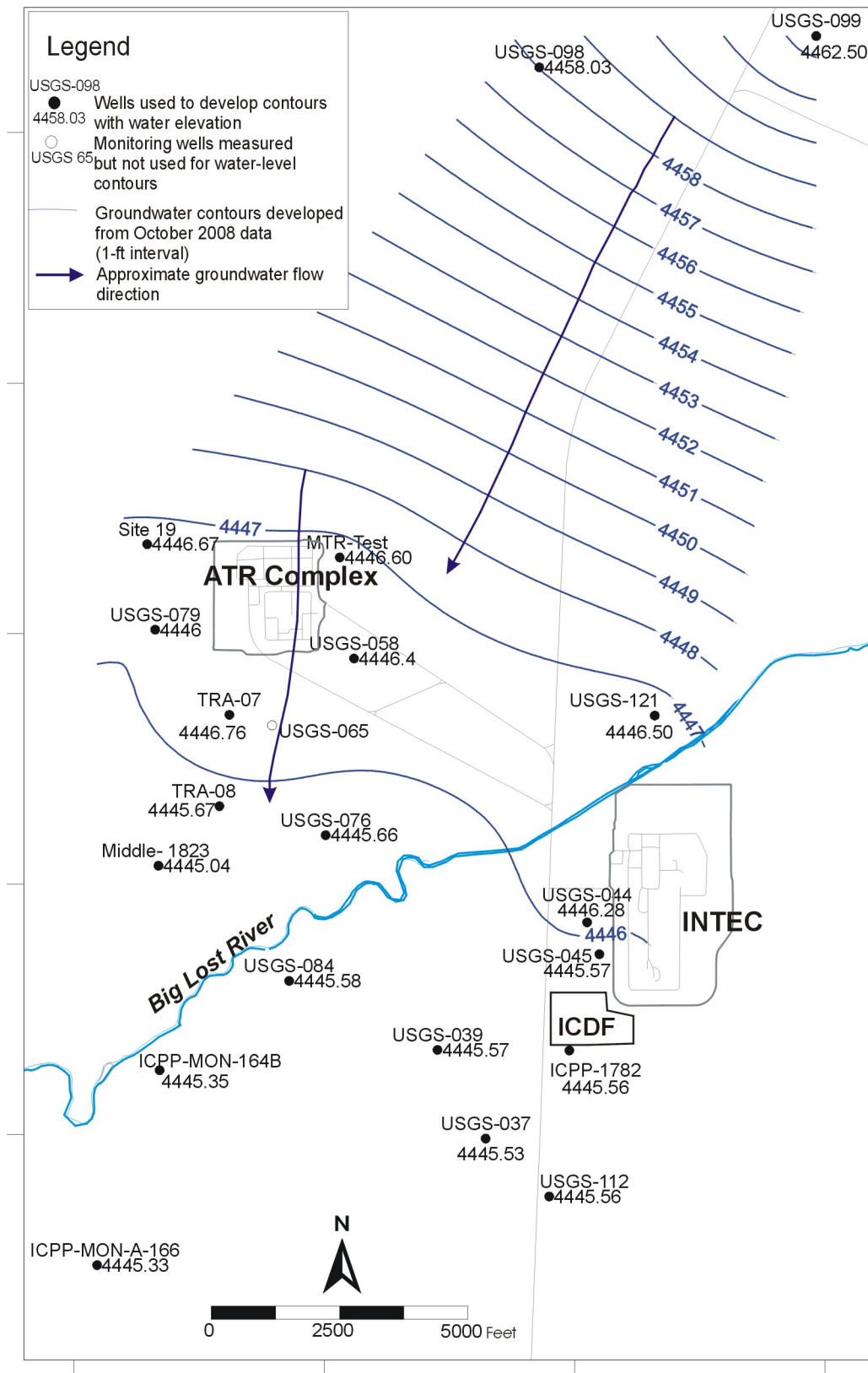


Figure 2-20. Snake River Plain Aquifer groundwater elevation contour map – October 2008.

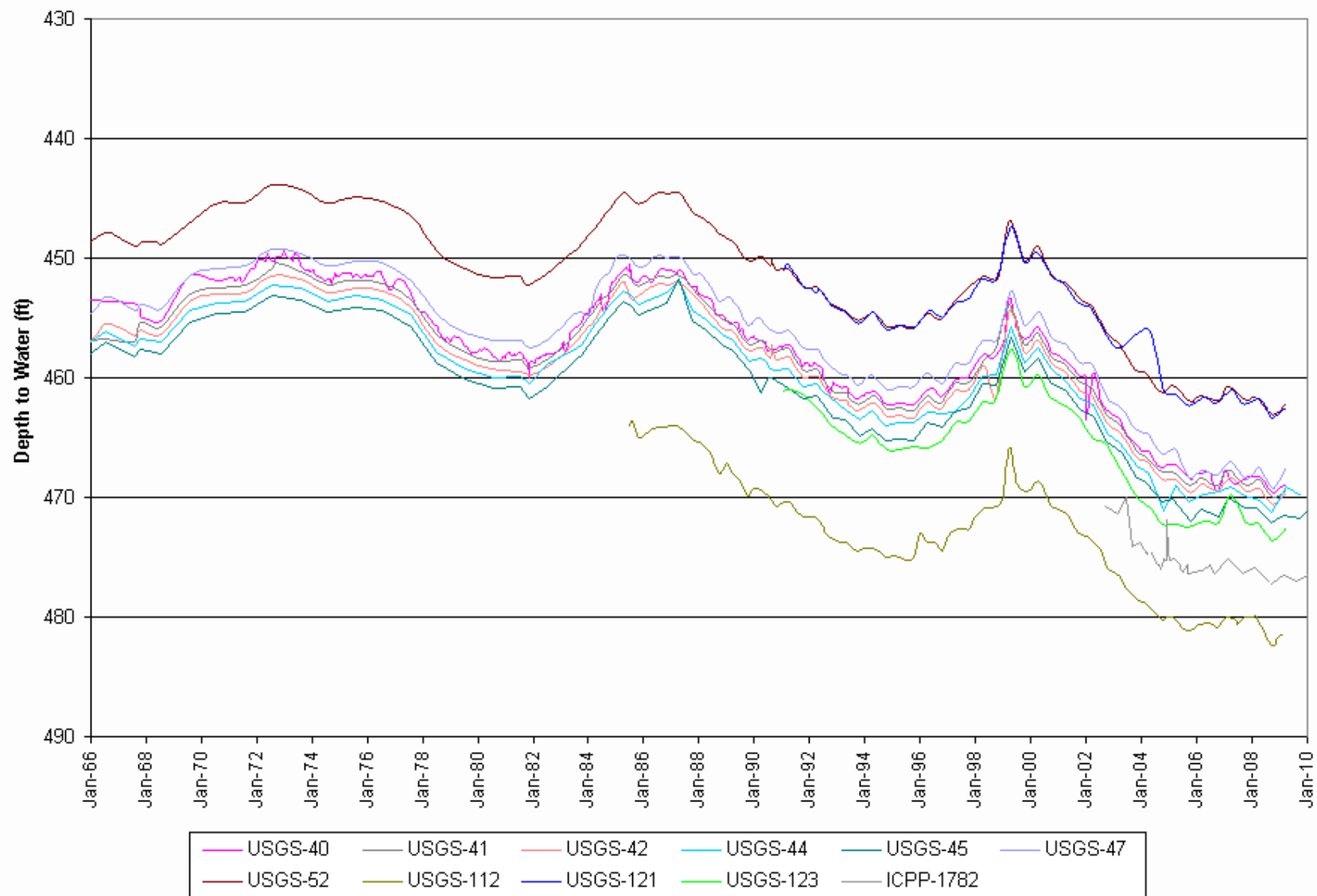


Figure 2-21. Hydrographs for selected Snake River Plain Aquifer wells.

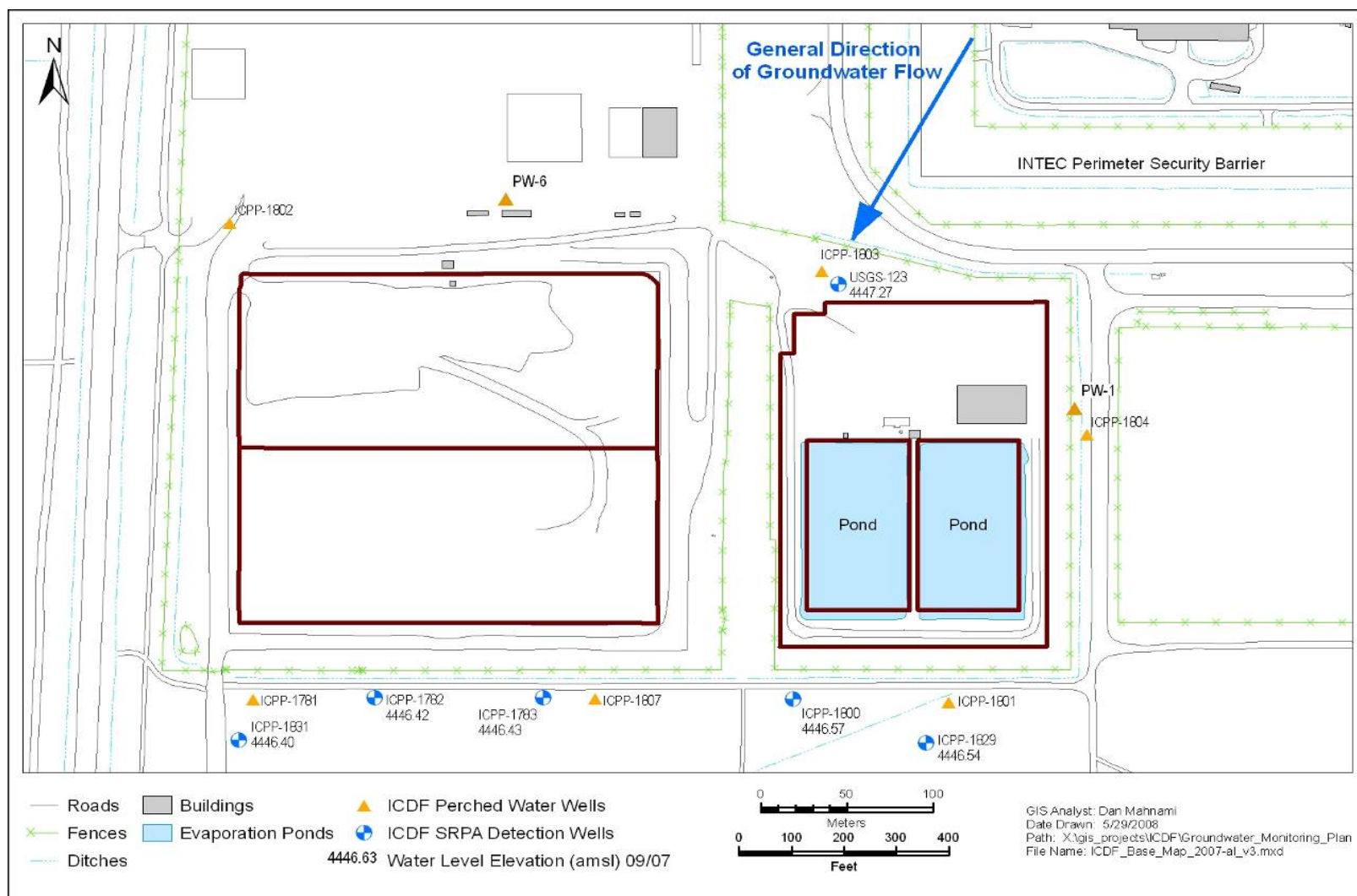


Figure 2-22. ICDF monitoring well locations.

samples are currently being collected twice per year and analyzed for a suite of indicator parameters. During 2006–2007, indicator parameters included total Cr, Hg, Sr-90, and Tc-99. During 2007, however, the indicator parameters were revised to include constituents found in higher concentrations in ICDF leachate, as compared with SRPA groundwater. Current indicator parameters include bicarbonate alkalinity, sulfate, U-233/234, and U-238. Based on the results of the detection monitoring program, there has been no evidence of any groundwater quality impacts attributable to ICDF operations (DOE-ID 2008a).

2.1.6 Geochemistry

A number of studies have characterized the geochemistry of the perched water (EDF-5758) and the ESRP aquifer (McLing 1994; DOE-ID 2003g). These studies indicate that groundwater beneath the INL Site has multiple source regions and that these source regions have subtle chemical signatures (Johnson et al. 2000) that are defined by the geologic media in which the water originates. Waters originating from the Basin and Range valleys north of the INL Site that contain Paleozoic carbonates and siliciclastic sediments are therefore enriched in Ca-Mg-HCO₃. In contrast, waters originating in the volcanics of the Yellowstone Plateau contain more Na-K relative to those derived from the sedimentary terrain to the west.

Based on isotopic evidence, groundwater flowing southward beneath INTEC and the ICDF is mostly derived from a fast flow corridor originating in the Little Lost River valley (Roback et al. 2001). The fast flow zone is characterized by colder groundwater dominated by Ca-Mg-HCO₃. SRPA groundwater is generally supersaturated with respect to calcite, which results in calcite precipitation in the sedimentary interbeds and as fracture and vesicle fillings within the basalt (McLing 1994).

Because most SRPA recharge comes in the form of snowmelt at high altitudes, groundwater entering the aquifer is quite cold ~9.0°C (Smith and McLing 2001). Groundwater warms predictably as residence time increases in the aquifer. Near the INTEC facility and ICDF, SRPA groundwater temperatures generally fall between 11°C and 13°C. In contrast, perched water temperatures beneath INTEC are much warmer as a result of anthropogenic recharge from hot water leakage from steam and steam condensate pipelines (DOE-ID 2008b).

Groundwater pH near INTEC and ICDF ranges from approximately pH 7 to pH 8, with most values close to pH 7.9 (DOE-ID 2008b). The observed pH values are consistent with the presence of calcite (CaCO₃) in the aquifer matrix, which tends to buffer the pH in this range.

SRPA groundwater at most well locations contains high concentrations of dissolved oxygen (>5 mg/L), which indicates that the groundwater is close to saturation with dissolved oxygen (DOE-ID 2008b). This is consistent with regional studies that confirm oxidizing conditions for the SRPA (McLing 1994).

Elevated concentrations of sodium and chloride still persist in groundwater downgradient (south) of INTEC as a result of past disposal of service waste at the former injection well and, later, at the former percolation ponds. Sodium and chloride levels at SRPA wells near the former percolation ponds remain more than five times above background concentrations more than 5 years after the ponds were taken out of service. The observed slow decline in the salinity of groundwater beneath the former percolation ponds is evidence of continuing drain out of high-salinity perched water and/or the diffusion of sodium and chloride out of low-permeability zones in the SRPA.

Total dissolved solids concentrations in SRPA groundwater typically fall within the range of 200 to 500 mg/L (DOE-ID 2008b), with the higher values observed at “skimmer wells” that are screened across only the upper few feet of the aquifer. As of 2009, the highest total dissolved solids value (499 mg/L) was observed at Well ICPP-MON-A-230 located north of the tank farm. The elevated groundwater total dissolved solids at this location are attributable to past high-salinity waste releases in and around the tank farm area.

Figure 2-23 shows a Piper trilinear diagram that illustrates SRPA groundwater quality variations. The diagram shows that most SRPA groundwater is of the calcium-bicarbonate type, which falls toward the left side of the diamond-shaped Piper plot. This is typical of the SRPA, which contains an abundance of calcite (CaCO_3). Upgradient monitoring well USGS-121 represents the most extreme calcium-bicarbonate water type. In contrast, USGS-51 contains water of the calcium-chloride type, presumably as a result of residual chloride from the former percolation ponds.

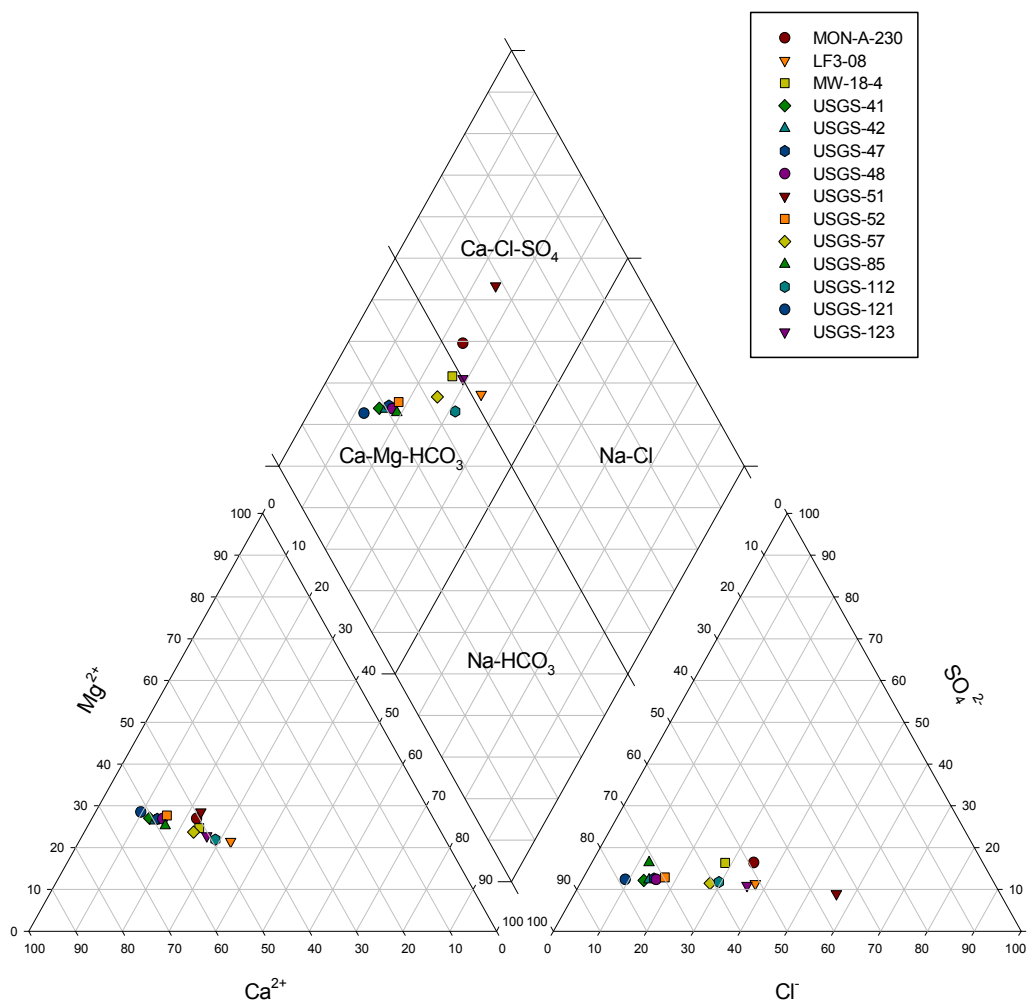


Figure 2-23. Piper trilinear diagram for selected Snake River Plain Aquifer wells near INTEC.

2.1.7 Natural Resources

The following section discusses the natural geologic and water resources of the INL Site.

2.1.7.1 Geologic Resources. Geologic resources at the INL Site are very limited. INL Site mineral resources include sand, gravel, pumice, silt, clay, and aggregate. These resources are extracted at several quarries or pits at the INL Site and used for road construction and maintenance, waste burial activities, and ornamental landscaping. The geologic history of the ESRP makes the potential for petroleum products at the INL Site very low. The potential for geothermal energy exists at the INL Site; however, a study by Mitchell, Johnson, and Anderson (1980) identified no economic geothermal resources.

2.1.7.2 Water Resources. The SRPA, one of the largest and most productive groundwater resources in the United States, underlies the INL Site and adjacent properties. The aquifer is listed as a Class I aquifer, and EPA designated it as a sole-source aquifer in 1991 (56 FR 50634). Groundwater from this aquifer supplies most of the water for the area surrounding the INL Site and essentially all drinking water consumed within the ESRP (SAR-II-8.4). The water from the aquifer is used for agriculture, food processing, aquaculture, and domestic, rural, public, and livestock water supplies. In total, nearly 17.8 trillion L (4.7 trillion gal) of water are drawn from the aquifer annually, with the majority going to agriculture (DOE-ID 2001).

Irrigated agriculture provides a significant portion of the economic base for the people of southern Idaho, and the SRPA plays a major role in meeting irrigation requirements. The aquifer provides groundwater for irrigation of over one-third of the 1.2 million hectares (3 million acres) of the ESRP that are irrigated. It is estimated that over 127,000 people depend on the aquifer for domestic and municipal water needs. Total domestic water consumption is approximately 5.7 million m³/year (46,000 acre-ft/year); groundwater discharge from well pumpage equals approximately 2.37 billion m³/year (1.92 million acre-ft/year) (56 FR 50634).

In addition to providing water for INL Site operations and agriculture, the aquifer supplies water for other industries. Water discharged from springs in the Twin Falls-Hagerman area is used to raise fish commercially. The spring water flow of 47.0 m³/s (1,660 ft³/s) constitutes 76% of the water used for the commercial production of fish in Idaho. Most of these fish farms discharge water directly into the Snake River. The discharges from Hagerman Springs also significantly contribute to the flow of the Snake River downstream of Twin Falls, Idaho.

Groundwater in the aquifer generally flows from the northeastern recharge areas to the southwestern discharge areas. Nearly 8.0E+09 m³/year (6.5E+06 acre-ft/year) of water is discharged by the aquifer annually. Most of the discharge occurs as spring flow between Hagerman and Twin Falls. About 2.6E+06 m³/year (2.1E+03 acre-ft/year) of irrigation water is pumped from the SRPA in a typical year. About half of this water reenters the ground as return flow to the aquifer (SAR-II-8.4). The altitude of the regional groundwater surface underlying the INL Site ranges from about 1,400 m (4,600 ft) in the north to about 1,300 m (4,400 ft) near the southwest boundary of the INL Site. The average hydraulic gradient slopes to the south and southwest on the INL Site at about 0.8 m/km (4 ft/mi). Within the INL Site boundaries, the depth below the land surface to the regional groundwater table ranges from 60 m (200 ft) in the northeast to 300 m (900 ft) in the west-southwest (SAR-II-8.4).

The SRPA is the only source of water used at the INL Site. The combined groundwater withdrawal averages approximately 3E+07 L/day (7E+06 gal/day) or 1E+07 m³/year (8,000 acre-ft/year). Table 2-4 lists the INL Site production wells, the depth of the well, the depth to water at the well, and the annual volume of water withdrawn from the well. All wells withdraw water from the main body of the SRPA. The water withdrawn from each well is used for potable water on the Site, for ground maintenance, and for necessary facility operations (SAR-II-8.4).

Table 2-4. Idaho National Laboratory Site production wells and annual volume pumped.^a (SAR-II-8.4)

Well Name	Depth of Well (ft bgs)	Depth to Water (ft bgs)	Annual Volume (gal)
ANP-01	360	208	2.561E+06
ANP-02	340	211	1.433E+06
ANP-08	309	218	3.908E+05
Badging Facility Well	644	489	5.760E+04
CFA-1	639	468	1.473E+07
CFA-2	681	471	1.448E+05
CPP-01	586	460	1.834E+08 ^b
CPP-02	605	460	1.834E+08 ^b
CPP-04	700	462	1.834E+08 ^b
CPP-05	695	447	1.834E+08 ^b
EBR-I	1075	596	4.491E+04
EBR II-1	745	632	2.767E+06 ^c
EBR II-2	753	630	2.767E+06 ^c
FET-1	330	199	1.427E+06
FET-2	455	200	5.067E+05
Fire Station Well	516	420	1.057E+04
NRF-1	535	363	2.594E+06
NRF-2	529	362	9.368E+06
NRF-3	546	363	9.802E+04
NRF-4	597	363	1.649E+07
Rifle Range Well	620	508	9.115E+04
RWMC Production	685	568	4.824E+05
SPERT-1	653	456	3.871E+05
SPERT-2	1,217	463	3.450E+05
TRA-01	600	453	3.595E+07
TRA-03	602	456	2.074E+06
TRA-04	965	463	9.006E+07

a. All wells are withdrawing water from the main body of the Snake River Plain Aquifer and are used as drinking water wells with the exception of Wells ANP-08, Fire Station Well, and NRF-4, which are production wells for facility operations.

b. Total for Wells CPP-01, CPP-02, CPP-04, and CPP-05.

c. Total for both Wells EBR II-1 and EBR II-2.

The underflow of the INL Site (i.e., the amount of water passing directly under the INL Site boundaries) is approximately 1.8E+12 L/year (4.7E+11 gal/year). The INL Site consumption is less than 1% of the INL Site underflow and less than 0.1% of the total annual aquifer discharge (SAR-II-8.4).

2.1.8 Natural Background Radiation

Measurement programs are conducted to characterize radiological conditions in the environment at the INL Site and in the surrounding region. Results of these programs show that exposures of workers and members of the public resulting from INL Site's airborne radionuclide emissions are well within applicable standards and are a small fraction of the dose from background sources.

DOE has compared radiation levels monitored on and near the INL Site with those monitored at distant locations. Radiation levels at on-Site and boundary community locations include contributions from background conditions and INL Site emissions. These data show that, over the most recent 5-year period for which results are available (2004 through 2008), average radiation exposure levels for boundary locations were no different than those at distant stations. The average annual dose measured by the Environmental Science and Research Foundation during 2003 was 118 mrem for distant locations and 117 mrem for boundary community locations (DOE-ID 2004b). The corresponding 5-year averages of these measurements were 126 mrem/year for the distant group and 124 mrem/year for the boundary group. The differences between these measurements are well within the range of normal variation and the uncertainty of radiation measurements.

The dose associated with radiological emissions is assessed annually to demonstrate compliance with the "National Emissions Standards for Hazardous Air Pollutants" (40 CFR 61) and "National Emission Standards for Emissions of Radionuclides Other Than Radon From Department of Energy Facilities" (40 CFR 61 Subpart H). The effective annual dose equivalent to the maximally exposed individual resulting from radionuclide emissions from INL Site facilities during 2006 and 2007 has been estimated at 0.039 mrem and 0.09 mrem, respectively (DOE-ID 2007c, 2008c). These doses are well below both the EPA dose limit (10 mrem/year) and the dose received from background sources (about 620 mrem/year).

The annual collective dose to the population surrounding the INL Site was estimated at 0.09 person-rem per year (DOE 2002). The annual collective dose to the population surrounding the INL Site, based on 2000 U.S. Census Bureau data, is estimated at 0.022 person-rem (DOE 2005). This dose applies to a total population of about 277,000 people, resulting in an average individual dose of less than 0.00008 mrem. For comparison, this population receives an annual collective dose from background sources of about 100,000 person-rem.

2.2 Principal Facility Design Features

The ICDF Landfill design capacity is roughly 389,923 m³ (510,000 yd³). The landfill is lined with a double composite liner system and includes leachate collection and leak detection recovery systems. After the landfilled waste is placed to its final grade, it will be covered with a robust cover barrier system engineered to minimize infiltration for 1,000 years (EDF-ER-281). The landfill is designed for an operational life of 15 years, a post-closure period of 30 years, and an expected landfill cover design life of 1,000 years.

The ICDF Landfill complies with the substantive requirements of the RCRA Subtitle C and TSCA design standards specified in IDAPA 58.01.05.008 (40 CFR 264 Subpart N) and the PCBs chemical waste landfill design requirements (40 CFR 761.75). It also complies with the requirements of RCRA Subtitle C closure requirements specified in IDAPA 58.01.05.008 (40 CFR 264.310).

The following subsections address the principal design features of the facility that contribute to the long-term isolation of disposed waste. These features serve to (1) minimize the infiltration of water through disposal units; (2) ensure integrity of disposal unit covers; (3) provide for the structural stability of backfill, waste, and covers; and (4) provide a barrier against intrusion.

2.2.1 Water Infiltration

Minimization of infiltration of water through the disposal unit of the ICDF Landfill is accomplished by incorporation of both a bottom liner system and a surface cover in the facility design. Information on the design features of the bottom liner and surface cover are provided in the following subsections.

2.2.1.1 Landfill Bottom Liner. The ICDF Landfill is lined with a double composite liner system with leak detection to minimize and detect percolation of liquids into the subsurface. A profile of the landfill liner system is provided in Figure 2-24. The composite landfill liner system consists of a primary high-density polyethylene (HDPE) geomembrane/geosynthetic clay liner (GCL) composite barrier and secondary HDPE geomembrane/soil bentonite liner (SBL) barrier. The primary composite barrier is designed to keep leachate from leaking into the underlying primary leak detection recovery system. The secondary barrier provides a means of identifying a leak from the primary system and provides an absorptive capacity of contaminants with a SBL. The composite liner system (i.e., primary geomembrane/GCL and secondary geomembrane/SBL) provides an added protection from leaks. The lower liner at the composite will mitigate leaks from the upper layer, reducing flow through a hole or defect by keeping the hole or defect from becoming larger over time.

The SBL was designed to have a maximum saturated permeability of $1\text{E-}07$ cm/second and a thickness of 0.9 m (3 ft). Studies of SBLs have shown that this permeability significantly reduces the amount of percolation (Peyton and Schroeder 1990).

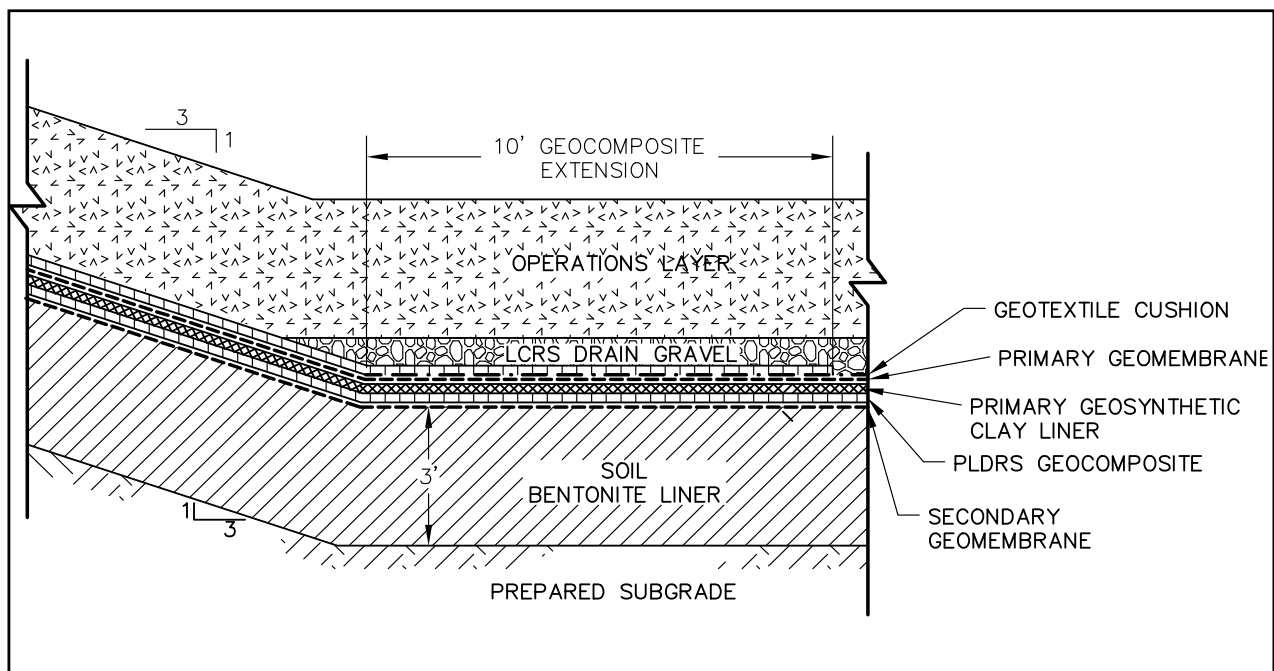


Figure 2-24. Landfill double composite liner system.

The permeability of the local clay borrow ranges from 1E-06 cm/second to 1E-07 cm/second (DOE-ID 2000). A soil amendment study was performed to determine the amount of bentonite needed in the clay to achieve the permeability requirement in the laboratory (EDF-ER-272). The study concluded that mixing the clay borrow (i.e., base soil) with 5% of bentonite by dry weight produced a SBL material having a maximum permeability of 1E-08 cm/second in the laboratory.

Between the primary and secondary barriers is a drainage material to detect leaks from the overlying primary barrier and divert the liquid to a main sump. Liquids in the sump can be removed by pumps through riser pipes installed in the landfill. The primary leak detection recovery system has been designed with a high transmissivity so that liquids can flow with little resistance to a central sump.

The recommended EPA action leakage rate is defined in the final rule (40 CFR 264.302) as the “maximum design flow rate that the leak detection system can remove without the fluid head on the bottom liner exceeding 1 ft.” Based on this leakage rate, the action leakage rate for the ICDF Landfill cell is 5,224 L/day (1,380 gal/day) and includes a factor of safety of two. Based on the design of the primary leak detection recovery system the leakage rate dictated the sump and pump size.

The ICDF Landfill also includes a secondary leak detection recovery system (SLDRS) located directly beneath the lowest barrier, which is the SBL. The SLDRS is positioned above a tertiary HDPE geomembrane located beneath the center of the landfill. Liquids would have to pass through two HDPE geomembranes, a GCL, and a 3-ft-thick low-permeable SBL before being detected in the SLDRS. The SLDRS will provide vadose zone monitoring and early detection.

The SLDRS was placed in a limited aerial extent only in the region of greatest probability of leachate collection and bottom liner leakage. The greatest probability of bottom liner leakage is near the LCRS sump. The hydraulic head is usually greatest over the liner near the LCRS sump, and the greatest density of seams in the geomembrane usually occurs at this location. Because the SLDRS was placed directly beneath and in contact with the bottom liner of the landfill, water capture in the SLDRS sump will be almost exclusively from leaks through the liner system. The SLDRS was extended under the center of the landfill along its north-south axis. This region would be the second greatest probability of bottom liner leakage. However, since a partial SLDRS was installed, there is some possibility that water outside of the landfill cell could seep in along its edges. For this reason, chemical analysis of any water captured in the SLDRS sump will be used to distinguish between leaks and outside groundwater influences.

Leachate generated in the landfill is managed with an LCRS. The LCRS consists of high-permeable gravel overlying the primary HDPE geomembrane on the landfill floor and a synthetic geocomposite material on the side slopes. The LCRS diverts leachate to a perforated pipe located along the center north-south axis of the landfill. Leachate then flows through the pipe to the LCRS sump where it can be pumped to the evaporation pond.

The LCRS design consisted of sizing the LCRS based on expected precipitation event and leachate generation to maintain less than 1 ft of hydraulic head over the liner system. The LCRS design is provided in the following three design studies: EDF-ER-269, “Leachate Generation Study”; EDF-ER-280, “Landfill Leachate Collection System Design Analysis”; and EDF-ER-274, “Leachate Contaminant Reduction Time Study.”

2.2.1.2 Landfill Surface Cover. Upon closure, a cover will be installed over the landfill. The ICDF Landfill cover is designed as an infiltration-limiting cover, to minimize long-term infiltration to the waste, thus reducing leachate generation and contaminant migration. The cover system will minimize infiltration and maximize run-off by maintaining a sloped surface, storing water for later release to the

atmosphere, providing lateral drainage, and providing a low-permeability composite liner barrier system. The low infiltration rate to the waste is attributed to the design of the final cover, which consists of three distinct functional sections, described below. A schematic of the final landfill cover functional systems is provided in Figure 2-25.

- Upper section: The upper water storage component provides water storage during wet periods for later release into the atmosphere during dry periods. The upper section comprises a surface consisting of a vegetated soil/gravel matrix system sloped to minimize infiltration and maximize run-off. Vegetation is used to enhance the evapotranspiration properties of the upper cover portion. Beneath the soil/gravel matrix is a layer of silty loam-type soil that provides water storage during wet periods for later release into the atmosphere during dry periods. Coupled with a capillary break provided by the underlying sand and gravel layers, it will store moisture from long-term, low-probability precipitation events for later release to the atmosphere by evapotranspiration. The evapotranspiration layer in the cover is an integral component that provides long-term minimization of migration of liquids through the closed landfill while functioning for the long term with minimal maintenance. Results from hydrologic modeling of the final cover indicate that the minimum water storage layer thickness needed to maximize water storage is 2 m (6.5 ft). Sensitivity analysis shows clearly that increasing the water storage thickness beyond the optimal thickness increases water storage capacity, but does not reduce the percolation rate.

The ICDF Landfill cover surface grade and erosion protection meet or exceed the requirements of RCRA Subtitle C design standards specified in IDAPA 58.01.05.008 (40 CFR 264.310). The function of the surface cover is to promote surface water drainage, minimize erosion, and provide a medium for vegetation. The surface will be sloped so that surface water run-off is directed to the side slopes of the landfill lined with basalt riprap armoring. The landfill side slopes will be sloped at 2.5H:1V (2.5 horizontal to 1 vertical) from the edge of the cover to the existing ground surface as shown in Figure 2-26. The riprap side-slope armor will dissipate the energy from water run-off from the cover until it reaches the existing ground surface at a distance of over 30.5 m (100 ft) from the edge of the waste mass. A final grade of 7% was determined for the cover (EDF-ER-267). This will ensure that a minimum slope of 3% is maintained after consolidation to promote surface water drainage off the cover system through its 1,000-year life.

- Middle section: The biointrusion layer provides protection from burrowing animals and a capillary break. Biointrusion protection is provided by a layer of 5- to 12.7-cm (2- to 5-in.) -diameter gravel. Two filter layers of sand and gravel provide smooth transitions between the biointrusion gravel layer and the overlying and underlying layers. The filter layers above the biointrusion layer prevent fine-grained soil from the upper section from migrating into the coarser materials. The filter layers also provide capillary breaks due to the contrast in unsaturated permeabilities. The capillary breaks provide redundancy for limiting infiltration in the cover. The relatively coarser materials in the middle section compared to the upper section will also provide lateral drainage in the event breakthrough occurs through the upper cover layers.
- Lower section: The lower section includes a composite liner system that has a permeability less than or equal to the permeability of the landfill bottom liner system that complies with IDAPA 58.01.05.008 (40 CFR 264.310). The composite liner system consists of a single HDPE geomembrane over an SBL. The composite system will intercept water in the event breakthrough occurred from the upper cover sections and divert it laterally through the overlying sand and gravel layers.

The geomembrane and SBL designed for the bottom liner system will function for the cover as well. Consequently, similar analyses used for the bottom liner are applicable for the cover system.

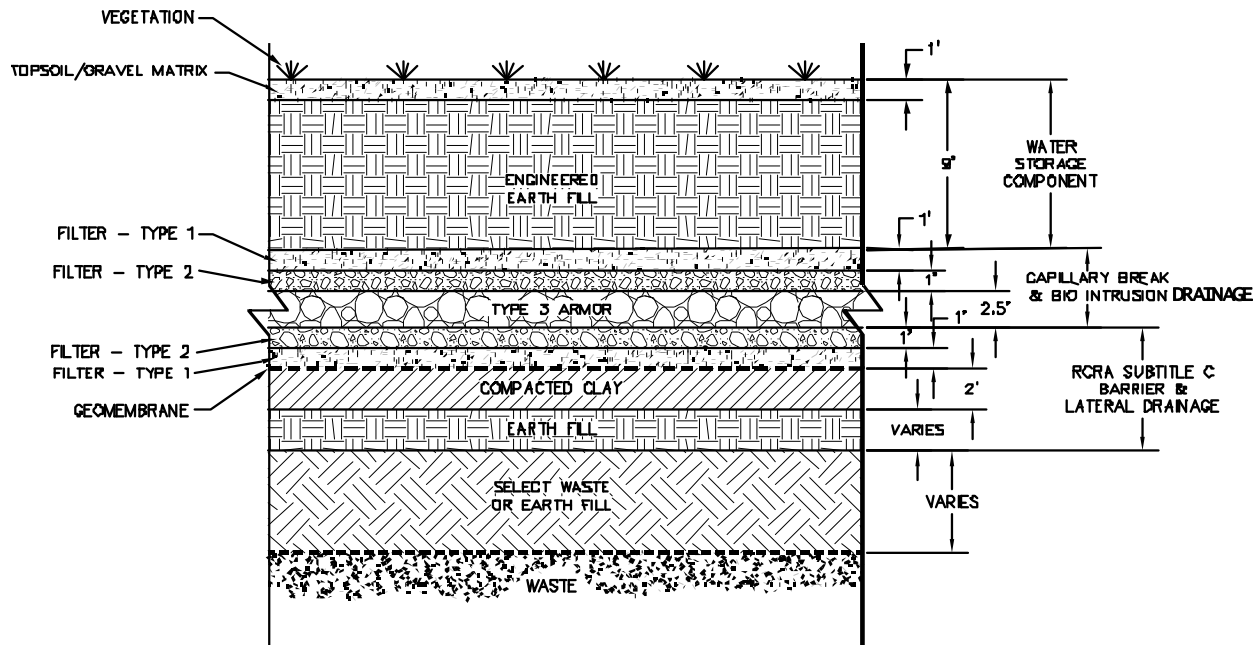


Figure 2-25. Schematic of the final landfill cover functional sections.

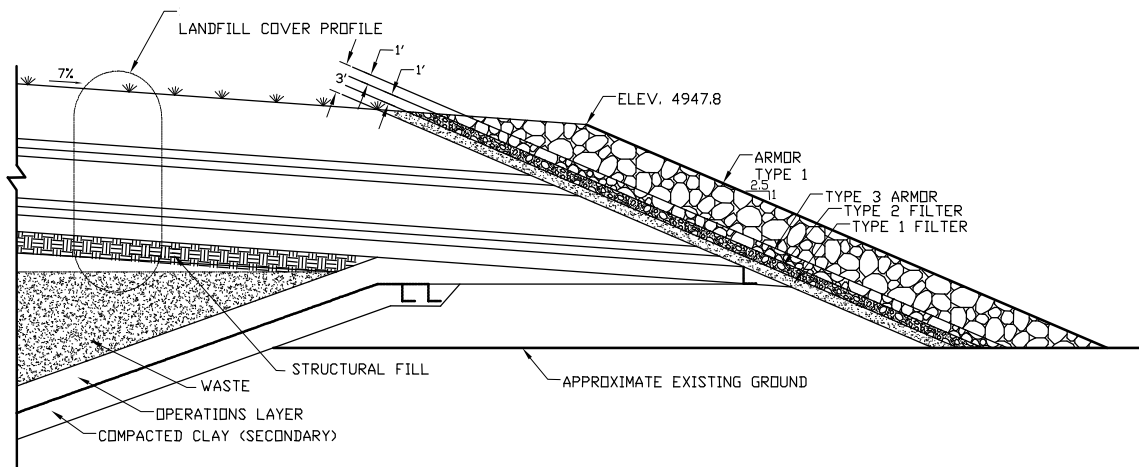


Figure 2-26. Landfill cover section.

The results of hydrologic modeling of the cover predict a low infiltration rate over the next 1,000 years at the base of the cover system (EDF-ER-279).

2.2.2 Disposal Unit Cover Integrity

Erosion and subsidence protection of the disposal unit cover integrity is discussed below.

2.2.2.1 Erosion Protection. Surface water and wind erosion analyses were performed to determine the amount of soil loss from the cover due to sheet flow (EDF-ER-281). Analysis of erosion due to surface water was completed using the Modified Universal Soil Loss Equation as recommended by the Nuclear Regulatory Commission (NRC) for long-term (i.e., 1,000-year) soil loss (NRC 1986). The surface of the cover was assumed to be fine-grained soils such as those found at the Rye Grass Flats area

at the INL Site without accounting for the protection of the soil/gravel matrix. The analysis consisted of determining the probable maximum precipitation (PMP) event and calculating soil loss per year using the Modified Universal Soil Loss Equation. Approximately 0.6 m (2 ft) of soil could erode from the surface of the cover over a 1,000-year time period. The minimum water storage layer thickness needed to maximize water storage is 2 m (6.5 ft) based on the “Hydrologic Modeling of the Final Cover” (EDF-ER-279). The water storage layer will be constructed with an additional 0.76 m (2.5 ft) of material to provide a sacrificial layer in the event that the surface would erode due to water erosion.

Landfill covers must maintain a positive slope to promote surface water run-off (40 CFR 264.310). The EPA recommends a final top slope between 3 and 5%, after settlement has occurred (EPA 1989a). The proposed cover surface will have a slope of 7% (EDF-ER-281) and a length of 118 m (387 ft) measured on its shortest side. A cover slope constructed at a maximum slope of 7% has been shown to be stable and resistant to wind and water erosion (EDF-ER-281).

The landfill cover surface will be seeded and fertilized to promote plant growth. Vegetation will minimize erosion and accelerate removal of water from the water storage layer. Long-term considerations include periods of drought or fire so erosion and hydrologic modeling studies have assumed a poor stand of vegetation. The vegetation will consist of local plant species based on vegetation studies performed for disturbed areas at the INL Site (DOE-ID 1989).

The maximum allowable noxious weed percentage (by dry weight) will be 0.5%. The maximum allowable wet and other crop percentage will be 1.5%. The engineered seed mix will provide superior vegetation, providing more transpiration and erosion control than the surrounding natural vegetation.

The ICDF is situated outside the Big Lost River flood plain. The ICDF Landfill lies within alluvial, aeolian, and lacustrine sediments deposited over millions of years ago by the Big Lost River system. A massive precipitation event may conceivably create floodwaters that would impact the permanent cover barrier. The rock armor on the permanent cover side slopes has been sized based on the PMP event. The PMP for the INL Site is 9 in. of rain in 1 hr. The average annual rainfall is 8.6 in. per year based on the 44-year period of record at the CFA at the INL Site. The PMP would generate a probable maximum flood event from the surface cover of approximately 13,600 gpm across a 100-ft section of the cover. Flood waters at the base of the cover would have to rise over 10 ft above the existing ground surface to overtop the rock armoring on the landfill cover side slopes. The existing ground surface surrounding the ICDF Landfill has little relief (less than 2%). Consequently, floodwaters would be relatively slow-moving as compared to run-off from a 7% sloping surface like the ICDF cover. Beyond the geological deposits left by the Big Lost River system, there is no evidence that a large precipitation event would cause massive flooding of the magnitude necessary to erode the permanent ICDF side-slope rock armor.

Basalt is a durable volcanic rock that provides excellent erosion protection; however, it may vary in its density and competency. Durability and abrasion-type tests will be performed on the rock armor selected for the ICDF cover prior to construction to determine its long-term durability. Based on the results of these tests, rock armor will be oversized if necessary to ensure that it performs its function for the life of the cover system.

Extensive wind tunnel studies performed at the Hanford facility show that a mixture of fine-grained soil and pea gravel significantly reduced erosion due to wind forces. Soil/pea gravel armoring can reduce erosion rates from 96.5 to more than 99% at wind speeds of 45, 56, and 67 mph (Ligotke 1993). The average wind speed at the INL Site based on the period of record is 9 mph with peak gusts up to 82 mph. Based on these studies, a soil/pea gravel matrix will provide sufficient protection against aeolian forces for the ICDF cover through its 1,000-year life and conceivably beyond.

Tornado-type winds are expected to be extremely rare at the ICDF. The cover side-slope armor consisting of large heavy basalt riprap will resist tornado-type winds. The surface of the permanent cover will consist of vegetation and a soil/pea gravel matrix. The soil/pea gravel matrix has been shown to be resistant to high wind forces generated in wind tunnel tests performed at the Hanford facility.

2.2.2.2 Subsidence Protection. Stresses will be induced in the cover SBL and geomembrane components due to settlement in the foundation soils, waste, and the cover itself. The settlement calculation for the foundation and liner soils is provided in the subsurface consolidation design study (EDF-ER-266). The amount of settlement in the waste and cover itself are provided in the landfill compaction/subsidence study (EDF-ER-267). In October 2007, DOE commissioned an Independent Technical Review Team to review and critique operations at the ICDF Landfill. In its report (DOE 2007b), the team identified several issues to be addressed to ensure the landfill would meet its long-term performance objectives. These issues included the impacts of differential settlement caused by variations in stiffness, collapse of voids, and long-term creep settlement of the wastes being disposed of in the landfill. Subsequent evaluations were performed by the original designers of the landfill to evaluate the issues (Reimbold and Murdock 2008a,b). The evaluations concluded: (1) no additional engineering measures for the final cover system are required to withstand tensile stresses generated by total settlement; (2) without additional engineering measures, localized settlements could occur that would impact the performance of the SBL; and (3) localized settlement issues associated with the potential for void collapse may require modifications to the current proposed final cover design. As a result of these evaluations, alternatives for improving the final cover system and reducing the potential for localized settlement will be considered during the final cover design to ensure the system is protective of the environment and complies with the appropriate regulatory requirements.

The geomembrane liner will be subject to puncture from the filter layers loaded by overlying materials. A nonwoven geotextile was installed between the geomembrane and filter gravel to provide a cushion. The required puncture resistance of the geotextile was determined based on the analysis performed for the bottom liner system. The round alluvium sand and gravels excavated from the landfill were screened to remove particles over 5 cm (2 in.) in diameter for the filter layer. The minimum puncture resistance is 56 kg (124 lb), including a factor of safety of two based on the maximum particle size in the LCRS (EDF-ER-281).

The geomembrane overlying the SBL was terminated in trenches constructed around the perimeter of the cover. The ends of the liners were buried under 0.6 m (2 ft) of earth to protect from wind uplift and pull out (EDF-ER-281).

The SBL can sustain irreversible damage caused by freeze-thaw cycles. Extreme frost penetration at the INL Site is estimated to be 114 cm (45 in.). The ICDF Landfill SBL is protected from frost by 4.7 m (15.5 ft) of overlying soil layers in the cover.

The HDPE membranes have been used in landfills for containment for several decades. The engineering properties of these materials are well understood. They are manufactured to perform a specific function, including hydraulic barriers, erosion control, and drainage.

2.2.3 Structural Stability

The ICDF Landfill contains CERCLA-generated contaminated bulk soil, debris (i.e., rubble, concrete, wood, drums, boxes, personal protective equipment, and metals), and treated waste that are generated at the INL Site and meet the Agency-approved WAC for the ICDF Landfill (DOE-ID 2010b). Total subsidence in the cover will be a cumulative of settlement amounts due to deformation in the landfill components listed below:

- Consolidation of the waste that is soil
- Consolidation of the waste due to degradation of waste debris
- Consolidation due to voids left in containerized waste
- Consolidation of the compacted clay liner and foundation soils
- Consolidation of the cover itself.

The total predicted settlement (EDF-ER-267) in the ICDF Landfill cover is summarized in Table 2-5.

Table 2-5. Summary of predicted cover settlement.

Landfill Component	Long-Term Predicted Settlement (ft)
Foundation and liner	1.2
Waste as soil	0 ^a
Waste as degradable debris	Varies (dependent on debris thickness)
Cover	0.1
<u>Total predicted cover settlement without degradable debris</u>	1.3

a. Settlement will be immediate during operation and cover construction.

Waste forms at the ICDF Landfill include solid debris, metals, activated metals, beryllium, graphite, soils, personal protective equipment, concrete, asphalt, glass, steel, wood, metals, plastic, grout, piping, filters, etc. Waste containers for packaged waste disposals include metal drums, metal boxes, wood boxes, concrete boxes, and cloth soil sacks. The bulk waste, mainly soils and debris (pipe, building rubble, etc.), are hauled to the landfill in dump trucks and roll-offs. Nonstandard waste disposals include the V-9 tank from TAN, the Engineering Test Reactor vessel, and the Power Burst Facility reactor vessel. The heavy waste objects (i.e., reactor vessels) are evaluated operationally to ensure there is no negative effect on the landfill liner system.

Waste stabilization is maintained by minimizing the void space in containerized debris waste by filling void areas in waste boxes with grout to 95% capacity. Waste soils are compacted to 90% to minimize settlement.

Debris can be categorized as nondegradational and degradational. Nondegradational debris includes materials such as asphalt and concrete. Material such as wood, plastic, and metal can degrade due to biochemical, oxidation, and corrosion-type reactions, creating voids in the waste that may result in long-term settlement. Containerized waste (e.g., drums) may contain a void space up to 5% (DOE-ID 2010b) that can collapse due to loads from the overlying waste. Debris will be preprocessed if necessary to minimize mechanical compression resulting from distortion, bending, or reorientation. Debris will be placed to maximize compaction efforts and minimize subsidence.

The soils underlying the landfill consist of dense alluvial deposits overlying basalt bedrock ranging in thickness from 4.6 to 7.6 m (15 to 25 ft). The alluvium consists of gravels, gravel-sand mixtures, and sand-gravel-cobble mixtures to poorly sorted gravels with sand and silt. An intermittent layer of fine sand, silt, and clay (i.e., “old alluvium”) between the bedrock and gravels ranges in thickness from 0.6 to 2.1 m

(2 to 7 ft) based on the borings located within the landfill footprint. The SRPA is located approximately 134 m (440 ft) below the bottom of the landfill (EDF-ER-275).

The existing sand and gravelly foundation soils provide a structurally stable subgrade for the ICDF Landfill liner system. Additionally, the foundation layer is relatively thin, dense, and not influenced by a changing groundwater table. As a worst-case estimate, total settlement was determined on the assumption that the SBL is overlying 4.6 m (15 ft) of the “old alluvium” soil. This provides a conservative settlement estimate, because the “old alluvium” will have the largest amount of consolidation. This also takes into account the small amount of immediate settlement in the gravels and secondary consolidation that could occur. Note that these assumptions are to provide a conservative subsurface consolidation amount and may not be valid for other calculations.

The foundation is loaded by the waste, operations layer, and the landfill cover. The stress increase caused by this load is calculated at various depths utilizing published solutions to the Boussinesq Equation. Terzaghi’s consolidation theory is then used to determine the settlement in the subgrade soils caused by the increase in effective stress due to the load (Holtz and Kovacs 1981). The maximum long-term differential settlement in the liner and foundation soils is estimated to be 0.4 m (1.2 ft) (EDF-ER-266).

The loads will be the largest near the middle of the landfill rather than on the sideslopes, resulting in potential differential settlement. Given that the settlement on the sides of the landfill will be very small, the total settlement calculated at the middle of the landfill floor will be the maximum differential settlement. Differential settlement will create strain in the liner system components. The predicted 0.001% strain on the liner component of the landfill is below the allowable 0.1% strain for SBL, the 1.0% strain for GCLs, and the 20% strain for geomembranes (EDF-ER-266).

To provide adequate drainage, the minimum bottom slope of 1% is required for leak detection recovery systems in landfills (40 CFR 264.301). The current practice and minimum technology guidance for bottom slopes of landfills is a minimum of 2% (EPA 1989b). The ICDF Landfill floor was designed at a 2.5% slope, steeper than 2% to allow for differential settlement. A maximum differential settlement of 0.4 m (1.2 ft) near the middle of the landfill floor would result in a floor slope of approximately 2%, meeting the regulatory requirement and suggested minimum landfill slope guidance.

The cover is comprised mainly of earthen materials that will settle due to this weight. The cover layers composed of fine-grain soil will consolidate the most over the long term. These include the SBL barrier layer and engineered structural fill water storage layer. Cover settlement is calculated to be 0.03 m (0.1 ft) (EDF-ER-267).

The integrity of the cover must be maintained for the long term (the design life of 1,000 years). This is achieved by overbuilding the cover to accommodate predicted settlement and minimize strain in the cover components.

2.2.4 Inadvertent Intruder Barrier and Biointrusion Layer

To deter the inadvertent intrusion of humans into the waste, a marker system will be used to warn future generations of the dangers of the buried waste. Permanent markers that identify the potential exposure hazards will be installed at all corner boundaries for each cell of the landfill (DOE-ID 2002). DOE intends to maintain active control of the INL Site (using fences, patrols, alarms, and monitoring instruments) per the ROD requirements discussed previously in Section 1.2.2 (DOE-ID 1999). During the operational phase, a 1.8-m (6-ft) woven mesh fence will be placed around the site to prevent animals and unauthorized persons from entering. If these measures should cease, other passive-type measures will

warn the inadvertent intruder from waste buried beneath the permanent cover barrier. The measures may include recognizable warning markers and other physical features. Site information will be provided on an Internet website, USGS maps, libraries, and other information repositories that would be readily available to the public (EDF-ER-281). Land use restrictions and institutional controls will be placed on the ICDF Landfill and its adjacent buffer zone to permanently preclude development until unacceptable risk no longer remains at the site (DOE-ID 2010a, 1999).

The ICDF Landfill will have a steep rocky side slope of basalt riprap. This feature clearly delineates the boundaries of the surface barrier by providing a distinct contrast with the surrounding flat terrain. The side slopes are engineered structures. It will be obvious that the structure had been built by humans. These distinct riprap side slopes in combination with warning signs will minimize the risk of human intrusion. The riprap basalt is a durable volcanic rock; however, it may vary in its density and competency. Durability and abrasion-type tests will be performed on the rock armor selected for the ICDF cover prior to construction to determine its long-term durability. Based on the results of these tests, rock armor will be oversized if necessary to ensure that it performs its function for the life of the cover system.

As discussed above, the ICDF Landfill cover also contains a biointrusion layer consisting of gravel. The function of this layer is to prevent small burrowing animals and ants from penetrating the underlying cover components and the waste material. Past barrier studies at the INL Site, Hanford, and other facilities have shown that a thin layer of gravel is effective in preventing animals and ants from penetrating underlying waste materials (Morris and Bleu 1997; Wing 1993). The biointrusion material will consist of gravel screened from the local available alluvium at the INL Site. The alluvium gravels at the INL Site are composed of granite, quartz, and other durable minerals that make it ideally suited for long-term applications.

2.3 Waste Characteristics

The IWTS database provides the actual waste disposal information for the ICDF Landfill. Only CERCLA waste streams that meet the WAC (DOE-ID 2010b) are acceptable for disposal in the ICDF Landfill.

The following sections discuss the waste volumes, radionuclide inventories, waste forms, and release mechanisms for the waste disposed of to the ICDF Landfill.

2.3.1 Waste Volumes

The net volume of waste disposed of at the ICDF Landfill from the start in September 2003 through FY 2009 was 239,630 m³ (313,436 yd³). After 6 years of operation, 56% of the available volume of the ICDF Landfill has been filled based on an aerial survey (EDF-9071). At the start of FY 2010, approximately 172,000 m³ (224,976 yd³) remain of the total landfill capacity. A total of 21,390 m³ (27,978 yd³) of waste was disposed of at the ICDF Landfill in FY-09 compared to 35,270 m³ (46,133 yd³) disposed of in FY-08 and 27,613 m³ (36,117 yd³) disposed of in FY-07. Figure 2-27 shows the actual and projected volumes of waste disposal through FY-18.

2.3.2 Radionuclide Inventories

The IWTS database provides a best estimate of the actual waste disposal information for the ICDF Landfill. The inventory of radionuclides and the total curies of each radionuclide disposed of in the landfill through FY 2009 are shown in Table 2-6.

The disposed inventory is defined as all waste emplaced from the beginning of disposal operations through FY 2009. The disposed inventory information was obtained from the IWTS database.

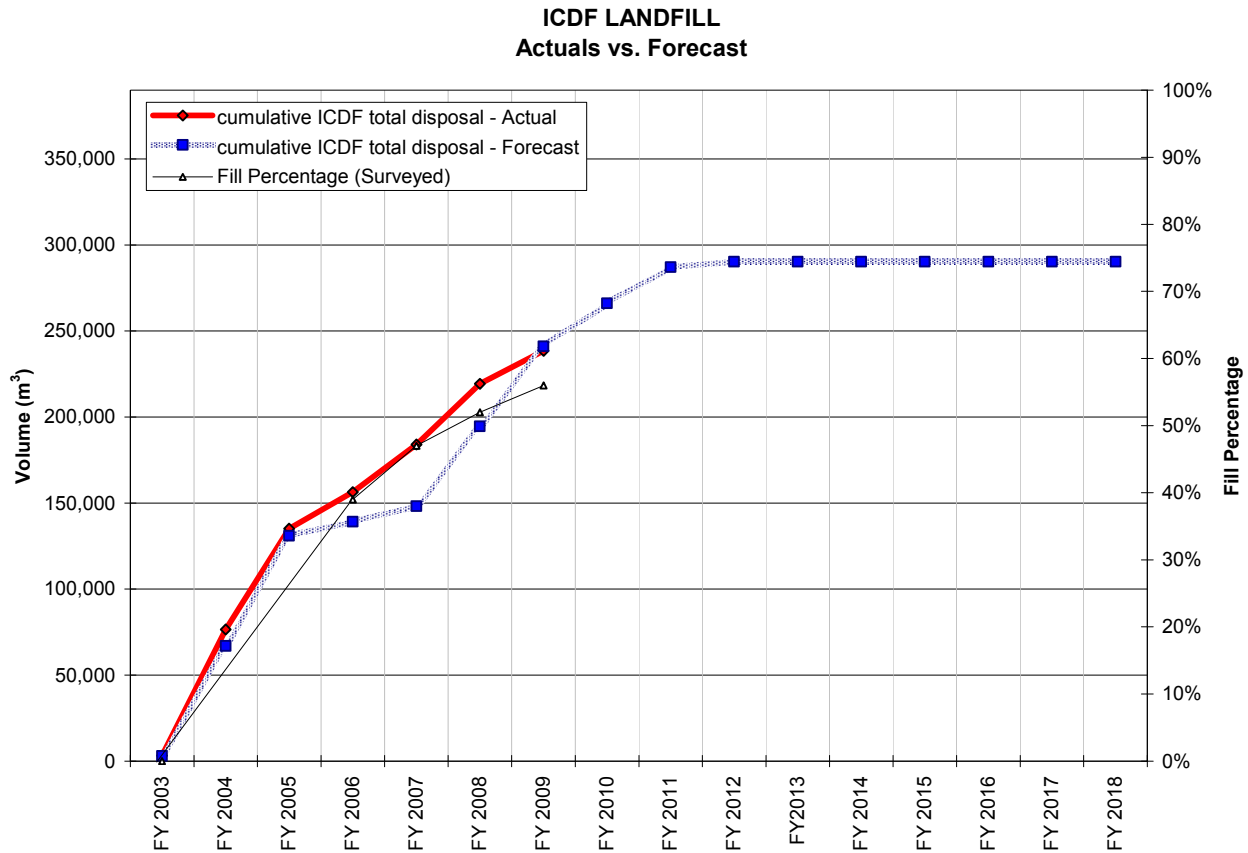


Figure 2-27. Actual and projected cumulative ICDF Landfill disposals through FY 2018.

Table 2-6. Radionuclide inventory for the performance assessment.

Radionuclide	Disposed Inventory 9/16/03–9/30/09 (Ci) ^a	Projected Inventory 10/1/09–9/30/18 (Ci) ^b	Total Inventory 2003–2018 (Ci) ^c
Ac-227	1.13E-06	3.59E-06	4.73E-06
Ac-228	3.80E-03	1.14E-02	1.52E-02
Ag-108m	5.17E-01	9.56E-01	1.47E+00
Ag-110m	3.55E+00	2.89E+00	6.44E+00
Am-241	4.27E-01	1.46E+00	1.89E+00
Am-242m	7.47E-04	2.24E-03	2.99E-03
Am-243	6.13E-03	1.85E-02	2.46E-02
Ba-133	0.00E+00	3.23E-01	3.23E-01
Ba-137m	3.64E+03	3.53E+03	7.17E+03
Be-10	3.84E-01	1.20E+00	1.58E+00
Bi-212	3.00E-03	9.01E-03	1.20E-02
Bi-214	3.53E-03	1.06E-02	1.41E-02
C-14	2.52E+01	8.53E+01	1.10E+02
Ca-41	0.00E+00	1.46E-03	1.46E-03
Ce-141	0.00E+00	4.09E-21	4.09E-21
Ce-144	1.05E-01	2.92E-03	1.08E-01
Cf-249	9.70E-05	2.91E-04	3.88E-04
Cf-250	9.77E-04	2.93E-03	3.91E-03

Table 2-6. (continued).

Radionuclide	Disposed Inventory 9/16/03–9/30/09 (Ci) ^a	Projected Inventory 10/1/09–9/30/18 (Ci) ^b	Total Inventory 2003–2018 (Ci) ^c
Cf-251	1.90E-05	5.70E-05	7.60E-05
Cf-252	5.15E-04	1.55E-03	2.06E-03
Cl-36	1.34E-01	5.85E-01	7.19E-01
Cm-242	4.28E-06	4.00E-03	4.01E-03
Cm-243	2.57E-02	2.65E-03	2.84E-02
Cm-244	3.49E-01	1.08E+00	1.43E+00
Cm-245	1.92E-04	5.75E-04	7.67E-04
Cm-246	2.54E-03	7.61E-03	1.02E-02
Cm-247	2.46E-06	7.38E-06	9.84E-06
Cm-248	6.77E-04	2.03E-03	2.71E-03
Cm-250	6.62E-13	1.99E-12	2.65E-12
Co-58	3.26E-03	9.53E-03	1.28E-02
Co-60	1.99E+03	1.49E+04	1.69E+04
Cr-51	0.00E+00	4.61E-01	4.61E-01
Cs-134	1.42E-01	8.86E-02	2.30E-01
Cs-135	0.00E+00	9.51E-07	9.51E-07
Cs-137	4.06E+03	4.26E+03	8.32E+03
Eu-152	5.24E+01	1.72E+02	2.24E+02
Eu-154	4.02E+01	1.28E+02	1.68E+02
Eu-155	9.24E-02	1.93E+00	2.03E+00
Fe-55	5.99E-02	1.73E+03	1.73E+03
Fe-59	0.00E+00	3.31E-15	3.31E-15
Gd-153	0.00E+00	1.56E-04	1.56E-04
H-3	3.11E+04	9.37E+04	1.25E+05
Hf-175	0.00E+00	2.25E-14	2.25E-14
Hf-178m	0.00E+00	1.05E-01	1.05E-01
Hf-181	0.00E+00	3.72E-16	3.72E-16
Ho-166m	0.00E+00	3.63E-02	3.63E-02
I-129	1.50E-01	3.94E-04	1.50E-01
I-131	9.82E-04	0.00E+00	9.82E-04
Ir-192	0.00E+00	1.34E-09	1.34E-09
K-40	6.24E-01	3.43E-01	9.68E-01
Kr-85	6.55E-05	1.96E-04	2.62E-04
Mn-53	0.00E+00	8.41E-04	8.41E-04
Mn-54	1.06E-03	9.92E-01	9.93E-01
Mo-93	0.00E+00	1.34E-01	1.34E-01
Na-22	0.00E+00	8.14E-05	8.14E-05
Nb-92m	0.00E+00	2.44E-07	2.44E-07
Nb-93m	1.39E-04	4.16E-04	5.55E-04
Nb-94	3.14E+00	9.45E+00	1.26E+01
Nb-95	2.17E-03	1.93E-03	4.11E-03
Ni-59	1.33E+02	4.56E+02	5.89E+02
Ni-63	2.42E+04	7.92E+04	1.03E+05
Np-237	5.46E-02	2.22E-02	7.68E-02
P-32	0.00E+00	9.03E-49	9.03E-49

Table 2-6. (continued).

Radionuclide	Disposed Inventory 9/16/03–9/30/09 (Ci) ^a	Projected Inventory 10/1/09–9/30/18 (Ci) ^b	Total Inventory 2003–2018 (Ci) ^c
Pa-231	1.64E-06	5.17E-06	6.81E-06
Pa-234	3.27E-07	0.00E+00	3.27E-07
Pb-205	0.00E+00	4.15E-07	4.15E-07
Pb-210	6.04E-03	1.81E-02	2.42E-02
Pb-212	3.46E-03	1.04E-02	1.38E-02
Pb-214	3.81E-03	1.14E-02	1.52E-02
Pm-145	0.00E+00	2.10E-04	2.10E-04
Pm-147	4.10E+03	3.75E-02	4.10E+03
Pu-238	1.45E+01	4.40E+00	1.89E+01
Pu-239	1.16E+01	7.66E+00	1.93E+01
Pu-240	9.39E+00	1.05E+00	1.04E+01
Pu-241	3.57E+00	2.60E+01	2.95E+01
Pu-242	1.60E-04	4.80E-04	6.40E-04
Pu-243	1.97E-06	0.00E+00	1.97E-06
Pu-244	1.56E-09	4.68E-09	6.25E-09
Ra-224	1.80E-07	0.00E+00	1.80E-07
Ra-226	8.89E-01	1.18E-01	1.01E+00
Ra-228	1.45E-03	0.00E+00	1.45E-03
Ru-103	6.06E-05	0.00E+00	6.06E-05
Ru-106	2.62E-01	6.41E-03	2.68E-01
S-35	0.00E+00	2.89E-08	2.89E-08
Sb-124	0.00E+00	8.15E-11	8.15E-11
Sb-125	3.46E-01	1.74E-01	5.19E-01
Se-75	0.00E+00	8.24E-06	8.24E-06
Se-79	6.02E-06	1.64E-04	1.70E-04
Si-32	0.00E+00	1.55E-11	1.55E-11
Sm-146	0.00E+00	5.24E-11	5.24E-11
Sm-151	3.78E-02	1.77E-01	2.15E-01
Sn-121m	0.00E+00	1.06E-03	1.06E-03
Sr-89	0.00E+00	6.80E-16	6.80E-16
Sr-90	8.74E+02	1.03E+03	1.90E+03
Ta-182	0.00E+00	1.72E-10	1.72E-10
Tb-158	0.00E+00	6.45E-04	6.45E-04
Tb-160	0.00E+00	1.55E-12	1.55E-12
Tc-99	1.22E-01	5.38E-01	6.59E-01
Th-228	9.46E-02	4.13E-03	9.87E-02
Th-229	1.34E-06	4.30E-06	5.64E-06
Th-230	1.01E-01	2.33E-03	1.04E-01
Th-232	9.07E-02	2.64E-03	9.33E-02
Th-234	2.23E-03	6.70E-03	8.93E-03
Tl-208	9.72E-04	2.92E-03	3.89E-03
U-232	1.77E-04	5.35E-04	7.12E-04
U-233	8.16E-02	3.74E-02	1.19E-01
U-234	4.24E-01	2.67E-01	6.91E-01
U-235	1.04E-01	5.03E-02	1.55E-01

Table 2-6. (continued).

Radionuclide	Disposed Inventory 9/16/03–9/30/09 (Ci) ^a	Projected Inventory 10/1/09–9/30/18 (Ci) ^b	Total Inventory 2003–2018 (Ci) ^c
U-236	1.32E-03	2.62E-03	3.94E-03
U-238	3.39E-01	1.58E-01	4.97E-01
W-185	0.00E+00	4.57E-09	4.57E-09
Y-90	8.23E+02	8.08E+02	1.63E+03
Zn-65	1.04E-02	2.57E-03	1.30E-02
Zr-93	0.00E+00	1.05E-05	1.05E-05
Zr-95	1.10E-03	9.16E-04	2.01E-03

a. From Integrated Waste Tracking System database, information pulled on April 27, 2010.
b. See EDF-9463.
c. Sum of disposed and projected inventories.

The projected inventory is a combination of the annual average disposal rate and some large planned disposals (see EDF-9463). This projected inventory includes all future disposals from FY 2010 through the end of facility disposal operations at the end of FY 2018. Disposals of DD&D waste over the last 2 to 3 years were assumed to be most representative of upcoming planned disposals at the ICDF Landfill. Thus, the average annual disposal rate was calculated from the annual rate of disposal from October 2006 through FY 2009. The projected inventory also explicitly includes several large planned disposals that differ from typical DD&D waste (e.g., EBR-II, Materials Test Reactor, Advanced Test Reactor Complex waste).

2.3.3 Waste Forms and Release Mechanisms

Waste forms at the ICDF Landfill include solid debris, activated metals, graphite, soils, personal protective equipment, concrete, asphalt, glass, steel, wood, metals, plastic, grout, piping, filters, etc. Waste containers for packaged waste disposals include metal drums, metal boxes, wood boxes, concrete boxes, and cloth soil sacks. The bulk waste, mainly soils and debris (pipe, building rubble, etc.), are hauled to the landfill in dump trucks and roll-offs. Nonstandard waste disposals include the V-9 tank from TAN, the Engineering Test Reactor vessel, and the Power Burst Facility reactor vessel. Much of the debris disposed of from DD&D activities was grouted in place to minimize subsidence.

An analysis of the total inventory waste form was performed as described in EDF-9463. As a result of this analysis, two waste forms were assumed in the PA analysis:

- Activated metal
- Miscellaneous waste.

Activated metals have been disposed of at the ICDF (the Power Burst Facility in-pile tube, the test reactor pressure vessel (Engineering Test Reactor), graphite balls and graphite blocks from Materials Test Reactor, and Materials Test Reactor plugs); and there are three large upcoming disposals comprised of activated metals that were explicitly accounted for in the projected inventory portion of the total inventory (e.g., EBR-II, Materials Test Reactor, and Advanced Test Reactor Complex waste). Miscellaneous waste is comprised of all other waste that is not activated metals. Compacted soils and debris from DD&D activities comprise a large portion of the waste included in the miscellaneous waste category.

For waste at the ICDF Landfill that was disposed of in containers, release from the container was not included in the PA analysis. The miscellaneous waste form was assumed to release by surface wash or dissolution. This is a conservative assumption because it assumed the radionuclides are immediately

available for leaching to the environment; in practice, nearly all waste received into the ICDF is grouted. Therefore, the radionuclides would release at a slower rate than assumed in this analysis. Activated metals are assumed to release by corrosion of the metal. The activated metals are released more slowly than the miscellaneous waste, which will tend to decrease the contaminant flux, particularly in the early times of the PA analysis.

The heavy waste objects (i.e., reactor vessels) are evaluated operationally to ensure there is no negative effect on the landfill liner system (Reimbold 2006). Offload and placement of the Engineering Test Reactor and Power Burst Facility vessels and bearing strength analyses on the GCL are presented in EDF-8269 and EDF-8754, respectively. These heavy objects should not impact the PA as the geomembrane liners are not simulated in the PA analysis.

2.4 Radionuclide Inventory Screening for the Groundwater Pathway

There are 115 individual radionuclides in the PA inventory as shown in Table 2-6. The large number of radionuclides causes difficulties in estimating future dose impacts and distracts resources from radionuclides that are most important. Therefore, screening was used to reduce the number of radionuclides to a manageable number and focus resources on those radionuclides that are most important for detailed analysis.

A screening process can be set up in different ways, for example (a) make the screening model as realistic as possible and set a low screening criteria (such as 100 times less than the performance measure) or (b) have a conservative screening model and a less restrictive screening level (such as 10 times the performance measure). Both approaches are technically justifiable and demonstrably conservative. The second approach was used for the ICDF PA. The inventory screening methodology utilized for the PA was a similar approach as reported for the previous ICDF PA (DOE-ID 2003a) and was consistently used across the INL Site for other PA analyses (DOE-ID 2007d).

The groundwater pathway screening method uses an absolute criterion coupled with a conservative fate and transport model and exposure scenario. An absolute criteria method computes a conservative estimate of the individual radionuclide dose. This screening dose is then compared against a criterion. If the screening dose is greater than the criterion, then the radionuclide is retained for further evaluation. If the dose is less than the criterion, then the radionuclide is screened out and not considered in any further evaluations.

The groundwater pathway screening method was performed in two phases (Figure 2-28). Phase I screening eliminated radionuclides based on their half-lives. Phase II addressed radionuclide screening for the groundwater pathway. The Phase II screening used a simple and conservative application of the GWSCREEN (Rood 2003a) semianalytical model to calculate a screening dose. The GWSCREEN application considers dilution, dispersion, and unsaturated transit time. Details related to the specific steps required to perform the screening analysis are described in EDF-9453.

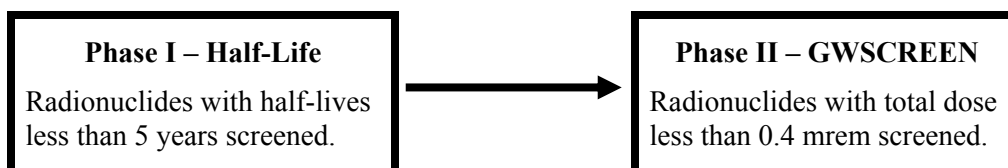


Figure 2-28. Inventory screening methodology flow chart.

2.4.1 Phase I Inventory Screening

Some radionuclides can be eliminated from consideration early in the screening process based on their half-lives. Radionuclides with half-lives of less than 5 years were eliminated from further consideration based on their rate of decay. Assuming a 16.8-m sedimentary interbed thickness, the default infiltration rate (10 cm/year) (DOE-ID 1994), and a moisture content of 30% yields a mean unsaturated travel time of 50 years. After 50 years, a radionuclide with a 5-year half-life would only have 9.2E-04 of its original activity. Therefore, radionuclides with half-lives of 5 years or less are not expected to contribute significantly to the dose from the groundwater pathway.

PA Phase I screening results are presented in Table 2-7. Sixty-seven of the 115 radionuclides in the original inventory had half-lives greater than 5 years. These 67 radionuclides were retained after Phase I screening calculations and 48 were eliminated from the inventory. Some of the radionuclides eliminated in Phase I were short-lived progeny of longer-lived parent radionuclides. These short-lived progeny generally do not exist without the presence of their parent. It is important to note that these radionuclides were only screened from the disposal inventory and that the Phase II groundwater pathway screening (GWSCREEN methodology) included the ingrowth of these progeny from their parent nuclides over time.

Table 2-7. Phase I screening results for all radionuclides currently in the ICDF PA total inventory. Radionuclides and associated half-lives are listed. Radionuclides with half-lives greater than 5 years were retained for further analysis and are shown in **bold**.

Radionuclide	Half-Life (years) ^a	Is Half-Life Greater than 5 Years?	Radionuclide	Half-Life (years) ^a	Is Half-Life Greater than 5 Years?
Ac-227	2.18E+01	Yes	Nb-95	9.58E-02	
Ac-228	7.02E-04		Ni-59	7.60E+04	Yes
Ag-108m	4.18E+02	Yes	Ni-63	1.00E+02	Yes
Ag-110m	6.84E-01		Np-237	2.14E+06	Yes
Am-241	4.32E+02	Yes	P-32	3.90E-02	
Am-242m	1.41E+02	Yes	Pa-231	3.28E+04	Yes
Am-243	7.37E+03	Yes	Pa-234	7.64E-04	
Ba-133	1.05E+01	Yes	Pb-205	1.53E+07	Yes
Ba-137m	4.85E-06		Pb-210	2.23E+01	Yes
Be-10	1.51E+06	Yes	Pb-212	1.21E-03	
Bi-212	1.15E-04		Pb-214	5.10E-05	
Bi-214	3.78E-05		Pm-145	1.77E+01	Yes
C-14	5.73E+03	Yes	Pm-147	2.62E+00	
Ca-41	1.03E+05	Yes	Pu-238	8.77E+01	Yes
Ce-141	8.90E-02		Pu-239	2.41E+04	Yes
Ce-144	7.80E-01		Pu-240	6.56E+03	Yes
Cf-249	3.51E+02	Yes	Pu-241	1.43E+01	Yes
Cf-250	1.31E+01	Yes	Pu-242	3.73E+05	Yes
Cf-251	8.98E+02	Yes	Pu-243	5.65E-04	
Cf-252	2.65E+00		Pu-244	8.00E+07	Yes
Cl-36	3.01E+05	Yes	Ra-224	1.00E-02	
Cm-242	4.46E-01		Ra-226	1.60E+03	Yes
Cm-243	2.91E+01	Yes	Ra-228	5.75E+00	Yes
Cm-244	1.81E+01	Yes	Ru-103	1.07E-01	
Cm-245	8.50E+03	Yes	Ru-106	1.02E+00	
Cm-246	4.76E+03	Yes	S-35	2.40E-01	
Cm-247	1.56E+07	Yes	Sb-124	1.65E-01	
Cm-248	3.48E+05	Yes	Sb-125	2.76E+00	
Cm-250	9.70E+03	Yes	Se-75	3.28E-01	

Table 2-7. (continued).

Radionuclide	Half-Life (years) ^a	Is Half-Life Greater than 5 Years?	Radionuclide	Half-Life (years) ^a	Is Half-Life Greater than 5 Years?
Co-58	1.94E-01		Se-79	1.10E+06	Yes
Co-60	5.27E+00	Yes	Si-32	1.72E+02	Yes
Cr-51	7.58E-02		Sm-146	1.03E+08	Yes
Cs-134	2.07E+00		Sm-151	9.00E+01	Yes
Cs-135	2.30E+06	Yes	Sn-121m	5.50E+01	Yes
Cs-137	3.01E+01	Yes	Sr-89	1.38E-01	
Eu-152	1.35E+01	Yes	Sr-90	2.88E+01	Yes
Eu-154	8.59E+00	Yes	Ta-182	3.13E-01	
Eu-155	4.76E+00		Tb-158	1.80E+02	Yes
Fe-55	2.74E+00		Tb-160	1.98E-01	
Fe-59	1.22E-01		Tc-99	2.11E+05	Yes
Gd-153	6.58E-01		Th-228	1.91E+00	
H-3	1.23E+01	Yes	Th-229	7.34E+03	Yes
Hf-175	1.92E-01		Th-230	7.54E+04	Yes
Hf-178m	1.27E-07		Th-232	1.41E+10	Yes
Hf-181	1.16E-01		Th-234	6.60E-02	
Ho-166m	1.20E+03	Yes	Tl-208	5.80E-06	
I-129	1.57E+07	Yes	U-232	6.89E+01	Yes
I-131	2.20E-02		U-233	1.59E+05	Yes
Ir-192	2.02E-01		U-234	2.46E+05	Yes
K-40	1.27E+09	Yes	U-235	7.04E+08	Yes
Kr-85	1.08E+01	Yes	U-236	2.34E+07	Yes
Mn-53	3.74E+06	Yes	U-238	4.47E+09	Yes
Mn-54	8.55E-01		W-185	2.06E-01	
Mo-93	4.00E+03	Yes	Y-90	7.30E-03	
Na-22	2.60E+00		Zn-65	6.69E-01	
Nb-92m	2.78E-02		Zr-93	1.53E+06	Yes
Nb-93m	1.61E+01	Yes	Zr-95	1.75E-01	
Nb-94	2.03E+04	Yes	—	—	—

a. Radionuclide half-lives obtained from the Integrated Waste Tracking System database with its data source the National Nuclear Data Center, Brookhaven Laboratory.

2.4.2 Phase II Inventory Screening

The Phase II screening analysis used a conservative implementation of the semianalytical model, GWSCREEN Version 2.5 (Rood 2003a), to calculate groundwater concentrations and ingestion doses for radionuclides that remained after Phase I. The GWSCREEN model was developed to address CERCLA sites at the INL Site. The code, coupled with a set of default parameter values identified in the CERCLA Track 2 risk assessment process (DOE-ID 1994), provides conservative estimates of groundwater concentrations and ingestion doses at the INL Site.

The GWSCREEN conceptual model is illustrated in Figure 2-29. Radionuclides disposed of in the ICDF Landfill were assumed to be mixed homogeneously with soil and placed in a volume represented by the volume of the landfill. One-dimensional transport in a 16.8-m-thick unsaturated zone comprised of sedimentary interbeds was assumed. This assumption is consistent with the previous PA calculations where transport time through the basalt in the vadose zone was assumed to be instantaneous (DOE-ID 2003a).

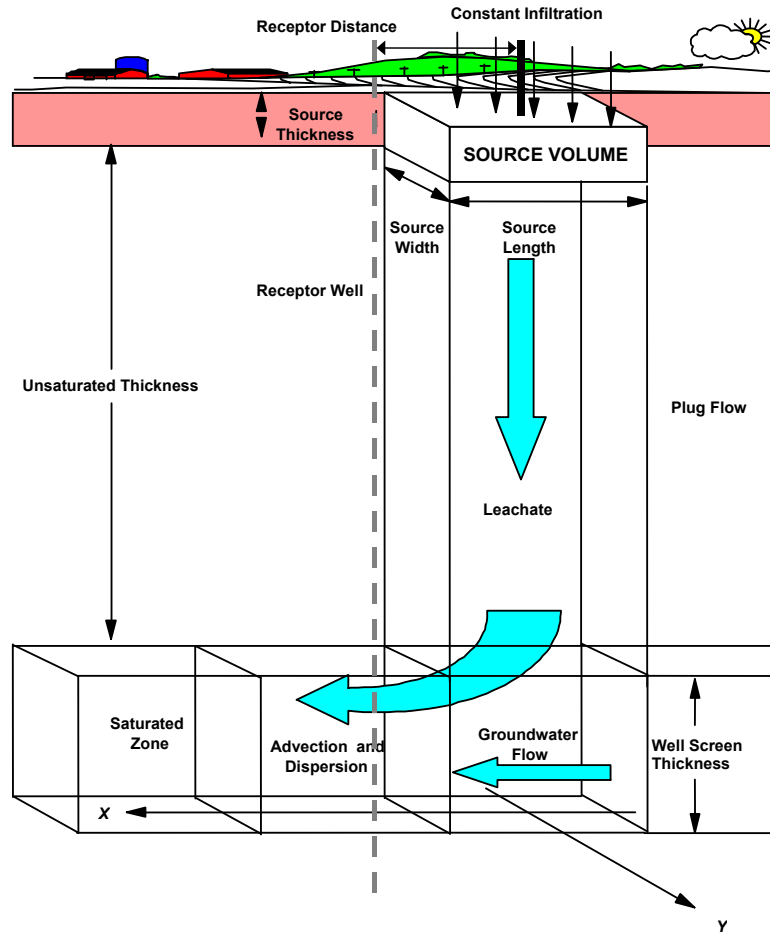


Figure 2-29. Conceptual model for GWSCREEN Phase II screening.

The receptor well was placed on the downgradient edge of the source. Note that the receptor distance was measured from the center of the source; therefore, the distance to the receptor well used for the PA was $160 \text{ m} \div 2 = 80 \text{ m}$. It was assumed that contaminant movement was not limited by containers or engineered barriers. The waste was then assumed to be exposed to infiltrating water and contaminants were leached from the waste and move into the subsurface. The Track 2 default infiltration rate for screening is 10 cm/year.

No dispersion in the unsaturated zone was assumed. The subsurface environment beneath the INL Site is comprised of basalt flows separated by sedimentary interbeds. The basalt flows are often fractured, allowing water to move freely in the vertical direction. The Track 2 methodology (DOE-ID 1994) recognized this feature of the system and assumed water transport time through the fractured basalt is relatively instantaneous and ultimately controlled by the presence of sedimentary interbeds. Therefore, only transport through sedimentary interbeds was considered when computing contaminant transport in the unsaturated zone. The aquifer was assumed to be homogeneous isotropic media of infinite lateral extent and finite thickness. Contaminants entering the aquifer from the unsaturated zone mix with water in the aquifer over a depth defined by a typical well screen of 15 m (DOE-ID 1994). Concentrations were then evaluated at the downgradient edge of the source. This receptor is the point where the highest concentrations in the aquifer were computed.

GWSCREEN simulated one-dimensional flow in the aquifer with contaminant flux from the vadose zone to the aquifer. GWSCREEN does not simulate the water flux from the vadose zone to the aquifer. The code accounts for this by diluting the aquifer concentrations based on the additional water expected from the vadose zone. For screening, the infiltration rate in the vadose zone was assumed to be insignificant compared to the volume of water flowing in the aquifer across the same area (i.e., dilution factor assumed to be 1).

The GWSCREEN model also considered transport of radioactive progeny. For simplicity, progeny were assumed to travel at the same rate as their parent. Under most circumstances, this assumption leads to conservative dose estimates at the receptor point. However, when considering the transport of a short-lived immobile parent that has a long-lived mobile progeny, results can be distorted and in many cases are not conservative. This situation occurs for several of the decay chains (e.g., the $\text{Pu-241} \Rightarrow \text{Am-241} \Rightarrow \text{Np-237}$ and $\text{Pu-238} \Rightarrow \text{U-234}$). To handle these cases, it was assumed for GWSCREEN calculations that the short-lived immobile parent nuclide never leaves the waste zone and instead decays to its more mobile long-lived progeny. Therefore, the sorption characteristics of the progeny were used as input to GWSCREEN to determine the overall transit time of the decay chain along with accompanying radiation dose. For conservatism, the entire activity of the short-lived immobile parent was converted to the equivalent progeny activity by the relationship:

$$A_{\text{Prog}} = A_{\text{Parent}} \frac{T_{\text{parent}}}{T_{\text{Prog}}} \quad (2-6)$$

Where

- A_{Prog} = equivalent activity of the long-lived mobile progeny (Ci)
- A_{Parent} = original activity of the short-lived immobile parent (Ci)
- T_{Prog} = half-life of the long-lived mobile progeny (years)
- T_{Parent} = half-life of the short-lived immobile parent (years).

For Phase II screening of the groundwater pathway, it was assumed a person drinks 2 L of water per day for 365 days per year. Ingestion doses for the groundwater pathway were computed using dose conversion factors published in Federal Guidance Report 13 (EPA 2002) and include contributions from all progeny.

The screening criteria for Phase II were set at 1/10th of the allowable drinking water dose for beta-gamma emitters of 4 mrem/year as stated in 40 CFR 141. Although this standard applies only to beta-gamma-emitting radionuclides and was calculated using International Commission on Radiological Protection (ICRP) 2 methodology (ICRP 1960), the 0.4-mrem screening criteria coupled with other conservative assumptions were believed to be stringent enough to avoid screening any radionuclides of importance from the inventory.

A combination of the Track 2 parameters and some conservative site-specific parameters for the ICDF were used for input to the GWSCREEN code for the Phase II calculations (Table 2-8). The basis for the input data was obtained from the Track 2 guidance document (DOE-ID 1994). The dimension of the waste disposal site, Darcy velocity in the aquifer, and the sedimentary interbed thickness in the unsaturated zone are site-specific values. The site-specific input values were obtained from the previous PA (DOE-ID 2003a) and the OU 10-08 Site-wide Groundwater RI/BRA (DOE-ID 2008d). The infiltration rate was set at 10 cm/year, which is a factor of 10 times the undisturbed soil infiltration assumed for INL Site soils.

The distribution coefficients (K_d s) used for Phase II screening (Table 2-9) were chosen to be consistent with the Track 2 guidance (Jenkins 2001). The Track 2 recommendations for the INL Site include several sources, including K_d values assumed for various locations at the INL Site, as well as the literature (Sheppard and Thibault 1990). For some radionuclides, more recent site-specific K_d values were reported in the OU 3-14 Tank Farm RI/BRA (Cahn et al. 2006). For radionuclides listed in both Jenkins (2001) and Cahn et al. (2006), the most conservative value (i.e., smallest K_d between the two reports) was used for the screening analysis.

Appropriate conservative K_d values were assumed for the source zone, vadose zone, and aquifer as shown in Table 2-9. Except for plutonium, the source zone and unsaturated zone were assigned the same K_d value. The values chosen for Phase II screening were assumed to be applicable to sedimentary rocks and materials that make up the source zone fill, surface alluvium, and interbeds at the ICDF. It was assumed there was no sorption in the aquifer.

The Phase II GWSCREEN results are shown in Table 2-10. The GWSCREEN total screening dose is the maximum value calculated during the time period of the GWSCREEN simulation. If there were progeny, then the total screening dose is the sum of the maximum dose from each of the progeny. These results show that 12 out of 67 radionuclides had a GWSCREEN total screening dose greater than the screening criteria of 0.4 mrem.

The 12 radionuclides retained in the PA inventory are shown in Table 2-11. There were 55 radionuclides eliminated in Phase II of screening. Therefore, 12 radionuclides were retained for a detailed analysis of dose and concentrations for the PA groundwater pathway base case analysis as described in Section 3.

The built-in conservatism of the screening groundwater pathways model is illustrated by comparing the screening dose and base case dose results. When considered in the PA, the analysis of the 12 radionuclides identified for the groundwater pathway base case analyses (C-14, Cl-36, H-3, I-129, Np-237, Pu-239, Pu-240, Tc-99, U-233, U-234, U-235, and U-238) resulted in predicted cumulative base case doses that are at least four orders of magnitude smaller than the screening dose during the compliance period and at least a factor of 16 smaller than the screening dose during the post-compliance period, as shown in Section 4.5.1. This is a relative dose comparison since the screening and base case analysis doses are not calculated in the same way; the screening dose is ingestion only and the base case is all-pathways EDE.

2.4.3 Screening Thresholds

Screening thresholds were calculated to ensure that the inventories for contaminants that were screened out in the revised PA do not become large enough so they are retained (see EDF-9453). As explained in Section 1.2.1, inventory limits have been set in the form of a WAC for the ICDF for the primary contaminants of concern (i.e., all radionuclides included in the base case analysis). Screening thresholds provide a check to ensure that the inventories for contaminants screened out in the PA (e.g., those without a WAC) do not become large enough so they would have been retained for the base case analysis.

Table 2-8. Input parameters used for Phase II screening calculations for the performance assessment.

GWSCREEN Variable	Parameter Description	Value	Reference
Source			
L	Source length parallel to groundwater flow	160 m	2003 PA (DOE-ID 2003a).
W	Source width perpendicular to groundwater flow	194 m	2003 PA (DOE-ID 2003a).
PERC	Percolation rate through source into vadose zone	10 cm/yr	DOE-ID (1994, p. C-11).
THICKS	Thickness of source	10.4 m	2003 PA (see Figure 3-5, DOE-ID 2003a).
RHOS	Bulk density of source zone	1.5 g/m ³	DOE-ID (1994, p. C-11).
THETAS	Moisture content of source	0.3 cm ³ /cm ³	DOE-ID (1994, p. C-11).
Unsaturated Zone			
DEPTH	Depth from base of source to top of aquifer	16.8 m	Unsaturated zone interbed thickness (i.e., transport time through basalt assumed to be instantaneous consistent with DOE-ID 1994).
RHOU	Bulk density-unsaturated zone	1.9 g/cm ³	DOE-ID (1994, p. C-11).
AUX	Longitudinal dispersivity – unsaturated zone	0 m	Assumed plug flow through unsaturated zone.
THETAU	Volumetric moisture content of unsaturated zone	0.3 cm ³ /cm ³	DOE-ID (1994, p. C-11). Note that this value is consistent with Magnuson and Sondrup (1998). It is the value for interbeds because instantaneous transport through the unsaturated zone basalts was assumed.
Aquifer			
AX	Longitudinal dispersivity	9 m	DOE-ID (1994, p. C-11).
AY	Transverse dispersivity	4 m	DOE-ID (1994, p. C-11).
AZ	Vertical dispersivity	N/A	Assumed 2-dimensional vertically averaged model as per Track 2 guidance. Radionuclides are mixed vertically in an aquifer that is as thick as the well screen DOE-ID (1994, p. C-11).
B	Aquifer thickness	76 m	2003 PA (DOE-ID 2003a).
Z	Well screen thickness	15 m	DOE-ID (1994, p. C-11).
U	Darcy velocity in aquifer	21.9 m/yr	2003 PA (DOE-ID 2003a).

Table 2-8. (continued).

GWSCREEN Variable	Parameter Description	Value	Reference
PHI	Porosity of aquifer	0.06 cm ³ /cm ³	OU 10-08 (DOE-ID 2008d).
RHOA	Bulk density of aquifer	1.9 g/cm ³	DOE-ID (1994).
Receptor Distance from Center of Source			
XREC(I)	Receptor distance parallel to groundwater flow (measured from center of source)	80 m	One-half the length of source (AL/2).
YREC(I)	Receptor distance perpendicular to groundwater flow (measured from center of source)	0 m	Receptor located along flow path through center of source.
Dose			
BW	Body mass of receptor	70 kg	Track 2 default (DOE-ID 1994, p. C-8).
AT	Time the exposure is averaged over	25,550 d	Track 2 default - 70 years (DOE-ID 1994, p. C-8).
WI	Water intake rate for receptor	2 L/d	Track 2 default (DOE-ID 1994, p. C-8).
EF	Exposure frequency	365 d/yr	Assume continuous exposure.
ED	Exposure duration	1 yr	If ED is set at 1 year or less, then GWSCREEN will use the maximum dose for calculating results.
DLIM	Acceptable level of health impacts	0.4 mrem/yr	For screening, assume one-tenth PA dose limit.
OU	operable unit		
PA	performance assessment		

Table 2-9. Distribution coefficient (K_d) values used for screening calculations.

Element Name	Symbol	K_d Unsaturated			Reference
		K_d Source (mL/g) ^a	Zone (mL/g) ^b	K_d Aquifer (mL/g) ^c	
Actinium	Ac	450	450	0	Jenkins (2001)
Americium ^d	Am	340	340	0	Jenkins (2001)
Barium	Ba	50	50	0	Jenkins (2001)
Beryllium	Be	250	250	0	Jenkins (2001)
Calcium	Ca	5	5	0	Jenkins (2001)
Californium	Cf	510	510	0	Jenkins (2001)
Carbon ^d	C	1.6	1.6	0	Cahn et al. (2006)
Cesium ^d	Cs	50	50	0	Cahn et al. (2006)
Chlorine	Cl	0	0	0	Jenkins (2001)
Cobalt	Co	10	10	0	Jenkins (2001)
Curium	Cm	4,000	4,000	0	Jenkins (2001)
Europium ^d	Eu	340	340	0	Jenkins (2001)
Holmium	Ho	250	250	0	Jenkins (2001)
Hydrogen ^d	H	0	0	0	Jenkins (2001)
Iodine ^d	I	0	0	0	Jenkins (2001)
Krypton	Kr	0	0	0	Jenkins (2001)
Lead	Pb	100	100	0	Jenkins (2001)
Manganese	Mn	50	50	0	Jenkins (2001)
Molybdenum	Mo	10	10	0	Jenkins (2001)
Neptunium ^d	Np	2	2	0	Cahn et al. (2006)
Nickel	Ni	100	100	0	Jenkins (2001)
Niobium	Nb	100	100	0	Jenkins (2001)
Plutonium ^d	Pu	140	22	0	Jenkins (2001)
Potassium	K	15	15	0	Jenkins (2001)
Promethium	Pm	240	240	0	Jenkins (2001)
Protactinium	Pa	550	550	0	Jenkins (2001)
Radium	Ra	100	100	0	Jenkins (2001)
Samarium	Sm	240	240	0	Jenkins (2001)
Selenium	Se	4	4	0	Jenkins (2001)
Silicon	Si	35	35	0	Jenkins (2001)
Silver	Ag	90	90	0	Jenkins (2001)
Strontium ^d	Sr	12	12	0	Jenkins (2001)
Technetium ^d	Tc	0	0	0	Cahn et al. (2006)
Terbium	Tb	240	240	0	Jenkins (2001)
Thorium	Th	100	100	0	Jenkins (2001)

Table 2-9. (continued).

Element Name	Symbol	K _d Unsaturated		K _d Aquifer (mL/g) ^c	Reference
		K _d Source (mL/g) ^a	Zone (mL/g) ^b		
Tin	Sn	130	130	0	Jenkins (2001)
Uranium ^d	U	1.6	1.6	0	Cahn et al. (2006)
Zirconium ^d	Zr	600	600	0	Jenkins (2001)

a. Waste soil designation from Jenkins (2001) unless otherwise noted.

b. Interbed designation from Jenkins (2001) unless otherwise noted.

c. Basalt K_d in aquifer assumed to be zero.

d. Radionuclide listed in both Jenkins (2001) and Cahn et al. (2006). For screening, assumed the most conservative value (i.e., smallest K_d between the two reports).

Table 2-10. Phase II groundwater pathway screening results for all radionuclides currently in the Idaho CERCLA Disposal Facility Performance Assessment total inventory using the GWSCREEN semianalytical model. Radionuclides with a total dose >0.4 mrem are shown in **bold**.

Radionuclide	Progeny	Ingestion Dose Conversion Factor (rem/Ci) ^a	Decay Chain Maximum Dose (mrem/y) ^b	Total Screening Maximum Dose (mrem/y)
Ac-227		1.2E+06	0.0E+00	0.0E+00
Ag-108m		8.7E+03	2.1E-23	2.1E-23
Am241 (Np-237)		4.0E+05	5.1E-03	5.1E-03
	U-233	1.9E+05	7.2E-06	
	Th-229	1.9E+06	2.3E-06	
Am-242m (U-234)		1.8E+05	1.0E-05	1.1E-05
	Th-230	7.9E+05	2.3E-07	
	Ra-226	1.0E+06	3.3E-08	
	Pb-210	2.6E+06	7.7E-08	
Am-242m (Pu-242)		8.8E+05	8.8E-08	8.8E-08
	U-238	1.6E+05	1.8E-14	
	U-234	1.8E+05	2.0E-16	
	Th-230	7.9E+05	1.9E-17	
	Ra-226	1.0E+06	1.1E-17	
	Pb-210	2.6E+06	2.8E-17	
Total Am-242				1.1E-05
Am-243		7.5E+05	1.5E-07	9.6E-05
	Pu-239	9.3E+05	9.6E-05	
	U-235	1.7E+05	8.8E-09	
	Pa-231	1.8E+06	6.8E-08	
	Ac-227	1.2E+06	4.5E-08	
Ba-133		5.7E+03	0.0E+00	0.0E+00
Be-10		4.2E+03	1.9E-03	1.9E-03
C-14		2.1E+03	8.8E+00	8.8E+00
Ca-41		7.2E+02	1.5E-05	1.5E-05
Cf-249 (Np-237)		4.0E+05	8.4E-07	8.4E-07
	U-233	1.9E+05	1.2E-09	
	Th-229	1.9E+06	3.8E-10	

Table 2-10. (continued).

Radionuclide	Progeny	Ingestion Dose Conversion Factor (rem/Ci) ^a	Decay Chain Maximum Dose (mrem/y) ^b	Total Screening Maximum Dose (mrem/y)
Cf-250 (Pu-242)		8.8E+05	6.2E-08	6.2E-08
	U-238	1.6E+05	1.2E-14	
	U-234	1.8E+05	1.4E-16	
	Th-230	7.9E+05	1.3E-17	
	Ra-226	1.0E+06	7.6E-18	
	Pb-210	2.6E+06	1.9E-17	
Cf-251 (Pu-239)		9.3E+05	1.1E-06	1.1E-06
	U-235	1.7E+05	1.6E-12	
	Pa-231	1.8E+06	1.2E-12	
	Ac-227	1.2E+06	8.1E-13	
Cl-36		3.4E+03	8.7E-01	8.7E-01
Cm-243 (Pu-239)		9.3E+05	1.4E-05	1.4E-05
	U-235	1.7E+05	1.9E-11	
	Pa-231	1.8E+06	1.5E-11	
	Ac-227	1.2E+06	9.8E-12	
Cm-244 (Pu-240)		9.3E+05	9.0E-04	9.0E-04
	U-236	1.7E+05	5.1E-08	
	Th-232	8.5E+05	5.0E-14	
	Ra-228	2.6E+06	1.5E-13	
	Th-228	2.7E+05	1.6E-14	
Cm-245 (Np-237)		4.0E+05	4.0E-05	4.0E-05
	U-233	1.9E+05	5.7E-08	
	Th-229	1.9E+06	1.8E-08	
Cm-246 (Pu-242)		8.8E+05	5.9E-05	5.9E-05
	U-238	1.6E+05	1.2E-11	
	U-234	1.8E+05	1.3E-13	
	Th-230	7.9E+05	1.2E-14	
	Ra-226	1.0E+06	7.2E-15	
	Pb-210	2.6E+06	1.8E-14	
Cm-247 (Pu-239)		9.3E+05	2.5E-03	2.5E-03
	U-235	1.7E+05	3.6E-09	
	Pa-231	1.8E+06	2.8E-09	
	Ac-227	1.2E+06	1.8E-09	
Cm-248		1.4E+07	5.5E-05	5.5E-05
	Pu-244	3.3E+06	6.5E-07	
	Pu-240	9.3E+05	1.8E-07	
	U-236	1.7E+05	8.6E-10	
	Th-232	8.5E+05	1.0E-13	
	Ra-228	2.6E+06	3.2E-13	
Cm-250		7.8E+07	0.0E+00	0.0E+00
Co-60		1.3E+04	0.0E+00	0.0E+00
Cs-135		7.4E+03	1.0E-08	1.0E-08
Cs-137		5.0E+04	0.0E+00	0.0E+00
Eu-152		5.1E+03	0.0E+00	0.0E+00
Eu-154		7.6E+03	0.0E+00	0.0E+00
H-3		7.1E+01	1.8E+02	1.8E+02
Ho-166m		7.3E+03	7.6E-25	7.6E-25

Table 2-10. (continued).

Radionuclide	Progeny	Ingestion Dose Conversion Factor (rem/Ci) ^a	Decay Chain Maximum Dose (mrem/y) ^b	Total Screening Maximum Dose (mrem/y)
I-129		3.9E+05	2.1E+01	2.1E+01
K-40		2.3E+04	1.1E-01	1.1E-01
Kr-85		0.0E+00	0.0E+00	0.0E+00
Mn-53		1.1E+02	1.3E-07	1.3E-07
Mo-93		1.2E+04	6.6E-03	6.6E-03
Nb-93m		4.6E+02	0.0E+00	0.0E+00
Nb-94		6.4E+03	2.0E-02	2.0E-02
Ni-59		2.3E+02	7.4E-02	7.4E-02
Ni-63		5.6E+02	0.0E+00	0.0E+00
Np-237		4.0E+05	1.0E+00	1.0E+00
	U-233	1.9E+05	1.5E-03	
	Th-229	1.9E+06	4.6E-04	
Pa-231		1.8E+06	4.0E-08	6.7E-08
	Ac-227	1.2E+06	2.7E-08	
Pb-205	Pb-205	1.0E+03	3.0E-10	3.0E-10
Pb-210	Pb-210	2.6E+06	0.0E+00	0.0E+00
Pm-145	Pm-145	4.3E+02	0.0E+00	0.0E+00
Pu-238 (U-234)		1.8E+05	4.9E-02	5.1E-02
	Th-230	7.9E+05	1.1E-03	
	Ra-226	1.0E+06	1.6E-04	
	Pb-210	2.6E+06	3.7E-04	
Pu-239		9.3E+05	7.6E+00	7.6E+00
	U-235	1.7E+05	1.1E-05	
	Pa-231	1.8E+06	8.4E-06	
	Ac-227	1.2E+06	5.5E-06	
Pu-240		9.3E+05	2.4E+00	2.4E+00
	U-236	1.7E+05	1.4E-04	
	Th-232	8.5E+05	1.3E-10	
	Ra-228	2.6E+06	4.1E-10	
	Th-228	2.7E+05	4.2E-11	
Pu-241 (Np-237)		4.0E+05	2.6E-03	2.6E-03
	U-233	1.9E+05	3.7E-06	
	Th-229	1.9E+06	1.2E-06	
Pu-242		8.8E+05	2.9E-04	2.9E-04
	U-238	1.6E+05	5.8E-11	
	U-234	1.8E+05	6.5E-13	
	Th-230	7.9E+05	6.1E-14	
	Ra-226	1.0E+06	3.6E-14	
	Pb-210	2.6E+06	9.1E-14	
Pu-244		3.3E+06	1.1E-08	1.2E-08
	Pu-240	9.3E+05	1.6E-09	
	U-236	1.7E+05	3.4E-14	
	Th-232	8.5E+05	2.1E-20	
Ra-226		1.0E+06	7.2E-07	2.6E-06
	Pb-210	2.6E+06	1.9E-06	
Ra-228		2.6E+06	0.0E+00	0.0E+00

Table 2-10. (continued).

Radionuclide	Progeny	Ingestion Dose Conversion Factor (rem/Ci) ^a	Decay Chain Maximum Dose (mrem/y) ^b	Total Screening Maximum Dose (mrem/y)
Se-79		1.1E+04	3.3E-05	3.3E-05
Si-32		2.1E+03	1.6E-33	1.6E-33
Sm-146		2.0E+05	3.2E-12	3.2E-12
Sm-151		3.6E+02	0.0E+00	0.0E+00
Sn-121m		1.4E+03	0.0E+00	0.0E+00
Sr-90		1.0E+05	3.4E-38	3.4E-38
Tb-158		4.2E+03	0.0E+00	0.0E+00
Tc-99		2.4E+03	5.6E-01	5.6E-01
Th-229		1.9E+06	3.8E-07	3.8E-07
Th-230		7.9E+05	4.5E-02	2.5E-01
	Ra-226	1.0E+06	5.8E-02	
	Pb-210	2.6E+06	1.5E-01	
Th-232		8.5E+05	5.8E-02	2.5E-01
	Ra-228	2.6E+06	1.8E-01	
	Th-228	2.7E+05	1.8E-02	
U-232		1.2E+06	1.2E-04	1.5E-04
	Th-228	2.7E+05	2.8E-05	
U-233		1.9E+05	9.1E-01	1.4E+00
	Th-229	1.9E+06	4.7E-01	
U-234		1.8E+05	5.0E+00	5.2E+00
	Th-230	7.9E+05	1.1E-01	
	Ra-226	1.0E+06	1.6E-02	
	Pb-210	2.6E+06	3.8E-02	
U-235		1.7E+05	1.1E+00	1.3E+00
	Pa-231	1.8E+06	1.3E-01	
	Ac-227	1.2E+06	8.4E-02	
U-236		1.7E+05	2.7E-02	2.7E-02
	Th-232	8.5E+05	3.7E-09	
	Ra-228	2.6E+06	1.1E-08	
	Th-228	2.7E+05	1.2E-09	
U-238		1.6E+05	3.2E+00	3.2E+00
	U-234	1.8E+05	5.7E-03	
	Th-230	7.9E+05	6.5E-05	
	Ra-226	1.0E+06	6.3E-06	
	Pb-210	2.6E+06	1.4E-05	
Zr-93		4.1E+03	4.8E-09	4.8E-09

a. Dose conversion factors from EPA (2002), unless otherwise noted.

b. GWSCREEN result. Drinking water doses were based on ingestion of 2 L of water per day for 365 days per year.

c. The radionuclide in the parentheses was the decay chain modeled in the simulation (i.e., transport properties of the daughter were used for the screening calculation). Total parent inventory activity was converted to equivalent activity of the daughter before the calculation.

d. No dose conversion factor listed in EPA (2002); therefore, dose conversion factor from EPA (1988) was used.

Table 2-11. Radionuclides remaining after Phase II screening for base case analysis.

Radionuclide	Total Inventory 2003–2018 (Ci) ^a	Maximum Screening Dose (mrem/yr) ^b
C-14	1.10E+02	8.8E+00
Cl-36	7.19E-01	8.7E-01
H-3	1.25E+05	1.8E+02
I-129	1.50E-01	2.1E+01
Np-237	7.68E-02	1.0E+00
Pu-239	1.93E+01	7.6E+00
Pu-240	1.04E+01	2.4E+00
Tc-99	6.59E-01	5.6E-01
U-233	1.19E-01	1.4E+00
U-234	6.91E-01	5.2E+00
U-235	1.55E-01	1.3E+00
U-238	4.97E-01	3.2E+00

a. Total inventory from Table 2-6.

b. Screening dose from Table 2-10.

Screening thresholds were determined for the entire PA inventory of 115 radionuclides (see Appendix C). Screening thresholds of “No Limit” were selected if one or more of the following occurs:

- The radionuclide was screened during the Phase I screening step (i.e., half-life less than 5 years), and, hence, no GWSCREEN dose was calculated.
- The predicted dose is equal to zero.
- The GWSCREEN calculated maximum allowable inventory is greater than 1E+10 Ci.
- The radionuclide is a noble gas (e.g., Kr-85 does not have a dose conversion factor).

None of the screening thresholds are less than the total PA inventory (as shown in Table A-1, Appendix C); however, this is a set of conservative thresholds. As shown in Table 2-10, seven radionuclides were screened in the PA groundwater pathway Phase II screening that had a screening dose greater than 0.01 mrem/year but less than the screening limit of 0.4 mrem/year (K-40, Nb-94, Ni-59, Pu-238, Th-230, Th-232, and U-236). These seven radionuclides were screened largely because their projected inventories are relatively small. A significant increase in inventory could change the screening dose results so they should not be screened out.

To ensure no radionuclides are left out of the base case analyses, the screening thresholds are checked annually to decide if a radionuclide previously screened out should be carried forward and added for more detailed analysis in the base case. The screening threshold check ensures that any radionuclides previously screened out would be added to the list of base case radionuclides and evaluated through more detailed analysis (i.e., groundwater pathway base case analysis) if conditions (i.e., dramatic increase in inventory) in the future indicate this is necessary.

3. ANALYSIS OF PERFORMANCE

The following sections document the technical basis for determining the long-term performance of the ICDF Landfill based on the total radionuclide inventory of the disposed waste (including both projected and past disposals). The first section outlines the different migration and exposure pathways considered. The next section discusses the conceptual models for the source term, the different components of the groundwater pathway, and the exposure analysis. The discussion of the conceptual models is followed by a description of the modeling implementation for the groundwater pathway. Conceptual models for the atmospheric, biotic, and radon pathways are provided after the discussion of the groundwater pathway. The chapter concludes with a discussion of the dose analysis approach.

3.1 Overview of Analysis

The method of analysis used to assess the long-term performance of the ICDF Landfill is briefly described in this section with more detailed information following in later sections. Performance is defined in terms of the on-Site and off-Site exposures and doses from radionuclides that may be inadvertently contacted and/or that might migrate from the disposal facility. Analysis of performance therefore requires estimates of the (1) source term of radionuclides in the facility, (2) release rate of these radionuclides from the facility, and (3) migration rates and concentrations of radionuclides released from the facility in environmental media (air, soil, water). The estimates of radionuclide concentrations in environmental media are then used to estimate doses to a hypothetical individual based on an assumed exposure scenario. The various pathways of possible exposure are illustrated in Figure 3-1. The most important exposure pathway for hydrologic transport is groundwater use for drinking water, irrigation, livestock watering, and biotic transport. The surface water pathway is not a possible exposure pathway for the disposal facility because surface water on the INL Site is very limited and there are no uses of this water. Atmospheric exposure scenarios are also limited because only a few gas-phase radionuclides are present in the inventory. However, a conservative atmospheric pathways dose analysis is presented. Therefore, the main focus of this analysis of performance is on estimating the groundwater all-pathways dose to a hypothetical receptor that consumes contaminated groundwater, leafy vegetables and produce that were irrigated with contaminated groundwater, and milk and meat from animals that consume contaminated water and pasture grass irrigated with contaminated groundwater.

3.2 Conceptual Model of Facility Performance

When assessing a combination of waste, engineered features, and a complex natural environment, it is necessary to make simplifying assumptions to be able to represent the system in a form that can be modeled. This section provides perspective regarding the complexity of the different components in the actual system to be modeled and then summarizes how the complex system is simplified to permit it to be modeled for the scale and timeframes necessary for the PA. For each simplifying assumption, the bias towards conservatism is addressed to provide assurance that the simplified representation does not yield a nonconservative result that could compromise the conclusions of the PA.

3.2.1 Source Term

The source term is arguably the most important part of a PA. The source term includes the inventory of radionuclides and processes associated with releases of radionuclides from the waste forms and containers into the natural environment. In this manner, the source term controls the rate at which radionuclides become available for transport through groundwater and atmospheric pathways. The inventory used in the source term model for the ICDF includes waste disposed of from 2003 through FY 2009 and projected to be disposed of from FY 2010 through the end of disposals in FY 2018. Waste

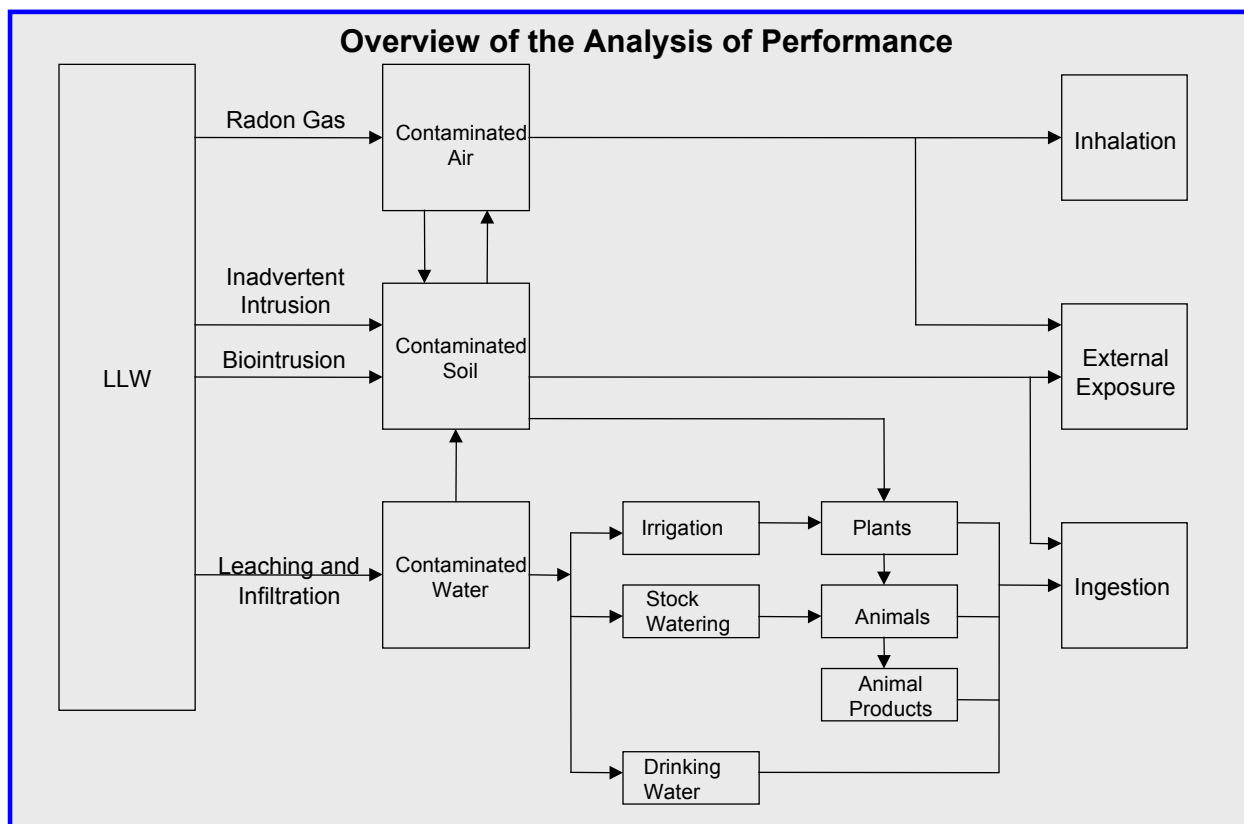


Figure 3-1. Overview of the analysis of performance for the ICDF Landfill performance assessment.

types received at the ICDF Landfill include contaminated soil from the INTEC area, debris, and CERCLA investigation-derived waste, including activated metal. The disposals are assumed to be contaminated soils, grouted debris, or activated metals. The contaminated soils and grouted debris were grouped together and treated as miscellaneous waste while activated metals were treated separately as briefly described below:

- The miscellaneous wastes are compacted at the time of ICDF Landfill disposal to avoid subsidence issues in the future. Contamination is most readily released to the subsurface environment from the miscellaneous waste form by leaching.
- Debris primarily comes from INL Site DD&D activities. Debris is grouted to reduce void space and prevent future subsidence issues. In addition, grouted waste delays radionuclide releases to the environment and spreads the releases out over time. Grouted waste will tend to reduce mobility of radionuclides. For purposes of this conceptual model, the delay and reduction of releases from the grouted waste forms were neglected. Radionuclides in the grouted waste forms were conservatively assumed to behave as contaminated soils and were grouped together as miscellaneous waste.
- Activated metals include decommissioned reactors and a variety of scrap metal from past INL Site activities. The primary radionuclide contaminants of concern evaluated in activated metals are C-14, Cl-36, H-3, and Tc-99. I-129 is also evaluated, but there is very little I-129 in activated metals. In order for the radionuclides in activated metal to enter the subsurface environment, the metal must corrode (dissolution). A significant fraction of these mobile radionuclide inventories are in the activated metal waste form. Therefore, the C-14, Cl-36, H-3, I-129, and Tc-99 inventory in activated metals is evaluated separately from the miscellaneous waste form.

The source term model predicts release of contaminants from waste buried in the ICDF Landfill into the subsurface below the clay liner. Input parameters include the disposal pit dimensions, radionuclide inventory and waste form, infiltration rates, and the release rate constant for activated metals. Output from the source term model is then used as input for the subsurface and biotic transport model. A description of the conceptual model for each aspect of the source term is provided in the following paragraphs.

3.2.1.1 Inventory. The inventory assumed for base case source term modeling is shown in Table 3-1 with associated daughter products for the parent, if applicable. For this PA, radionuclide inventories were summed across all years of disposal operation and placed in the ICDF as an initial condition where contaminant release began after facility closure. No decay was accounted for during the disposal period from 2003 through facility closure in 2018. That is, the inventory is assumed to all be placed in the ICDF Landfill in 2018. This simplification is justified because decay of the long-lived radionuclides important for the groundwater pathway would be negligible. Furthermore, this simplification is conservative for the shorter-lived radionuclide H-3 because decay is neglected during the disposal period.

Table 3-1. Radionuclides included in ICDF Landfill performance assessment groundwater pathway base case calculations.

Radionuclide	Performance Assessment Inventory 2003–2018	
	(Ci) ^a	Daughter Products
C-14	1.10E+02	None
Cl-36	7.19E-01	None
H-3	1.25E+05	None
I-129	1.50E-01	None
Np-237	7.68E-02	U-233, Th-229
Pu-239	1.93E+01	U-235, Pa-231, Ac-227
Pu-240	1.04E+01	U-236, Th-232, Ra-228, Th-228
Tc-99	6.59E-01	None
U-233	1.19E-01	Th-229
U-234	6.91E-01	Th-230, Ra-226, Pb-210
U-235	1.55E-01	Pa-231, Ac-227
U-238	4.97E-01	U-234, Th-230, Ra-226, Pb-210

a. Total inventory taken from Table 2-6.

3.2.1.2 Waste Form. Two waste forms were considered in this PA: miscellaneous waste and activated metals. Miscellaneous waste includes nonactivated metals such as contaminated soil, building debris, concrete, and surface-contaminated objects such as personal protection gloves. Radionuclides in the miscellaneous waste form were assumed to be homogeneously mixed with soil and modeled as an initial condition in the model. The radionuclides are distributed homogeneously throughout the waste volume and are readily leachable at the start of the simulation in the year 2019. Activated metals were modeled as a first-order process where the release rate constant represents the fraction of activity released to a waste soil matrix per unit time. The radionuclide inventory, waste stream description, and release mechanism for the radionuclides of concern evaluated in the groundwater pathway analysis are shown in Table 3-2.

Table 3-2. Inventory, waste stream description, and release mechanisms for radionuclides evaluated in the groundwater pathway for the performance assessment.

Radionuclide	Disposed Inventory 9/16/03–9/30/09 (Ci) ^a	Projected Inventory 10/1/09–9/30/18 (Ci) ^a	Total Inventory 2003–2018 (Ci) ^a	Waste Stream Description ^b	Release Mechanism ^{c,d}	Portion in Waste Stream (%)
C-14	1.40E+01	5.16E+01	6.56E+01	Activated metal	Metal corrosion	59.4
	1.12E+01	3.37E+01	4.49E+01	Miscellaneous waste	Leaching	40.6
Total C-14	2.52E+01	8.53E+01	1.10E+02			100.0
Cl-36	1.33E-01	5.84E-01	7.18E-01	Activated metal	Metal corrosion	99.8
	3.01E-04	9.03E-04	1.20E-03	Miscellaneous waste	Leaching	0.2
Total Cl-36	1.34E-01	5.85E-01	7.19E-01			100.0
H-3	3.11E+04	9.36E+04	1.25E+05	Activated metal	Metal corrosion	100.0
	4.23E+00	1.27E+01	1.69E+01	Miscellaneous waste	Leaching	0.0
Total H-3	3.11E+04	9.37E+04	1.25E+05			100.0
I-129	4.36E-06	9.05E-05	9.49E-05	Activated metal	Metal corrosion	0.1
	1.50E-01	3.03E-04	1.50E-01	Miscellaneous waste	Leaching	99.9
Total I-129	1.50E-01	3.94E-04	1.50E-01			100.0
Np-237	5.46E-02	2.22E-02	7.68E-02	Miscellaneous waste	Leaching	100.0
Pu-239	1.16E+01	7.66E+00	1.93E+01	Miscellaneous waste	Leaching	100.0
Pu-240	9.39E+00	1.05E+00	1.04E+01	Miscellaneous waste	Leaching	100.0
Tc-99	6.33E-03	2.12E-01	2.18E-01	Activated metal	Metal corrosion	33.1
	1.15E-01	3.26E-01	4.41E-01	Miscellaneous waste	Leaching	66.9
Total Tc-99	1.22E-01	5.38E-01	6.59E-01			100.0
U-233	8.16E-02	3.74E-02	1.19E-01	Miscellaneous waste	Leaching	100.0
U-234	4.24E-01	2.67E-01	6.91E-01	Miscellaneous waste	Leaching	100.0
U-235	1.04E-01	5.03E-02	1.55E-01	Miscellaneous waste	Leaching	100.0
U-238	3.39E-01	1.58E-01	4.97E-01	Miscellaneous waste	Leaching	100.0

a. Total inventory numbers from Table 2-6. Curies in activated metal from EDF-9463. Curies in miscellaneous waste are difference between total and activated metal.

b. Miscellaneous waste form includes anything that is not in an activated metal waste stream, primarily soils and DD&D debris.

c. Corrosion release parameter is the corrosion rate constant for stainless steel (1.19E-05 per year, Adler Flitton et al. 2001) as assumed for RWMC PA (DOE-ID 2007d).

d. Release parameter for leaching is dependent on the infiltration rate, moisture content, source K_d value, and thickness of the waste.

DD&D deactivation, decontamination, and decommissioning

PA performance assessment

RWMC Radioactive Waste Management Complex

3.2.1.3 Container Failure Rates. No waste containers were modeled in this performance assessment.

3.2.1.4 Release Mechanisms and Release Rates. The release of radionuclides from the miscellaneous waste form was modeled as a first-order leaching process. The radionuclide inventory in this waste form is assumed to be homogeneously mixed in the entire volume of the ICDF Landfill. Radionuclides partition into a liquid and sorbed phase as described by the soil water partitioning coefficient (K_d). The liquid phase is free-moving with the downward-moving infiltrating water, through the clay liner, and into the vadose zone. This waste form is generally the most conservative because no credit is taken for waste forms that must first dissolve or corrode before releasing radionuclides to the soil or for containment vessels that restrict radionuclide content with soil and infiltrating water.

Radionuclide releases from activated metal waste forms were modeled as a first-order process and assigned a first-order rate constant of $1.19\text{E-}05$ per year based on the corrosion rate constant for activated metals used in the RWMC Active LLW Disposal Facility Performance Assessment (see Table 3-2 in DOE-ID 2007d). Nagata and Banaee (1996) assessed the metals buried in the RWMC Subsurface Disposal Area and concluded that the majority is a form of stainless steel or inconel (nickel-based alloy). Nagata and Banaee (1996) provided a corrosion rate of 1 mm in 4,500 years ($2.22\text{E-}05$ cm/year) for irradiated stainless steel in INL Site soil. Review of available data showed the surface-area-to-volume ratio for typical INL Site-type reactor components to be 0.535/cm (Oztunali and Roles 1985). Most of the activated metal waste forms (disposed and projected) are from disposed reactors and reactor components. The reactors included in this evaluation are the Power Burst Facility, Experimental Test Reactor, Materials Test Reactor, and EBR-II. Combining the corrosion rate and geometry data provided a fractional release from stainless steel of $1.19\text{E-}05$ per year. Activated metal waste form was applied to long-lived mobile radionuclides (C-14, Cl-36, H-3, I-129, and Tc-99). Actinide activity assigned to activated metals represented surface contamination and, for this reason, were modeled as miscellaneous waste because release of surface contamination does not require corrosion of the metal. Tritium was conservatively assumed to be in the miscellaneous waste form because preliminary base case calculations showed that this radionuclide contributed very little to the total dose.

The use of a maximum release rate for radionuclides due to corrosion could potentially move the peak dose from activated metal to an unrealistically early time and not be captured in the cumulative dose. Figure 3-2 was developed to show that, for the assumed corrosion rate in activated metals at the ICDF, the use of the maximum release rate due to corrosion will always be conservative for the compliance period and up to 100,000 years in the future. Figure 3-2 illustrates the radionuclide flux from corroding metal for four corrosion rate constants ranging from the base case PA value of $1.19\text{E-}05$ 1/year to an order of magnitude lower ($1.19\text{E-}06$ 1/year). For a corrosion rate of a factor of 2 lower than the base case value ($5.95\text{E-}06$ 1/year, see the red dashed line), the flux exceeds the base case flux around year 120,000. After 120,000 years, the flux is about $\frac{1}{4}$ the peak base case flux (i.e., the base case flux at $t=0$ of about $1.2\text{E-}05$ Ci/year). For lower corrosion rates, the flux exceeds the base case flux even further in the future. Therefore, during the 1,000-year compliance period and well into the post-compliance period, a decrease in the corrosion rate constant will always result in lower fluxes to the groundwater and, consequently, lower groundwater concentrations and dose. The use of the maximum release rate assures a conservative cumulative dose calculation for this ICDF PA.

Activated metal waste forms were assumed to be uniformly distributed throughout the ICDF disposal cell. Radionuclides released from the activated metals go directly into waste soil and leach from there to the underlying unsaturated zone.

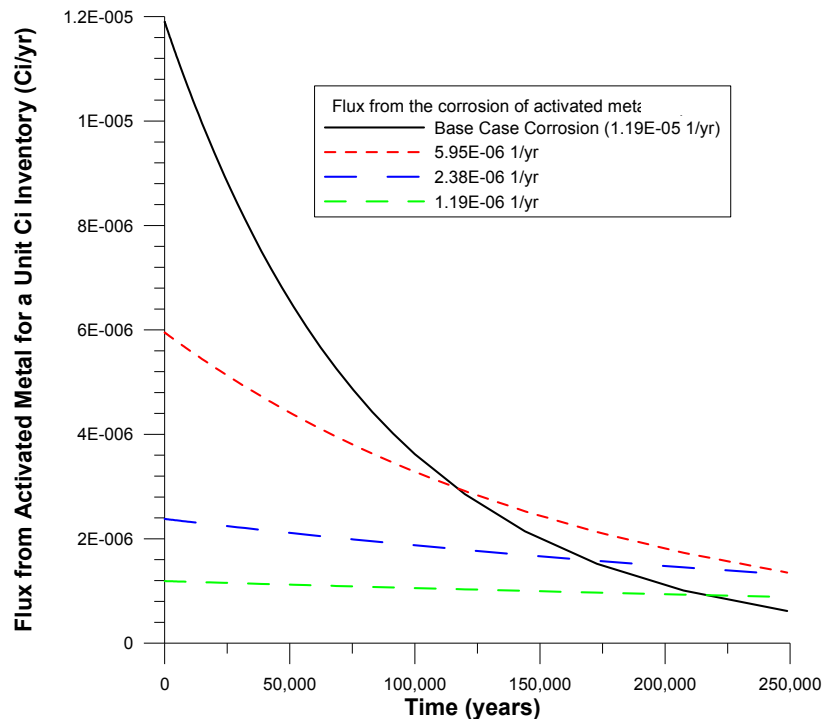


Figure 3-2. Flux from corrosion of activated metals with a unit inventory for four rate constants.

Although the MCM is capable of incorporating solubility limit controls, the waste concentrations in the ICDF Landfill were sufficiently low such that solubility limits would not be approached. Therefore, infinite solubility was assumed for all radionuclides.

3.2.1.5 Source Term Modeling Approach. It is assumed that the ICDF disposal cell is represented by a homogeneous porous media. The porous media assumption is supported by the fact that a large fraction of the disposal inventory in the ICDF Landfill is contaminated soil. Other waste forms, such as activated metal components, are also assumed to be homogeneously distributed in the disposal cell.

Hydrologic properties of the ICDF waste soils were determined in the previous PA and used without modification in this revision. Although much of the waste originates from INTEC alluvium, the hydrologic properties assigned to material disposed of in the ICDF Landfill are different because the alluvium is disturbed during excavation and is compacted in the disposal process.

3.2.2 Radionuclide Transport for the Groundwater Pathway

The conceptual model for radionuclide transport is separated into a source and unsaturated zone model and an aquifer model. The source and unsaturated model are coupled because of the interrelationship between the infiltration through the facility and water movement through the unsaturated zone. The source and unsaturated zone conceptual model is discussed first followed by the aquifer conceptual model discussion.

3.2.2.1 Source and Unsaturated Zone. The conceptual model for radionuclide transport in the source and unsaturated zone is based on detailed numerical modeling of the INTEC area reported in the OU 3-14 RI/BRA (Cahn et al. 2006). Based on the detailed three-dimensional modeling of the INTEC area using the TETRAD (Shook et al. 2003) numerical model, it was found that, in the absence

of anthropogenic water and influence from the Big Lost River, water flow is characterized as one-dimensional and vertically downward. Mean water travel time is controlled by the presence of horizontal sedimentary interbeds. Flow through fractured basalt is rapid and essentially vertical; and little sorption occurs within this media (Magnuson 1995).

In the past, perched water has been detected underneath the present location of the ICDF. The source of the perched water was the percolation ponds located to the east of the ICDF and not natural sources such as the Big Lost River. The percolation ponds were taken off-line in August 2002 and perched water rapidly declined. By 2004, nearly all the perched water in monitoring wells near ICDF had gone dry.

Given the findings of the OU 3-14 RI/BRA, the fact that little perched water exists underneath the ICDF, there are no additional sources of anthropogenic water in the vicinity of the ICDF, and there is no influence from the Big Lost River, then a one-dimensional model is suitable for modeling performance of the ICDF. The one-dimensional model incorporates interbeds underlying the ICDF as interpreted in cross sections presented earlier in this report. This relatively simple conceptual model is sufficient for development of a numerical model that addresses the assessment question. Its simplicity allows for numerous model simulations to be made that are necessary for the uncertainty analysis requirement of the PA.

The conceptual model for unsaturated flow and radionuclide transport is illustrated in Figure 3-3 during operation of the ICDF Landfill, in Figure 3-4 while the engineered cover remains intact, and in Figure 3-5 for after failure of the cover. The conceptual model for the time-dependent infiltration rate is shown in Figure 3-6. During operations, all water that infiltrates through the waste is collected in the drainage layer and removed via the leachate collection system. The geosynthetic and clay liner prevents infiltration through and below the ICDF Landfill and, therefore, creates an infiltration shadow below the ICDF. Water flow is assumed to be vertically downward. This assumption is justified on the basis of lack of anthropogenic water sources and because the ICDF is outside the 500-year flood plain and influence of the Big Lost River. However, initially the unsaturated zone beneath the ICDF is saturated to a level consistent with an infiltration rate of 18 cm/year based on the analysis of INTEC infiltration in the OU 3-14 RI/BRA, which assumed a largely gravel topsoil when the ICDF Landfill was constructed (Cahn et al. 2006).

The infiltration rate across the ICDF site prior to construction of the disposal site is assumed to be 18 cm/year (Cahn et al. 2006). During operation of the ICDF Landfill from 2003 through 2018, the infiltration rate through the bottom of the landfill liner is assumed to be zero because of the presence of the liner and operation of the leachate collection system. Therefore, there are no radionuclide releases from the facility during active disposal. After the end of operations, the engineered cover placed over the disposal cell limits infiltration to 0.01 cm/year.

The leachate collection system records indicate that, on average since the beginning of facility operations, the system has removed about a million gallons ($3,785 \text{ m}^3$) of water a year from the ICDF. Water removed from the ICDF is pumped to the adjacent evaporation pond. Assuming this removal rate continues until facility closure, and a facility floor area of $31,040 \text{ m}^2$ ($160 \text{ m} \times 194 \text{ m}$), this results in an annual infiltration rate through the waste (source zone) and into the leachate collection system of 12 cm/year. The leachate collection system is designed to operate for 45 years. The ROD for the ICDF (DOE-ID 1999, page 8-8) states “Leachate will be collected and treated using physical/chemical treatment (i.e., evaporation). Residues from the evaporation process will be managed in the ICDF as necessary during the active life and post-closure period of the ICDF cells.” Therefore, the collection system could potentially operate for another 30 years. Since it is not known how long the leachate collection system will actually operate and it is likely it will operate for some time after closure, it was assumed the system

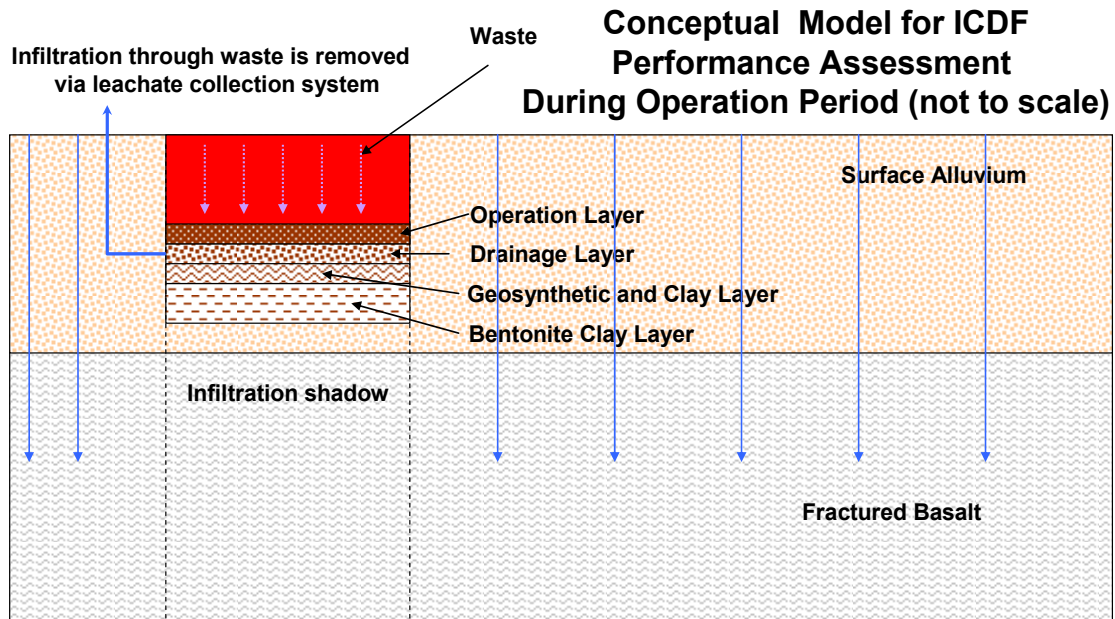


Figure 3-3. Conceptual model for the ICDF Landfill during operations.

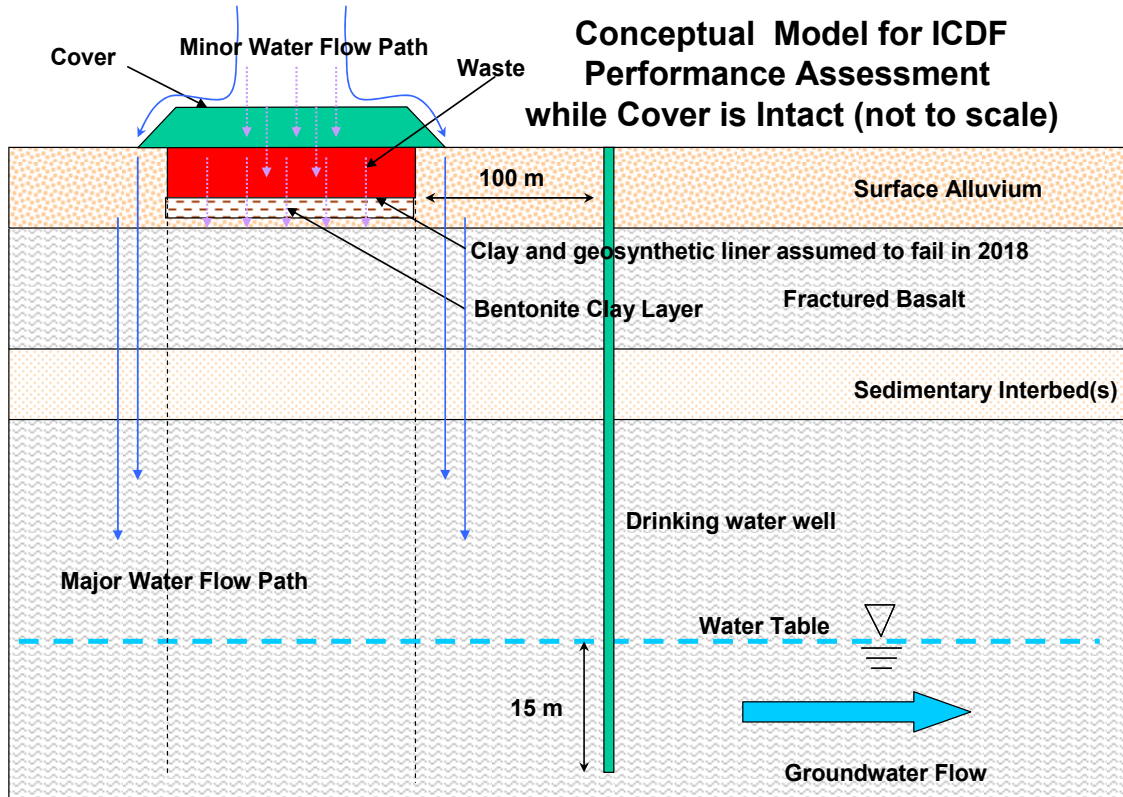


Figure 3-4. Conceptual model for the ICDF Landfill performance assessment while the cover is intact.

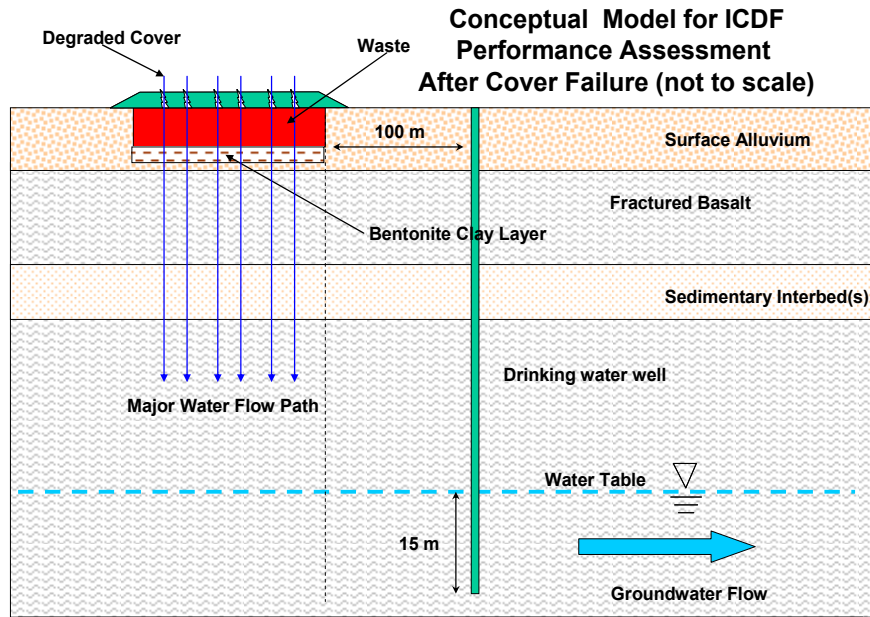


Figure 3-5. Conceptual model for the ICDF Landfill performance assessment after cover failure.

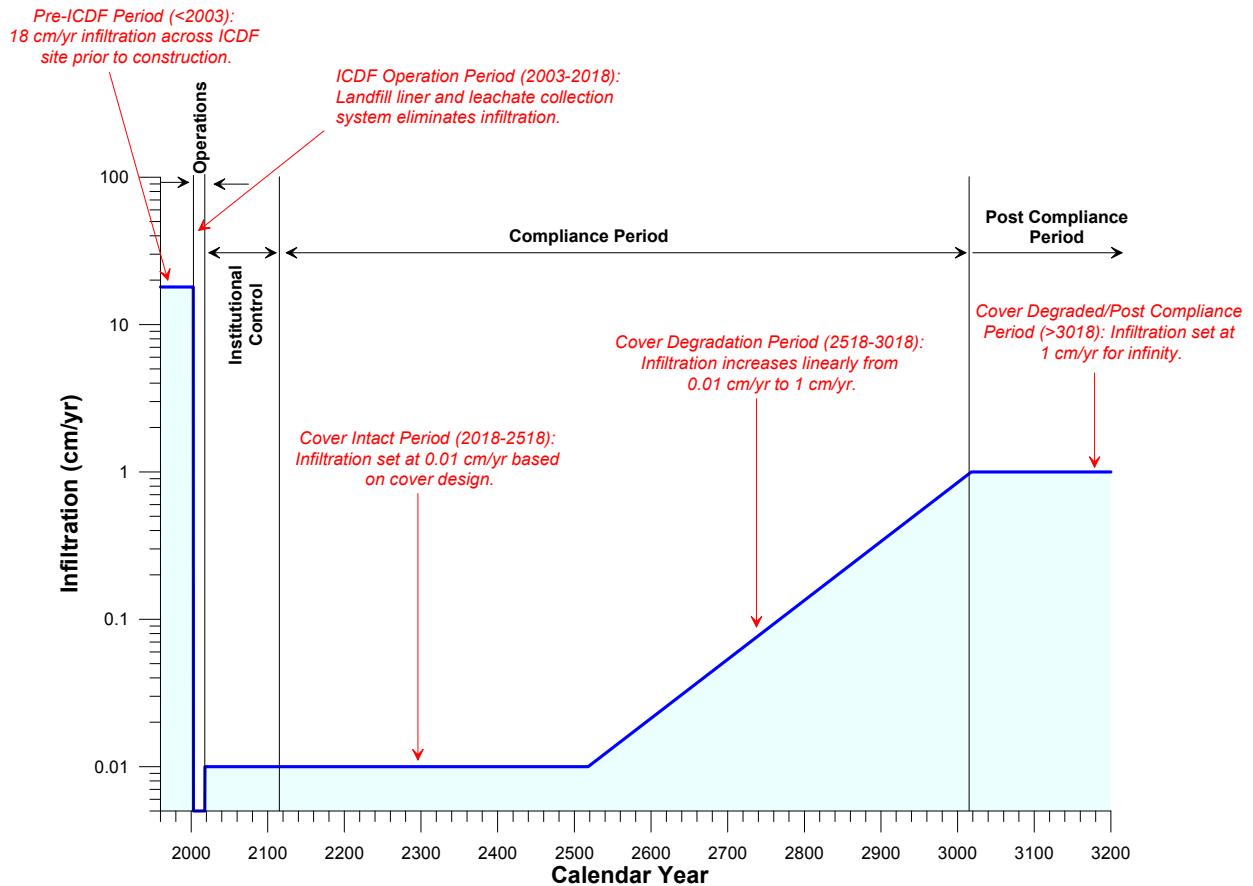


Figure 3-6. Conceptual model for time-dependent infiltration through the ICDF disposal facility.

will operate for 5 years after facility closure, resulting in drainage of some of the moisture retained in the waste. Therefore, the initial moisture content in the source zone is calculated from an infiltration rate of 12 cm/year for 15 years (the annual rate estimated from leachate collection system records) followed by 5 years at an infiltration rate of 0.01 cm/year (the designed cover infiltration rate). The cover infiltration rate is then imposed as an upper boundary while the cover remains intact. The bentonite clay layer at the time of closure is assumed to be near saturation. A sensitivity case was used to evaluate the impacts of a failure of the leachate collection system and liner prior to closure of the facility.

Infiltration through the source zone and into the unsaturated zone is controlled by the cap while the cap remains intact. Based on NRC guidance, the cap is assumed to perform at its design-base infiltration rate for 500 years. After 500 years, the cap degrades and is fully degraded 1,000 years after installation. Infiltration increases linearly from 500 years to 1,000 years. At 1,000 years, the infiltration through the degraded cap is equal to the background infiltration rate assumed for the INL Site in undisturbed soils of 1 cm/year (Cecil et al. 1992).

To summarize the infiltration assumptions:

- Pre-ICDF Period (<2003): Steady-state infiltration rate for disturbed soil of 18 cm/year across ICDF site prior to construction to define the moisture content in the unsaturated zone.
- ICDF Disposal Operation Period (2003–2018): Landfill liner and leachate collection system eliminates infiltration. Drainage of residual moisture in vadose zone from the pre-ICDF period.
- Cover Intact Period (2018–2518): Leachate collection system ceases operation 5 years after cover installation and infiltration is 0.01 cm/year. Geosynthetic liner is assumed to fail and initial moisture content in waste and bentonite clay layer is based on infiltration rate of 12 cm/year for 15 years (until year 2018) followed by 5 years of 0.01 cm/year. This modeling is needed to set the initial moisture content in the vadose zone for the flow and transport model.
- Cover Degradation Period (2518–3018): Cover gradually fails over a 500-year period. Infiltration increases linearly from 0.01 cm/year to the background rate of 1 cm/year.
- Cover Degraded/Post-Compliance Period (>3018): Infiltration set at INL Site background rate of 1 cm/year for infinity.

A cross section of the modeled lithology is illustrated in Figure 3-7. This figure shows the ICDF disposal cell waste, operation layer, bentonite clay layer, and unsaturated lithology to the top of the SRPA. The lithology was based on Wells ICPP-1781, ICPP-1782, ICPP-1783, ICPP-1800, ICPP-1801, ICPP-1802, ICPP-1803, ICPP-1807, and USGS-57 (shown in Figure 2-9). The interbeds identified as the 110-ft, 140-ft, and 380-ft interbeds are contiguous throughout the INTEC area. Two additional interbeds at 70 m and 100 m were shown to be contiguous underneath the ICDF, but may not be contiguous throughout the INTEC area. High hydraulic conductivity properties were assigned to interbeds except a portion of the interbed at a depth of 120 m (380-ft interbed). A low conductivity unit was assigned at this depth because of the presence of perched water in this interbed that was detected in 2002 in Wells ICPP-1807 and ICPP-1804. In general, the high hydraulic conductivity interbeds will result in faster water and radionuclide transit times in the unsaturated zone compared to low-conductivity units. Configuration of the ICDF disposal cell, operation liner, and bentonite clay liner was taken from the facility design provided in the 2003 PA (DOE-ID 2003a). Actual waste thickness was 10.4 m for a trapezoidal disposal cell geometry, but, for modeling purposes in the 2003 PA, this thickness was increased to 12.56 m to accommodate a modeled rectangular geometry of the facility. In this assessment, waste thickness was set at 10.4 m, representing a one-dimensional cross section through the facility and unsaturated zone.

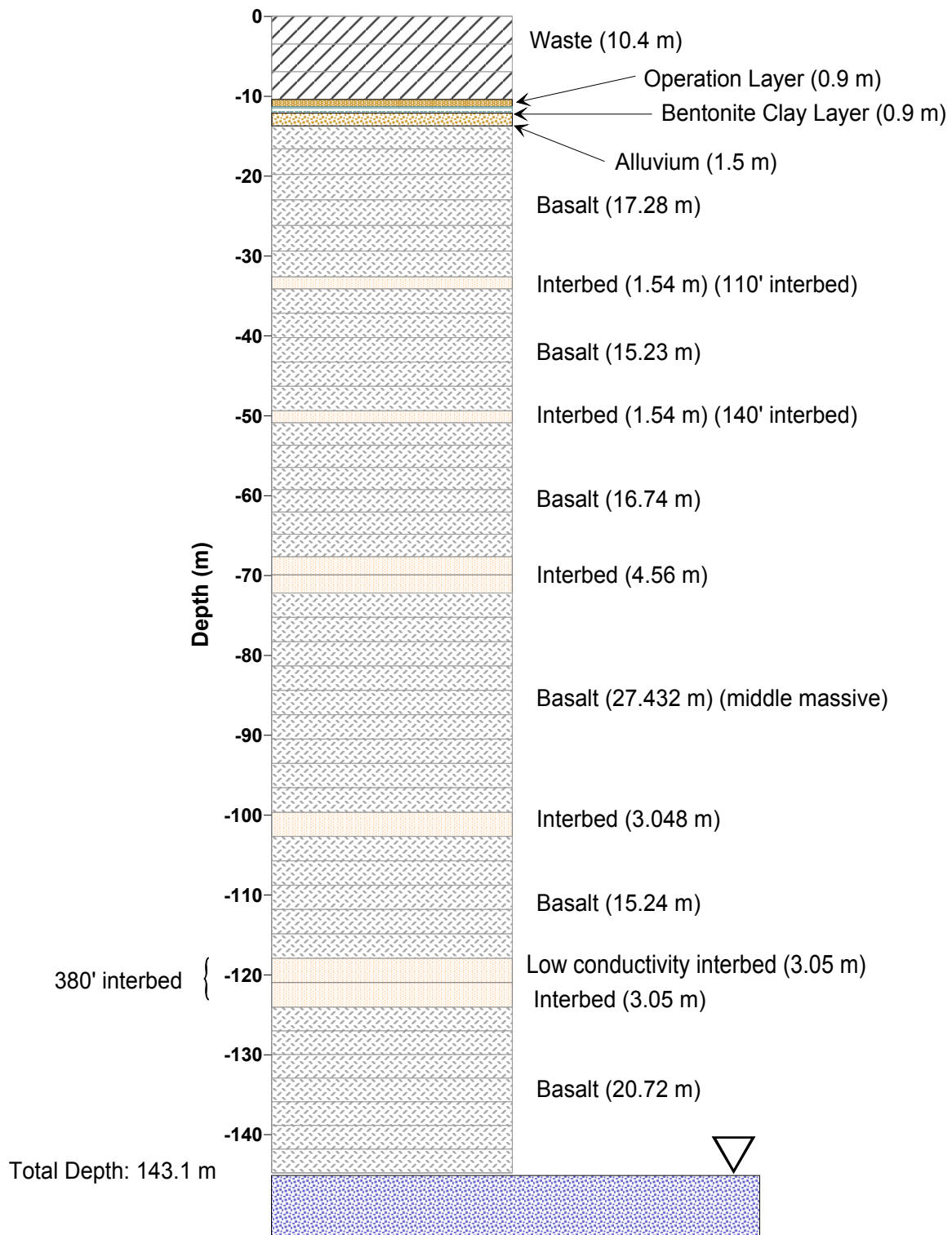


Figure 3-7. Modeled cross section of the ICDF Landfill and underlying unsaturated zone to the Snake River Plain Aquifer. The waste, basalt, and sedimentary interbeds are discretized into compartments.

Although C-14 and H-3 can move in both the vapor phase and dissolved aqueous phase, only single-phase aqueous-phase transport was considered in this PA. Vapor-phase transport would release a large fraction of the available inventory to the atmosphere and, thereby, reduce the source term available to the vadose zone and aquifer. Therefore, the assumption of aqueous-phase transport is conservative for the water pathway analysis. Potential dose from vapor-phase atmospheric releases was calculated by assuming the entire inventory was released to the atmosphere. This “double counting” was justified because performance objectives were achieved using this conservative approach.

3.2.2.2 Aquifer Conceptual Model. The aquifer conceptual model is relatively simple because (1) the transport distance in the aquifer is less than the thickness of the unsaturated zone and (2) characterization data of the aquifer on this scale (~100 m) are lacking. The model assumes one-dimensional flow in a homogeneous and isotropic equivalent porous media of infinite lateral extent and finite thickness with no sources or sinks of water. Radionuclides enter the surface of the aquifer from the unsaturated zone and disperse in three dimensions while moving downgradient with the advective flow in the aquifer. The no source or sink of water assumption is justified because (1) no anthropogenic water sources are anticipated in the future, (2) there is meager natural infiltration, and (3) the distance from the Big Lost River is large enough that influences from the river are negligible. The model domain for the aquifer is limited to about a 100-m radius around the ICDF.

3.2.2.3 Summary of Assumptions for the Groundwater Pathway Conceptual Model. A summary of the underlying assumptions for fate and transport of radionuclides disposed of in the ICDF Landfill is as follows:

- Initial moisture conditions in the unsaturated zone are based on an INTEC-average infiltration rate of 18 cm/year (Cahn et al. 2006) (see Section 3.2.2.1).
- Water flow in the absence of anthropogenic water and influences of the Big Lost River is one-dimensionally vertically downward (Cahn et al. 2006). Flood inundation maps (Ostenaa and O’Connell 2005, Appendix E) showing water depths near the ICDF Landfill indicate the landfill is outside the inundation area through the 2,000-year flood plain, beyond the 1,000-year period of compliance defined by DOE O 435.1 Chg 1 (see Sections 2.1.5.1 and 3.2.2.1).
- Water and radionuclide transit times are primarily controlled by the presence of sedimentary interbeds. Characterization studies at the INL Site indicate that the vadose zone water travel times through fractured basalt are relatively fast, leaving only travel times through the sedimentary interbeds to be important. Numerical experiments using the 3-D model for the OU 3-14 RI/BRA (Cahn et al. 2006) support this conclusion. The PA conceptual model is that the vadose zone basalt has low water content and very high permeability. The water or nuclides spend very little time in the vadose zone basalt rock. The vadose zone sediments have much higher water content and relatively low permeability. Therefore, it is assumed that sedimentary interbeds in the subsurface will primarily control flow and transport rates in the vadose zone (see Section 3.2.2.1).
- The leachate collection system precludes release of radionuclides from the disposal facility while the facility is in operation (EDF-ER-279). Therefore, no releases are assumed to occur during operations (see Section 3.2.2.1).
- Waste is assumed to be uniformly distributed in the disposal cell, resulting in constant radionuclide concentrations throughout the cell (see Section 2.3.3).
- Waste form is primarily miscellaneous waste consisting of both soil and DD&D debris, with some activated metals. Both waste forms are assumed to be uniformly distributed throughout the disposal cell. Release of radionuclides from activated metal waste forms is through corrosion of the metal (see Sections 2.3.3 and 3.2.1.2).

- A cover will be placed over the entire ICDF Landfill in the year 2018. The cover is designed to limit infiltration to 0.01 cm/year through the waste and into the vadose zone. The 0.01 cm/year is based on the design of the cover (EDF-ER-279 and EDF-ER-281). The cover is assumed to limit infiltration as designed for 500 years then gradually degrade over the next 500 years. The infiltration rate through the cover in 1,000 years is 1 cm/year. The infiltration rate remains 1 cm/year for all time greater than 1,000 years from closure (see Section 3.2.2.1).
- The conceptual and numerical models for the vadose zone are assumed to be one-dimensional based on site characteristics, field studies, and numerical studies (see Section 2.1 and Appendix B).
- Although the SRPA is comprised of relatively complex geologic formations, for risk assessment purposes, the uncertainty in the source term and vadose zone transport is much larger than the uncertainty introduced by the aquifer complexity, especially for a near-field receptor located only 100 m from the downgradient end of the facility. Therefore, for purposes of the PA, the aquifer is comprised of an equivalent homogeneous porous medium of infinite lateral extent and finite thickness (see Sections 3.2.1.5, 3.2.2.2, and 3.2.2.3).
- For the PA calculations, the average linear velocity in the aquifer was 365 m per year (Darcy velocity of 21.9 m per year and porosity of 0.06, see Section 3.3.1.3.1) and is representative of the velocity underlying and immediately south of the ICDF.
- Seismic stability evaluations have been conducted for the landfill and they indicate the factor of safety requirements have been met (EDF-ER-282). It was concluded the ICDF Landfill and final cover design are stable under seismic loading conditions.

3.2.3 Exposure Pathways and Scenarios

The conceptual model for exposure pathways and scenarios includes several potential means for an exposure to occur. A summary of the migration and exposure pathways is illustrated in Figure 3-1. Exposure scenarios are the link between contaminated environmental media and the exposure of a hypothetical receptor. They are essentially statements and parameter values that describe the behavior of a hypothetical receptor. The exposure scenarios considered for this PA are relatively typical. A receptor is assumed to reside at the INL Site boundary during the institutional control period and 100 m downgradient from the ICDF at the end of institutional control.

3.2.3.1 Hydrologic Exposure Pathways and Scenarios. The important exposure pathways for hydrologic transport include groundwater use for drinking water, irrigation, livestock watering, and biotic transport. The groundwater all-pathways scenario assumes a receptor consumes: (1) contaminated groundwater, (2) leafy vegetables and produce that were irrigated with contaminated groundwater, and (3) milk and meat from animals that consume contaminated water and pasture grass irrigated with contaminated groundwater. The methodology used to calculate the all-pathways dose is based on the methodology presented in NRC (1977) and Peterson (1983). During the institutional control period (2018–2118), the receptor is located downgradient of the ICDF at the INL Site boundary. During the compliance period (2119–3018), the receptor is assumed to be located 100 m downgradient from the ICDF Landfill.

Groundwater resources impacts are also evaluated through comparison of predicted groundwater radionuclide concentrations with MCLs reported in *Radionuclides Notice of Data Availability Technical Support Document* (EPA 2000) in support of 40 CFR 141, “National Primary Drinking Water Regulations.” For evaluation of groundwater resources impacts, the receptor is assumed to consume 2 L of water per day for 365 days per year from a well that is impacted by contaminant plumes. There are no surface water uses on the INL Site; therefore, the hydrologic transport of surface water was not considered in this PA.

3.2.3.2 Atmospheric Exposure Pathways and Scenarios. Atmospheric transport of volatile radionuclides from the ICDF Landfill is the only potential dose contributor through the air pathway. Based on the projected land use for the ICDF and the assumption that the closure cover precludes biotic intrusion of buried waste, nonvolatile radionuclides were not assessed. The air pathway exposures include direct inhalation, external exposure, and ingestion of contaminated food due to the contamination of crops, soil, livestock, and dairy products. During the institutional control period, the receptor is located at the INL Site boundary, and, during the compliance period, the receptor is assumed to be located 100 m downgradient from the ICDF Landfill.

3.2.4 Alternative Conceptual Models for the Site Hydrology

Previous subsections provide the base case conceptual model for the site hydrology. This section provides five plausible alternative conceptual models for the site hydrology. These plausible conceptual models are chosen to evaluate the impact on the predicted all-pathways dose if the hydrologic assumptions of the base case conceptual model are not conservative. The alternative conceptual models for the site hydrology are all evaluated in the one factor at a time (OFAT) sensitivity analysis in Section 4.6 and Appendix B, which presents the numerical experiments justifying the one-dimensional vadose zone model. The all-pathways doses were compared to the base case results and the performance objectives. The plausible alternative conceptual models for site hydrology considered and where in the report they are evaluated are:

1. Infiltration rates are higher through the engineered cap than its design infiltration rate. Alternative model 1 was addressed in Case 2 (infiltration rate of 1 cm/year for ∞) of the OFAT analysis (Section 4.6.1).
2. Fast flow paths through the sedimentary interbed or lack of some sedimentary interbeds below the ICDF. Alternative model 2 was addressed in Cases 4, 5, and 8 of the OFAT analysis (Sections 4.6.4, 4.6.5, and 4.6.8). In Case 4 of the OFAT analysis, the bentonite clay layer is assumed to be replaced with alluvium. In Case 5 of the OFAT analysis, one of the vadose zone interbeds is assumed to be missing and replaced with basalt. In Case 8, non-failure of the HDPE liner is assessed. This scenario assumes the facility fills with water and overflows, resulting in focused infiltration and rapid vadose zone transit times. This scenario also bounds fast flow paths within the landfill because the water flux in the overflow case operates on the entire ICDF inventory; whereas, in the fast flow-path case, the water flux only operates on the inventory that is in contact with fast flow path. Therefore, while both scenarios may provide high water fluxes to the vadose zone compared to the base case, the overflow scenario will provide higher radionuclide fluxes because it is operating on the entire ICDF inventory, not just a fraction of it.
3. Preferential flow through parts of the ICDF resulting in focused infiltration. Alternative model 3 was addressed in Case 8 of the OFAT analysis (Section 4.6.8). In Case 8, non-failure of the HDPE liner is assessed. This scenario assumes the facility fills with water and overflows, resulting in focused infiltration and rapid vadose zone transit times. This scenario also bounds fast flow paths within the landfill because the water flux in the overflow case operates on the entire ICDF inventory; whereas, in the fast flow-path case, the water flux only operates on the inventory that is in contact with fast flow path. Therefore, while both scenarios may provide high water fluxes to the vadose zone compared to the base case, the overflow scenario will provide higher radionuclide fluxes because it is operating on the entire ICDF inventory not just a fraction of it.
4. Liner and leachate collection system do not operate as intended. Alternative model 4 was addressed in Cases 3, 6, 7, and 8 of the OFAT analysis (Sections 4.6.3, 4.6.6, 4.6.7, and 4.6.8). These sensitivity cases make a variety of assumptions regarding both the infiltration rate through the cap and the lifespan of the leachate collection system. In Case 3, the liner is assumed to fail before

the facility has completely drained, resulting in a flush of water from the facility early in the compliance period. In Case 6 the ICDF cover is assumed to operate as designed, but the liner remains intact until the facility fills completely with water 850 years after closure, and the HDPE liner then fails. In Case 7 the ICDF cover fails after institutional control, and the ICDF fills completely with water 230 years after closure, and the HDPE liner then fails. In Case 8, non-failure of the HDPE liner is assessed. This scenario assumes the facility fills with water and overflows, resulting in focused infiltration and rapid vadose zone transit times (i.e., the bathtub effect).

5. Lateral water flow in perched water from the Big Lost River to interbeds underlying the ICDF. Alternative model 5 is discussed in Appendix B, which provides justification for a one-dimensional vadose zone model. The ICDF is far enough from the Big Lost River that it is unlikely to see influence of the Big Lost River in terms of perched water on interbeds underlying the ICDF. If perched water is present, then radionuclides will be spread laterally to a greater extent, resulting in greater dilution in the aquifer. Perched water may also produce higher water fluxes in the vadose zone, resulting in shorter radionuclide transit times. Shorter radionuclide transit times in the vadose zone are also addressed in the one-factor-at-a-time uncertainty analysis by removing a sedimentary interbed, allowing for rapid flow and transport.

As shown in the OFAT sensitivity analysis (Section 4.6), in all cases the predicted dose meets the ICDF PA performance objectives. However, the results of the sensitivity analysis are significantly larger than the base case doses for some scenarios.

3.3 Environmental Transport of Radionuclides

This section provides the method of analysis used for the transport of radionuclides for the hydrologic and atmospheric pathways. The section also includes a discussion of the model selection and descriptions of the mathematical models. The text addresses issues of model structure, quality assurance, and applicability to the ICDF Landfill PA. Efforts have been undertaken to provide consistency with recent modeling at INTEC documented in the OU 3-14 RI/BRA (Cahn et al. 2006) and RWMC CA (DOE-ID 2008e) modeling for compliance with DOE O 435.1 Chg 1.

3.3.1 Hydrologic Pathway

The hydrologic pathway addresses dissolved-phase transport from the ICDF Landfill, through the vadose zone below the surface sediments, into the aquifer, and through the aquifer to the receptor. This discussion contains explanations of the following: (1) model selection, (2) MCM source term and vadose zone transport of radionuclides, and (3) GWSCREEN aquifer transport of radionuclides.

3.3.1.1 Model Selection. A comprehensive model selection was not performed for this analysis because this is a continuation of a long-term analysis addressing both CERCLA and DOE O 435.1 Chg 1 related objectives. The flow and transport codes GWSCREEN Version 2.5 (Rood 2003a) and Subsurface Transport Over Multiple Phases (STOMP) (PNNL 1996) were used for comparisons in the 2003 ICDF PA (DOE-ID 2003a). TETRAD and GWSCREEN have been used for CERCLA, PAs, and CA evaluations at the INL Site for the last 15 years and are still being used today. STOMP is a multiphase flow and transport code that is capable of simulating complex geologic structures. GWSCREEN is a relatively simple model that includes the primary physical mechanisms of flow and transport but cannot simulate many of the mechanisms that STOMP can simulate, such as multiphase flow, subsurface heterogeneity, variable rate infiltration, differential transport of radionuclide progeny, or 3-D flow in the subsurface. However, it was shown that, for the ICDF PA question (i.e., concentrations of radionuclides in the aquifer 100 m downgradient from the ICDF Landfill), GWSCREEN provided comparable results to that of STOMP. For that reason along with the fact that GWSCREEN takes a fraction of time to run

compared to STOMP, GWSCREEN was calibrated to the original STOMP runs and was used thereafter for all groundwater calculations in the 2003 ICDF PA.

The OU 3-14 RI/BRA (Cahn et al. 2006) used TETRAD (Shook et al. 2003) to model the tank farm area at INTEC. The three-dimensional model included complex statistical representation of stratigraphy, transient inputs of large volumes of anthropogenic and natural water, complex geochemical reactions, and transient inputs of radionuclides and chemicals. This model was both retrospective and prospective, and model results were calibrated to historical perched water levels and contaminant concentrations. The ICDF was not included in the OU 3-14 RI/BRA model. As a practical matter, computer run times were excessively long for this model, and, for production runs, a response surface was developed. Prospective modeled concentrations were calculated by the convolution of the response surface with transient inputs, along with scaling factors for decay and retardation. One of the key findings of this work was that, in the absence of anthropogenic water and influences from the Big Lost River, water flow in the vadose zone is one-dimensional vertically downward. This finding, along with the calibrated hydrologic and geochemical parameters, was incorporated into this PA.

This PA also includes effects of transient infiltration and initial moisture content in the vadose zone based on calibrated infiltration rates in the INTEC area as determined by the calibrated OU 3-14 RI/BRA TETRAD model. In order to include these effects in the model and keep simulation time to a minimum, the OU 3-14 RI/BRA model was not used directly; rather, a simple, yet robust, model was selected for vadose zone flow and transport simulations for this PA.

The subsurface flow and radionuclide transport models used for this PA include:

- MCM (Rood 2005) for the source and vadose zone. The MCM comprises two submodels: one for water flow (MCMF) and the other for transport (MCMT). The MCM adapts well to the conceptual model for the source term release and the vadose zone water flow and contaminant transport. In particular, MCM's ability to simulate variable infiltration rates in response to cap failure and differential transport of parent and progeny in the vadose zone allows it to simulate the primary mechanisms defined in the conceptual model. The output of the MCM modeling is radionuclide mass flux to the aquifer for input to an aquifer model.
- GWSCREEN for the aquifer. The GWSCREEN model adapts well to the conceptual model for transport in the aquifer. GWSCREEN was developed for assessment of the groundwater pathway from leaching of radioactive and nonradioactive substances from surface or buried sources. The code was designed for implementation in the Track 1 and Track 2 assessment of CERCLA sites identified as low-probability hazards at the INL Site (DOE-ID 1994). The code uses a mass conservation approach and can model three processes: contaminant release from a source volume, vertical contaminant transport in the unsaturated zone, and two- or three-dimensional contaminant transport in the saturated zone. In this case, only the aquifer portion was used and fluxes from the vadose zone to the aquifer were provided from the MCM.

Figure 3-8 shows the models used for different contaminants of concern.

3.3.1.2 Vadose Zone Transport of Radionuclides Using the MCM. The MCM is used in two steps, one to establish the initial moisture conditions in the vadose zone prior to construction and operation of the ICDF and one to simulate leaching from the source, transport through the vadose zone, and mass flux to the aquifer. Initial moisture conditions in the vadose zone were estimated by specifying 18 cm/year infiltration over the ICDF Landfill, allowing it to run to steady state, followed by 15 years (2003–2018) of reduced infiltration, representing construction of the ICDF and operation of the leachate collection system. The moisture profile determined in this simulation was input into the second MCM simulation as an initial condition.

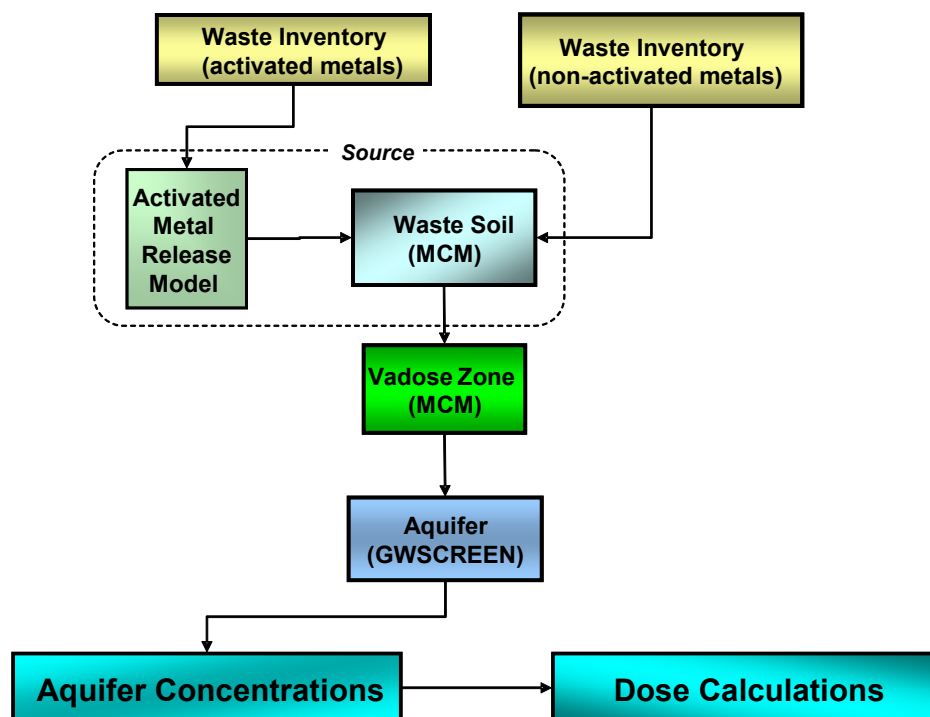


Figure 3-8. Numerical models used to calculate the predicted aquifer concentrations used for this performance assessment.

The second MCM simulation begins in year 2019 after the cover is installed and the leachate collection system has ceased operation. Infiltration is reduced at the start of the simulation to the design-base infiltration rate of the cover of 0.01 cm/year for 500 years. Infiltration is then increased linearly over the next 500-year period to a maximum of 1 cm/year.

Radionuclide inventories were placed in the waste soil at the start of the simulation in 2019. Activated metal inventories were released into the waste soil according to the corrosion rate constant and an exponentially declining function. Radionuclide releases from the activated metals were calculated external to MCM and input as an external source.

The basis for the MCM is described in Rood (2005). The MCM is essentially a first-order approximation to the second-order advection-dispersion equation and is similar in form to the EPA assessment model SESOIL (Scott and Hetrick 1994). The conceptual model defines the unsaturated subsurface environment as a series of individual mixing cells (Figure 3-9). Within each mixing cell, the moisture content (fraction of the mixing cell volume composed of water) and contaminant concentration are uniform and assumed to equilibrate instantaneously in response to a change in the amount of water or contaminant entering the cell. Each mixing cell may have its own unique properties that include vertical dimensions, bulk density, hydraulic characteristics (e.g., porosity, residual moisture content, and hydraulic conductivity), and sorptive properties. Water balance within each cell is maintained by the difference between inflow and outflow. The water flux or specific discharge entering the uppermost mixing cell (q) is assumed to be the net infiltration rate past the root zone. The net infiltration rate may change with time and, in turn, affect the specific discharge through all remaining cells below it. Water movement is assumed to be downward and under unit gradient conditions within a mixing cell. Specific discharge is assumed to be less than the saturated hydraulic conductivity of any of the materials composing the vadose zone.

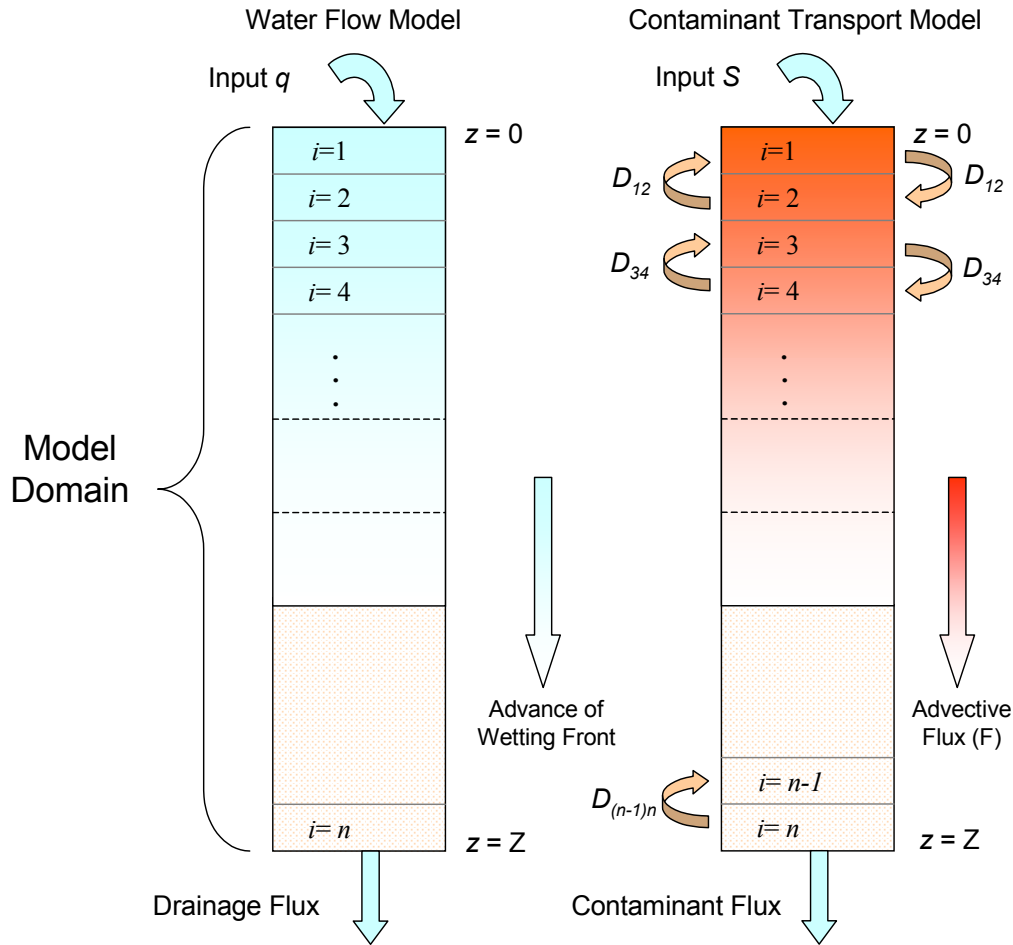


Figure 3-9. The MCM conceptual model for water flow (left) and contaminant transport (right). The model domain is discretized into n cells and extends to a depth of $z = Z$. Interchange between cells is indicated by the variable $D_{i,j}$ where i is the index of the donor cell and j is the index of the receiving cell.

The conceptual model for contaminant transport considers two processes: advection and dispersion. Advective processes (F in Figure 3-9) move the contaminant downward while dispersive processes (D in Figure 3-9) can move the contaminant upward or downward, depending on the concentration gradient between two adjacent cells. Dispersion results in greater spreading of the contaminant among the mixing cells. As shown later, dispersion effects can be simulated through the implicit dispersion inherent in a mixing cell model or may be simulated by including interchange between adjacent mixing cells.

Contaminant degradation is assumed to be a first-order process described by a half-life. The contaminant may degrade into one or more degradation products, each formed from the preceding product and, thereby, forming a chain of degradation products, such as in the case of a radionuclide decay chain.

Contaminants entering a cell mix, sorb, decay, and are eventually removed by the downward movement of water. Contaminants sorb onto the solid matrix as described by the soil-to-water partition coefficient or K_d . Sorption retards the overall downward movement of contaminants. The rate of transport of the degradation products that form during vertical transport is governed by the sorptive properties of the degradation product and not those of the originating contaminant.

As formulated, contaminants may be present in one or more of the mixing cells at the start of the simulation, or, alternatively, the contaminant may be placed over time through an external source (S in Figure 3-9), as done for the high-mobility nuclides in activated metals. Concentrations of contaminants in pore water are not allowed to exceed their element- or compound-specific solubility limit.

3.3.1.2.1 MCM Water Flow—A simple one-dimensional water-balance model, coupled with material-specific moisture characteristic curves, is used to calculate the net water flux through each mixing cell, assuming unit gradient conditions exist throughout each cell. Additionally, water is assumed to be incompressible, its density remains constant, vapor-phase flow is inconsequential, and hydrostatic conditions are assumed to never exist (i.e., a net water flux of zero). The unit gradient model assumes water infiltration in the soil column is downward and driven by gravitational forces only. The specific discharge (sometimes referred to as the Darcy velocity or Darcy flux) is a one-dimensional, vertically aligned, unsaturated soil column that may be described by:

$$q = -K \left(\frac{\partial H}{\partial z} + \frac{\partial \psi}{\partial z} \right) \quad (3-1)$$

Where

q	=	specific discharge ($L T^{-1}$)
θ	=	volumetric moisture content ($L^3 L^{-3}$)
H	=	elevation head (L)
ψ	=	suction or pressure head from capillary forces (L)
K	=	unsaturated hydraulic conductivity of the column ($L T^{-1}$)
z	=	distance positive downward from the top of the column (L).

Under unit gradient conditions, $\partial \psi / \partial z = 0$ and $\partial H / \partial z = 1$. Therefore, $q = K$, provided q is less than the saturated hydraulic conductivity. That is, the amount of water discharged from a mixing cell is equal to the unsaturated hydraulic conductivity at a given volumetric moisture content. The volumetric moisture content is the fraction of the bulk media that is filled with water. When a porous media is saturated (i.e., all the pore spaces are filled with water), the volumetric moisture content is equal to the effective porosity of the media. In this model, the effective porosity was assumed equal to the total porosity. Unit gradient conditions are assumed to exist at all times within a mixing cell. That is, once water enters the mixing cell, it is instantaneously and uniformly distributed within the mixing cell. Capillary forces are explicitly excluded from the model by assuming unit gradient conditions exist at all times. However, as shown in Rood (2005), these forces are implicitly accounted for through model discretization. Each cell is treated as an independent unit that may receive water from a cell above it and discharge water to the cell beneath it.

The continuity equation (assuming constant water density) states that the change in the water stored in a unit volume of soil must equal the difference between the flux into and out of the unit volume and is given by:

$$\frac{\partial \theta}{\partial t} = - \frac{\partial q}{\partial z} \quad (3-2)$$

Combining Equations 3-1 and 3-2 with $\partial H/\partial z = 1$ gives the traditional formulation for one-dimensional unsaturated flow in a porous medium known as Richard's equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left(K \frac{\partial \psi}{\partial z} - K \right). \quad (3-3)$$

The unsaturated hydraulic conductivity is a function of the moisture content and described by the moisture characteristic curve. Combining Equations 3-1 and 3-2, with the assumption of unit gradient conditions (i.e., $\partial \psi/\partial z = 0$) gives:

$$\frac{\partial \theta}{\partial t} = - \frac{\partial K(\theta)}{\partial z}. \quad (3-4)$$

The term $\partial K(\theta)/\partial z$ is approximated for the MCM by:

$$\frac{\partial \theta_i}{\partial t} = \frac{K_{i-1}(\theta_{i-1}) - K_i(\theta_i)}{z_i - z_{i-1}} \quad (3-5)$$

Where

- i = the cell index number
- z_i = the depth of cell i below a datum at index $i = 0, z = 0$.

The water storage in the i^{th} mixing cell (ϕ_i) is given by:

$$\phi_i = \theta_i T_i \quad (3-6)$$

Where

- T_i = the thickness of the i^{th} mixing cell, which is equivalent to $z_i - z_{i-1}$.

Equation 3-5 is now rewritten in terms of the change in water storage with respect to time and given by:

$$\begin{aligned} \frac{d\phi_i}{dt} \frac{1}{T_i} &= \frac{K_{i-1}(\theta_{i-1}) - K_i(\theta_i)}{T_i} \\ \frac{d\phi_i}{dt} &= K_{i-1}(\theta_{i-1}) - K_i(\theta_i). \end{aligned} \quad (3-7)$$

For the uppermost mixing cell ($i = 1$), $K_{i-1}(\theta_{i-1}) = K_0(\theta_0) = q(t)$ where $q(t)$ is the net infiltration rate as a function of time into the uppermost mixing cell. Note that volumetric flow rates are achieved by multiplying Equation 3-7 by the horizontal surface area of the cells.

The functional relationship between the unsaturated hydraulic conductivity and moisture content is made using established empirical relationships that relate suction head to volumetric moisture content and unsaturated hydraulic conductivity. The relationship between these three parameters is referred to hereafter as the moisture characteristic curve. For this model, the unsaturated hydraulic conductivity as a function of moisture content as described by van Genuchten (1980) was used and is given by:

$$K(\theta) = K_{sat} \left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^{1/2} \left\{ 1 - \left[1 - \left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^{\frac{1}{m}} \right]^m \right\}^2 \quad (3-8)$$

and

$$\left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right) = \left(\frac{1}{1 + (\alpha \psi)^{ng}} \right)^m \quad (\theta_r \leq \theta \leq \theta_s) \quad (3-9)$$

Where

θ	=	volumetric moisture content ($L^3 L^{-3}$)
θ_r	=	residual moisture content ($L^3 L^{-3}$)
θ_s	=	saturated moisture content ($L^3 L^{-3}$)
K_{sat}	=	saturated hydraulic conductivity ($L T^{-1}$)
ψ	=	soil water matric suction pressure (L)
α	=	empirical fitting parameter (L^{-1})
ng	=	empirical fitting parameter
m	=	$1 - 1/ng$.

Equations 3-8 and 3-9 are valid when $q < K_{sat}$. Hydraulic properties that consider hysteresis were not included in this formulation.

The moisture content in the i^{th} mixing cell is used in combination with the moisture characteristic curve to determine $K_i(\theta_i)$, the specific discharge through the i^{th} mixing cell. The value of $K_i(\theta_i)$ as a function of time is then passed to the transport model.

3.3.1.2.2 MCM Flow Model Parameters—The discretization of the model domain in MCM was illustrated in Figure 3-7. The parameters used to simulate contaminant leaching from the waste and transport through the bentonite clay layer were taken from the 2003 ICDF Landfill PA (DOE-ID 2003a). Hydrologic properties of the alluvium and sedimentary interbeds were taken from OU 3-14 RI/BRA (Cahn et al. 2006). Hydrologic parameters for the basalt were taken from the RWMC Active LLW Disposal Facility PA (DOE-ID 2007d) (Table 3-3).

The clay hydraulic properties reported in DOE-ID (2003a) were apparently taken from Carsel and Parrish (1988). However, the saturated hydraulic conductivity was reduced from 17.52 m/year to 0.0315 m/year without changing the fitting parameters (α and n). Simulations using the 0.0315 m/year resulted in excessively long simulation times. Increasing the saturated hydraulic conductivity to a more conservative value of 0.06 m/year resulted in much faster simulation times, with no apparent change in the predicted concentrations. Therefore, the higher saturated hydraulic conductivity values were used.

The source in MCM is discretized into three equal-thickness cells. The disposal cell is underlain by a 0.9-m-thick operational layer and a 0.9-m bentonite clay layer. The operational layer is included in source cells because it is composed of essentially the same material and is relatively thin. The bentonite clay layer is modeled as a separate cell.

Table 3-3. Hydrologic properties of the various lithologies in the vadose zone underlying the ICDF Landfill.

Name of Lithology	Saturated Hydraulic Conductivity (m/yr)	Total Porosity	Residual Volumetric Moisture Content	Van Genuchten Fitting Parameter, n	Van Genuchten Fitting Parameter, α (m ⁻¹)	Bulk Density (g/cm ³)	Reference
Waste	31.5	0.266	0.072	1.53	1.066	1.946	DOE-ID (2003a; Table 3-8)
Bentonite clay layer	0.06 ^a	0.39	0.07	1.09	0.8	1.586	DOE-ID (2003a; Table 3-8)
High-permeability alluvium	8,799	0.32	0.0002	1.40	100	1.82 ^b	Cahn et al. (2006; Table A-7-1 unless otherwise noted)
High-permeability interbed	1,041	0.6	0.11	1.29	10.5	1.34 ^c	Cahn et al. (2006; Table A-7-1 unless otherwise noted)
Low-permeability interbed	0.76	0.49	0.0002	1.38	0.01	1.34 ^c	Cahn et al. (2006; Table A-7-1 unless otherwise noted)
Unsaturated basalt	91	0.05	0.001	10	2.5	2.0	DOE-ID (2007d; Table 3-3)

a. The specified hydraulic conductivity in DOE-ID (2003a) was 0.0315 m/yr. Simulation took excessively long using this value. Therefore, the conductivity was conservatively increased to 0.06 m/yr, which resulted in significantly faster simulation times with no appreciable change in predicted concentrations.

b. Bulk density is the arithmetic average from Table A-3-1 in Cahn et al. (2006).

c. Bulk density is the arithmetic average from Table A-3-3 in Cahn et al. (2006).

The MCM unsaturated zone model is comprised of both basalt and interbeds. Site-specific lithology is specified based on recent analyses of the unsaturated zone beneath the ICDF and consistent with the parameter values used in the OU 3-14 RI/BRA modeling. In total, USGS and DOE investigations have provided 125 wells around INTEC, with 75 of those completed in the vadose zone and 49 penetrating into the SRPA (Anderson 1991, INEEL 2003; and Cahn and Ansley 2004). A detailed study of the borehole data from most of these wells was completed during the preparation of the OU 3-13, Group 4, Monitoring Well and Tracer Study (DOE-ID 2003g). The study evaluated basalt/interbed core, geochemical, paleomagnetic, K-Ar age date, and petrographic data. Results of the study indicated that several distinct lithologic layers exist beneath INTEC that can be used as marker units.

Figure 3-7 shows the lithologic cross section below the ICDF Landfill that was incorporated into the MCM simulation. The hydrologic properties of each of the lithologies are provided in Table 3-3. Hydrologic data available for the INTEC vadose zone include soil moisture characteristics, particle size distribution, porosity, effective porosity, bulk density, and moisture content. These data are available from various sources, including Appendix F of the OU 3-13 RI/BRA (DOE-ID 1997) and the OU 3-13, Group 4, remedial activities (DOE-ID 2003g). The former document reviews the results of perched water tests, and the latter reviews the analysis of core samples collected during drilling of perched water wells at the INTEC. A total of 37 surficial alluvium and interbed samples were collected during the OU 3-13, Group 4, remedial work Phase I drilling. The laboratory analysis developed soil moisture characteristic curves and determined material particle size distribution, porosity, effective porosity, bulk density, and initial moisture content. The vadose zone model was calibrated as part of the OU 3-14 tank farm soil and underlying groundwater RI/BRA efforts (Cahn et al. 2006). The calibrated values are consistent with measured hydrologic parameter values and were selected for use in the base case analysis of this PA (see Table 3-3).

The vadose zone model was discretized into 46 cells with an average thickness of about 2.8 m, although individual layer thickness varied depending on the lithology (see Figure 3-7).

3.3.1.2.3 MCM Contaminant Transport—The model for solute transport explicitly treats advective processes and implicitly or explicitly treats dispersive processes. The model is based on the one-dimensional partial differential equation for mass transport in a variably saturated porous medium. The general transport equation for a single contaminant with first-order decay is given by (Codell, Key, and Whelan 1982):

$$Rd A \theta \frac{\partial C}{\partial t} = A \frac{\partial}{\partial z} \left(\theta D \frac{\partial C}{\partial z} \right) - A \frac{\partial q C}{\partial z} - \left(Rd \theta \lambda + Rd \frac{\partial \theta}{\partial t} \right) A C \quad (3-10)$$

Where

- C = solute concentration ($M L^{-3}$)
- D = dispersion coefficient ($L^2 T^{-1}$)
- A = cross sectional area perpendicular to flow (L^2)
- Rd = retardation coefficient (unitless)
- q = specific discharge or Darcy velocity ($L T^{-1}$)
- λ = first-order decay constant (T^{-1}).

The mixing cell approximation is written in terms of the mass balance around fully mixed volume elements. Assuming unidirectional flow in the positive z direction, the mixing cell model formulation for interior cells (i.e., $i \neq 1$ and $i \neq n$ where n is the number of cells) of equal thickness, T , is given by:

$$T_i R d_i A \theta_i \frac{dC_i}{dt} = A \sum_k \frac{D_{ik}}{T_{ik}} (\theta_k C_k - \theta_i C_i) + A(q_{i-1} C_{i-1}) - A(q_i C_i) - T_i A R d_i \theta_i \lambda C_i + S_i \quad (3-11)$$

Where

- i = cell index
- k = index for cells adjacent cell i (i.e., $i-1$ and $i+1$)
- D_{ik} = dispersion coefficient between cell i and k ($L^2 T^{-1}$)
- T_{ik} = distance separating the center of cell i and k (L)
- S_i = an external source to cell i ($M T^{-1}$).

The first term in Equation 3-11 represents dispersion, the second and third terms represent advection, and the last term represents decay. The variables, θ and q , can be time-variable or constant depending on whether transient infiltration or steady-state flow is considered.

The term $R d \partial \theta / \partial t$ in Equation 3-10 enforces continuity between the moisture content and solute concentration. This term is zero under steady-state flow conditions. Continuity between the two quantities (θ and C) under transient flow conditions is achieved by determining the time-dependent moisture content at each time step. Moisture content as a function of time is calculated in the water flow portion of the code. The concentration in each cell at a given time-step is adjusted for the moisture content by:

$$C_i^m = \frac{Q_i^m}{\theta_i^m A T \left(1 + \frac{K_{di} \rho_i}{\theta_i^m} \right)} \quad (3-12)$$

Where

- C_i^m = contaminant pore water concentration in cell i at time-step m ($M L^{-3}$)
- Q_i^m = mass of contaminant in cell i at time step m (M)
- K_{di} = equilibrium partition coefficient for mixing cell i ($L^3 M^{-1}$)
- ρ_i = bulk density of mixing cell i ($M L^{-3}$)
- θ_i^m = the moisture content in mixing cell i at time step m ($M L^{-3}$).

The term $1 + K_{di} \rho_i / \theta_i$ is the retardation coefficient (Rd) and is unity for a K_d of zero. Darcy fluxes in each cell and at each time-step are calculated using the time-dependent value of θ and the material-specific moisture characteristic curve. If C_i as given by Equation 3-12 exceeds the solubility limit, then $C_i = C_{sl}$ where C_{sl} is the solubility limit of the contaminant. The solubility adjustment does not affect the total mass of contaminant in the cell. The left-hand side of Equation 3-11 and the decay terms can now be rewritten in terms of the state variable (contaminant mass) by substituting the right-hand side of Equation 3-12 for C .

$$\frac{dQ_i}{dt} = A \sum_k \frac{D_{ik}}{T_{ik}} (\theta_k C_k - \theta_i C_i) + A(q_{i-1} C_{i-1}) - A(q_i C_i) - \lambda Q_i + S_i \quad (3-13)$$

Where

Q_i = contaminant mass in the cell i .

Equation 3-13 is valid for all nonboundary cells. Imposing the following boundary conditions:

$$D \frac{dC}{dz} = 0 \quad \text{at} \quad z = 0 \quad \text{and} \quad z = Z \quad (3-14)$$

then gives the mass balance equations for the first ($i = 1$) and last ($i = n$) cell in the system:

$$\begin{aligned} \frac{dQ_1}{dt} &= A \frac{D_{12}}{T_{12}} (\theta_2 C_2 - \theta_1 C_1) - A(q_1 C_1) - \lambda Q_1 + S_1 & \text{for } i=1 \\ \frac{dQ_n}{dt} &= A \frac{D_{n-1n}}{T_{n-1n}} (\theta_{n-1} C_{n-1} - \theta_n C_n) - A(q_n C_n) + A(q_{n-1} C_{n-1}) - \lambda Q_n + S_n & \text{for } i=n \end{aligned} \quad (3-15)$$

Implementation of Equation 3-14 in the MCM code is performed differently than what is presented in Rood (2005). A simple procedure is used where each cell is treated as an independent unit and advective and dispersive rate constants are defined. Sources are only considered for the first cell. The advective (κ) and dispersion (δ) rate constants are defined as follows:

$$\kappa_i = \frac{q}{T_i \theta_i R d_i} \quad \text{and} \quad \delta_i = \frac{D_i}{T_i^2}. \quad (3-16)$$

The advective rate constant is equivalent to the leach rate constant as described in Baes and Sharp (1983). An optional rate constant (designated kx) is also introduced into the governing equations that describes the transfer from cell i to cell $i+1$. This rate constant is provided by the user and is calculated external to the code. Assigning rate constants to the advection, dispersive, and optional transfer processes and expanding the summation term results in the following equation for interior cells:

$$\frac{dQ_i}{dt} = A[\delta_{i-1} C_{i-1} \theta_{i-1} T_{i-1} + \delta_{i+1} C_{i+1} \theta_{i+1} T_{i+1} - 2\delta_i C_i \theta_i T_i] + (kx_{i-1} + \kappa_{i-1}) Q_{i-1} - (kx_i + \kappa_i) Q_i - \lambda Q_i \quad (3-17)$$

and

$$\begin{aligned} \frac{dQ_1}{dt} &= A[\delta_2 C_2 \theta_2 T_2 - \delta_1 C_1 \theta_1 T_1] - (kx_1 + \kappa_1) Q_1 - \lambda Q_1 + S_1 & \text{for } i=1 \\ \frac{dQ_n}{dt} &= A[\delta_{n-1} C_{n-1} \theta_{n-1} T_{n-1} - \delta_n C_n \theta_n T_n] + (kx_{n-1} + \kappa_{n-1}) Q_{n-1} - (kx_n + \kappa_n) Q_n - \lambda Q_n & \text{for } i=n \end{aligned} \quad (3-18)$$

for the boundary cells. Equation 3-17 can now be expanded to include the transport of multiple decay products:

$$\begin{aligned} \frac{dQ_{i,j}}{dt} &= A[\delta_{i-1,j} C_{i-1,j} \theta_{i-1} T_{i-1} + \delta_{i+1,j} C_{i+1,j} \theta_{i+1} T_{i+1} - 2\delta_{i,j} C_{i,j} \theta_{i,j} T_i] \\ &+ (kx_{i-1,j} + \kappa_{i-1,j}) Q_{i-1,j} - (kx_{i,j} + \kappa_{i,j}) Q_{i,j} - \lambda_j Q_{i,j} + BR_j \lambda_{j-1} Q_{i,j-1} \end{aligned} \quad (3-19)$$

Where

- j = index for the decay chain member
- BR_j = fraction of decay product $j-1$ that decays to product j
- kx_{ij} = optional rate constant describing transfer from cell i to cell $i+1$ for contaminant j .

For the originating contaminant in a series of degradation products, the term, $BR_j \lambda_{j-1} Q_{i,j-1}$ is omitted from Equation 3-19. The decay rate constant is given by:

$$\lambda_j = \frac{\ln(2)}{th_j} \quad (3-20)$$

Where

- th_j = half-life of contaminant j .

Equation 3-19 describes the MCM with interchange. Equation 3-19 also gives the MCM without interchange except the dispersive terms are omitted (i.e., $\delta = 0$). The MCM without interchange is useful because relatively simple analytical solutions exist for the equations describing the system. These solutions are useful for simple conceptual models and model verification exercises.

The overall objective of the model is to provide a solute flux to the aquifer. The solute flux to the aquifer for degradation product j at $z=Z$ ($i=n$) for the stated boundary conditions is given by:

$$F_j = A(q_n C_{n,j}) = \frac{q_n Q_{n,j}}{\theta_n T_n R d_{n,j}} \quad (3-21)$$

Where

- F_j = solute flux to the aquifer from cell n for decay product j .

3.3.1.2.4 MCM Discretization and Solute Dispersion—The dispersive behavior of the MCM is similar to that of the advection dispersion equation and is related to the physical dispersion of the system (Zvirin and Shinnar 1976; Van Ommen 1985; Appelo and Willemssen 1987; Shanahan and Harleman 1984). Shanahan and Harleman (1984) use the term implicit dispersion to describe the dispersion that is inherent in the formulation of mass transport around fully mixed volume elements (cells) and is described in terms of ordinary differential equations. The dimensionless Peclet number characterizes dispersion and is given by:

$$Pe = \frac{Z}{D} \frac{q}{\theta} \quad (3-22)$$

Where

- Pe = Peclet number
- Z = length of the vadose zone (L)
- D = dispersion coefficient ($L^2 T^{-1}$).

The dispersion coefficient is given by:

$$D = \alpha_L q / \theta + D_m \quad (3-23)$$

Where

$$\begin{aligned} D_m &= \text{effective molecular diffusion coefficient (L}^2 \text{ T}^{-1}\text{)} \\ \alpha_L &= \text{longitudinal dispersivity (m).} \end{aligned}$$

Molecular diffusion may be important for systems with extremely low specific discharge. Equation 3-22 is referred to here as the scale-length Peclet number because it is the ratio of advection to dispersion for the entire system. If molecular diffusion is neglected, Equation 3-22 reduces to Z/α_L .

Levenspiel and Bischoff (1963) established a relationship between the number of equal-thickness mixing cells and the scale-length Peclet number for the MCM without interchange. They concluded that the number of mixing cells is approximately related to the Peclet number as given by:

$$\frac{1}{n} = \frac{2}{Pe^2} (Pe - 1 + e^{-Pe}) \quad (3-24)$$

which can be approximated by Shanahan and Harleman (1984)

$$n = \frac{Pe + 1}{2} \quad (3-25)$$

or as n becomes large

$$n \cong \frac{Pe}{2} \quad (3-26)$$

Zvirin and Shinnar (1976) as reported in Shanahan and Harleman (1984) defined the relationship between an equivalent Peclet number (Pe) and n for the mixing cell model with interchange as:

$$Pe = \frac{2n}{1 + 2\beta} \quad (3-27)$$

Where

$$\beta = \text{ratio of the exchange flow to through-flow and all cells are of equal size.}$$

The influence of cell interchange is to decrease the Peclet number (increase dispersion) by the factor $1 + 2\beta$. Shanahan and Harleman (1984) define exchange flow as $D A/T$ and through-flow as $A q/\theta$, where T is the distance separating adjacent mixing cells. If molecular diffusion is neglected, β can be written in terms of the local dispersivity:

$$\beta = \frac{D A}{A q / \theta T} = \frac{\alpha_{L*} q \theta}{T q \theta} = \frac{\alpha_{L*}}{T} \quad (3-28)$$

The term β is essentially the inverse of the local (or grid) Peclet number. The term α_{L^*} represents the equivalent local dispersivity accounting for implicit dispersion. If the dispersivity of the overall system is α_L , then the equivalent local dispersivity can be derived from Equations 3-22, 3-27, and 3-28:

$$\alpha_{L^*} = \left[\frac{2n\alpha_L}{Z} - 1 \right] \frac{T}{2} . \quad (3-29)$$

It can be shown that as $n \rightarrow \infty$, $\alpha_{L^*} \rightarrow \alpha_L$. If α_{L^*} is negative, then implicit dispersion is greater than the dispersion defined by α_L and additional cells must be added. For the case where molecular diffusion is not negligible, an equivalent local dispersion coefficient (D^*) is calculated for each cell and given by Equation 3-30:

$$D^* = \left[\frac{2D_i}{q_i/\theta_i} - 1 \right] \frac{T q_i/\theta_i}{2} . \quad (3-30)$$

3.3.1.2.5 MCM Transport Model Parameters—The transport model parameters needed for the MCM source and vadose zone models are the radionuclide-specific inventories, chemical-specific K_d values, chemical solubility, soil bulk densities, and the dispersivities. Information used from the flow model is the water velocities calculated for the unsaturated zone. The lithology illustration in Figure 3-7 for the water flow simulation was also used for the transport simulation.

The radionuclide-specific inventories for the screened list of radionuclides are shown in Table 3-4. Radionuclide inventories in soils are assigned to the first three cells of the MCMT model as an initial condition. The activity is equally distributed among the three cells. Release of radionuclides from activated metal waste forms is calculated externally and input into MCMT as an exogenous source.

Table 3-4. Radionuclide waste forms assumed for the base case analysis.

Radionuclide	Inventory Modeled as Miscellaneous Waste (Ci)	Inventory Modeled as Activated Metals (Ci)
C-14	4.49E+01	6.56E+01
Cl-36	1.20E-03	7.18E-01
H-3	1.69E+01	1.25E+05
I-129	1.50E-01	9.49E-05
Np-237	7.68E-02	0
Pu-239	1.93E+01	0
Pu-240	1.04E+01	0
Tc-99	4.41E-01	2.18E-01
U-233	1.19E-01	0
U-234	6.91E-01	0
U-235	1.55E-01	0
U-238	4.97E-01	0

The element-specific K_d values are shown in Table 3-5. The primary source of K_d values for the waste, interbeds, and alluvium was Appendix D of Cahn et al. (2006), which contains a detailed analysis of geochemical conditions in the INTEC alluvium and interbeds. K_d values for the bentonite clay layer were taken from the 2003 ICDF Landfill PA (DOE-ID 2003a). If Cahn et al. (2006) did not have a K_d value for an element in the screened list of radionuclides, then the K_d values from the 2003 ICDF PA were used. In Cahn et al. (2006), basalt K_d values were zero for all elements except plutonium, strontium, cesium, europium, and americium. For this analysis, it was conservatively assumed that all basalt K_d values were zero for all elements. Appendix D of Cahn et al. (2006) also provided uncertainty ranges for the K_d values. These ranges provided the basis for assigning K_d distributions in the uncertainty analysis. Because the radionuclide concentrations are relatively dilute in the ICDF, chemical-specific solubility limits were not considered.

Table 3-5. Lithology-specific sorption coefficients for the contaminants of concern for the base case calculations. Values in parenthesis represent the range of K_d values provided in Cahn et al. (2006), which was used as the basis for assigning uncertainty distributions.

Element	Lithology-Specific Sorption Coefficient (K_d) (mL/g)				
	Waste	Clay ^a	Interbed	Basalt ^b	Reference for Waste and Interbed
Ac	450	2,400	450	0	Jenkins (2001)
C	1.6 (0.5–2.8)	1	1.6 (0.5–2.8)	0	Cahn et al. (2006)
Cl	0	0	0	0	Jenkins (2001)
H	0	0	0	0	Cahn et al. (2006)
I	1.5 (0.04–8.7)	1	0.7 (0.04–3)	0	Cahn et al. (2006)
Np	2 (0.1–0.6)	55	2 (0.1–0.6)	0	Cahn et al. (2006)
Pa	550	2,700	550	0	Jenkins (2001)
Pb	100	710	100	0	Jenkins (2001)
Pu	1,000 (96–12,712)	1,700	1,000 (96–12,712)	0	Cahn et al. (2006)
Ra	100	9,100	100	0	Jenkins (2001)
Tc	0 (-0.1–0.4)	1	0 (-0.1–0.4)	0	Cahn et al. (2006)
Th	100	1,700	100	0	Jenkins (2001)
U	1.6 (0.12–12)	63	1.6 (0.12–12)	0	Cahn et al. (2006)

a. Clay K_d values from DOE-ID (2003a).

b. Basalt K_d values in unsaturated zone and aquifer assumed to be zero.

Dispersivity was not explicitly modeled. Instead, the implicit dispersion inherent in the MCM was relied on to simulate dispersion. The implicit dispersivity can be estimated using Equations 3-24 and 3-25. The source and vadose zones were discretized into 50 cells that are on average 2.86 m thick for a total thickness of 143.1 m. The implicit dispersivity can be calculated as:

$$\frac{1}{n} = \frac{2}{Pe^2} (Pe - 1 + e^{-Pe}), \quad Pe \cong 2n - 1, \quad Pe = \frac{Z}{\alpha_L} \quad \therefore \quad \alpha_L = \frac{Z}{2n - 1} = \frac{143.1 \text{ m}}{2(50) - 1} = 1.44 \text{ m} \quad (3-31)$$

For comparison, the OU 3-14 RI/BRA (Cahn et al. 2006) used a calibrated value of 1.0 m. Implicit dispersion is explained in Section 3.3.1.2.4.

3.3.1.3 GWSCREEN Aquifer Transport of Radionuclides. The aquifer conceptual model described in Section 3.2.2 is relatively simple and adapts very well to the conceptual model for transport in the saturated zone using the GWSCREEN code (Rood 2003a). The built-in source model and vadose zone model in GWSCREEN are disabled in this application and radionuclide fluxes to the aquifer are provided by the MCM source term and vadose zone models described in Section 3.3.1.2. Transport in the aquifer is calculated with a three-dimensional semianalytical solution to the advection dispersion equation in groundwater.

The saturated zone model is based on an analytic solution to the advection dispersion equation for contaminants in a saturated porous medium. This solution is published in Codell, Key, and Whelan (1982) and has been used for assessment of radionuclide transport in groundwater. The model contains the following assumptions and limitations:

1. The model uses a Cartesian coordinate system (x, y, z) as a frame of reference. The positive x direction is in the direction of flow.
2. The flow is uniform and unidirectional. No sources or sinks are accounted for.
3. GWSCREEN simulates one-dimensional flow in the aquifer with contaminant flux from the vadose zone to the aquifer. If the additional water from the vadose zone is significant compared to the flow in the aquifer across the source, GWSCREEN can compute the dilution in the aquifer based on the water flux from the vadose zone and the water flux in the aquifer. Water flow in the saturated zone beneath the ICDF was sufficiently high such that this was not an issue.
4. The aquifer is modeled as an isotropic, homogeneous porous medium of infinite lateral extent and finite thickness.
5. Molecular diffusion is assumed to be negligible.
6. The source can be represented by a rectangular area of length, L , and width, W , and centered at the origin $(0,0,0)$.
7. The dispersion coefficients remain constant over time.
8. Transport is limited to a single specie that may decay or degrade as a function of time. Radioactive progeny are assumed to grow in during transport through the vadose zone and are input to the aquifer separately from their parent nuclide. The calculated doses from the parent and progeny are then summed over time to provide a total dose from a parent nuclide.
9. The contaminant is assumed to move as a dissolved substance. Transport in liquid organic and vapor phases is not considered.
10. Solid and liquid phases are in equilibrium and concentrations are related by the linear distribution coefficient (K_d).

The mass balance equation that describes contaminant transport for the stated assumptions is:

$$\frac{\partial C}{\partial t} + \frac{U}{R_d} \frac{\partial C}{\partial x} = \frac{D_x}{R_d} \frac{\partial^2 C}{\partial x^2} + \frac{D_y}{R_d} \frac{\partial^2 C}{\partial y^2} + \frac{D_z}{R_d} \frac{\partial^2 C}{\partial z^2} - \lambda_d C \quad (3-32)$$

Where

- C = concentration (mg or Ci/m³)
- U = average linear velocity or groundwater pore velocity (m/year)

- D_x, D_y, D_z = dispersion coefficient in the x, y, and z direction (m²/year)
 R_d = retardation factor in the aquifer
 t = time (year)
 x = distance from center of area source to receptor parallel to groundwater flow (m)
 y = distance from center of area source to receptor perpendicular to groundwater flow (m)
 z = distance downward from the surface of the aquifer (m).

The retardation factor in the aquifer is given by:

$$R_d = 1 + K_{da} \frac{\rho_a}{\eta} \quad (3-33)$$

Where

- η = the effective porosity of the aquifer (m³/m³)
 K_{da} = the distribution coefficient in the aquifer (mL/g)
 ρ_a = the bulk density in the aquifer (g/cm³).

The dispersion coefficients (D_x, D_y, D_z) are given by:

$$D_x = \alpha_L U \quad D_y = \alpha_T U \quad D_z = \alpha_V U \quad (3-34)$$

Where

- α_L = the longitudinal dispersivity (m)
 α_T = the transverse dispersivity (m)
 α_V = the vertical dispersivity (m).

The vertically averaged Green's function solution to Equation 3-32 for instantaneous release of mass M_a , at $t = 0$ at the surface of an area defined by L and W and initial concentration of zero everywhere in the model domain is given by:

$$\begin{aligned}
 C(x, y, t) = & \frac{M_a}{\eta R_d} \frac{1}{2L} \frac{1}{b} \left(\operatorname{erf} \left(\frac{x + \frac{L}{2} - \frac{Ut}{R_d}}{\sqrt{\frac{4D_x t}{R_d}}} \right) - \operatorname{erf} \left(\frac{x - \frac{L}{2} - \frac{Ut}{R_d}}{\sqrt{\frac{4D_x t}{R_d}}} \right) \right) \\
 & \times \frac{1}{2W} \left(\operatorname{erf} \left(\frac{\frac{W}{2} + y}{\sqrt{\frac{4D_y t}{R_d}}} \right) + \operatorname{erf} \left(\frac{\frac{W}{2} - y}{\sqrt{\frac{4D_y t}{R_d}}} \right) \right) e^{-\lambda_d t}
 \end{aligned} \quad (3-35)$$

Where

- b = the well screen thickness or mixing depth (m)
- M_a = the initial total mass in the volume defined by $L \times W \times b$
- erf = the error function
- L = length of source parallel to groundwater flow (m)
- W = width of source perpendicular to groundwater flow (m)
- DF = dilution factor (unitless).

The terms L and W represent the length parallel to groundwater flow and the width perpendicular to groundwater flow, respectively. For conservatism, the L and W terms are assumed to be the same as the actual length and width of the facility. Therefore, the implicit assumption is that water in the vadose zone only travels vertically and transverse dispersion in the unsaturated zone is zero.

For the 3-D solution, Equation 3-35 is multiplied by Z_1 .

$$Z_1 = \left(1 + 2 \sum_{m=1}^{\infty} \exp\left(-\frac{m^2 \pi^2 D_z t}{b^2 R_d}\right) \cos\left(m\pi \frac{z}{b}\right) \right) \quad (3-36)$$

Where

- z = receptor distance below the surface of the aquifer (m).

The 3-D solution gives the concentration at a point specified by (x, y, z) in the aquifer. Often, the average concentration over a screened interval is more useful than concentration at a point. The average concentration over a screened well interval, b_w (from the surface of the aquifer to depth b_w), for the three-dimensional solution is given by:

$$C_{3Davg}(x, y, z, t) = \frac{\int_0^{b_w} C(x, y, z, t) dz}{b_w} \quad (3-37)$$

For an arbitrary release, the concentration may be found by the convolution integral as given by Equation 32 in Rood (2003a).

To evaluate the movement of radioactive progeny, the model makes the simplifying assumption that radioactive progeny travel at the same rate as the parent. This assumption has been shown to be conservative (Codell, Key, and Whelan 1982) and greatly simplifies the calculations. Furthermore, a zero K_d in the aquifer basalt for all elements makes this assumption accurate, because parents do travel at the same rate as their progeny. The concentration of the i^{th} progeny in a decay chain at the receptor location is:

$$C_i = C_{parent} \frac{DIF_i R_{d_{parent}}}{DIF_{parent} R_{d_i}} \quad (3-38)$$

Where

- DIF_i = decay-ingrowth factor of the i^{th} progeny
- DIF_{parent} = decay-ingrowth factor of the parent

- R_{di} = retardation factor of the i^{th} progeny
 $R_{d\ parent}$ = retardation factor of the parent
 C_{parent} = groundwater concentration of the parent (Ci/m³).

The decay ingrowth factor for an n member chain is given by (Scrabble et al. 1974):

$$DIF_i(t) = \frac{\lambda_i}{\lambda_1} \left[\left(\prod_{i=1}^{n-1} \lambda_i \right) \sum_{i=1}^n \frac{e^{-\lambda_i t}}{\prod_{\substack{j=1 \\ j \neq i}}^n (\lambda_j - \lambda_i)} \right] \quad (3-39)$$

Where

- λ_1 = decay constant for the parent (year)
 λ_i = decay constant for the i^{th} progeny (year)
 t = time from waste emplacement or release to from the source (years).

The decay and ingrowth of radioactive progeny were treated explicitly in the unsaturated zone, and fluxes of parent and progeny were provided to the GWSCREEN aquifer model. However, further ingrowth of radioactive progeny after entering the aquifer was not considered because transport times in the aquifer are relatively short compared to those in the unsaturated zone. Higher pore velocities and zero sorption coefficients are the primary factors for relatively rapid aquifer transport times.

3.3.1.3.1 GWSCREEN Aquifer Model Parameters—Parameter values for the groundwater pathway GWSCREEN models are summarized in Table 3-6 for nuclide-independent parameters and Table 3-5 for nuclide-dependent K_d values. The parameter values are basically consistent with the 2003 ICDF Landfill PA (DOE-ID 2003a). The receptor is located 100 m downgradient from the landfill. The length of the landfill parallel to groundwater flow is 160 m and the receptor distance in GWSCREEN is measured from the center of the source. Therefore, the receptor distance input into GWSCREEN is 160 m/2 + 100 m = 180 m.

The value for Darcy velocity in the aquifer was reviewed to see if it was consistent with the OU 10-08 Site-wide groundwater model (DOE-ID 2008d). Figures B-5-13 and B-5-15 in DOE-ID (2008d) indicate that the pore velocity near the ICDF is about 0.5–1.5 m/day. The OU 10-08 porosity is 0.06; therefore, the Darcy velocity is

$$0.5 \text{ m/d} \times 0.06 = 0.03 \text{ m/d or } 10.9 \text{ m/yr} \quad (3-40)$$

and

$$1.5 \text{ m/d} \times 0.06 = 0.09 \text{ m/d or } 32.9 \text{ m/yr.} \quad (3-41)$$

The Darcy velocity from the 2003 PA (DOE-ID 2003a) is approximately the modal value between the minimum and maximum values given above. Therefore, the original estimate of Darcy velocity in the aquifer of 21.9 m/year was retained in this analysis.

Table 3-6. Nuclide-independent parameter values for the GWSCREEN performance assessment simulation.

Parameter		Value	Reference/Comments
Source length entering the aquifer (m)		160	2003 PA (DOE-ID 2003a)
Source width entering the aquifer (m)		194	2003 PA (DOE-ID 2003a)
Aquifer thickness (m)		76	2003 PA (DOE-ID 2003a)
Well screen thickness (m)		15	2003 PA (DOE-ID 2003a)
Darcy velocity in aquifer (m/yr)		21.9	2003 PA (DOE-ID 2003a)
Porosity of aquifer (m ³ /m ³)		0.06	OU 10-08 (DOE-ID 2008d)
Bulk density of aquifer (g/cm ³)		1.9	OU 10-08 (DOE-ID 2008d)
Receptor location (meters south from center of source)		180	100 m downgradient from the ICDF
Longitudinal dispersivity in the aquifer (m)		3.31	2003 PA (DOE-ID 2003a)
Transverse dispersivity in the aquifer (m)		0.662	Ratio of $\alpha_T/\alpha_L = 0.2$ (Whelan, McDonald, and Sato 1996)
Vertical dispersivity in the aquifer (m)		0.00384	Ratio of $\alpha_V/\alpha_L = 0.00116$ (Whelan, McDonald, and Sato 1996)
ICDF	Idaho CERCLA Disposal Facility		
OU	operable unit		
PA	performance assessment		

3.3.2 Atmospheric Pathway

The EPA code EMSOFT (EPA 1997a) was used to compute the atmospheric pathway source term (radionuclide fluxes) from the ICDF to the ground surface. The CAP88-PC, Version 3, code (EPA 2007) was used to model atmospheric dispersion of volatile radionuclides emitted from the ICDF Landfill and dose to the receptor. CAP88-PC, Version 3, is one of the codes that EPA allows for demonstration of compliance with the applicable performance objective (40 CFR 61, Subpart H, “National Emission Standards for Emissions of Radionuclides Other Than Radon from Department of Energy Facilities”).

3.3.2.1 Atmospheric Pathway Source Term Screening. The atmospheric pathway source term screening procedure consisted of: (1) screening out all radionuclides in the inventory that do not migrate in the gas phase and (2) using the screening factors developed by NCRP (1996) for air screening to further eliminate radionuclides from the air pathway source term. The radionuclides that can potentially migrate in the gas phase through the subsurface include C-14, H-3, I-129, and Kr-85.

The NCRP provides a series of simple screening factors (SFs) that can be used to demonstrate compliance with environmental standards or other administratively set reference levels for releases of radionuclides to the atmosphere, surface water, or ground. The air pathway SF is essentially a dose conversion factor having units of total EDE per unit of activity (Sv/Bq or rem/Ci) per volume of contaminated air. These factors are used to calculate the annual total EDE to a hypothetical receptor per unit of activity concentration of the volatile radionuclide in air. The NCRP air pathway exposure scenario assumes the person is exposed to the air concentration continuously for a period of a year. To estimate an air concentration the person is exposed to, the entire inventory of each volatile radionuclide was assumed to be mixed in a 1-m-high box above the ICDF. Therefore, the volume of air the volatile radionuclide inventory is mixed in is $160 \text{ m} \times 194 \text{ m} \times 1 \text{ m} = 31,000 \text{ m}^3$. The NCRP screening dose for each radionuclide is calculated using the formula:

$$D_i = \frac{M_{0,i}}{V_{air}} \times SF_i \quad (3-42)$$

Where

- D_i = effective NCRP screening dose for radionuclide i (Sv or rem)
 $M_{0,i}$ = disposed inventory (Bq or Ci)
 V_{air} = volume of air in the area of the ICDF (31,000 m³)
 SF_i = screening factor for the air pathway for radionuclide i and all progeny for the period of maximum exposure (Sv-m³/Bq or rem-m³/Ci).

The NCRP calculations are shown in Table 3-7. Nuclides with an NCRP screening dose of less than 1 mrem (1E-05 Sv) were removed from further consideration. Of the four nuclides, only Kr-85 has an NCRP screening dose less than 1 mrem. The C-14, H-3, and I-129 NCRP screening doses are much larger than 1 mrem. C-14, H-3, and I-129 are included in the atmospheric pathway analysis.

Table 3-7. NCRP screening results for the ICDF Landfill atmospheric pathway.

Radionuclide	ICDF Projected Inventory (Ci)	Activity Concentration in Air (Ci/m ³)	Air Pathways NCRP Screening Factor		Screening Dose		Is Screening Dose <1 mrem
			(Sv-m ³ /Bq)	(rem-m ³ /Ci)	(rem)	(mrem)	
C-14	110	3.54E-03	2.60E-04	9.62E+08	3.41E+06	3.41E+09	No
H-3	1.25E+05	4.03E+00	1.90E-06	7.03E+06	2.83E+07	2.83E+10	No
I-129	0.15	4.83E-06	5.60E-01	2.07E+12	1.00E+07	1.00E+10	No
Kr-85	2.62E-04	8.44E-09	2.80E-09	1.04E+04	8.74E-05	8.74E-02	Yes

ICDF Idaho CERCLA Disposal Facility
 NCRP National Council on Radiation Protection

3.3.2.2 Atmospheric Pathway Exposure Scenarios. Doses were evaluated for receptors most affected by air emissions during the institutional control and compliance periods. During the institutional control period, the receptor was assumed to be located at the INL Site boundary that yields the highest dose. For the ICDF Landfill, the location of highest dose at the INL Site boundary was 12.7 km (7.89 mi) south of the ICDF Landfill. This location was based on a review of receptor locations that have been established for NESHAP compliance (Staley, Abbott, and Ritter 2004). After the institutional control period, the receptor was assumed to be located 100 m from a point where all emissions occur from sources at the ICDF Landfill, in the direction where meteorological conditions result in the highest air concentrations at that range. Emissions were assumed to be from point sources at ground level for both analyses.

3.3.2.3 Atmospheric Pathway Model Source Term. Based on the projected land use for INTEC and the assumption that the closure cover precludes biotic intrusion of buried waste, only volatile radionuclides are potential dose contributors through the air pathway. The inventories addressed in the PA include H-3, C-14, and I-129. These radionuclides potentially can migrate in gas phase through the subsurface. Table 3-8 presents the inventories of C-14, H-3, and I-129 in the two waste forms, contaminated soil and activated metals, that are addressed in the PA air pathway analysis.

Table 3-8. Volatile radionuclide inventories by waste form and unit dose factors.

Radionuclide	ICDF Landfill Inventory		Unit Dose Calculated with CAP88	
	Contaminated Soil (Ci)	Activated Metals (Ci)	INL Site Boundary (mrem/Ci)	100 m From Facility Boundary (mrem/Ci)
C-14	44.9	65.6	2.1E-04	3.7E-01
H-3	16.9	1.25E+05	1.8E-05	2.4E-02
I-129	0.15	9.49E-05	6.1E-03	7.1E+00
ICDF Idaho CERCLA Disposal Facility INL Idaho National Laboratory				

Iodine-129 can form gaseous compounds, although it has never been detected in soil pore gas in INL Site disposal areas. Tritium and C-14 are known to migrate in gas phase from disposed waste. Denham, Kaplin, and Yeager (2009) and Denham (2010) researched radioiodine biogeochemistry and determined the primary iodine species that would be present in the vapor phase would be molecular iodine (I₂) and hydrogen iodine (HI). Chemical forms of H-3 include tritiated water (HTO) and hydrogen-tritium gas (HT) and tritium gas (T₂). Carbon-14 would transport in the form of carbon dioxide (CO₂). The formation of I₂, HI, and CO₂ depend on the geochemical conditions in the waste and surrounding media. Emissions were assumed to be from point sources at ground level for both analyses.

Radionuclides in contaminated soil can be readily leached and released to the environment. The activated metal waste form contains radionuclides within the metal structure. The waste form must corrode before the radionuclide is released to the environment. General model assumptions include:

- The inventory of volatile radionuclides in contaminated soils was assumed to be available for both vapor phase and aqueous transport. A two-phase diffusion model was used to estimate the gas-phase radionuclide flux at the surface of the ICDF cover.
- The contaminated soils simulation begins after final installation of the ICDF cover in year 2018, and no radionuclide release was assumed prior to this time. This assumption is conservative because volatile radionuclides would be released during the disposal process; thereby, the available inventory for diffusion would be reduced.

Added to the diffusion release are the releases from activated metal. For activated metal releases, diffusion from the source to the land surface is assumed to be instantaneous and the entire amount released from the activated metal is assumed to diffuse to the surface. Once the metal corrodes, the radionuclide is assumed to be available for release. The corrosion rate constant used in the groundwater assessment was 1.19E-05 per year. The annual release rate is then given by

$$R = k \times I \times e^{-(\lambda+k)t} \quad (3-43)$$

Where

- R = annual release rate from activated metals (Ci/year)
 I = radionuclide inventory in activated metal
 λ = radioactive decay constant (1/year)
 k = corrosion rate constant (1/year).

The release rate from activated metals decreases exponentially over time, and the releases are assumed to start in year 2018, after final placement of the cover. The total release to the atmosphere is the sum of the diffusion release plus the release from activated metals.

3.3.2.4 CAP88 Modeling. CAP88 was used to model atmospheric transport from the ICDF to a potential receptor and radiation doses to that receptor from exposure to radionuclides released from the ICDF Landfill to the atmosphere. The doses were modeled assuming a subsistence-farming scenario, consistent with dose calculations used for the INL Site's annual NESHAP compliance evaluation. The local food production option was selected to simulate a subsistence-farming scenario, and other model parameters were set to CAP-88 default values, with the exception of I-129 and C-14, which were modeled as a vapor instead of the particulate form (the default form in CAP88 for these two radionuclides). Default physical form for H-3 is vapor. Ten-year averaged meteorological data (i.e., 1994 through 2003), gathered at the 10-m elevation of the GRID 3 station located at CFA, about 3.5 km (2.17 mi) south of the ICDF Landfill, were used for the calculation.

CAP88 was run for a unit release rate (1 Ci/year) for the chemical forms CO₂, I₂, and HT and then scaled for the actual release rate. These unit dose factors are presented in Table 3-8. Other site-specific and nuclide-specific parameters were obtained from the 2009 NESHAP report (DOE-ID 2010d). Site-specific parameters included:

- Mixing height (800 m)
- Mean temperature (280.2°K)
- Annual precipitation (20.80 cm/year)
- Absolute humidity (3.54 g/m³).

During institutional control, the receptor is at the INL Site boundary at the location of maximum dose. This location (based on the 2009 annual NESHAP report (DOE-ID 2010d)) is 12.7 km south from the ICDF. After institutional control, the receptor is 100 m from the edge of the ICDF Landfill. Because a point source was modeled, the modeled receptor distance was the distance from the center of the ICDF Landfill to its edge plus 100 m. The edge of the ICDF Landfill was estimated by the effective radius of the source. The ICDF source dimensions are 160 m × 194 m. Therefore, the effective radius was $([160 \text{ m} + 194 \text{ m}]/\pi)^{0.5} = 99.4 \text{ m}$.

3.3.2.5 Diffusion Modeling. The diffusion model for transport of volatile radionuclides from the ICDF Landfill to the soil surface was taken from the EPA EMSOFT software (EPA 1997a). The EMSOFT code was written for volatile chemicals. However, the equations for diffusion are equally applicable to volatile radionuclides. EMSOFT was used to compute the flux of volatile radionuclides as a function of time at the soil surface for a unit mass concentration (1 Ci/kg). Actual fluxes were scaled by the actual radionuclide mass concentration in soil. The following summarizes the governing equations discussed in the EMSOFT User's Guide (EPA 1997a).

The one-dimensional mass balance equation for a volatile radionuclide that can partition and transport in the aqueous and gas phase is given by (EPA 1997a):

$$\frac{\partial C_T}{\partial t} = D_E \frac{\partial^2 C_T}{\partial z^2} - V_E \frac{\partial C_T}{\partial z} - \lambda C_T \quad (3-44)$$

Where

C_T = total concentration – total mass of radionuclide per unit volume of soil (Ci/m³)

- D_E = effective diffusion coefficient in the air-filled pore space (m²/s)
 V_E = effective pore water velocity (m/s)
 λ = radioactive decay constant (1/s).

The total concentration in soil can be expressed as

$$C_T = \rho_b C_S + \theta C_L + a C_G \quad (3-45)$$

Where

- ρ_b = bulk soil density (kg/m³)
 C_S = concentration in the solid phase in soil (Ci/kg)
 θ = moisture content
 C_L = concentration in the aqueous phase (Ci/m³)
 a = air-filled porosity
 C_G = concentration in the gas phase (Ci/m³).

Using the air-water partitioning relationships (i.e., the Henry's Law constant), Equation 3-45 can be re-written as:

$$C_T = R_S C_S = R_L C_L = R_G C_G \quad (3-46)$$

$$R_S = \rho_b + \frac{\theta}{K_D} + \frac{a K_H}{K_D} \quad (3-47)$$

$$R_L = \rho_b K_D + \theta + a K_H \quad (3-48)$$

$$R_G = \frac{\rho_b K_D}{K_H} + \frac{\theta}{K_H} + a \quad (3-49)$$

Where

- K_D = soil water partition coefficient (m³/kg)
 K_H = dimensionless Henry's Law constant.

The Henry's law constant describes the equilibrium partitioning between air and water and is defined by:

$$K_H = \frac{P_{vp}}{S} \times \frac{1}{RT} \quad (3-50)$$

Where

- P_{vp} = vapor pressure (atm)
 S = solubility (mol/m³)

R = universal gas constant (8.2E-05 atm-m³/(mol-K))
 T = temperature (K).

The effective diffusion coefficient is defined by

$$D_E = \frac{K_H D_G + D_L}{R_L} \quad (3-51)$$

Where

D_G = soil gas diffusion coefficient = $[a^{10/3}/\phi^2] D_{air}$ (Millington-Quirk model)
 D_{air} = the free air diffusion coefficient (m²/s)
 ϕ = total soil porosity ($\theta + a$)
 D_L = liquid diffusion coefficient = $[a^{10/3}/\phi^2] D_{water}$
 D_{water} = the diffusion coefficient in water (m²/s).

The effective pore water velocity is given by

$$V_E = \frac{q}{R_L} \quad (3-52)$$

Where

q = the Darcy velocity in the vadose zone (m/s).

Equation 3-44 is solved for the boundary conditions:

- $J(z=0,t) = -hC_g(z=0,t)$

Where

J = the volatilization flux across a stagnant boundary layer at the soil surface of depth d
 h = the transport coefficient across the boundary layer
 C_g = the gas-phase concentration at the surface of the ICDF cover (above this layer, the concentration is zero).

- $C_T = 0$ for $z=\infty$

And the initial condition, $C_T = C_o$ at $t = 0$ from the surface down to some depth L .

The transport coefficient across the boundary layer (h) is defined by

$$h = \frac{D_{air}}{d} \quad (3-53)$$

Where

D_{air} = the free air diffusion coefficient (m²/s).

The boundary layer thickness is estimated by:

$$d = \frac{26\nu}{0.01V(6.1 + 0.63V)^{0.5}(D_{air}/\nu)^{1/3}} \quad (3-54)$$

Where

$$\begin{aligned} \nu &= \text{kinematic viscosity of air (1.5E-05 m}^2\text{/s)} \\ V &= \text{ambient wind speed (3.22 m/s).} \end{aligned}$$

The solution to 3-44 is given in the EPA code EMSOFT (EPA 1997a).

$$\begin{aligned} C_T(z, t, L) &= \frac{1}{2} C_o \exp(-\lambda t) \left[\operatorname{erfc}\left(\frac{z-L-V_E t}{2\sqrt{D_E t}}\right) - \operatorname{erfc}\left(\frac{z-V_E t}{2\sqrt{D_E t}}\right) \right] \\ &+ \frac{1}{2} C_o \exp(-\lambda t) \left[1 + \frac{V_E}{H_E} \right] \exp\left[\frac{V_E z}{D_E}\right] \left[\operatorname{erfc}\left(\frac{z+L+V_E t}{2\sqrt{D_E t}}\right) - \operatorname{erfc}\left(\frac{z+V_E t}{2\sqrt{D_E t}}\right) \right] \\ &+ \frac{1}{2} C_o \exp(-\lambda t) \left[2 + \frac{V_E}{H_E} \right] \exp\left[\frac{H_E(H_E + V_E)t + (H_E + V_E)z}{D_E}\right] \\ &\times \left[\operatorname{erfc}\left(\frac{z + (2H_E + V_E)t}{2\sqrt{D_E t}}\right) - \exp\left[H_E \frac{L}{D_E}\right] \operatorname{erfc}\left(\frac{z + L + (2H_E + V_E)t}{2\sqrt{D_E t}}\right) \right] \end{aligned} \quad (3-55)$$

The volatile flux at the soil surface is:

$$\begin{aligned} J_s(t, L) &= \frac{1}{2} C_o \exp(-\lambda t) V_E \left[\operatorname{erfc}\left(\frac{V_E t}{2\sqrt{D_E t}}\right) - \operatorname{erfc}\left(\frac{L + V_E t}{2\sqrt{D_E t}}\right) \right] \\ &+ \frac{1}{2} C_o \exp(-\lambda t) [2H_E + V_E] \exp\left[\frac{H_E(H_E + V_E)t}{D_E}\right] \\ &\times \left[\operatorname{erfc}\left(\frac{L + (2H_E + V_E)t}{2\sqrt{D_E t}}\right) \exp\left[H_E \frac{L}{D_E}\right] - \operatorname{erfc}\left(\frac{(2H_E + V_E)t}{2\sqrt{D_E t}}\right) \right] \end{aligned} \quad (3-56)$$

Equation 3-56 gives the flux at the surface for a single contaminated layer of thickness L and no clean cover over the contaminated layer. The solution for an arbitrary number of contaminated layers is obtained through applying the principles of superposition. For n layers of thickness D_i and overlain with a clean cover of thickness DB_i , the total concentration as a function of depth and time is:

$$C_{BT}(z, t) = \sum_{i=1}^n [C_T(z, t, D_i + DB_i) - C_T(z, t, DB_i)] \quad (3-57)$$

The following summarizes the EMSOFT assumptions:

- Steady-state pore water flux.
- Homogeneous environment through the entire model domain. All layers must have the same properties (i.e., bulk density, porosity, moisture content, K_D , diffusion coefficients, and K_H). However, each layer may have a different initial concentration.
- Radionuclides are present in dissolved form at low concentrations. The equilibrium partitioning equations are not valid at very high concentrations. In the case of radionuclides disposed of in the ICDF Landfill, the mass concentrations are very low, which is consistent with this EMSOFT conceptual model assumption.

Figure 3-10 illustrates a 1-dimensional cross section through the cap and the waste, showing the different material types that compose the proposed ICDF cap. The following summarizes the assumptions necessary to apply the EMSOFT model to the ICDF:

- Physical properties assigned to the model domain were the weighted-average values for all the different materials from the base of the waste in the ICDF Landfill to the top of the cap.
- For computational purposes, these materials were assumed to remain the same down to the water table. For the atmospheric source term, this assumption maximizes the flux to the surface because of the strong concentration gradient between the soil surface and the waste. Also, if basalt properties were considered below the waste, then radionuclide transport to the water table would be more rapid via both aqueous phase and vapor phase transport because of low moisture content and high pore water velocities. Consequently, less activity would be released out the cap surface because more activity would be released to the aquifer.
- Material thickness of the ICDF cap was obtained from Figure 1-1 in EDF-ER-279, “Hydrological Modeling of Final Cover.” The thickness for the “select earth fill” material was reported in EDF-ER-279 as variable, and, for these simulations, it was assumed to be 3 m.
- Properties of the ICDF waste material, bentonite clay, and top soil (assumed to be high-permeability alluvium) were taken from Table 3-3.
- The moisture content in the ICDF cap was based on an infiltration rate of 1 cm/year for the layers above the bentonite clay layer (the drainage layers) and 0.1 mm/year for bentonite clay layer and layers below. The 1-cm/year value is the background infiltration rate for undisturbed soils at the INL Site.
- The moisture characteristic curves presented in Appendix C of EDF-ER-279 were used to estimate the moisture content for cap materials, with the exception of bentonite clay, waste materials, and top soil. The van Genuchten parameters in Table 3-3 were used to estimate the moisture content for the bentonite clay, waste materials, and the top soil.
- The bulk density for ICDF Landfill cover materials was estimated by an approximate average of the specific gravity for the material listed in Appendix C of EDF-ER-279 multiplied by $1-n$ where n was the total porosity of the material.
- K_D values for waste materials in Table 3-5 were used in EMSOFT.
- Subsurface temperature was assumed to be a constant 60°F (288.5 K).

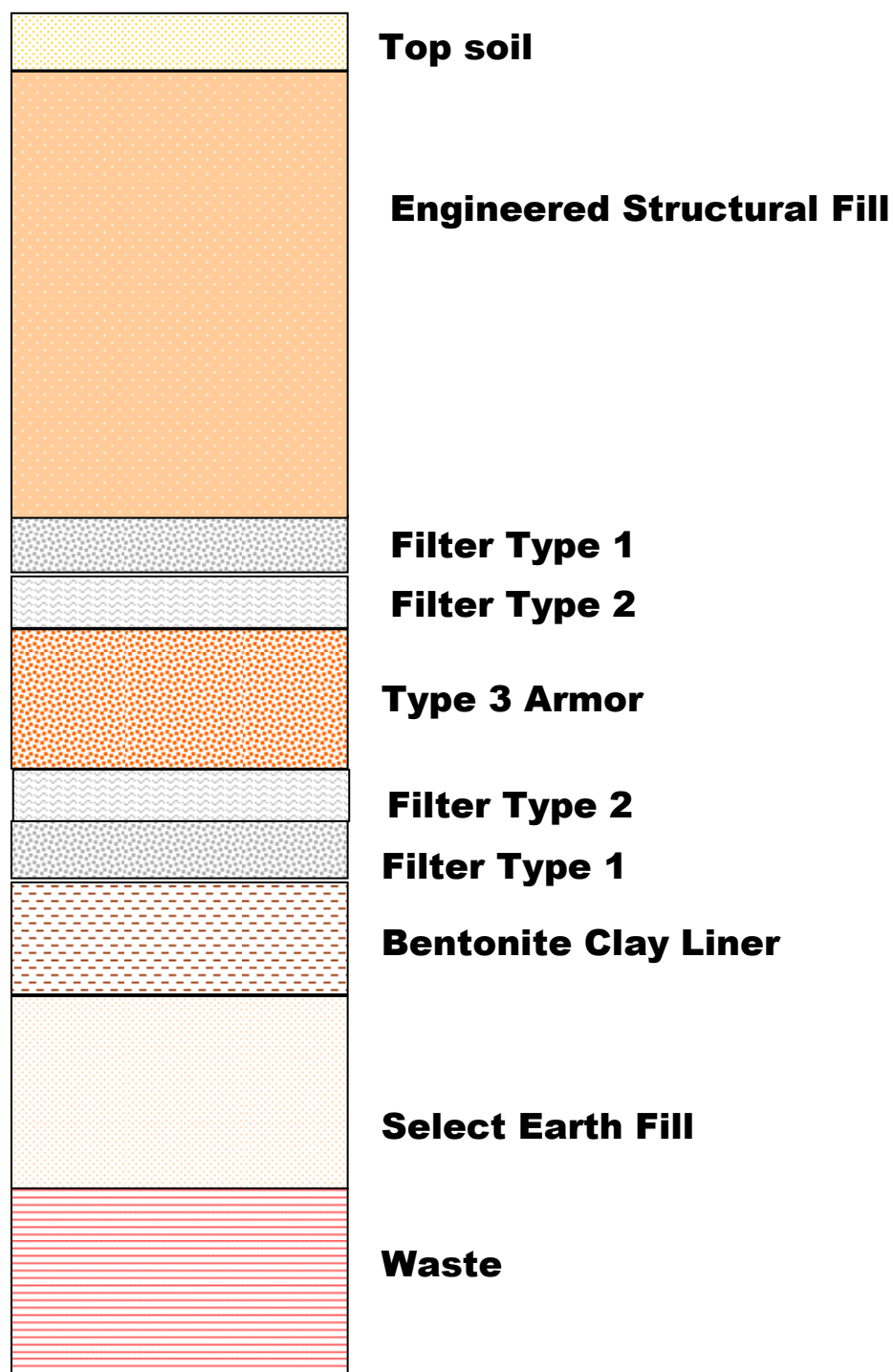


Figure 3-10. One-dimensional cross section of the Idaho CERCLA Disposal Landfill cover and waste materials that were used to develop weighted average properties (porosity, moisture content, bulk density) for use in EMSOFT.

The weighted average property was given by:

$$W_{avg} = \sum_{i=1}^n W_i \frac{T_i}{T_T} \quad (3-58)$$

Where

- W_i = the value of the property for material i
- T_i = the thickness for material i
- T_T = the total thickness from the soil surface to the base of the waste
- n = the number of material types.

Table 3-9 presents the material properties of the cap and waste materials and the weighted-average values used in EMSOFT.

Table 3-9. Material properties of the cap and waste materials and the weighted-average values used in EMSOFT.

Material	Thickness (m)	Porosity	Moisture Content	Bulk Density (g/cm ³)	Description of Assumed Material
Topsoil	0.31	0.32	0.072	1.82	High-permeability alluvium
Engineered structural fill	2.43	0.440	0.20	1.46	Silty loam
Filter Type 2	0.31	0.387	0.18	1.65	Fine sand
Filter Type 1	0.31	0.265	0.10	1.95	Coarse sand
Type 3 armor	0.76	0.265	0.15	1.91	Cobble
Filter Type 2	0.31	0.387	0.18	1.66	Fine sand
Filter Type 1	0.31	0.265	0.10	1.95	Coarse sand
Bentonite clay	0.61	0.390	0.36	1.59	Bentonite
Select earth fill	3.0	0.266	0.11	1.95	Waste
Waste	10.4	0.266	0.11	1.95	Waste
Weighted average	NA	0.297	0.137	1.86	Weighted average value
NA	not applicable				

Radionuclide-specific inverse Henry's law constants are presented in Table 3-10, and diffusion coefficients in air and water are shown in Table 3-11. The inverse Henry's law constant was obtained from Sander (2010) and Denham (2010), who provided inverse Henry's law constants for different geochemical conditions in grouted tank waste at the Savannah River Site. The rationale for selection of the Henry's law constant is provided below:

- C-14 – CO₂ is the only gaseous form of C-14 considered. Denham (2010) provides Henry's Law constants of 2.8 and 0.038 mol/kg-atm for pH environments of 8.3 and 5.4, respectively. The pH in the ICDF Landfill is expected to be slightly basic because the groundwater near INTEC and the ICDF have pH values between 7 and 8. Therefore, an inverse Henry's law constant for a geochemical environment with a pH of 8.3 was selected (2.8 mol/kg-atm).

Table 3-10. Radionuclide-specific inverse Henry's Law parameter values for EMSOFT diffusion simulation for the air pathway. Soil water partitioning coefficients (K_d) are assumed to be the same for waste materials as listed in Table 3-5.

Chemical Form	Inverse Henry's Law Value (H)	Dimensionless Henry's Law (K_H)	Reference
CO ₂	2.8 mol/atm·kg ^a	0.0151	Denham (2010) for pH 8.3, Eh 0.73 V
CO ₂	0.038 mol/atm·kg	1.11	Denham (2010) for pH 5.4, Eh 0.37 V
I ₂	1.1 – 3.3 mol/atm·L ^b	0.0384–0.0126	Sander (2010)
I ₂	1.3E29 mol/atm·kg	3.25E-31	Denham (2010) for pH 8.3, Eh 0.73 V
HI	6.3E14 mol/atm·kg	6.71E-17	Denham (2010) for pH 5.4, Eh 0.37 V
HT, T ₂	7.8E-4 mol/atm·L ^c	54.2	Sander (2010)
HTO	2,100 mol/atm·kg	2.01E-5	Denham (2010)

a. The value used for CO₂ in EMSOFT because groundwater near the ICDF has pH values that range from 7.8 to 9.

b. The value used for I₂ in EMSOFT was 1.1 mol/atm·L. This was the most conservative value for vapor-phase transport.

c. The value used for HT and T₂ in EMSOFT. This value is the most conservative for vapor-phase transport of H-3

CO ₂	carbon dioxide
HI	hydrogen iodine
HT	hydrogen-tritium gas
HTO	tritiated water
I ₂	molecular iodine
ICDF	Idaho CERCLA Disposal Facility
T ₂	tritium gas

Table 3-11. Radionuclide-specific diffusion coefficients in air and water for EMSOFT diffusion simulation for the air pathway. Diffusion coefficients were based on a temperature of 15°C (60°F).

Chemical Form	Diffusion Coefficient (cm ² /s)	Reference
CO ₂ (D _{air})	0.153	EPA (2010)
HT, T ₂ (D _{air})	0.794	EPA (2010)
I ₂ (D _{air})	0.0871	EPA (2010)
CO ₂ (D _{water})	1.55E-05	EPA (2010)
HT, T ₂ (D _{water})	3.52E-05	EPA (2010)
I ₂ (D _{water})	9.06E-06	EPA (2010)

CO ₂	carbon dioxide
HT	hydrogen-tritium gas
I ₂	molecular iodine
T ₂	tritium gas

- I-129 – Sander (2010) provides a value for I₂ between 1.1 and 3.3 mol/L-atm. However, these are at ideal conditions for the formation of I₂, and Denham, Kaplin, and Yeager (2009) shows that I₂ is unlikely to be stable in pH conditions of greater than about 4 (see Figure 6, page 24 of Denham, Kaplin, and Yeager 2009). Since this acidic condition is not evident in the ICDF Landfill, the formation of I₂ is not expected; instead, HI is to be the dominant iodine specie under the slightly basic conditions in the ICDF. The inverse Henry's law constants for HI calculated by Denham (2010) are many orders of magnitude higher than the Sander (2010) value for I₂; this essentially eliminates iodine exposure via the atmospheric pathway because very little iodine will exist in the vapor phase. However, for ICDF atmospheric dose calculations, I₂ was conservatively assumed to be the dominant species, and an inverse Henry's Law constant of 1.1 mol/L-atm was used. The Denham, Kaplin, and Yeager (2009) calculations indicate that I₂ will not exist in significant quantities in the ICDF; therefore, this assessment can be considered biased high.
- H-3 – For tritium dose calculations, HT and T₂ were assumed to be the dominant tritium specie. HT and T₂ have lower inverse Henry's law constants and higher air diffusion coefficients compared to HTO, resulting in more vapor-phase partitioning and rapid transport via diffusion in pore air to the surface.

Conversion of the dimensioned Henry's Law constant to the dimensionless quantity is given by:

$$K_H = \frac{1}{H \times \frac{1 \text{ kg}}{\text{L}} \times 0.082 \frac{\text{atm} \cdot \text{L}}{\text{mol} \cdot \text{K}} \times 288.5^\circ \text{K}} \quad (3-59)$$

Where

H	=	dimensioned inverse Henry's Law constant (mol/kg-atm)
$0.082 \text{ atm} \cdot \text{L} / \text{mol} \cdot \text{K}$	=	universal gas constant
288.5°K	=	assumed temperature in the ICDF.

If the dimensioned inverse Henry's law constant was in units of mol/L-atm, then the density of water (1 kg/L) is omitted in Equation 3-59. All calculations and parameter values associated with the atmospheric pathways analysis are documented in EDF-9917.

3.4 Radon Analysis

The PA waste inventory is not a significant radon source. Radium-226 concentrations (1.6 pCi/g) in the ICDF Landfill are near background concentrations found in INL Site soils (0.75 to 1.4 pCi/g) assuming secular equilibrium with Th-230 (Rood, Harris, and White 1996). However, because the performance objectives include a radon flux limit or a maximum concentration in air at the point of compliance 1,000 years after closure (40 CFR 61), a radon analysis was performed (EDF-9907).

The RESRAD computer code (Yu et al. 2001) was used to estimate the surface radon flux because it includes a radon pathway suitable for buried waste and has been used widely by DOE for deriving limits for radionuclides in soil. RESRAD keeps track of ingrowth of progeny, includes the progeny in the dose calculations, and meets the software quality assurance requirements for analysis at the INL Site. The input data used to estimate the radon flux included site-specific data shown in Table 3-12 (inventory taken from Table 2-6). All other input parameters were RESRAD default values. No credit was taken for any engineered features that may be used in the final cover. All calculations and parameter values associated with the radon analysis are documented in EDF-9907.

Table 3-12. Data used in the radon flux calculations.

Parameter	Value	Comments
Radon diffusion coefficient	2.0E-06 m ² /s	RESRAD default value
Rn-222 emanation coefficient	0.25	RESRAD default value
Total porosity of cover alluvium	0.5	DOE-ID (2006d)
Total porosity of waste zone	0.4	RESRAD default value
Volumetric water content of cover alluvium	0.28	DOE-ID (2006d)
Volumetric water content of waste zone	0.28	DOE-ID (2006d)
Bulk density of cover alluvium ^a	1.5 g/cm ³	RESRAD default value
Bulk density of waste zone ^b	1.95 g/cm ³	EDF-ER-275
U-234 concentration	1.1 pCi/g	Based on isotope total inventory (6.91E-01 Ci), waste bulk density of 1.5E+06 g/m ³ , and waste volume of 322,816 m ³
U-238 concentration	0.79 pCi/g	Same comment as above (4.97E-01 Ci)
Ra-226 concentration	1.6 pCi/g	Same comment as above (1.01E+00 Ci)
Th-230 concentration	0.17 pCi/g	Same comment as above (1.04E-01 Ci)
Waste area	31,040 m ²	DOE-ID (2003a) (160 m × 194 m)
Waste thickness	10.4 m	DOE-ID (2003a)
Cover thickness	1 m	DOE-ID (2003c)
a. No credit is taken for any engineered features that may be used in the final cover. The cover bulk density is based on the RESRAD default value.		
b. Bulk density of the compacted waste zone alluvium.		

3.5 Biotic Pathways

The biotic transport and uptake of radionuclides have been studied rather extensively at the INL Site. Groves and Keller (1983) identified 10 species of small mammals nesting on or near the RWMC. Four species were the most numerous: deer mice (*Peromyscus maniculatus*), montane voles (*Microtus montanus*), Ord's kangaroo rats (*Dipodomys ordii*), and Townsend's ground squirrels (*Spermophilus townsendii*). Reynolds and Wakkinen (1987) studied the burrow depths of these four species in undisturbed soils. None of the deer mice burrows extended past 60 cm (20 in.), none of the montane vole burrows extended past 70 cm (30 in.), and none of the Ord's kangaroo rat burrows extended past 100 cm (40 in.). The maximum reported burrow depths for undisturbed soil was 138 cm (54.3 in.) for the Townsend's ground squirrel.

Harvester ants (*Pogonomyrmex salinus*) also were considered. Harvester ants burrow deeper than the small mammals. Blom, Clark, and Johnson (1991) state that harvester ants have been found as deep as 2.7 m (9 ft) in Wyoming and at the Hanford Site.

Reynolds and Fraley (1989) studied plant root profiles at the INL Site and determined the maximum rooting depth for big sagebrush (*Artemisia tridentata*) was 225 cm (88.6 in.), green rabbitbrush (*Chrysothamnus viscidiflorus*) was 190 cm (75 in.), and Great Basin wild rye (*Leymus cinereus*) was 200 cm (80 in.).

Biointrusion at the ICDF Landfill is not expected because of the depth (7.5 m) of the proposed final cover for the landfill and the incorporation of a biobarrier component (EDF-ER-279). However, for completeness of the PA, a biotic pathways analysis was performed. Evidence suggests that harvester ants burrow deeper than the small mammals, are active at the INL Site, and are probably the limiting case for fauna. Because big sagebrush is the dominant plant species and has the deepest root penetration, estimates of biointrusion for flora are based on the big sagebrush data. For the biotic pathways analysis, only 2 m (6.5 ft) of final cover is assumed to remain during the 1,000-year compliance period. However, a thickness of 2 m (6.5 ft) provides a basis to conduct some screening calculations for the depths of plant roots and burrows that are considered in the analysis. The biotic intrusion assessment includes consideration of the total activity that could be brought to the land surface as a result of biointrusion. This is considered a conservative screening-level calculation for the compliance period (100 through 1,000 years after closure).

Biointrusion by plant roots and harvester ants is assessed as a mechanism to move radioactive material to the land surface. Big sagebrush roots and harvester ants are assumed to penetrate to depths of 2.25 and 2.7 m (7.4 and 9 ft), respectively, during the compliance period and contact the disposed waste (under 2 m [6.5 ft] of cover). This will provide a biotic pathway for radionuclide migration to the surface. The contamination was assumed to remain on the surface where a hypothetical resident is exposed through the all-pathways scenario. While this is a conservative assumption (assumes no dispersion and assumes receptor is located directly on the disposal facility), it provides an upper bound on the material that a receptor could be exposed to. The basis for determining the amount of activity brought to the surface via biotic intrusion is described below. All calculations and parameter values associated with this biotic pathways analysis are documented in EDF-9913.

3.5.1 Fauna

To account for the burrowing of harvester ants into the waste, a model (Kennedy, Cadwell, and McKenzie 1985) was used to determine the total activity of contaminated material brought to the surface:

$$\text{Activity on the surface (Ci/m}^2\text{)} = \text{waste concentration (Ci/m}^3\text{)} \times \text{burrow volume (m}^3\text{/colony)} \times \text{fraction of burrow in waste} \times \text{colony density (colonies/m}^2\text{)}. \quad (3-60)$$

The model is based on harvester ants burrowing into the waste and bringing contaminated material to the surface. The volume of contaminated material that a single harvester ant colony brings to the surface is calculated using the burrow volume and the fraction of the burrow that was deep enough to encounter the waste. The waste is assumed to be 2 m (6.5 ft) below the surface and 5% of the burrow volume is estimated to encounter the waste to a depth of 2.7 m (9 ft) (Kennedy, Cadwell, and McKenzie 1985). An average burrow volume per colony is assumed to be 0.002 m³ (Kennedy, Cadwell, and McKenzie 1985). Based on data for harvester ant colony densities in big sagebrush (*Artemisia tridentata*) communities on the INL Site (Blom, Clark, and Johnson 1991), a density of 35.6 colonies/10,000 m² was used.

3.5.2 Flora

To estimate the amount of radioactive material that plant roots could bring to the surface, a model similar that used in GENII (Napier et al. 1988) and Kennedy, Cadwell, and McKenzie (1985) was used. First, the dominant plant species (big sagebrush) in terms of absolute cover was determined. Anderson and Inouye (1988) found that big sagebrush has an absolute cover of 13% at the INL Site. The aboveground biomass of big sagebrush on the INL Site is estimated to be 46 g/m² (Fraley 1978). Five percent of the plant roots were estimated to encounter the waste at depths greater than 2 m (6.5 ft) below the surface (Kennedy, Cadwell, and McKenzie 1985). The activity/m² brought to the surface by the plant roots was estimated by multiplying the radionuclide concentration in the waste, the inverse of the soil bulk density, the fraction of the roots that can encounter the waste, the concentration ratio, and the biomass:

$$\begin{aligned} \text{Activity on the surface (Ci/m}^2\text{)} = & \text{waste concentration (Ci/m}^3\text{)} \times 1/\text{soil bulk density} \\ & (\text{g/m}^3) \times \text{fraction of roots in waste} \times \text{CR (Ci/g} \\ & \text{plants/Ci/g waste)} \times \text{biomass (g/m}^2\text{)}. \end{aligned} \quad (3-61)$$

Dry weight concentration ratios for pasture from Baes et al. (1984) were used. The total activity brought to the surface through plant uptake is then available for resuspension, atmospheric transport, and deposition followed by direct exposure through external, inhalation, soil ingestion, and ingestion of contaminated food stuff (milk, beef, and plant).

For the purposes of this biotic intrusion screening analysis, the total activity brought to the surface by harvester ants and plant roots was conservatively assumed to be contacted by a resident through the chronic residential scenario used for the intruder analysis (via the following pathways: external, inhalation, soil ingestion, ingestion of contaminated plant, meat, and milk – see Section 5). While this is a conservative assumption (assumes no dispersion and assumes receptor is located on the disposal facility not 100 m from the facility), it puts an upper bound on the material to which a receptor could be exposed.

The RESRAD computer code (Yu et al. 2001) was used to calculate the dose per unit concentration in the source at the time of exposure (including radioactive decay and ingrowth of progeny, as applicable), or dose-to-source ratios (DSRs) for the chronic resident scenario (see Section 5.2). The dose to the hypothetical resident was calculated as follows:

$$\text{Dose} = \sum_i (C_i * \text{DSR}_i) \quad (3-62)$$

Where

- $Dose$ = dose to receptor (mrem/year)
- C_i = waste activity concentration of radionuclide i (pCi/g); assuming soil bulk density of 1.5 g/cm³ and contaminated soil depth on surface of 0.61 m
- DSR_i = dose-to-source ratio in mrem/year per pCi/g for the chronic intruder scenario (see Section 5).

3.6 Dose Analysis

The methodology used to calculate the all-pathways dose is based on the methodology presented in NRC (1977) and Peterson (1983). The all-pathways scenario assumes a receptor consumes (1) contaminated groundwater, (2) leafy vegetables and produce that were irrigated with contaminated groundwater, and (3) milk and meat from animals that consume contaminated water and pasture grass

irrigated with contaminated groundwater. The receptor is located at the INL Site southern boundary during the institutional control period and 100 m downgradient from the disposal facility during the compliance period. Tables 3-13 and 3-14 contain the parameter values used in the all-pathways dose calculation followed by equations used to calculate the dose from each exposure pathway. Values listed in Table 3-15 are only for the nuclides that were deemed significant through the screening process (see Section 2.4).

Table 3-13. Element-independent parameter values used in the all-pathways dose calculation.

Parameter	Symbol	Units	Value	Reference
Water ingestion rate (human)	U	L/yr	7.30E+02	EPA (1989c)
Water ingestion rate (beef cow)	Q _W	L/d	5.00E+01	NRC (1977)
Water ingestion rate (milk cow)	Q _W	L/d	6.00E+01	NRC (1977)
Feed consumption, beef cow (dry weight)	Q _F	kg/d	1.20E+01	NCRP (1984)
Feed consumption, milk cow (dry weight)	Q _F	kg/d	1.60E+01	NCRP (1984)
Meat consumption	U _B	kg/yr	8.50E+01	Rupp (1980)
Milk consumption	U _M	L/yr	1.12E+02	Rupp (1980)
Produce consumption	U _P	kg/yr	1.76E+02	Rupp (1980)
Leafy vegetable consumption	U _{LV}	kg/yr	1.80E+01	Rupp (1980)
Irrigation rate	I	L/m ² -d	8.47E+00	Site-specific
Washoff constant	K	1/mm	2.50E-02	Peterson (1983)
Yield, leafy vegetables (wet weight)	R/Y _v	kg/m ²	7.60E-02	Calculated from Baes and Orton (1979) and Baes et al. (1984)
Yield, produce (wet weight)	R/Y _v	kg/m ²	3.20E-02	Calculated from Baes and Orton (1979) and Baes et al. (1984)
Yield, pasture grass (dry weight)	R/Y _v	kg/m ²	2.00E+00	Calculated from Baes and Orton (1979) and Baes et al. (1984)
Areal density (dry weight)	P	kg/m ²	2.25E+02	DOE-ID (1987)
Irrigation time	T _i	d	9.00E+01	Site-specific
Buildup time	t _b	d	3.65E+02	Site-specific
Fraction of year irrigated	f _i	—	2.50E-01	Site-specific
Translocation factor (leafy veg)	T	—	1.00E+00	Ng, Colsher, and Thompson (1979)
Translocation factor (produce)	T	—	1.00E-01	Ng, Colsher, and Thompson (1979)
Washing factor (leafy veg.)	DF	—	5.00E-01	Ng, Colsher, and Thompson (1979)
Washing factor (produce)	DF	—	1.00E+00	Ng, Colsher, and Thompson (1979)
Fraction of produce produced locally	FV	—	7.00E-01	EPA (1989c)
Fraction of beef produced locally	FB	—	4.42E-01	EPA (1989c)
Fraction of milk produced locally	FM	—	3.99E-01	EPA (1989c)

Table 3-14. Element-specific parameter values used in the all-pathways dose calculation.^a

Element	Meat Transfer Coefficient (d/kg)	Milk Transfer Coefficient (d/L)	Concentration Ratio (wet weight)	Concentration Ratio ^b (dry weight)
Actinium	2.50E-05	2.00E-05	1.50E-04	3.50E-03
Carbon	NA	NA	NA	NA
Chlorine	8.00E-02	1.50E-02	3.00E+01	7.00E+01
Hydrogen	NA	NA	NA	NA
Iodine	7.00E-03	1.00E-02	2.10E-02	1.50E-01
Lead	3.00E-04	2.50E-04	3.90E-03	4.50E-02
Neptunium	5.50E-05	5.00E-06	4.30E-03	1.00E-01
Plutonium	5.00E-07	1.00E-07	1.90E-05	4.50E-04
Protactinium	1.00E-05	5.00E-06	1.10E-04	2.50E-03
Radium	2.50E-04	4.50E-04	6.40E-04	1.50E-02
Technetium	8.50E-03	1.00E-02	6.40E-01	9.50E+00
Thorium	6.00E-06	5.00E-06	3.60E-05	8.50E-04
Uranium	2.00E-04	6.00E-04	1.70E-03	8.50E-03

a. All values from Baes et al. (1984).

b. Represents nonfruit portion of plant for use with animal feed, not appropriate for human consumption.

NA not applicable - specific activity model used.

Table 3-15. Nuclide-specific all-pathways dose per unit concentration.

Nuclide	Progeny	All-Pathways Dose/Unit Concentration (rem-m ³ /Ci-year) ^a
C-14		5.55E+03
Cl-36		1.24E+05
H-3		1.16E+02
I-129		4.54E+05
Np-237		3.05E+05
	U-233	1.54E+05
	Th-229	1.82E+06
Pu-239		7.10E+05
	U-235	1.41E+05
	Pa-231	1.36E+06
	Ac-227	3.01E+07
Pu-240		7.10E+05
	U-236	1.40E+05
	Th-232	6.54E+05
	Ra-228	2.07E+06
	Th-228	4.04E+05
Tc-99		3.37E+03
U-233		1.54E+05
	Th-229	1.82E+06

Table 3-15. (continued).

Nuclide	Progeny	All-Pathways Dose/Unit Concentration (rem-m ³ /Ci-year) ^a
U-234		1.46E+05
	Th-230	6.05E+05
	Ra-226	8.26E+05
	Pb-210	7.35E+07
U-235		1.41E+05
	Pa-231	1.36E+06
	Ac-227	3.01E+07
U-238		1.45E+05
	U-234	1.46E+05
	Th-230	6.05E+05
	Ra-226	8.26E+05
	Pb-210	7.35E+07

a. Effective dose coefficients from EPA (2002) for 50-year commitment period

The dose from human consumption of drinking water is calculated using

$$D = C_{GW} \times U_W \times DCF \quad (3-63)$$

Where

- D = dose (cumulative EDE) from 1 year's consumption of contaminated media, in this case groundwater (rem/year)
- C_{GW} = radionuclide concentration in groundwater (Ci/L)
- U_W = human consumption rate of water (L/year)
- DCF = ingestion dose conversion factor (rem/Ci).

The beef and dairy exposure route assumes cattle drink contaminated stock water and the receptor, in turn, consumes the contaminated beef and milk from the cattle. Meat and milk are treated separately. The dose is calculated using

Meat:

$$D = C_{GW} \times Q_W \times F_f \times U_B \times DCF \times FB \quad (3-64)$$

Milk:

$$D = C_{GW} \times Q_W \times F_m \times U_M \times DCF \times FM \quad (3-65)$$

Where

- Q_W = consumption rate of water by beef or milk cattle (L/d)
- F_f = meat transfer coefficient (d/kg)
- U_B = human consumption rate of meat (kg/year)

- FB = fraction of beef produced locally (unitless)
 F_m = milk transfer coefficient (d/L)
 U_M = human consumption rate of milk (L/year)
 FM = fraction of milk produced locally (unitless).

The dose to humans from ingestion of contaminated leafy vegetables and produce is calculated assuming two contamination routes: (1) direct deposition of contaminated irrigation water on plants and (2) deposition of contaminated irrigation water on soil followed by root uptake by plants. Leafy vegetables and produce are treated separately. The dose through direct deposition is calculated using

Leafy Vegetables – Direct Deposition:

$$D = \frac{C_{GW} \times I \times r}{Y_v} \times \frac{1 - e^{-(\lambda_r + KI)t_i}}{\lambda_r + KI} \times U_{LV} \times DCF \times DF \times T \times FV \quad (3-66)$$

Produce – Direct Deposition:

$$D = \frac{C_{GW} \times I \times r}{Y_v} \times \frac{1 - e^{-(\lambda_r + KI)t_i}}{\lambda_r + KI} \times U_P \times DCF \times DF \times T \times FV \quad (3-67)$$

Where

- I = irrigation rate (L/m²-d)
 r = interception fraction (unitless)
 Y_v = agricultural yield (kg/m², wet weight)
 λ_r = radioactive decay constant (d⁻¹)
 k = washoff constant (mm⁻¹)
 t_i = irrigation time (d)
 U_{LV} = human consumption rate of leafy vegetables (kg/year)
 DF = fraction of activity remaining after preparation and processing (unitless)
 T = translocation factor (unitless)
 FV = fraction of leafy vegetables and produce produced locally (unitless)
 U_P = human consumption rate of produce (kg/year).

The product kI is also known as the weathering rate constant because of washoff (Peterson 1983). This quantity describes the rate at which material is removed from plant surfaces by water and is analogous to λ_e , the weathering rate constant used in nonirrigation situations. The value of kI is calculated using

$$kI = 0.025 \text{ mm}^{-1} \times \frac{8.47 \text{ L}}{\text{m}^2 \cdot \text{d}} \times \frac{1 \text{ m}^3}{1,000 \text{ L}} \times \frac{1,000 \text{ mm}}{1 \text{ m}} = 0.212/\text{d} \quad (3-68)$$

The dose from deposition of contaminated irrigation water on soil followed by root uptake by plants and human consumption of plants is calculated using the following equations. Credit is not taken for leaching of radionuclides from the root zone of plants.

Leafy Vegetables – Root Uptake:

$$D = \frac{C_{GW} \times I \times f_I}{P} \times \frac{1 - e^{-\lambda_r t_{bi}}}{\lambda_r + kI} \times CR \times U_{LV} \times DCF \times FV \quad (3-69)$$

Produce – Root Uptake:

$$D = \frac{C_{GW} \times I \times f_I}{P} \times \frac{1 - e^{-\lambda_r t_{bi}}}{\lambda_r + kI} \times CR \times U_P \times DCF \times FV \quad (3-70)$$

Where

- f_I = fraction of the year that crops are irrigated (unitless)
- P = areal density (kg [dry weight soil]/m²)
- CR = concentration ratio (pCi/kg [wet weight plant]/pCi/kg [dry weight soil])
- t_b = build-up time for radionuclides in soil (d).

The dose to humans from ingestion of contaminated animal products is also calculated assuming two contamination routes: (1) direct deposition and (2) root uptake; meat and milk are treated separately. All food (pasture or stored feed) eaten by cattle is assumed to be contaminated. The dose through direct deposition is calculated using

Meat – Direct Deposition:

$$D = \frac{C_{GW} \times I \times r}{Y_v} \times \frac{1 - e^{-(\lambda_r + KI)t_i}}{\lambda_r + kI} \times Q_F \times F_f \times U_B \times \frac{10^{-6} \mu Ci}{pCi} \times DCF \times \frac{1,000 mrem}{rem} \times FB \quad (3-71)$$

Milk – Direct Deposition:

$$D = \frac{C_{GW} \times I \times r}{Y_v} \times \frac{1 - e^{-(\lambda_r + KI)t_i}}{\lambda_r + kI} \times Q_F \times F_m \times U_M \times DCF \times FM \quad (3-72)$$

Where

- Y_v = agricultural yield (kg/m², dry weight)
- Q_F = animal consumption rate of pasture and feed (kg [dry]/d).

The dose through deposition on soil followed by root uptake is calculated using the following equations. As with produce and leafy vegetables, credit is not taken for leaching of radionuclides from the root zone of plants.

Meat – Root Uptake:

$$D = \frac{C_{GW} \times I \times f_I}{P} \times \frac{1 - e^{-\lambda_r t_{bi}}}{\lambda_r} \times CR \times Q_F \times F_f \times U_B \times DCF \times FB \quad (3-73)$$

Milk – Root Uptake:

$$D = \frac{C_{GW} \times I \times f_I}{P} \times \frac{1 - e^{-\lambda_r t_{bi}}}{\lambda_r} \times CR \times Q_F \times F_M \times U_M \times DCF \times FM \quad (3-74)$$

Where

CR = concentration ratio (pCi/kg [dry weight plant]/pCi/kg [dry weight soil]).

Note that the term CR in Equations 3-73 and 3-74 represents the concentration ratio for forage in dry weight. Dry-weight-based CR s are needed because animal consumption rates are based on dry weight of forage. Secondary and indirect pathways, such as inhalation of contaminated irrigation water, inhalation of contaminated dust, or external exposure from radionuclides deposited on the soil, were omitted from this scenario. These pathways were either not viewed as credible (e.g., a farmer standing under a center pivot irrigator while it was running and inhaling contaminated irrigation water) or would contribute relatively minor amounts when compared to direct pathways such as direct ingestion of contaminated water.

All-pathways doses were calculated for a unit groundwater concentration (1 Ci/L). These values could then be scaled to the actual groundwater concentration calculated for each radionuclide. Therefore, the all-pathways dose was calculated by multiplying the groundwater concentration in Ci/m³ by the all-pathways dose for a unit concentration (rem-m³/Ci-year), which yields the annual dose at the given time:

$$D_{ap} = DU_{ap} \times C \quad (3-75)$$

Where

D_{ap} = the all-pathways dose (rem/year)
 DU_{ap} = the all-pathways dose for a unit concentration (rem-m³/Ci-year)
 C = the groundwater concentration (Ci/m³).

For the radionuclides of concern, the all-pathways doses for unit concentrations are shown in Table 3-15.

For the drinking water scenario, the receptor is assumed to consume 2 L of water per day for 365 days per year from wells located at the INL Site southern boundary and 100 m downgradient from ICDF. Drinking water doses and concentrations are computed using the federal MCLs and Idaho Ground Water Quality Standards. Federal MCLs and Idaho Ground Water Quality Standards for beta-gamma-emitting radionuclides are based on the drinking water scenario given above and a 4-mrem/year dose equivalent for federal MCLs and 4-mrem/year EDE for Idaho Ground Water Quality Standards. Both federal MCLs and Idaho Ground Water Quality Standards have specific concentration limits for H-3 and Sr-90 of 20,000 pCi/L and 8 pCi/L, respectively; gross alpha-emitting radionuclide limit of 15 pCi/L (excluding radon and uranium); combined Ra-226/Ra-228 concentration limit of 5 pCi/L; and total uranium mass concentration of 30 µg/L. During the institutional control period (2018–2118), computed doses and concentrations in groundwater are compared to the federal MCLs at the INL Site southern boundary and compared to Idaho Ground Water Quality Standards at the 100-m receptor. During the compliance period (2119–3018), computed doses and concentrations in groundwater are compared to the federal MCLs at the 100-m receptor.

4. RESULTS OF ANALYSIS

This section describes the results of the analysis described in Section 3 and discusses the (1) source term, (2) environmental transport of radionuclides via the groundwater pathway, (3) radon analysis, (4) biotic pathways, (5) groundwater pathway dose analysis and assessment of groundwater protection, and (6) sensitivity and uncertainty analysis. The results of the analyses conducted for each part of the modeling effort are summarized independently, leading to the discussion of the all-pathways dose calculations presented in Section 4.5. Numerous figures illustrate intermediate results to show the influence of each analysis step on the overall result. Results are provided for three different timeframes: institutional control following facility closure (2018–2118), post-institutional control compliance period per DOE M 435.1-1 Chg 1 (2119–3018), and post-compliance period (up to 100,000 years from closure). Results are provided for the institutional and compliance period for a receptor 100 m downgradient from the ICDF Landfill. It is important to note that although some results are presented for illustrative purposes, no residential receptor could live 100 m from the ICDF Landfill during the institutional control period. Thus, doses calculated for that receptor are for assessment purposes only. Likewise, intermediate results and doses are projected out 100,000 years to identify peaks for some radionuclides that migrate slowly through the environment. These results are given for completeness, but these are not part of the compliance determination.

4.1 Source Term

As explained in Section 3.2.1, the source term used in this analysis is made up of several components, and the modeling process is somewhat different for radionuclides in miscellaneous waste and radionuclides in activated metal components. The different components of the source term and illustrative results are presented below.

Radionuclides in miscellaneous waste were modeled as an initial condition. That is, the waste is instantaneously placed in the ICDF Landfill in the year 2018 and infiltrating water is allowed to leach radionuclides from the landfill and release them to the subsurface. In reality, the waste is placed in the facility over a 15-year period (2003–2018). However, the leachate collection system collects all infiltrating water that seeps through the waste, which is collected in the drainage layer and removed. Therefore, it was assumed no releases occurred before the closure of the facility. It is also assumed that the leachate collection system operates for a period of time to allow moisture in the waste to drain before the start of the simulation. Sensitivity cases presented in a later section evaluated the impacts of a failure in the leachate collection system and the clay liner. Activated metal waste forms were assumed to start releasing radionuclides to the waste soil at the start of the simulation.

For the MCM simulation, the simulation starts with the placement of the cap. The initial moisture profile in the subsurface (below the bentonite clay layer) is based on a steady-state 18-cm/year infiltration rate in the INTEC area followed by a 15-year period under the infiltration shadow during active disposal where water drains from the vadose zone and virtually no infiltration occurs. Initial moisture in the waste is based on 12-cm/year infiltration (which is collected in the drainage layer and removed via the leachate collection system) for 15 years during operations (2003–2018) followed by 5 years of 0.01-cm/year infiltration while the leachate collection system is still operating and the cap is in place. During this period, no leachate moves to the vadose zone but the moisture content in the waste will decrease. The bentonite clay layer is assumed to be near saturation at the start of the simulation. After the end of operations, the engineered cover placed over the disposal cell limits infiltration to 0.01 cm/year and water is assumed to move through the waste, through clay layer, and into the vadose zone for migration to the aquifer. The cover is assumed to limit infiltration to 0.01 cm/year for 500 years. After 500 years, the cover degrades and is fully degraded 1,000 years after installation. Infiltration increases linearly from

500 years to 1,000 years. At 1,000 years, the infiltration through the degraded cover is equal to the background infiltration rate assumed for the INL Site in undisturbed soils of 1 cm/year.

Figure 4-1 shows the initial MCM moisture profile and the profile after 500 years in the ICDF Landfill and underlying vadose zone. Water fluxes as a function of time at various depths in the vadose zone are shown in Figure 4-2. Initially, water is draining from the vadose zone in response to the infiltration shadow imposed by the presence of the ICDF Landfill. By year 500, fluxes are near steady-state conditions throughout the vadose zone. By year 700, the moisture front in response to the cap failure penetrates down to 13 m, and, by 1,000 years, water flux is steady state throughout the vadose zone at the background infiltration rate of 1 cm/year.

The fission and activation product releases from the activated metals are illustrated in Figure 4-3 for a unit Ci inventory of each radionuclide. Releases decrease exponentially according to the corrosion rate constant and the radiological decay rate constant and are described by $F(t)$ in Figure 4-3.

Radionuclide fluxes from the ICDF Landfill are shown in Figure 4-4 for fission and activation products and Figure 4-5 for actinides. Fluxes were extracted from the bentonite clay layer that underlies the landfill. Fluxes show the response of the (1) drainage from the waste zone, (2) cap installation, and (3) cap failure. Activated metal releases are lower but persist for a longer time compared to releases from waste soil.

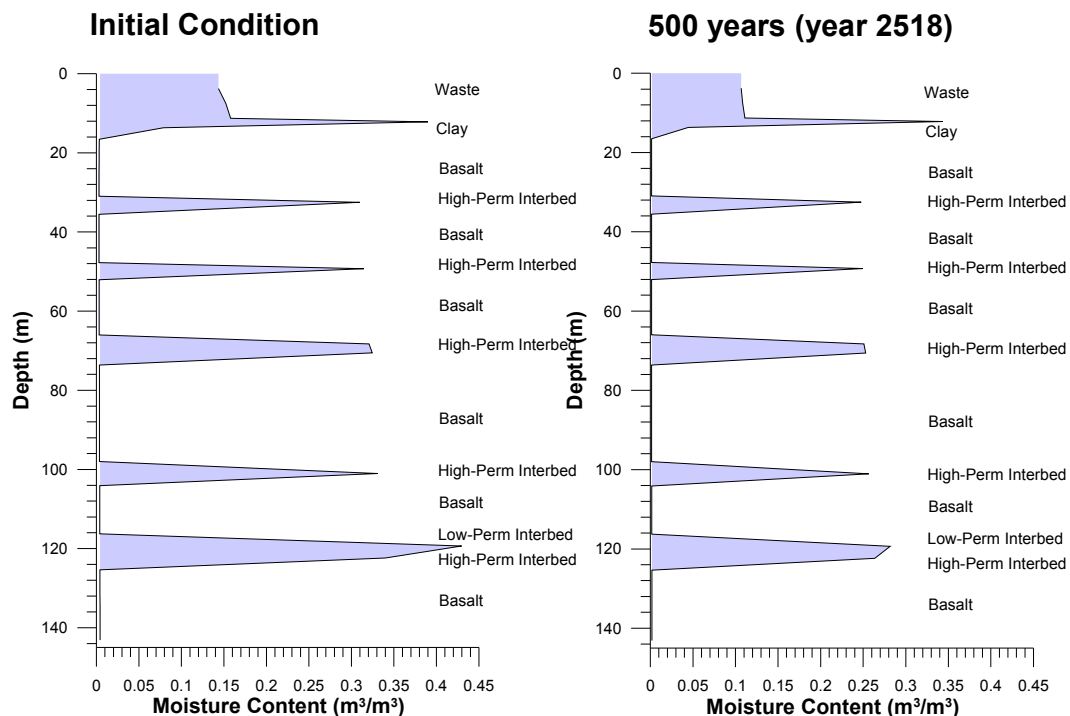


Figure 4-1. Moisture profile at the start of the simulation (year 2018, left graph) and 500 years later (year 2518, right graph). The profiles show the drying of the vadose zone in response to the placement of the cover.

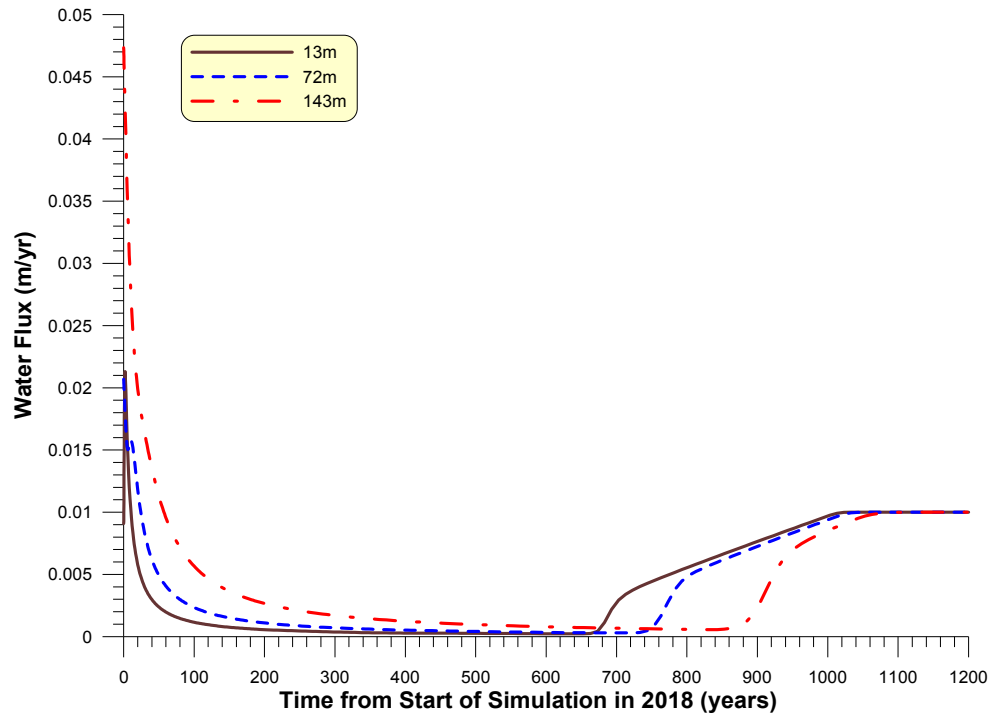


Figure 4-2. Downward water flux as a function of time at 13 m, 72 m, and 143 m (aquifer interface) below land surface.

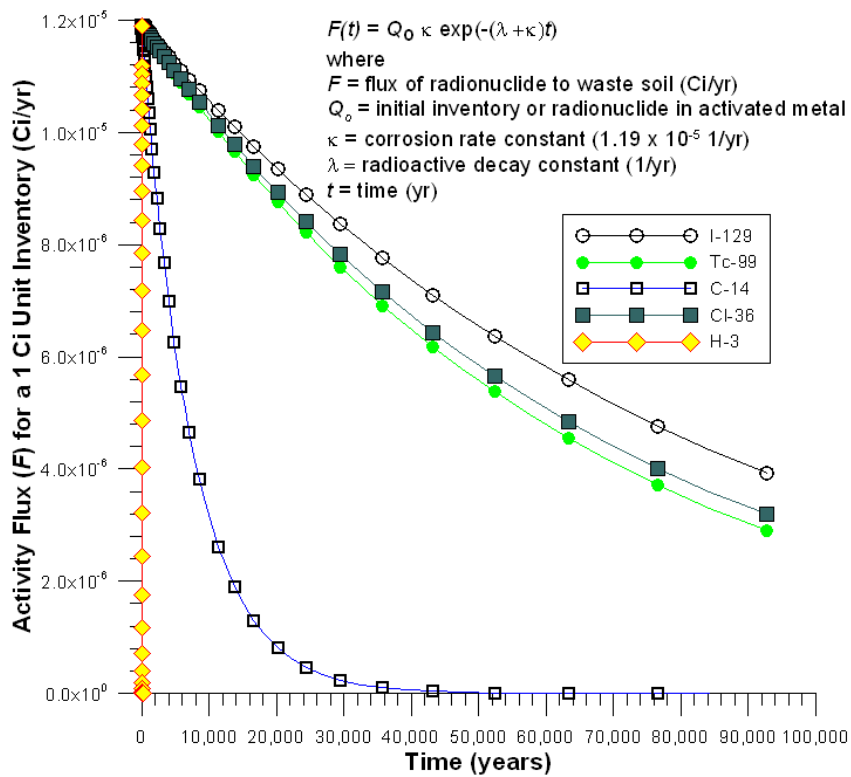


Figure 4-3. Fission and activation product releases from activated metals as a function of time for a unit Ci inventory. The actual release is the function $F(t)$ times the actual inventory.

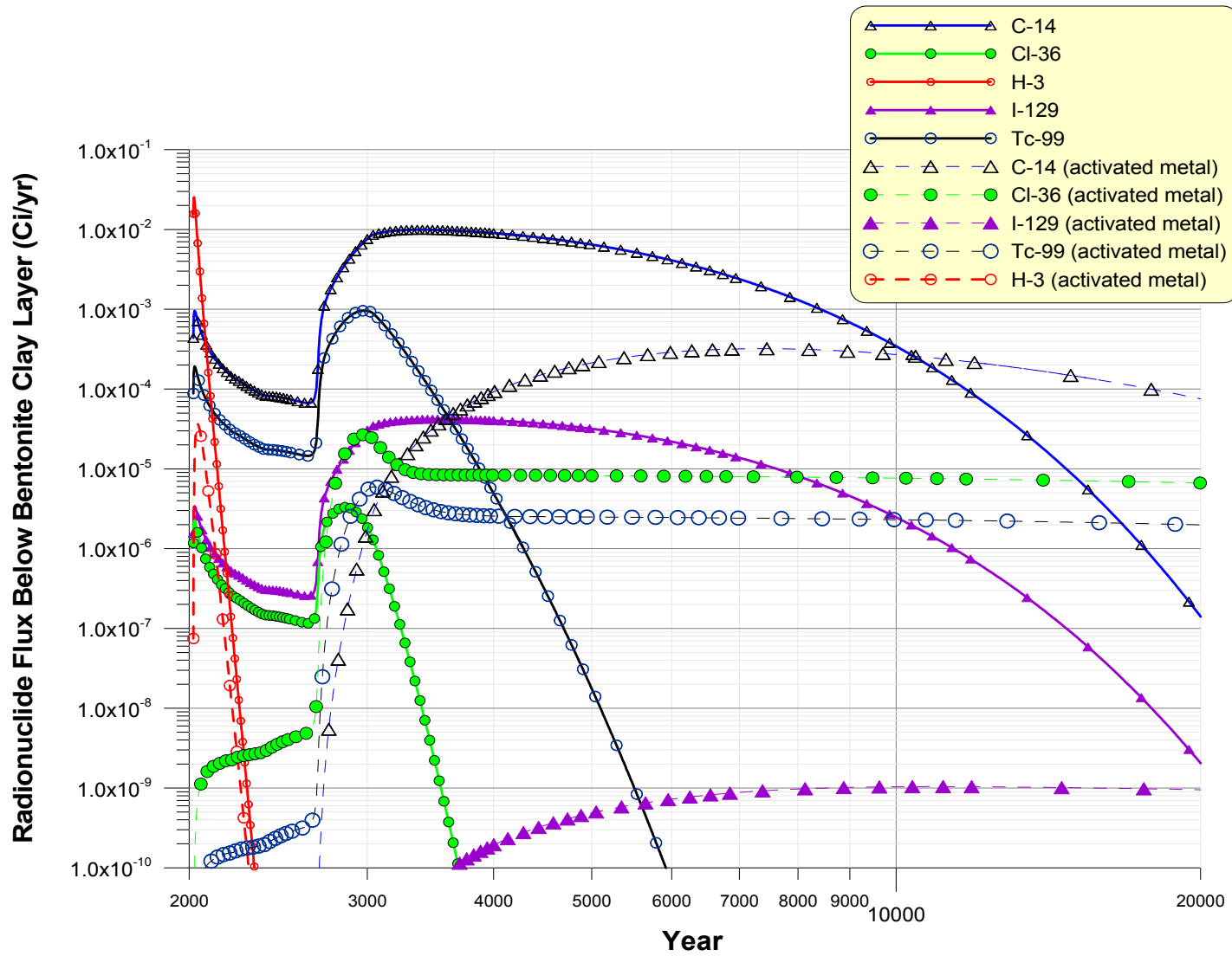


Figure 4-4. MCM-predicted radionuclide fluxes for fission and activation products from the base of the bentonite clay layer underlying the ICDF Landfill.

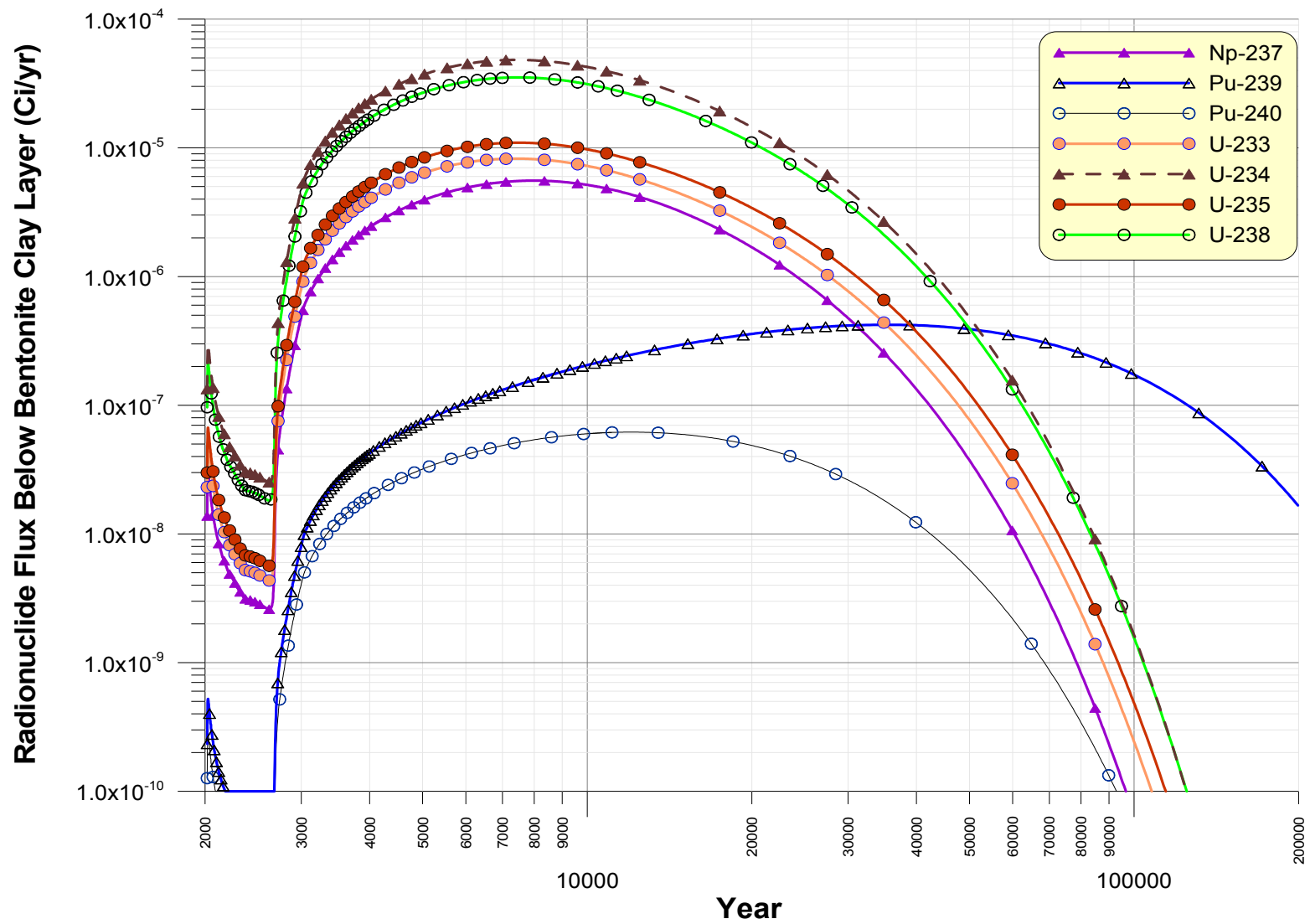


Figure 4-5. MCM-predicted radionuclide fluxes for actinides from the base of the bentonite clay layer underlying the ICDF Landfill.

4.2 Environmental Transport of Radionuclides for the Groundwater Pathway

This section summarizes the results of the groundwater pathway environmental transport of radionuclides after leaching from the source soils. The nuclide flux from the MCM vadose zone model to the aquifer is shown in Figure 4-6 for fission and activation products and Figure 4-7 for actinides. The fluxes for fission and activation products include those from waste soils and from activated metals. The long, relatively flat flux beyond 6,000 years for Tc-99 and Cl-36 represent releases from activated metals. A comparison of Figures 4-4 and 4-5 with Figures 4-6 and 4-7 shows some dispersion of the nuclides in the vadose zone as well as significant decay for many of the nuclides. Note, any fluxes below $1\text{E-}10$ Ci/year are assumed to be essentially zero.

The concentrations in the aquifer 100 m downgradient of the ICDF Landfill are shown in Figure 4-8 for fission and activation products and Figure 4-9 for actinides. A comparison of Figures 4-6 and 4-7 with Figures 4-8 and 4-9 shows that the relative aquifer concentrations are very consistent with the fluxes from the aquifer. During the institutional control period, the compliance point is the INL Site boundary because the INL will remain in control over the site. Concentrations are not shown at the site boundary because fluxes to the aquifer are either zero or minimal during this period.

The predicted maximum concentrations and time of maximum concentration are shown in Table 4-1. The table shows maximums for the institutional control period (2018–2118), the compliance period (2119–3018), and the post-compliance period (>3018). During the institutional control period, the receptor location is the INL Site boundary. During the compliance and the post-compliance periods, the receptor location is 100 m downgradient from the ICDF Landfill. During the institutional control period at the INL Site boundary, the predicted concentrations are all zero, as shown in Table 4-1. At 100 m downgradient of the ICDF Landfill, H-3 is the only radionuclide with a maximum concentration during the institutional control period ($1.4\text{E-}06$ pCi/L in year 2093, see Figure 4-8). As a result, during the compliance period, the maximum H-3 concentration is in year 2119 ($9.3\text{E-}07$ pCi/L). For all other radionuclides of interest, the maximum concentration during the compliance period is at the end of the compliance period (3018). All radionuclides but H-3 have predicted maximum concentrations during the post-compliance period.

4.3 Radon Pathways

As described in Section 3.4, the projected waste inventory is not a significant radon source. Radium-226 concentrations in the ICDF Landfill waste (1.6 pCi/g) are near background concentrations found in INL Site soils (0.75 to 1.4 pCi/g) assuming secular equilibrium with Th-230 (Rood, Harris, and White 1996).

The RESRAD code (Yu et al. 2001) was used to calculate the radon flux at the surface of the ICDF Landfill during the period of closure and institutional control (2018–2118) and for 1,000 years after closure. Results are shown in Table 4-2.

The peak radon flux associated with Ra-226 disposed of in the facility, within the 1,000-year compliance period, was estimated to be $0.6 \text{ pCi}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ at the time of facility closure. Note that the compliance point is at the landfill surface regardless of the timeframe. This flux is well below the 40 CFR 61, Subpart Q, standard of $20 \text{ pCi}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. See EDF-9907 for all calculations and results associated with the radon analysis.

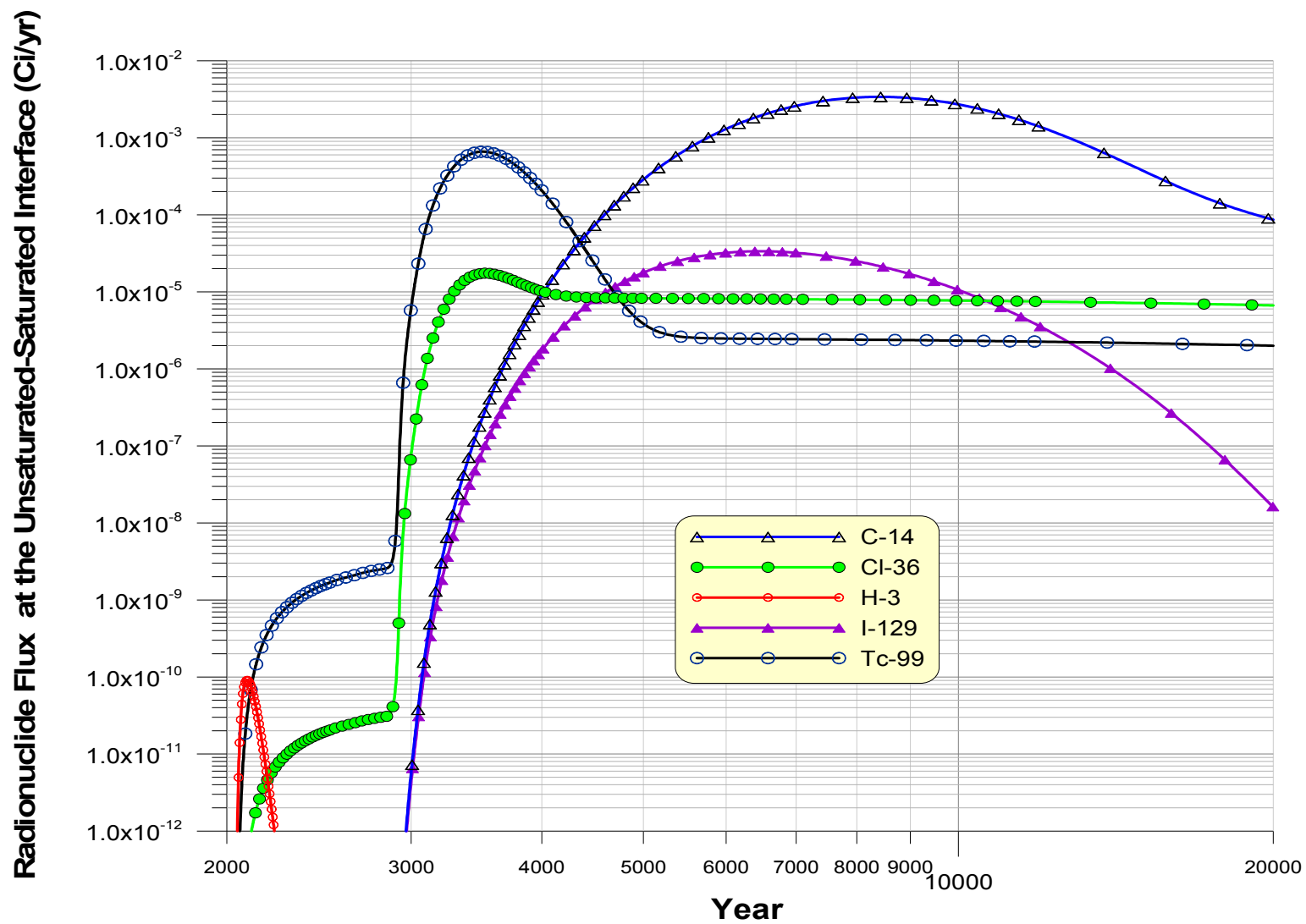


Figure 4-6. MCM-predicted radionuclide fluxes to the aquifer for mobile fission and activation products. Fluxes include both waste soil and activated metal sources.

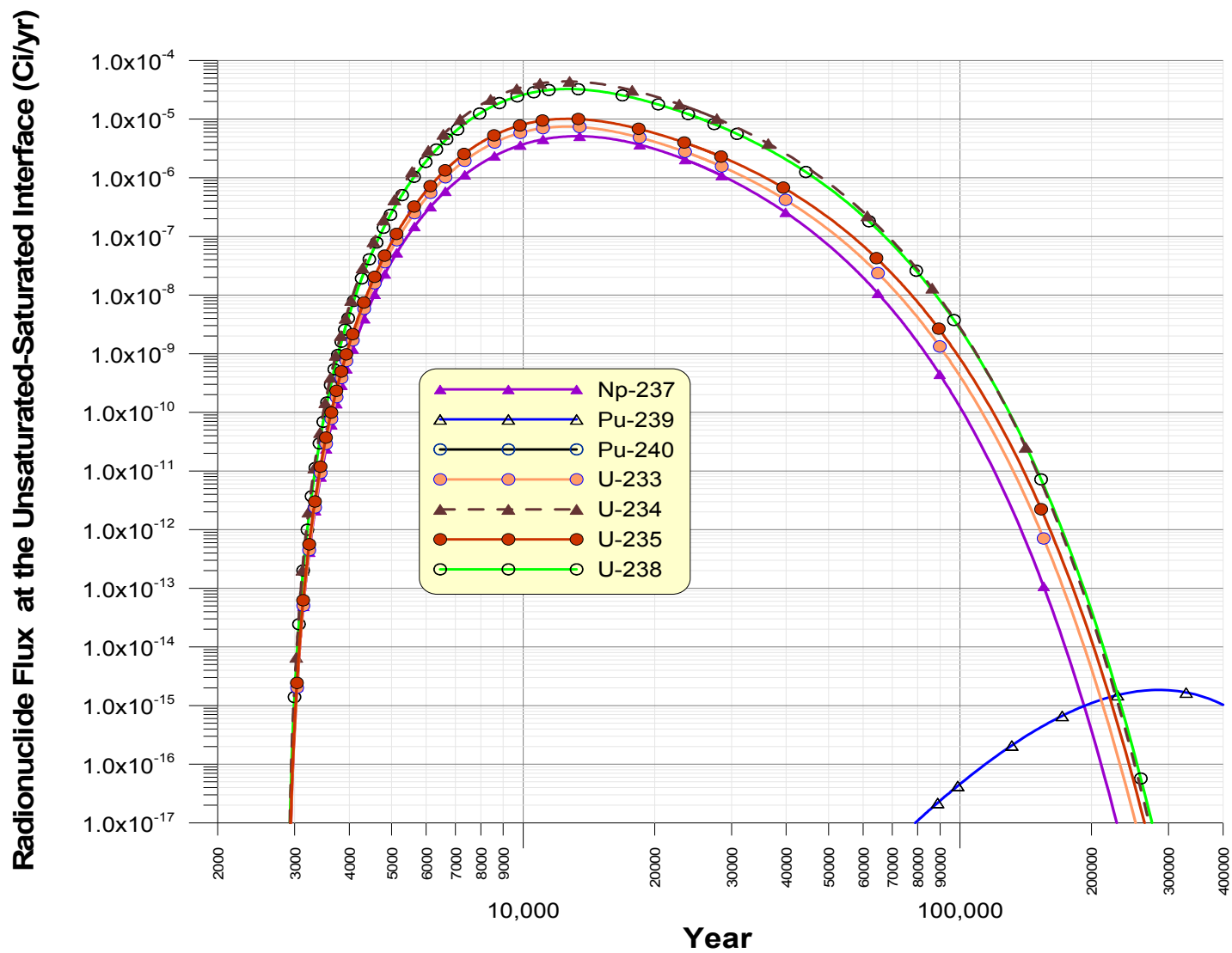


Figure 4-7. MCM-predicted radionuclide fluxes to the aquifer for actinides.

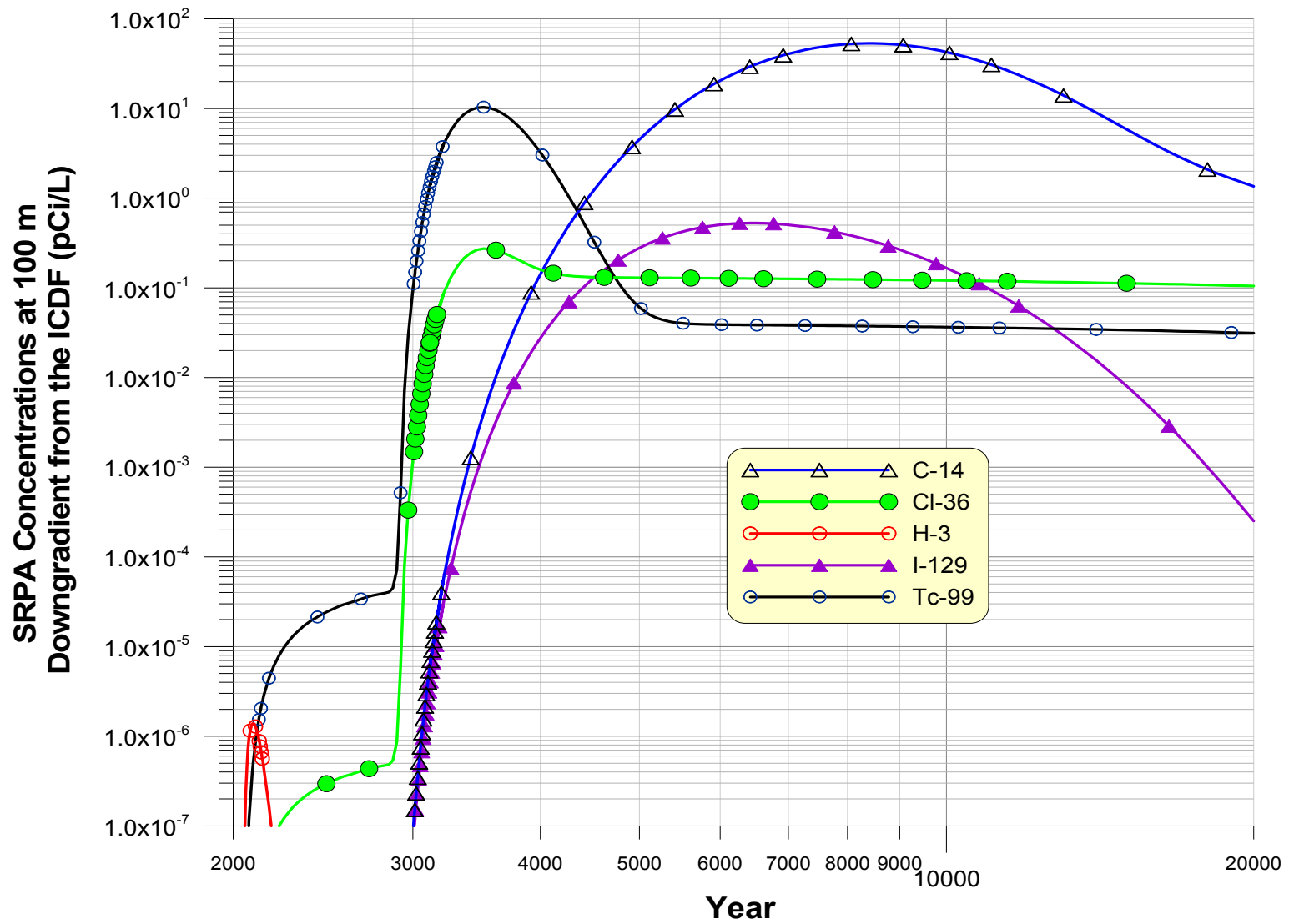


Figure 4-8. MCM-GWSCREEN-predicted groundwater concentrations for fission and activation products at 100 m downgradient from the ICDF Landfill.

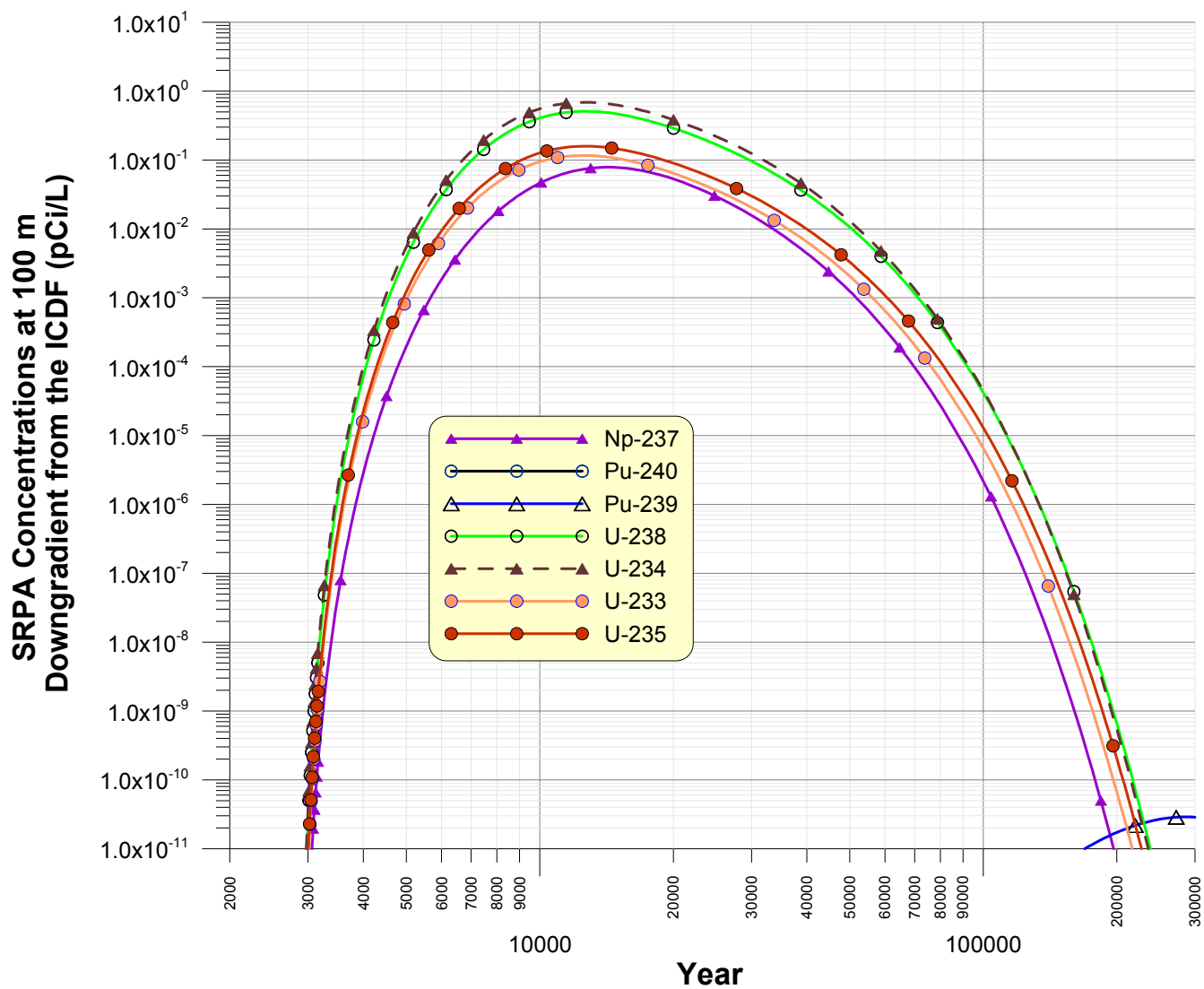


Figure 4-9. MCM-GWSCREEN-predicted groundwater concentrations for actinides at 100 m downgradient from the ICDF Landfill.

Table 4-1. Maximum radionuclide groundwater concentrations and time of maximum at 100 m downgradient from the ICDF Landfill.

		Predicted Time ^a to Maximum and Maximum Aquifer Concentration					
		Institutional Control Period ^b (2018–2118) (INL Site boundary)		Compliance Period (2119–3018) (100 m downgradient)		Post-Compliance Period (>3018) (100 m downgradient)	
Radionuclide	Progeny	Concentration (pCi/L)	Time (year)	Concentration (pCi/L)	Time (year)	Concentration (pCi/L)	Time (year)
C-14		0.00E+00	NA	1.87E-07	3018	5.33E+01	8368
Cl-36		0.00E+00	NA	2.12E-03	3018	2.73E-01	3556
H-3		0.00E+00	NA	9.33E-07	2119	6.35E-24	3018
I-129		0.00E+00	NA	1.39E-07	3018	5.28E-01	6484
Np-237		0.00E+00	NA	1.60E-12	3018	7.85E-02	14,268
	U-233	0.00E+00	NA	2.63E-14	3018	4.39E-03	15,518
	Th-229	0.00E+00	NA	1.70E-17	3018	5.18E-05	23,768
Pu-239		0.00E+00	NA	1.91E-35	3018	2.90E-11	284,018
	U-235	0.00E+00	NA	2.36E-16	3018	1.83E-04	25,768
	Pa-231	0.00E+00	NA	3.16E-20	3018	3.12E-07	59,268
	Ac-227	0.00E+00	NA	3.46E-21	3018	3.46E-07	60,268
Pu-240		0.00E+00	NA	9.56E-36	3018	2.32E-16	80,768
	U-236	0.00E+00	NA	3.76E-15	3018	1.75E-03	19,018
	Th-232	0.00E+00	NA	1.26E-24	3018	6.04E-11	308,018
	Ra-228	0.00E+00	NA	4.20E-25	3018	5.61E-11	308,018
	Th-228	0.00E+00	NA	2.16E-25	3018	4.84E-11	308,018
Tc-99		0.00E+00	NA	1.63E-01	3018	1.04E+01	3508
U-233		0.00E+00	NA	1.25E-11	3018	1.17E-01	12,518
	Th-229	0.00E+00	NA	8.15E-15	3018	1.21E-03	19,768
U-234		0.00E+00	NA	7.28E-11	3018	6.90E-01	12,518
	Th-230	0.00E+00	NA	4.61E-15	3018	1.43E-03	34,268
	Ra-226	0.00E+00	NA	1.07E-17	3018	1.42E-03	37,268
	Pb-210	0.00E+00	NA	2.18E-18	3018	1.39E-03	37,268

Table 4.1. (continued).

		Predicted Time ^a to Maximum and Maximum Aquifer Concentration					
		Institutional Control Period ^b (2018–2118) (INL Site boundary)		Compliance Period (2119–3018) (100 m downgradient)		Post-Compliance Period (>3018) (100 m downgradient)	
Radionuclide	Progeny	Concentration (pCi/L)	Time (year)	Concentration (pCi/L)	Time (year)	Concentration (pCi/L)	Time (year)
U-235		0.00E+00	NA	1.63E-11	3018	1.59E-01	12,518
	Pa-231	0.00E+00	NA	2.22E-15	3018	1.19E-04	26,768
	Ac-227	0.00E+00	NA	2.47E-16	3018	1.32E-04	28,768
U-238		0.00E+00	NA	5.25E-11	3018	5.10E-01	12,518
	U-234	0.00E+00	NA	1.47E-13	3018	1.67E-02	15,518
	Th-230	0.00E+00	NA	9.30E-18	3018	4.57E-05	41,768
	Ra-226	0.00E+00	NA	2.10E-20	3018	4.53E-05	44,768
	Pb-210	0.00E+00	NA	4.04E-21	3018	4.45E-05	44,768
a. The time represents the calendar year.							
b. No nuclides reach the INL Site boundary during the institutional control period.							
INL Idaho National Laboratory							
NA not applicable - no time of peak during the institutional control period at the INL Site boundary because the concentration is always zero.							

Table 4-2. Radon flux (pCi·m⁻²·s⁻¹) from soil surface.

Time	2018	2118	2518	3018
Ra-226	6.3E-01	6.0E-01	4.9E-01	3.8E-01
Th-230	0	2.7E-03	1.2E-02	2.2E-02
U-234	0	8.2E-06	1.9E-04	6.9E-04
U-238	0	5.6E-10	6.6E-08	4.8E-07
Total	6.3E-01	6.0E-01	5.0E-01	4.0E-01

4.4 Biotic Pathways

Biointrusion at the ICDF Landfill is not expected because of the depth of the proposed final cover for the facility and the incorporation of a biobarrier component (EDF-ER-279). However, as discussed in Section 3.5, a biointrusion analysis was performed.

Biointrusion by plant roots and harvester ants is assessed as a mechanism to move radioactive material to the land surface. Big sagebrush roots and harvester ants are assumed to penetrate to depths of 2.25 and 2.7 m (7.4 and 9 ft), respectively, during the compliance period and contact the disposed waste (under 2 m [6.6 ft] of cover). This will provide a biotic pathway for radionuclide migration to the surface. The contamination was assumed to remain on the surface where a hypothetical resident is exposed through the all-pathways scenario.

The RESRAD computer code (Yu et al. 2001) was used to calculate the dose-per-unit concentration in the source at the time of exposure (including radioactive decay and ingrowth of progeny, as applicable) or DSRs for the chronic resident scenario.

The maximum doses occurred at the end of institutional control (100 years after disposal facility closure) at estimated values of 0.0022 mrem/year and 0.0019 mrem/year for biointrusion by harvester ants and plant roots, respectively (see Section 3.5). The dominant dose contributor is Cs-137 for biointrusion via harvester ants and Cl-36 for biointrusion via plant roots. Both these doses are well below the DOE O 435.1 Chg 1 all-pathways dose limit of 25 mrem/year. Given the conservative assumptions regarding the potential for flora or fauna to actually contact the waste, the low doses projected in this screening analysis provide a solid basis to conclude that biotic intrusion will not significantly contribute to the all-pathways dose associated with the ICDF Landfill. See EDF-9913 for all calculations and results associated with the biotic pathways analysis.

4.5 Dose Analysis

The following sections present the results for the groundwater all-pathways dose analysis and the groundwater protection analysis.

4.5.1 Groundwater All-Pathways Dose Analysis

This section presents the groundwater all-pathways EDE results. The point of compliance for the all-pathways EDE during institutional control (2018–2118) is at the INL Site boundary approximately 12.7 km (8 mi) downgradient of the ICDF Landfill. Radionuclide fluxes to the aquifer during the institutional control period (2018–2118) were either zero or negligible; therefore, groundwater concentrations and all-pathways doses would also be either zero or negligible at the INL Site boundary. Doses for actinides include contributions from parent and progeny that grow in during transport.

The all-pathways EDE as a function of calendar year is presented in Figure 4-10 for mobile fission and activation products and Figure 4-11 for actinides. Table 4-3 shows the maximum all-pathways dose during the institutional control, compliance, and post-compliance periods. The maximum all-pathways dose during the compliance period was $8.1\text{E-}04$ mrem/year and occurred in the year 3018. The maximum all-pathways dose after the compliance period was 0.58 mrem/year and occurred in the year 8368. All doses are below the DOE all-pathways performance objective of 25 mrem/year.

Chlorine-36 and Tc-99 are the primary dose contributors during the compliance period. Carbon-14 and I-129 are the primary dose contributors during the post-compliance period.

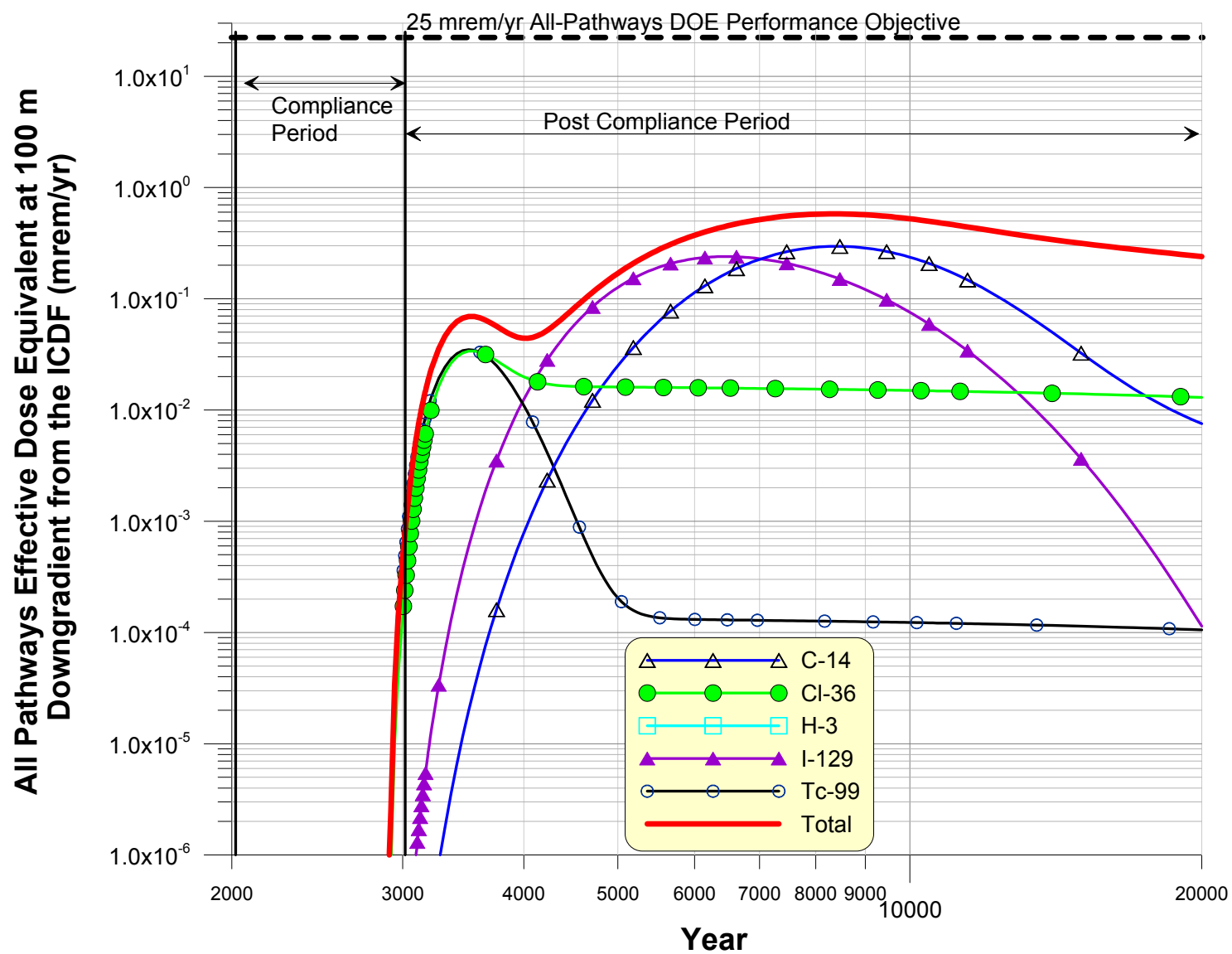


Figure 4-10. All-pathways effective dose equivalent as a function of time for fission and activation products at the 100-m receptor location.

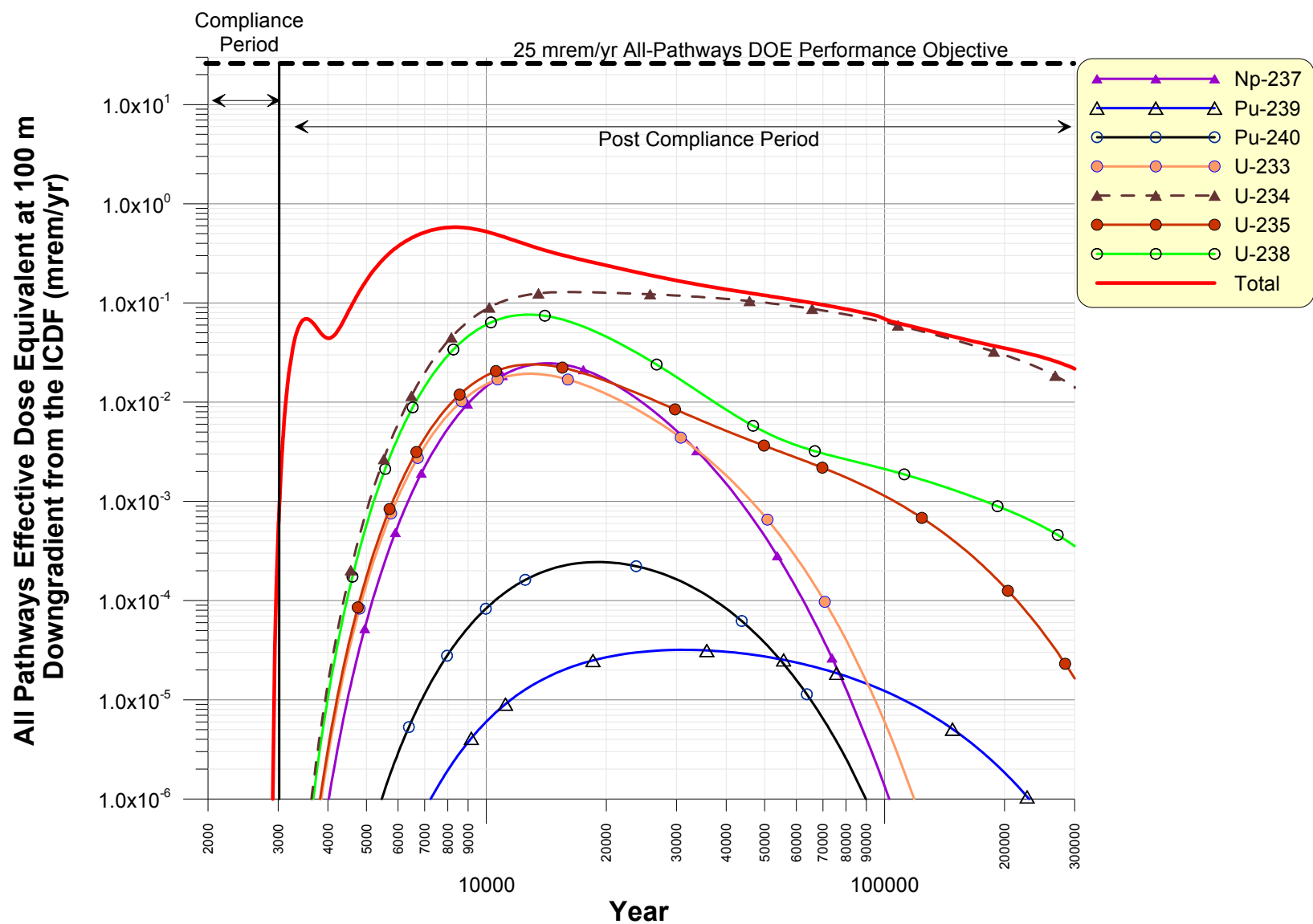


Figure 4-11. All-pathways effective dose equivalent as a function of time for actinides at the 100-m receptor location. Doses include contributions from parent and progeny. The “Total” line includes both actinides and fission and activation products.

Table 4-3. Maximum all-pathways effective dose equivalent and time of maximum at 100 m downgradient from the ICDF Landfill.

		Predicted Time ^a to Maximum and Maximum All-Pathways Effective Dose Equivalent					
		Institutional Control Period ^b (2018–2118) (INL Site boundary)		Compliance Period (2119–3018) (100 m downgradient)		Post-Compliance Period (>3018) (100 m downgradient)	
Radionuclide	Progeny	Dose (mrem/year)	Time (year)	Dose (mrem/year)	Time (year)	Dose (mrem/year)	Time (year)
C-14		0.00E+00	NA	1.04E-09	3018	2.96E-01	8368
Cl-36		0.00E+00	NA	2.63E-04	3018	3.38E-02	3556
H-3		0.00E+00	NA	1.08E-10	2119	7.22E-28	3019
I-129		0.00E+00	NA	6.31E-08	3018	2.40E-01	6484
Np-237		0.00E+00	NA	4.88E-13	3018	2.40E-02	14,018
	U-233	0.00E+00	NA	4.05E-15	3018	6.76E-04	15,518
	Th-229	0.00E+00	NA	3.10E-17	3018	9.44E-05	23,768
	Total	0.00E+00	NA	4.92E-13	3018	2.47E-02	14,518
Pu-239		0.00E+00	NA	1.35E-35	3018	2.06E-11	286,018
	U-235	0.00E+00	NA	3.32E-17	3018	2.59E-05	25,768
	Pa-231	0.00E+00	NA	4.30E-20	3018	4.25E-07	58,768
	Ac-227	0.00E+00	NA	1.04E-19	3018	1.04E-05	60,268
	Total	0.00E+00	NA	3.34E-17	3018	3.19E-05	30,768
Pu-240		0.00E+00	NA	6.79E-36	3018	1.65E-16	80,768
	U-236	0.00E+00	NA	5.27E-16	3018	2.45E-04	19,018
	Th-232	0.00E+00	NA	8.27E-25	3018	3.95E-11	308,018
	Ra-228	0.00E+00	NA	8.70E-25	3018	1.16E-10	308,018
	Th-228	0.00E+00	NA	8.73E-26	3018	1.96E-11	308,018
	Total	0.00E+00	NA	5.27E-16	3018	2.45E-04	19,018
Tc-99		0.00E+00	NA	5.49E-04	3018	3.49E-02	3508
U-233		0.00E+00	NA	1.93E-12	3018	1.80E-02	12,518
	Th-229	0.00E+00	NA	1.48E-14	3018	2.21E-03	19,518
	Total	0.00E+00	NA	1.94E-12	3018	1.93E-02	13,018

Table 4-3. (continued).

		Predicted Time ^a to Maximum and Maximum All-Pathways Effective Dose Equivalent					
		Institutional Control Period ^b (2018–2118) (INL Site boundary)		Compliance Period (2119–3018) (100 m downgradient)		Post-Compliance Period (>3018) (100 m downgradient)	
Radionuclide	Progeny	Dose (mrem/year)	Time (year)	Dose (mrem/year)	Time (year)	Dose (mrem/year)	Time (year)
U-234		0.00E+00	NA	1.06E-11	3018	1.01E-01	12,518
	Th-230	0.00E+00	NA	2.79E-15	3018	8.64E-04	34,268
	Ra-226	0.00E+00	NA	8.82E-18	3018	1.17E-03	37,268
	Pb-210	0.00E+00	NA	1.60E-16	3018	1.02E-01	37,268
	Total	0.00E+00	NA	1.06E-11	3018	1.29E-01	16,018
U-235		0.00E+00	NA	2.30E-12	3018	2.24E-02	12,518
	Pa-231	0.00E+00	NA	3.01E-15	3018	1.62E-04	26,768
	Ac-227	0.00E+00	NA	7.43E-15	3018	3.97E-03	28,768
	Total	0.00E+00	NA	2.31E-12	3018	2.41E-02	13,018
U-238		0.00E+00	NA	7.60E-12	3018	7.39E-02	12,518
	U-234	0.00E+00	NA	2.15E-14	3018	2.44E-03	15,518
	Th-230	0.00E+00	NA	5.63E-18	3018	2.77E-05	41,768
	Ra-226	0.00E+00	NA	1.74E-20	3018	3.75E-05	44,768
	Pb-210	0.00E+00	NA	2.97E-19	3018	3.27E-03	44,768
	Total	0.00E+00	NA	7.63E-12	3018	7.64E-02	13,018
Total (all nuclides)		0.00E+00	NA	8.13E-04	3018	5.80E-01	8368

a. The time represents the calendar year.

b. No nuclides reach the INL Site boundary during the institutional control period.

INL Idaho National Laboratory

NA not applicable - no time of peak during the institutional control period at the INL Site boundary because the concentration is always zero.

For some actinides, the dose is dominated by the progeny contribution. For example, the total dose predicted from the disposal of Pu-239 is dominated by the progeny U-235 and Ac-227. Since uranium is much more mobile than plutonium, the maximum dose from the decay products U-235 and Ac-227 occur much sooner than the maximum dose from Pu-239. Similarly, the dose from the disposal of Pu-240 is primarily from the progeny U-236. For actinides that are relatively mobile compared to their progeny (Np-237, U-233, U-234, U-235, and U-238), the total dose from the disposal of these nuclides is dominated by the parent radionuclide.

Sensitivity cases presented later in this report examine failure of the leachate system collection and bentonite clay liner.

4.5.2 Assessment of Groundwater Protection with State of Idaho Ground Water Quality Rule (IDAPA 58.01.11)

Groundwater protection is evaluated by comparing predicted concentrations in groundwater 100 m downgradient from the ICDF Landfill during institutional control with the State of Idaho Ground Water Quality Rule (IDAPA 58.01.11):

- Combined beta/gamma emitters 4 mrem/year effective dose equivalent (EDE): C-14 (2,625 pCi/L), Cl-36 (1,810 pCi/L), H-3 (85,600 pCi/L), I-129 (20 pCi/L), Ni-59 (26,120 pCi/L), and Tc-99 (3,750 pCi/L). A combined dose greater than 4 mrem/year indicates the predicted groundwater concentrations exceed the State of Idaho Groundwater Quality Rule standards.
- Gross alpha concentration (excluding uranium and radon) ≤ 15 pCi/L
- Ra-226/Ra-228 concentrations ≤ 5 pCi/L
- H-3 concentration $\leq 20,000$ pCi/L.

The State of Idaho Ground Water Quality Rule standard (IDAPA 58.01.11) concentration for a beta-gamma-emitting radionuclide is the concentration in the water resource that, if consumed at 2 L/day for 365 days/year, would yield an annual EDE of 4 mrem/year. Given that the State of Idaho Ground Water Quality Rule standard represent 4 mrem/year EDE, then the EDE for a given groundwater concentration (C) can be computed using the State of Idaho Ground Water Quality Rule standard (C_s) by

$$EDE = \frac{C}{C_s} \times 4 \text{ mrem/yr} . \quad (4-1)$$

The Idaho Ground Water Quality Rule is identical to the federal MCLs (See Section 4.5.3) with the exception that the standard for beta-gamma-emitting radionuclides is 4 mrem/year *effective* dose equivalent. The State of Idaho Ground Water Quality Rule also retains the 20,000-pCi/L limit for the individual radionuclide H-3.

As shown in Table 4-1 and Figures 4-8 and 4-9, maximum radionuclide concentrations for all times are much less than the State of Idaho Ground Water Quality Rule (IDAPA 58.01.11) limits, which only apply during institutional control. Table 4-4 compares the State of Idaho Ground Water Quality Rule (IDAPA 58.01.11) limits and the maximum concentration predicted during the institutional control period.

Table 4-4. Comparison of groundwater results to groundwater protection criteria for State of Idaho Ground Water Quality Rule during the institutional control period 100 m downgradient of the Idaho CERCLA Disposal Facility Landfill.

Groundwater Performance Measure State of Idaho Ground Water Quality Rule (IDAPA 58.01.11)	Institutional Control Period (100 m downgradient) 2018–2118	Comments
Beta-gamma EDE ≤ 4 mrem/yr	1.7E-09 mrem/yr	Tc-99 accounts for about 95% of the EDE. Minor contributors are C-14, Cl-36, H-3, and I-129.
Gross alpha activity concentration ≤ 15 pCi/L	$< 1\text{E-}10^a$ pCi/L	—
Ra-226/Ra-228 concentration ≤ 5 pCi/L	$< 1\text{E-}10$ pCi/L	Ingrowth from Pu-240, U-234, and U-238.
MCL of 8 pCi/L for Sr-90 ^b	NA	—
<u>H-3 concentration $\leq 20,000$ pCi/L</u>	1.4E-06 pCi/L	Peak H-3 concentration is in 2093.
a. Concentrations less than 1E-10 are essentially zero.		
b. Not applicable; Sr-90 is not a contaminant of interest at the ICDF Landfill.		
EDE	effective dose equivalent	
ICDF	Idaho CERCLA Disposal Landfill	
MCL	maximum contaminant level	
NA	not applicable	

The maximum drinking water EDE for beta-gamma-emitting radionuclides computed using the Idaho Ground Water Quality Rule was 1.7E-09 mrem/year during the institutional control period 100 m downgradient of the ICDF Landfill (see Table 4-4). This dose is dominated by Tc-99 and occurred in the year 2118.

The gross alpha peak concentration 100 m downgradient from the ICDF Landfill during the institutional control period (2018–2118) is less than 1E-10 pCi/L, well below the 15-pCi/L limit. The Ra-226/Ra-228 peak concentration 100 m downgradient from the ICDF Landfill during the institutional control period (2018–2118) is also less than 1E-10 pCi/L. The H-3 peak concentration 100 m downgradient from the ICDF Landfill during the institutional control period (2018–2118) is 1.4E-06 pCi/L in the year 2093. This concentration is 10 orders of magnitude below the limit of 20,000 pCi/L.

4.5.3 Assessment of Groundwater Protection with State of Idaho Rules for Public Drinking Water Systems (IDAPA 58.01.08)

Groundwater protection is also evaluated by comparing predicted concentrations in groundwater at the INL Site boundary during institutional control period and 100 m downgradient from the ICDF Landfill during the compliance period with the State of Idaho Rules for Public Drinking Water Systems (IDAPA 58.01.08):

- Combined beta/gamma emitters 4 mrem/year dose equivalent (DE): C-14 (2,000 pCi/L), Cl-36 (700 pCi/L), H-3 (20,000 pCi/L), I-129 (1 pCi/L), and Tc-99 (900 pCi/L) (65 FR 21575). A combined dose greater than 4 mrem/year indicates the predicted groundwater concentrations exceed the MCL.
- Gross alpha concentration (excluding uranium and radon) ≤ 15 pCi/L.
- Ra-226/Ra-228 concentrations ≤ 5 pCi/L.
- Total uranium mass concentration ≤ 30 $\mu\text{g/L}$.

- Sr-90 concentration ≤ 8 pCi/L. Sr-90 was screened out in this evaluation so it is not included in the evaluation.
- H-3 concentration $\leq 20,000$ pCi/L.

The federal MCL concentration for a beta-gamma-emitting radionuclide is the concentration in drinking water that, if consumed at 2 L/day for 365 days/year, would yield an annual DE of 4 mrem/year. Given that the MCLs represent 4 mrem/year dose equivalent, then the dose equivalent for a given groundwater concentration (C) can be computed by

$$DE = \frac{C}{MCL} \times 4 \text{ mrem/yr} . \quad (4-2)$$

The beta-gamma dose equivalent as a function of calendar year at the 100-m receptor is presented in Figure 4-12. The numerical results are tabulated in Table 4-5. The maximum dose equivalent was zero during the institutional control period at the INL Site boundary. The maximum dose equivalent was $7.4\text{E-}04$ mrem/year during the compliance period and 2.2 mrem/year after the compliance period. Technetium-99 dominates the peak dose during the compliance period and I-129 dominates the peak dose after the compliance period. During the institutional control period, the receptor is at the INL Site boundary and the maximum dose is zero. The H-3 contribution to dose is very small and does not show on the figure. Predicted groundwater concentrations were well below the gross alpha limit of 15 pCi/L, the Ra-226/Ra-228 limit of 5 pCi/L, the uranium mass concentration of 30 $\mu\text{g/L}$, and the federal MCL for H-3 of 20,000 pCi/L (see Table 4-5).

4.5.4 Atmospheric Pathway Results

The atmospheric pathway transport calculations are presented in Section 3.3.2, and the results are presented in Table 4-6 and Figure 4-13. Doses during the institutional control period and compliance and post-compliance periods were well below the 10-mrem/year dose limit. Doses during the institutional control period were calculated at the INL Site boundary, and the maximum dose ($2.7\text{E-}05$ mrem/year) occurred in year 2018, with H-3 as the major dose contributor. Maximum doses during the compliance time were dominated by C-14 and the total maximum dose ($5.8\text{E-}03$ mrem/year) occurred in the year 2380. All calculations and results associated with the atmospheric pathways analysis are documented in EDF-9917.

4.6 Sensitivity and Uncertainty Analysis

This section presents the methodology and results of a parameter uncertainty and sensitivity analysis performed for the groundwater pathway all-pathways dose analysis at the ICDF Landfill. A sensitivity/uncertainty analysis was not conducted for the atmospheric and radon flux analyses, as the results were significantly below applicable performance objectives using what were considered suitably conservative assumptions.

Uncertainty analysis identifies the range of results that could be expected when the possible range and distributions of inputs for key parameters are considered. Sensitivity analysis evaluates the sensitivity of model output to variability in model input. Uncertainty in models arises because of (a) errors in model formulation and (b) errors (or uncertainty) in model input parameters (parametric uncertainty). Model formulation errors are inherent in mathematical modeling because environmental models are only simplified representations of complex environmental systems. Errors in model parameterization occur because of lack of knowledge about a parameter's true, but unknown, value. Ideally, site-specific parameter values should be derived and used in the simulation, but, in reality, strictly quantitative information regarding parameter distributions is lacking, and distributions exhibit subjective judgment of the analyst.

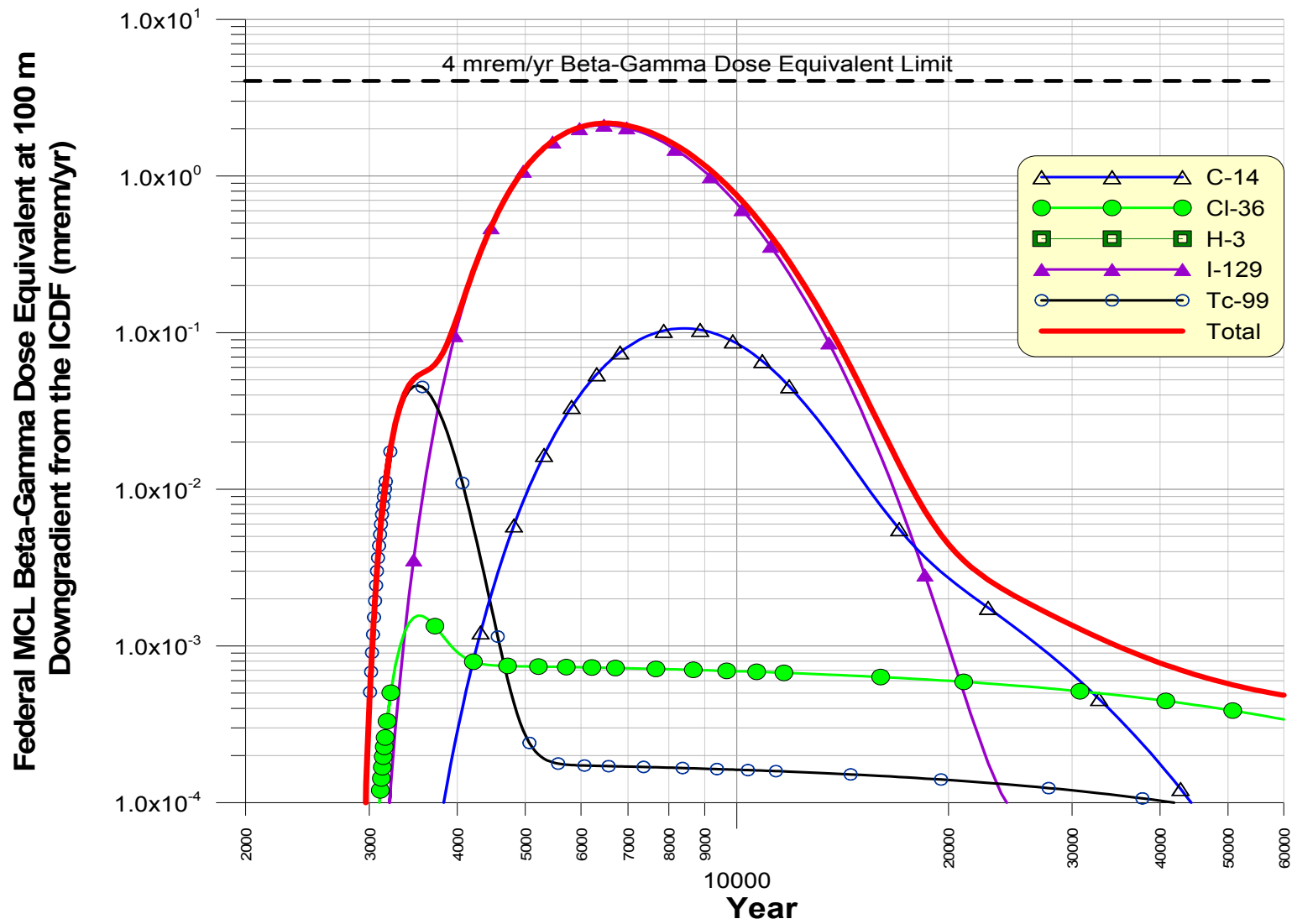


Figure 4-12. Beta-gamma dose equivalent based on federal MCLs for beta-gamma-emitting fission and activation products as a function of calendar year at the 100-m receptor location.

Table 4-5. Comparison of groundwater results to groundwater protection criteria for State of Idaho public drinking water systems.

Groundwater Performance Measure	Institutional Control Period (INL Site Boundary) 2018-2118	Compliance Period (100 m downgradient) 2119–3018	Post-Compliance Period (100 m downgradient) >3018	Comments
Beta-gamma dose equivalent ≤4 mrem/yr (based on federal MCL)	0	7.4E-04 mrem/yr	2.2 mrem/yr	Tc-99 accounts for about 98% of the dose equivalent during the compliance period and I-129 accounts for 97% of the dose equivalent during the post-compliance period. Minor contributors to dose are C-14, Cl-36, and H-3.
Gross alpha activity concentration ≤15 pCi/L	0	<1E-10 ^a pCi/L	8.2E-02 pCi/L	Np-237, Pu-239, Pu-240, Th-230, Ra-226, Ra-228, Pa-231.
Ra-226/Ra-228 concentration ≤5 pCi/L	0	<1E-10 pCi/L	1.5E-03 pCi/L	Ingrowth from Pu-240, U-234, and U-238.
Uranium concentration ≤30 µg/L	0	<1E-10 µg/L	3.4E-04 µg/L	—
MCL of 8 pCi/L for Sr-90 ^b	NA	NA	NA	—
H-3 concentration ≤20,000 pCi/L	0	9.3E-07 pCi/L	<1E-10 pCi/L	—
a. Concentrations less than 1E-10 are essentially zero.				
INL	Idaho National Laboratory			
MCL	maximum contaminant level			
NA	not applicable			

Table 4-6. Volatile radionuclide doses via the atmospheric pathway during institutional control and compliance periods.

Radionuclide	Institutional Control Period at the INL Site Boundary		Compliance Period 100 m from the ICDF Landfill	
	Time of Maximum (calendar year)	Maximum Air Pathway EDE (mrem/yr)	Time of Maximum (calendar year)	Maximum Air Pathway EDE (mrem/yr)
C-14	2118	9.5E-07	2380	5.3E-03
H-3	2018	2.7E-05	2118	9.3E-05
I-129	2118	2.6E-07	2274	5.3E-04
Total	2018	2.7E-05	2380	5.8E-03

EDE effective dose equivalent
ICDF Idaho CERCLA Disposal Facility
INL Idaho National Laboratory

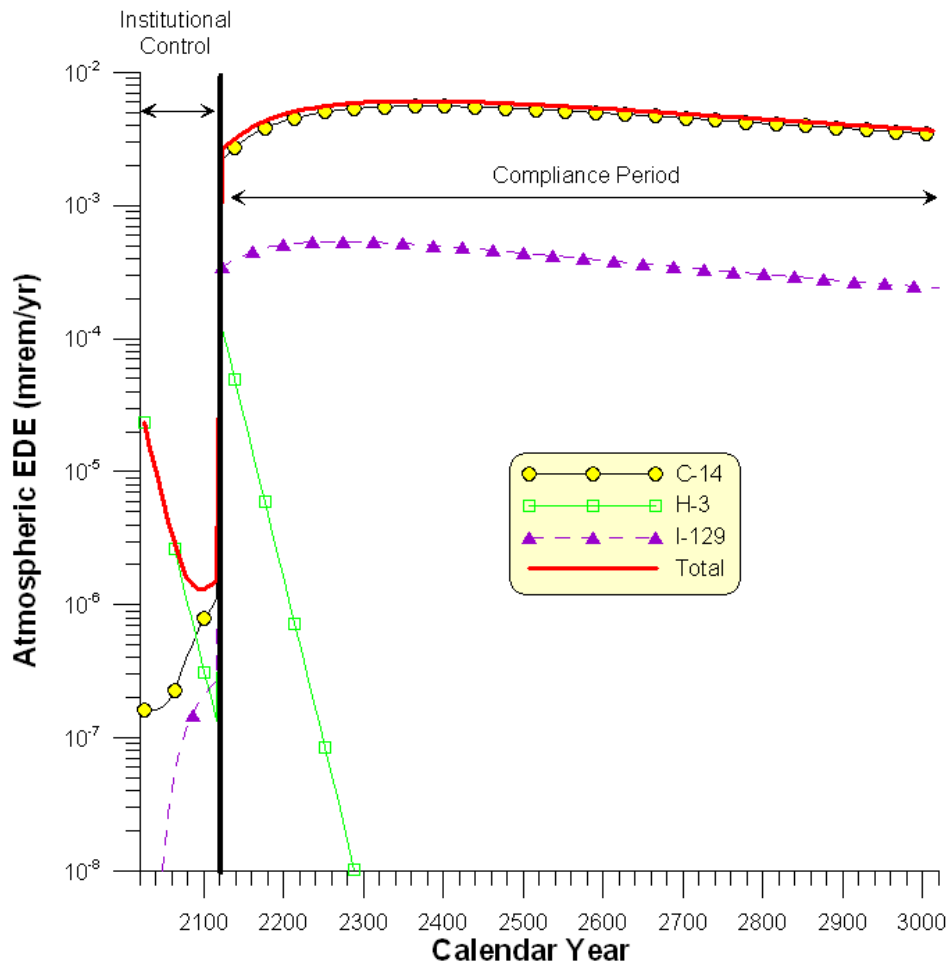


Figure 4-13. Atmospheric doses as a function of calendar year for the Idaho CERCLA Disposal Facility. Doses before year 2118 are at the Idaho National Laboratory Site boundary. After that, doses are at 100 m from the edge of the Idaho CERCLA Disposal Facility.

Uncertainty in model formulation can only truly be evaluated through model validation. Model validation answers the question “Does the model accurately simulate the behavior of the system?” To demonstrate a model is valid, an independent data set is required. Oftentimes, adequate independent data sets are not available and the analyst resorts to model calibration. In model calibration, parameter values are adjusted (within reason) so that model predictions match the field observations as close as possible. Model calibration only provides a measure of what the model can accurately simulate in the environment for the current timeframe. The use of the model for forecasting the release and transport of radionuclides far into the future can never be truly validated.

Because PA addresses impacts that occur far into the future, it is impossible to validate the model application for future predictions because measurements are unavailable. Review of environmental monitoring data is presented in *ICDF Detection Monitoring Biennial Report (2006-2007)* (DOE-ID 2008a). These measurements indicate that no activity has been released from the ICDF Landfill to the subsurface environment below the landfill liner.

Performance objectives for the groundwater pathway were met during the 1,000-year time of compliance and the post-compliance period using the models of performance described in Sections 3.2, 3.3, and 3.4. The important radionuclides contributing to the total all-pathways dose for the two timeframes of interest were Cl-36, Tc-99, I-129, C-14, U-234, and U-238. The number of radionuclides evaluated in the uncertainty analysis was limited to these primary dose contributors based on the base case results. All-pathways doses did not exceed the 25-mrem/year standard for *any* time in the future for the receptors considered in the analysis. In fact, the doses were all well below the 25-mrem/year performance objective.

The uncertainty/sensitivity analysis was conducted using one-factor-at-a-time and Monte Carlo analyses. One-factor-at-a-time analysis was applied to cover infiltration rates, operation of the leachate collection system, and presence of vadose zone sedimentary interbeds. Monte Carlo uncertainty analysis was applied to the important radionuclides and evaluated uncertainty in the all-pathways dose to uncertainty in cover infiltration and longevity, aquifer parameters, and radionuclide transport parameters.

Eight one-factor-at-a-time sensitivity analysis cases were examined:

- Cover infiltration remains at 0.1 cm/year for all time in the future.
- Cover infiltration is INL Site natural background (1 cm/year) for all time in the future.
- Leachate collection system and liner fails at the end of operations.
- Bentonite clay liner is absent.
- Alternative conceptual model – missing interbed.
- Liner remains intact until the facility fills with water 850 years after closure.
- Cover fails after 100 years. Liner remains intact until the facility fills with water 230 years after closure.
- Liner stays intact forever. Facility fills with water 850 years after closure and then overflows. Water moves through the vadose zone to the aquifer outside the facility.

A summary of the one-factor-at-a-time sensitivity analysis for the eight cases and the base case is presented in Table 4-7. Doses are all evaluated at the 100-m receptor in all cases.

Table 4-7. Summary of maximum doses during the institutional control period, compliance period, and post-compliance period for the base case and eight sensitivity cases.

Case	Institutional Control Year 2018–2118 (INL Site boundary) (mrem/yr)	Compliance Year 2119–3018 (100 m downgradient) (mrem/yr)	Post-Compliance Year >3018 (100 m downgradient) (mrem/yr)
Base case	<0.0001	0.0008	0.58
Sensitivity Case 1 (0.1 cm/yr for ∞)	<0.0001	0.000004	0.064
Sensitivity Case 2 (1 cm/yr for ∞)	<0.0001	0.048	0.61
Sensitivity Case 3 (failure of HDPE liner system)	<0.0001	0.0043	0.59
Sensitivity Case 4 (absence of bentonite clay layer)	<0.0001	0.0028	1.0
Sensitivity Case 5 (alternative conceptual model – missing interbed)	<0.0001	0.0067	0.68
Sensitivity Case 6 (liner does not fail until facility fills with water 850 yr after closure)	<0.0001	0.0025	0.53
Sensitivity Case 7 (cover fails after 100 yr and liner fails after facility fills with water 230 yr after closure)	<0.0001	0.046	0.55
Sensitivity Case 8 (liner never fails and the facility fills with water and overfills [bathtub effect])	<0.0001	0.58	7.8
HDPE	high-density polyethylene		
INL	Idaho National Laboratory		

4.6.1 One-Factor-at-a-Time Sensitivity Analysis: Case 1

Case 1 considered the sensitivity of the all-pathways EDE to a cover that does not degrade but performs at 0.1 cm/year infiltration for all time in the future. This is 10 times the infiltration rate assumed for the base case for the first 500 years but one-fifth the infiltration rate at 750 years and one-tenth the infiltration rate assumed for the base case after 1,000 years. The all-pathways EDE as a function of time is plotted in Figure 4-14. The maximum all-pathways EDE is 4.2E-06 mrem/year during the compliance period and 0.064 mrem/year during the post-compliance period. The major dose contributors were Tc-99 and Cl-36 during the compliance period and U-234 and U-238 during the post-compliance period peak time. The predicted maximum doses are compared in Table 4-7. The Case 1 sensitivity analysis maximum dose is 200 times smaller than the base case maximum dose during the compliance period and 10 times smaller during the post-compliance period. The maximum dose during the compliance and post-compliance periods is smaller than the base case dose because Sensitivity Case 1 has a lower infiltration rate during much of the compliance period and all of the post-compliance period.

4.6.2 One-Factor-at-a-Time Sensitivity Analysis: Case 2

Case 2 considered the sensitivity of the all-pathways EDE to a cover that only limits infiltration to the INL Site background rate of 1 cm/year for all time in the future. This infiltration rate is 100 times the infiltration rate assumed for the base case for the first 500 years, twice the infiltration rate at 750 years, and equal to the infiltration rate assumed for the base case after 1,000 years. The all-pathways EDE as a function of time is plotted in Figure 4-15. The maximum all-pathways EDE is 0.048 mrem/year during the compliance period and 0.61 mrem/year during the post-compliance period. The major dose contributors were Tc-99 and Cl-36 during the compliance period and C-14 and I-129 during the post-compliance period. The predicted maximum doses are compared in Table 4-7. The Case 2 sensitivity analysis maximum dose is 60 times larger than the base case maximum dose during the compliance period and approximately equal during the post-compliance period. The maximum dose during the compliance period is larger than the base case dose because Sensitivity Case 2 has a higher infiltration rate during the compliance period.

4.6.3 One-Factor-at-a-Time Sensitivity Analysis: Case 3

Case 3 considered the sensitivity of the all-pathways EDE to a failure in the leachate collection system and liner at the end of disposal operations. For this case, the initial moisture condition in the waste and bentonite clay layer was assumed to be near saturated. If the leachate collection system and liner were working properly (as assumed in the base case), the water draining from the waste would be recovered and removed. In this case, the water in the waste drains into the bentonite clay layer and into the vadose zone. Radionuclides in the waste partition into this infiltrating water according to the sorption coefficient. The cover is then assumed to be placed over the facility and limit further infiltration to 0.01 cm/year until the cover begins degrading 500 years after installation.

The all-pathways EDE as a function of time is plotted in Figure 4-16. The maximum all-pathways EDE is 0.0043 mrem/year during the compliance period and 0.59 mrem/year during the post-compliance period. The major dose contributors were Tc-99 and Cl-36 during the compliance period and C-14 and I-129 during the post-compliance period. The predicted maximum doses are compared in Table 4-7. The Case 3 sensitivity analysis maximum dose is five times larger than the base case maximum dose during the compliance period and approximately equal during the post-compliance period. The maximum dose during the compliance period is larger than the base case dose because Sensitivity Case 3 assumes that the leachate collection system fails and much more water initially moves into the vadose zone and pushes contaminants to the aquifer than assumed in the base case. Later, during the post-compliance period, there is little impact from the initial infiltration from the waste zone.

4.6.4 One-Factor-at-a-Time Sensitivity Analysis: Case 4

Case 4 considered the sensitivity of the all-pathways EDE to the presence of the bentonite clay layer, which lies below the liner. The bentonite clay layer acts as a radionuclide trap because sorption coefficients are typically higher in clay environments compared to a coarser matrix such as sand and gravel. In this simulation, the bentonite clay layer was replaced by alluvium.

The all-pathways EDE is illustrated in Figure 4-17. The maximum all-pathways EDE is 0.0028 mrem/year during the compliance period and 1.0 mrem/year during the post-compliance period. The major dose contributors were Tc-99 and Cl-36 during the compliance period and C-14, I-129, U-234, and U-238 during the post-compliance period. The predicted maximum doses are compared in Table 4-7. The Case 4 sensitivity analysis maximum dose is 3.5 times larger than the base case maximum dose during the compliance period and approximately twice the base case maximum dose during the post-compliance period. The maximum doses during the compliance and post-compliance periods are larger than the base case doses because Sensitivity Case 4 assumes smaller K_d values due to the clay liner than were assumed in the base case.

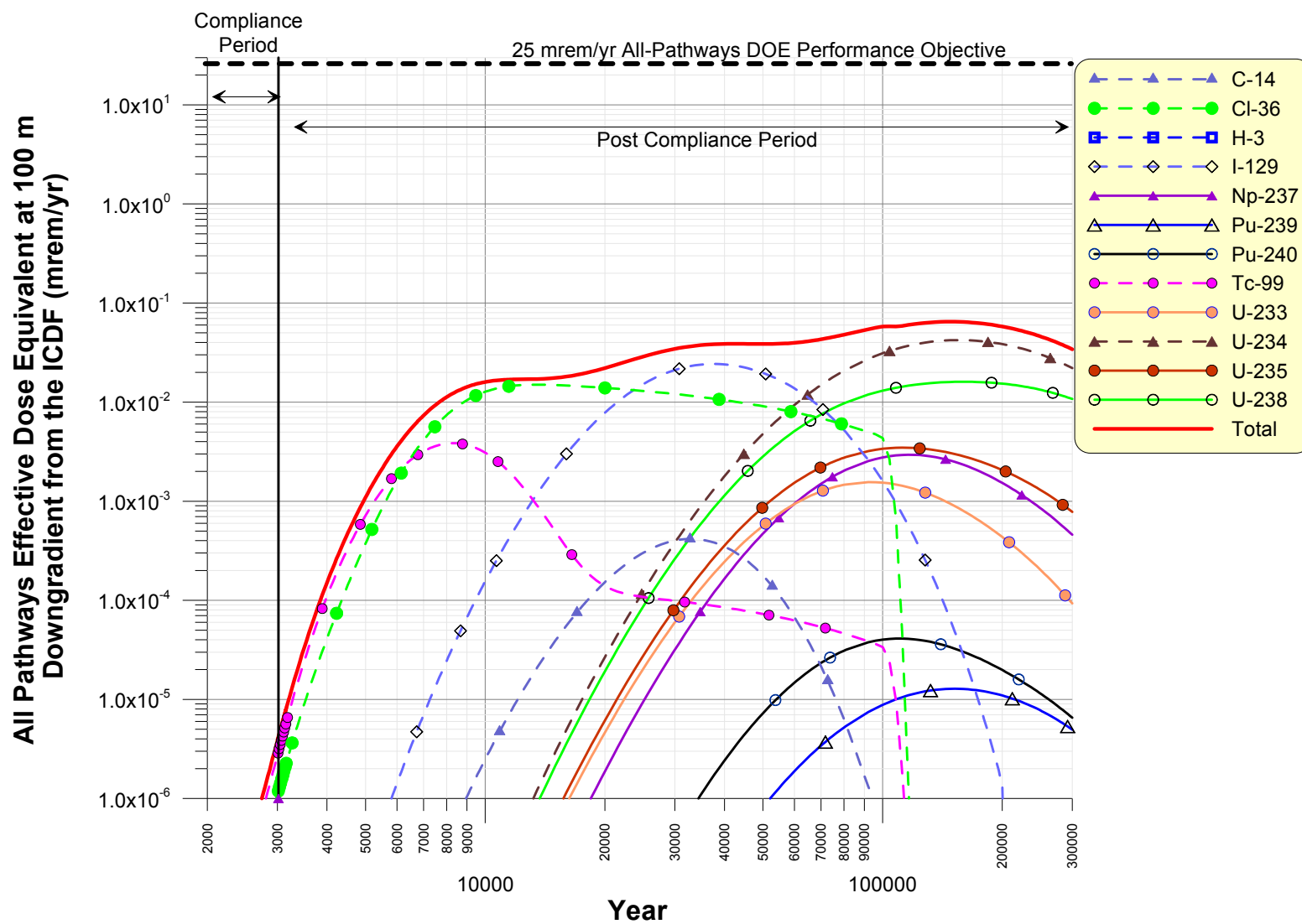


Figure 4-14. All-pathways dose as a function of time at the 100-m receptor for Case 1: a cover that remains intact and limits infiltration to 0.1 cm/year for all time.

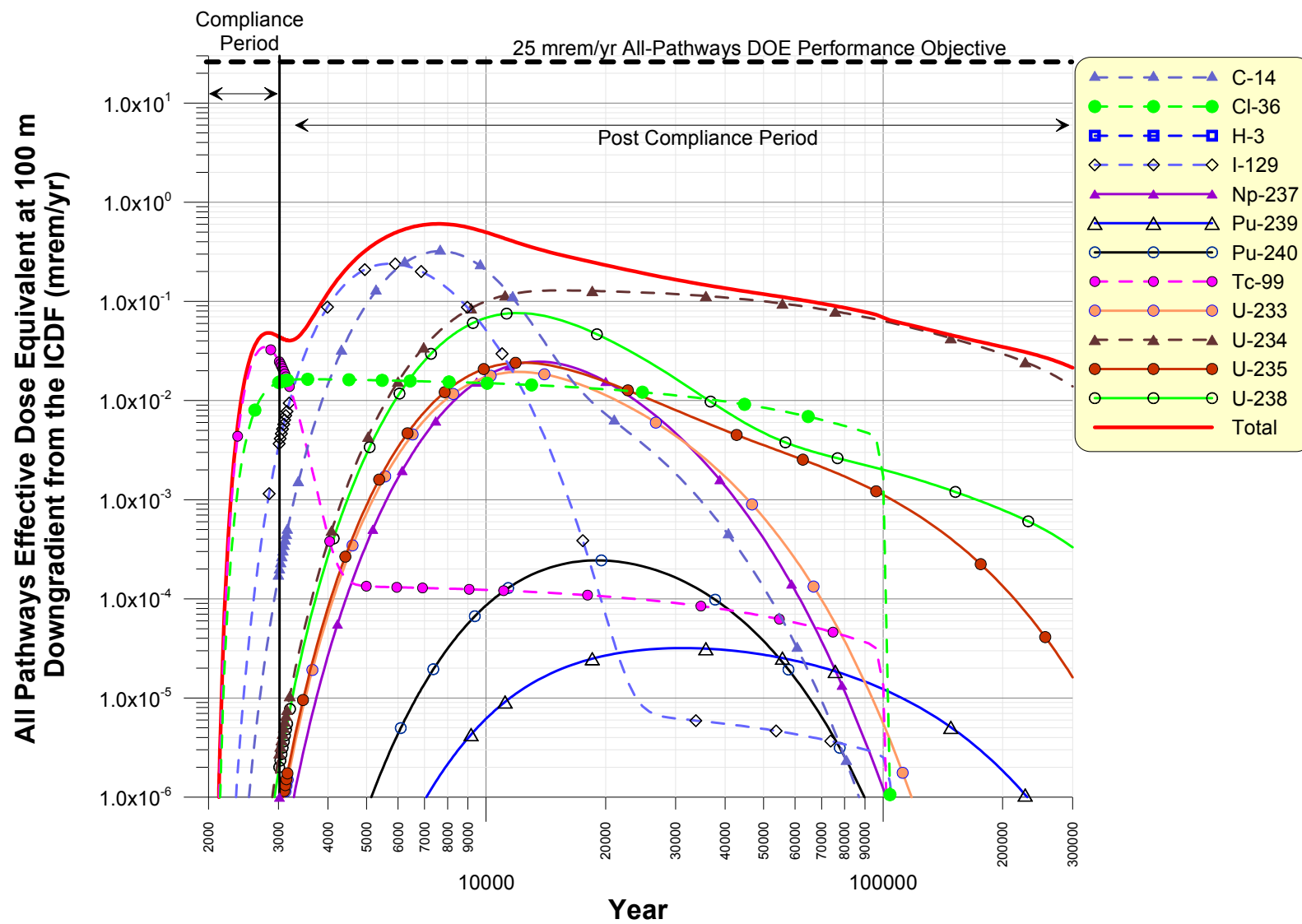


Figure 4-15. All-pathways dose as a function of time at the 100-m receptor for Case 2: a cover that performs at 1 cm/year for all time.

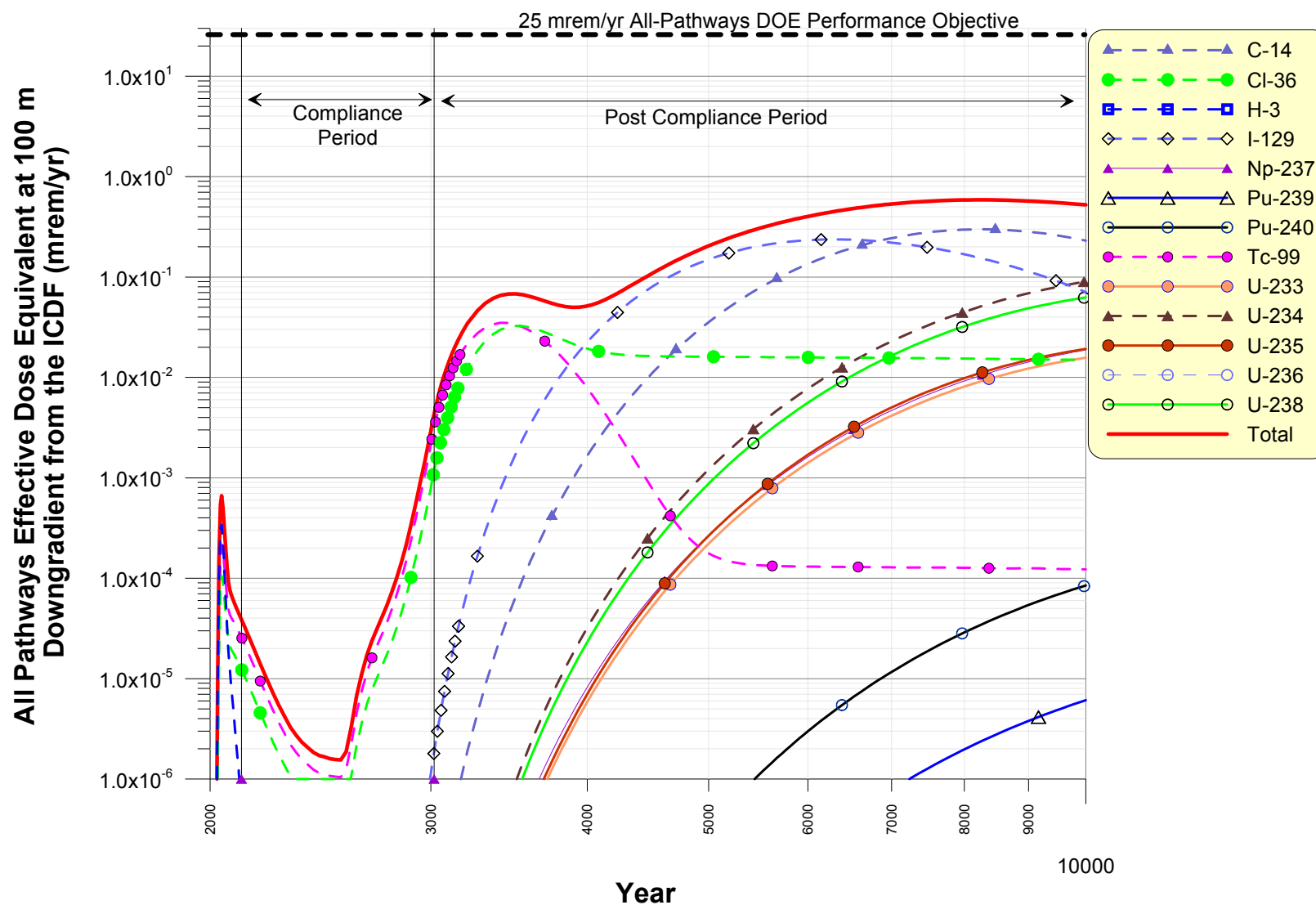


Figure 4-16. All-pathways dose as a function of time at the 100-m receptor for Case 3: the failure of the liner and leachate collection system during operations.

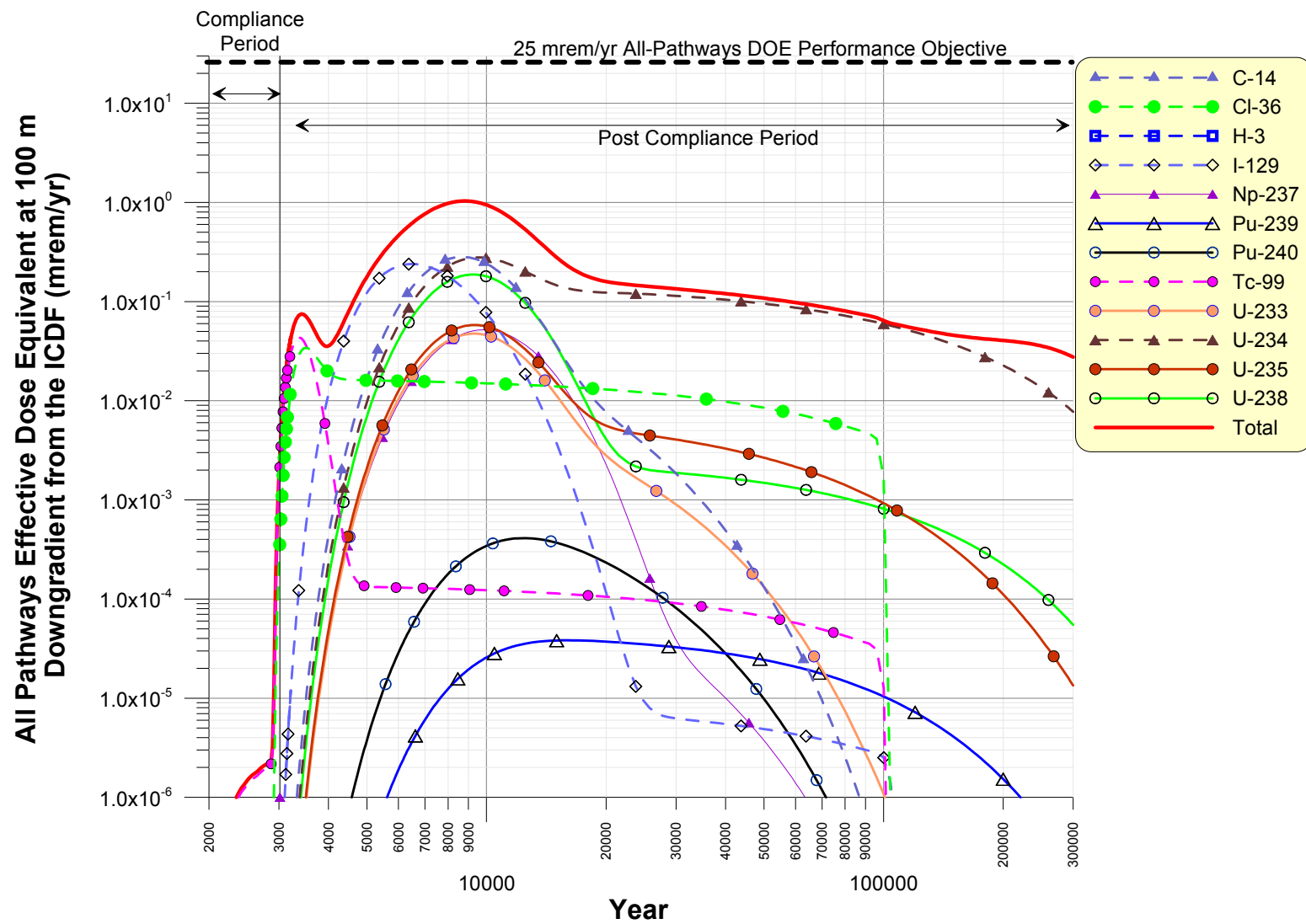


Figure 4-17. All-pathways dose as a function of time at the 100-m receptor for Case 4: the absence of the bentonite clay liner.

4.6.5 One-Factor-at-a-Time Sensitivity Analysis: Case 5

The base case conceptual model contains four high-permeability interbeds with a cumulative thickness of 10.7 m. Plausible alternative conceptual models for the site hydrology would include a vadose zone with either more or less vadose zone interbed. Less interbed would be conservative relative to the base-case-predicted all-pathways EDE. Interbeds (when compared with basalt) retard the movement of radionuclides because they have higher moisture contents and sorption coefficients. Therefore, replacing some high-permeability interbed with basalt results in shorter contaminant travel times in the vadose zone compared to the base case. Case 5 considered the sensitivity of the all-pathways EDE to the removal of a 4.56-m-thick high-permeability interbed and replacing it with basalt. The total interbed thickness in this alternative conceptual model for the site hydrology is about 57% of the thickness of the ICDF area interbeds when compared with the available data from the area wells.

The all-pathways EDE is illustrated in Figure 4-18. The maximum all-pathways EDE is 0.0067 mrem/year during the compliance period and 0.68 mrem/year during the post-compliance period. The major dose contributors were Tc-99 and Cl-36 during the compliance period and C-14, I-129, U-234, and U-238 during the post-compliance period. The predicted maximum doses are compared in Table 4-7. The Case 5 sensitivity analysis maximum dose is 8.4 times larger than the base case maximum dose during the compliance period and about 1.17 times higher than the base case maximum dose during the post-compliance period.

The maximum doses during the compliance and post-compliance periods are larger than the base case doses because this alternative conceptual model has much lower moisture content and zero K_d values in the basalt that replaced the 4.56 m of high-permeability interbeds that are used in the base case. These two changes shorten the contaminant travel time to the aquifer.

The net result of removing an interbed from the base case conceptual model is to shorten the radionuclide transit time in the unsaturated zone. The large increase in dose during the compliance time (factor of 8.4) is from a shift in dose curve to the left relative to the base case. This shift essentially moves more of the dose curve into the compliance timeframe, resulting in higher doses during the compliance timeframe and slightly lower doses later in the post-compliance timeframe relative to the base case. However, in both the base case and this sensitivity case, the predicted maximum dose during the compliance period is insignificant relative to the PA dose standard.

4.6.6 One-Factor-at-a-Time Sensitivity Analysis: Case 6

Case 6 considered the failure of the liner underlying the waste after the facility completely fills with water. In the base case, the liner is assumed to have failed after the leachate collection system is shut down or shortly thereafter, thereby allowing leachate to migrate to the vadose zone. While the cover remains intact, little water enters the facility because the net infiltration is 0.1 mm/year. After complete cover failure 1,000 years after facility closure, infiltration through the facility is two orders of magnitude higher. Assuming the liner does not fail, water will accumulate in the facility.

For this sensitivity case, ICDF is assumed to represent a rectangular volume with a height of 10.4 m. In reality, the sides of the ICDF are sloped, so that the total volume of water necessary to fill the facility is slightly greater than this estimate. Therefore, this estimate is considered conservative. The total porosity of the waste in the facility is 0.266 (Table 3-3), and, at the start of institutional control, the waste is estimated to have a moisture content of 0.14 (see Figure 4-1). Therefore, the height of a column of water necessary to fill the ICDF is given by

$$h = 10.4 \text{ m} \times (0.266 - 0.14) = 1.3 \text{ m} \quad (4-3)$$

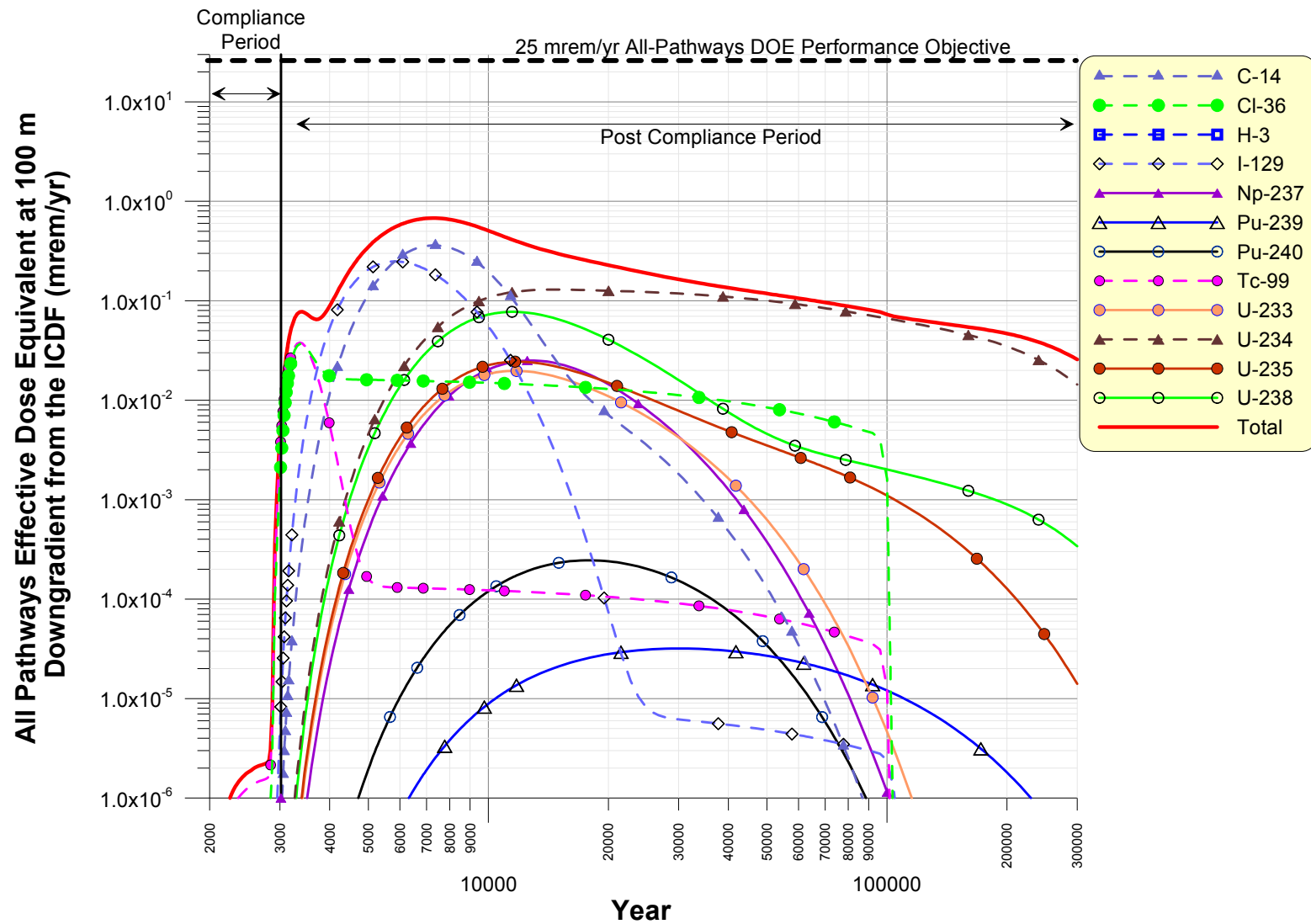


Figure 4-18. All-pathways dose as a function of time at the 100-m receptor for Case 5: the absence of 4.56 m of sedimentary interbed material.

Assuming the time-dependent infiltration rate illustrated in Figure 3-6 and an intact liner, the amount of water accumulated in the ICDF for the first 1,000 years is given by

$$qT = \int_0^{500 \text{ yr}} q_1 dt + \int_0^{500 \text{ yr}} q_1 + mt dt = q_1 500 \text{ yr} + q_1 500 \text{ yr} + \frac{m}{2} t^2 \quad (4-4)$$

Where

- qT = the total water height accumulated in 1,000 years
- q_1 = the cap infiltration rate (1E-04 m/year) for the first 500 years
- q_f = the failed cap infiltration rate (0.01 m/year) after 1,000 years
- m = slope of the infiltration rate as the cap fails from year 500 to 1,000.

The slope is given by.

$$m = \frac{q_f - q_1}{500 \text{ yr}} \quad (4-5)$$

The slope is therefore 1.98E-05 m/year².

The amount of water accumulated in the first 500 years is
1E-04 m/yr $\times$ 500 yr = 0.05 m.

The amount of water accumulated in the next 500 years is
1E-04 m/yr $\times$ 500 yr + (1.98E-05 m/yr²)/2 $\times$ (500 yr)² = 2.53 m.

Therefore, the facility will overflow during the second 500 years of the compliance period. After the first 500 years, an additional $Q = 1.3 \text{ m} - 0.05 \text{ m} = 1.25 \text{ m}$ of water is needed to fill the ICDF. The amount of water at the ICDF after the first 500 years of steady infiltration can be written as:

$$Q = \int (q_1 + mt) dt = q_1 t + \frac{m}{2} t^2 \quad (4-6)$$

The time at which the facility will overflow is found by solving the following polynomial for t

$$\frac{m}{2} t^2 + q_1 t - Q = 0 \quad (4-7)$$

Applying the quadratic equation to Equation 4-7, we have

$$t = \frac{-q_1 \pm \sqrt{(q_1)^2 - 4 \frac{m}{2} (-Q)}}{2 \frac{m}{2}} + 500 \text{ yr} \quad (4-8)$$

Rejecting the negative root of Equation 4-8, we have a time of 850 years to fill the ICDF. Therefore, at 850 years, the waste is fully saturated and this water is allowed to drain from the facility into the vadose zone. This condition is not readily modeled in MCM because the saturated conditions in the

waste resulted in a water flux through the bentonite clay liner that greatly exceeds the saturated hydraulic conductivity of the material. Therefore, for this case, the hydraulic properties of the bentonite clay layer are assumed to be compromised, allowing the water in the waste to pass freely through. However, the sorption characteristics of the bentonite clay are assumed to be unaltered. Therefore, for this case, hydraulic properties of the bentonite clay layer are assumed to be high-permeability alluvium, and the sorption coefficients are assumed to be those used in the base case.

The all-pathways dose for Case 6 is illustrated in Figure 4-19. Dose during the compliance time increases (from 0.0008 to 0.0025 mrem/year) by a factor of 3 over the base case dose and slightly decreases (from 0.58 to 0.53 mrem/year) during the post-compliance period. The increase in dose during the compliance period is in part from the increase in mass flux from the flushing of the pooled water in the ICDF and partially from the decrease in travel time to the aquifer. However, since the bottom liner fails 150 years before the end of the compliance period, the decrease in travel time is relatively small. The decrease in the dose during the post-compliance period is due to earlier arrival of the more mobile radionuclides during the compliance time.

4.6.7 One-Factor-at-a-Time Sensitivity Analysis: Case 7

Case 7 considered the failure of the liner underlying the waste after the facility completely fills with water, assuming the cap fails after 100 years. While the cover remains intact for 100 years, little water enters the facility because the net infiltration is 0.01 cm/year (0.0001 m/year). After complete cover failure 100 years following facility closure, infiltration through the facility is two orders of magnitude higher at 1 cm/year (0.01 m/year). This sensitivity analysis case is similar to Case 6; however, the ICDF fills with water and releases it to the vadose zone much sooner in this case.

As with Case 6, for this sensitivity case, ICDF is assumed to represent a rectangular volume with a height of 10.4 m. In reality, the sides of the ICDF are sloped, so that the total volume of water necessary to fill the facility is slightly greater than this estimate. Therefore, this estimate is considered conservative. The total porosity of the waste in the facility is 0.266 (Table 3-3), and, at the start of institutional control, the waste is estimated to have a moisture content of 0.14 (see Figure 4-1). Therefore, the height of a column of water necessary to fill the ICDF is given by

$$h = 10.4 \text{ m} \times (0.266 - 0.14) = 1.3 \text{ m} \quad (4-3)$$

For this sensitivity case, virtually no water is assumed to accumulate in the first 100 years at an infiltration rate of 0.01 cm/year (0.0001 m/year), but water accumulates fairly quickly starting in 100 years when the cap fails and the infiltration rate increases to 1 cm/year (0.01 m/year). To accumulate 1.3 m of water with an infiltration rate of 1 cm/year (0.01 m/year) will take 130 years. Therefore, 230 years after closure, the ICDF will be filled with water based on the assumptions of this sensitivity case. The liner is then assumed to fail, and this water is allowed to drain from the facility into the vadose zone when the facility is completely saturated 230 years after closure.

As with Sensitivity Case 6, this condition is not readily modeled in MCM because the saturated conditions in the waste resulted in a water flux through the bentonite clay liner that greatly exceeds the saturated hydraulic conductivity of the material. Therefore, for this case, the hydraulic properties of the bentonite clay layer are assumed to be compromised, allowing the water in the waste to pass freely through. However, the sorption characteristics of the bentonite clay are assumed to be unaltered. Therefore, for this case, hydraulic properties of the bentonite clay layer are assumed to be high-permeability alluvium, and the sorption coefficients are assumed to be those used in the base case.

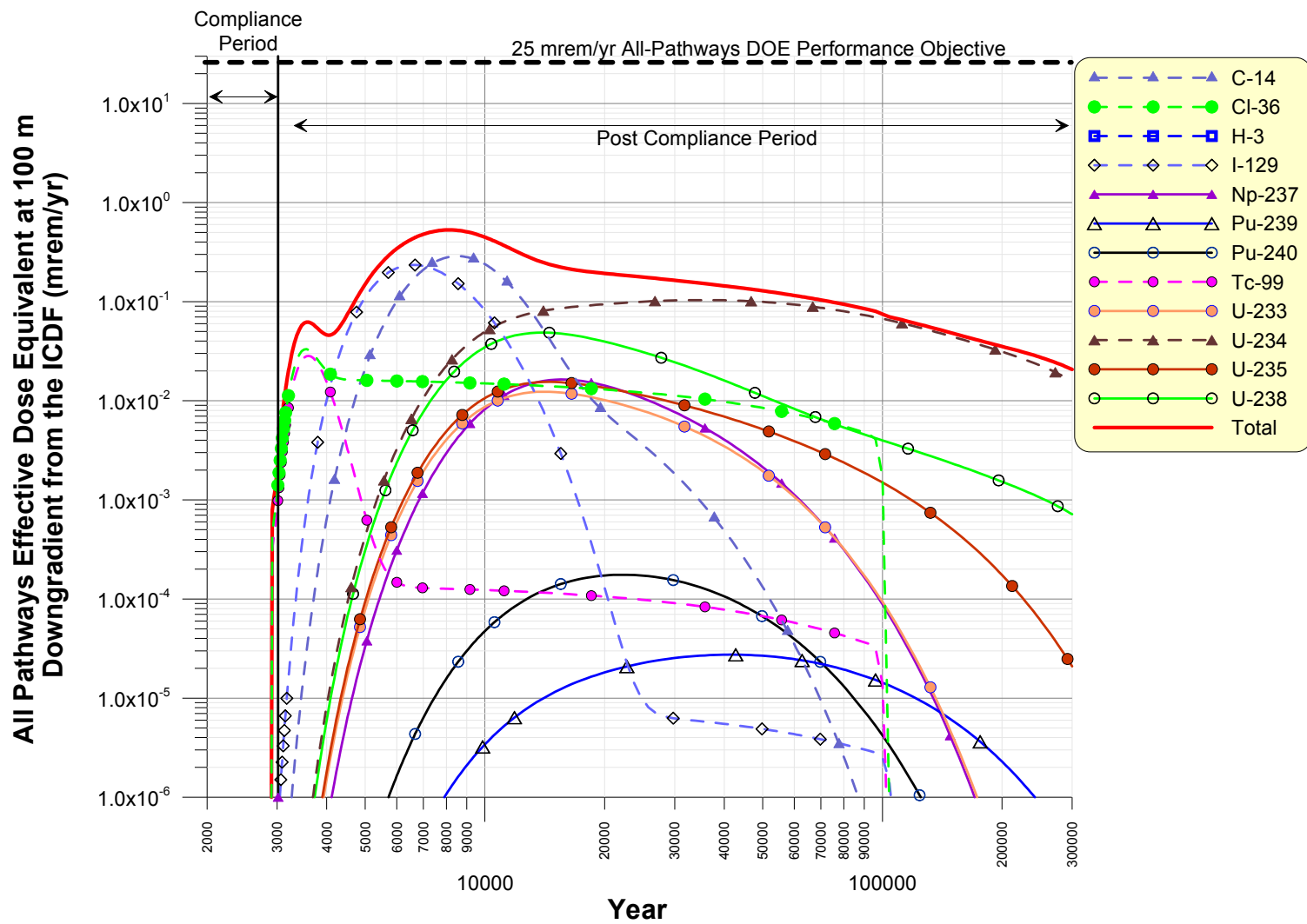


Figure 4-19. All-pathways dose as a function of time at the 100-m receptor for Case 6: failure of the liner after the facility fills with water in 850 years.

The all-pathways dose for Case 7 is illustrated in Figure 4-20. The maximum predicted all-pathways EDE calculated during the compliance time increases by a factor of 57 (from 0.0008 to 0.046 mrem/year) over the base case dose and slightly decreases (from 0.58 to 0.55 mrem/year) during the post-compliance period. The increase in dose during the compliance period is in part from the increase in mass flux from the flushing of the pooled water in the ICDF and partially from the decrease in travel time to the aquifer. Since the bottom liner fails 670 years before the end of the compliance period, the influence on the doses calculated during the compliance period are significant. The decrease in the dose during the post-compliance period is due to earlier arrival of the more mobile radionuclides during the compliance time.

4.6.8 One-Factor-at-a-Time Sensitivity Analysis: Case 8

The base case scenario assumes that the hydrologic liner will fail relatively soon after closure of the facility. Several other sensitivity cases (Cases 3, 6, and 7) considered the failure of the liner after the facility contains water. In this sensitivity case, the liner is assumed to never fail, resulting in overflow of the facility.

The time needed for the facility to completely fill with water was estimated to be 850 years, consistent with the assumptions in Sensitivity Case 6. For this case, since the HDPE liner is assumed not to fail, water was assumed to spill over one side of the ICDF and spread laterally 20 m beyond the side. The water is assumed to spill over the side of the ICDF that is parallel to groundwater flow (length is 160 m). For simplicity, the net infiltration through the cover is assumed to be 1 cm/year after the facility overflows 850 years after closure. The volume of water that spills over the side is estimated by:

$$160 \text{ m} \times 194 \text{ m} \times 0.01 \text{ m/yr} = 310 \text{ m}^3/\text{yr}.$$

The net infiltration rate of the spilled water is then

$$310 \text{ m}^3/\text{yr} / (160 \text{ m} \times 20 \text{ m}) = 0.097 \text{ m/yr}.$$

As the water moves through the vadose zone, some lateral spreading is also assumed, resulting in a 160-m $\times$ 40-m footprint at the aquifer where the 160-m length is parallel to groundwater flow. Assuming water spills over the side of the ICDF that is parallel to groundwater flow is conservative relative to assuming it spills over the side that is perpendicular to groundwater flow.

The radionuclide concentration in ICDF pore water is

$$C = \frac{Q}{L \times W \times T \times \theta \times Rd}$$

Where

Q = the inventory

L, W, T = the length, width, and thickness of the facility respectively (m)

θ = the moisture content

Rd = the retardation factor.

The radionuclide flux leaving the facility in the overflow water is

$$F = \frac{Q}{L \times W \times T \times \theta \times Rd} \times q(L \times W) = \frac{Q q}{T \theta Rd}$$

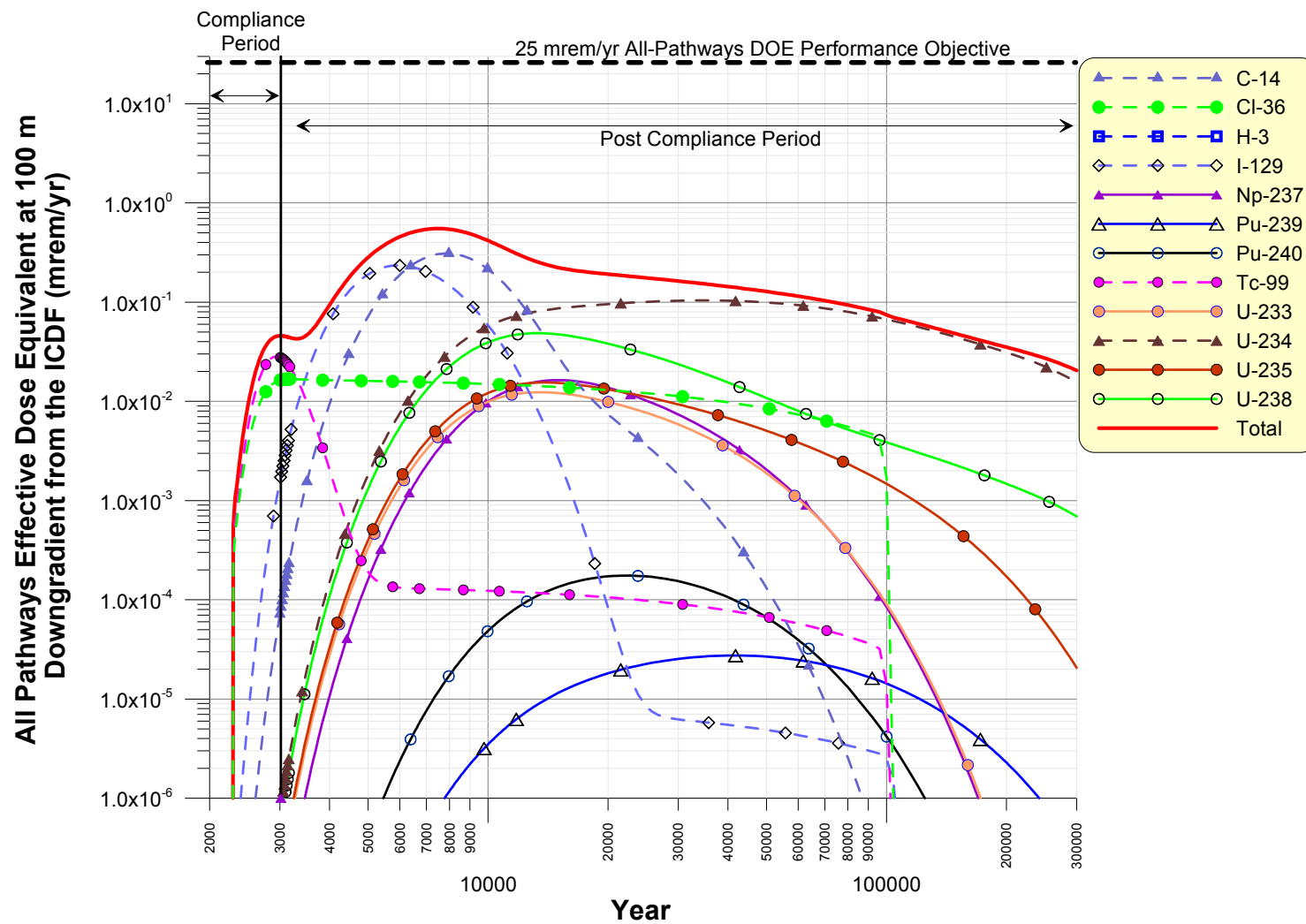


Figure 4-20. All-pathways dose as a function of time at the 100-m receptor for Case 7: failure of the liner after the facility fills with water after 230 years.

Where

q = the infiltration rate through the cover (0.01 m/year).

This flux is then applied as an exogenous source to a 160-m $\times$ 20-m area that has a net infiltration of 0.097 m/year. The MCM simulation includes the base case source and vadose zone models where the waste and bentonite clay layer have been replaced by high-permeability alluvium.

The all-pathways dose for Case 8 is illustrated in Figure 4-21. The maximum predicted all-pathways EDE calculated during the compliance time increases by a factor of 725 (from 0.0008 to 0.58 mrem/year) over the base case dose. During the post-compliance period, the maximum predicted all-pathways EDE increased by a factor of 13 (0.58 to 7.8 mrem/year) over the base case dose.

The increase in dose over the base case results during both the compliance and post-compliance periods are the result of:

- The contaminated water is assumed to enter the aquifer over an area about one-fifth the area assumed in the base case.
- Since the infiltrating water overflows the edge of the ICDF, it does not pass through the bentonite clay layer and, therefore, is not retarded by the higher K_d values in the clay.
- Water transit time (and radionuclide transit time) in the vadose zone is almost a factor of 10 higher because of focused infiltration (0.01 m/year compared to 0.097 m/year). In particular, very little of the C-14 decays in the vadose zone compared to the base case because the travel time to the aquifer is significantly reduced and the half life of C-14 is relatively short.

The contaminated area of the aquifer for this case is significantly smaller than the base case area and, as the plume moves downgradient, it will disperse and the concentrations will decrease at a faster rate than the base case.

4.6.9 Summary of One-Factor-at-a-Time Sensitivity Analysis

Table 4-7 summarizes the one-factor-at-a-time sensitivity analysis for the eight cases and the base case. Doses are evaluated at the 100-m receptor in all cases. Maximum doses in all cases are below the DOE performance objective of 25 mrem/year at any time in the future and are extremely small during the compliance period.

4.6.10 Parametric Uncertainty Analysis

A parametric uncertainty analysis quantifies the variability in model output resulting from variability in the model parameters. It is a measure of the precision of the model and cannot address the overall accuracy of the predictions. Numerous synonyms exist in the literature for this type of analysis, including error propagation (Gardner et al. 1980), impression analysis (Schwarz and Hoffman 1981), and statistical sensitivity analysis (Shaeffer 1980). The terminology adopted by Hoffman and Gardner (1983) is used in this document. As defined in Hoffman and Gardner (1983), a parametric uncertainty analysis is applicable when the structure of the model is relatively unbiased.

Parametric uncertainty was evaluated using Monte Carlo simulation combined with simple random sampling techniques. Uncertainty is expressed in terms of a probability density function of the output variable. Information provided by the uncertainty analysis was also used to do the sensitivity analysis. Model sensitivity was evaluated by calculating the rank correlation between the distribution of the output variable and each input parameter distribution.

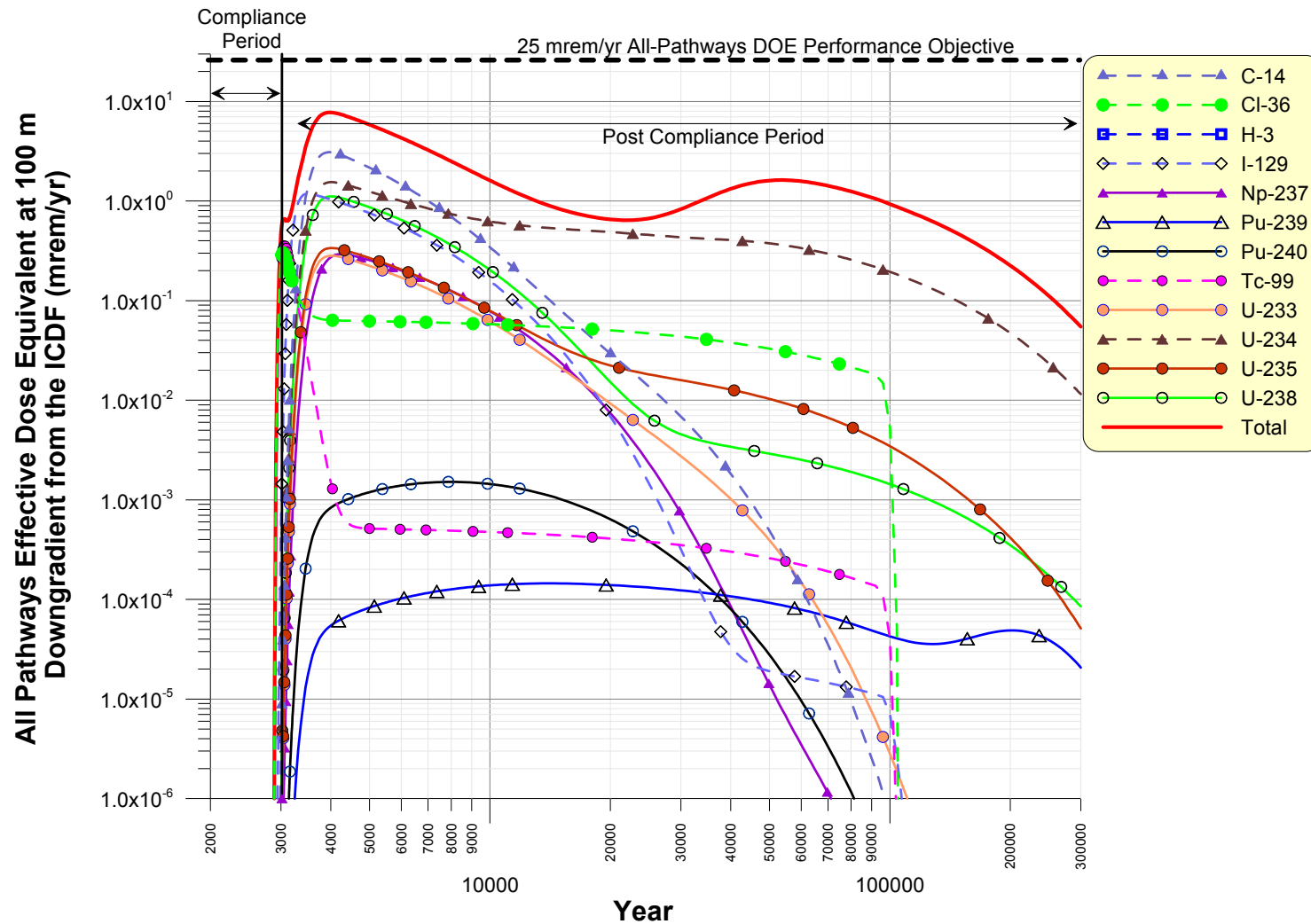


Figure 4-21. All-pathways dose as a function of time at the 100-m receptor for Case 8: liner does not fail. ICDF fills with water in 850 years and then overflows.

Parametric uncertainty analysis uses an estimated frequency distribution of values for each model parameter considered to be uncertain and produces a frequency distribution of model predictions. In Monte Carlo simulation, parameter values are randomly sampled from distributions developed by the analyst. The model is then run and the output variable stored. The process is repeated for multiple model realizations (typically greater than 100), resulting in an empirical distribution of the output variable. A Perl^e script was used as the Monte Carlo driver for the simulation and performed the following functions for each Monte Carlo trial:

- Sampled parameter values from assigned distributions
- Wrote MCM and GWSCREEN input files for each of the radionuclides
- Executed MCM and GWSCREEN models for each radionuclide
- Extracted and stored concentrations and doses at specific times from the GWSCREEN output
- Computed statistics of the total all-pathways dose output.

Hydrologic properties of the unsaturated materials were held constant in the analysis. Uncertainty was also not evaluated for the all-pathways exposure scenario or dose conversion factors. Uncertainty distributions were assigned to the infiltration rate through the cover, the infiltration rate after the cover failed, the time the cover remains intact (i.e., cover longevity), K_d values, radionuclide inventory, and aquifer flow and transport parameters. Uncertainty in the waste inventory was implemented through scaling factors. The corrosion rate constant for activated metals was not examined specifically because the dose contribution from activated metals was small. Instead, the amount of activity assigned to activated metals was considered uncertain.

Radionuclides included in the parametric uncertainty analysis were primary dose contributors during the compliance and post-compliance periods. These radionuclides were C-14, Cl-36, I-129, Tc-99, U-234, and U-238. For C-14, Cl-36, I-129, and Tc-99, only the contaminated soils inventory (not the activated metal) was included in the uncertainty analysis.

4.6.10.1 Parameter Distributions. Ideally, parameter distributions should be derived from site-specific measurements and information. In practice, parameter values are often inferred from limited measured data or derived from the literature. Additionally, model parameters may represent time and space scales that differ greatly from what can be measured in the field or laboratory. Natural variability also contributes to parameter uncertainty. The choice of a deterministic parameter value or its distribution is ultimately determined by the judgment of the analyst and is therefore considered to have an element of subjectivity. A distribution selected in this manner is essentially a statement of the analyst's belief that the parameter's true but unknown value lies within the stated distribution.

While the overall structure of the model presented here is believed to be unbiased, some of the deterministic input parameters were selected on the end of the distribution of possible values. These parameters include the sorption coefficients for chlorine and technetium and the cover infiltration rate. The choice of these parameter values tended to either bias doses high or low.

Parameter distributions used in the uncertainty analysis are presented in Table 4-8. In general, if sufficient data existed, then parameter distributions were constructed from relevant site-specific or literature data. The input parameters used for the deterministic base case calculations (see Section 3.2) were assumed to be the mode or central value for most parameter distributions. If relevant data were not available (such as the case with the longevity of the cover), then a distribution was assumed.

e. Perl (Practical Extraction Reporting Language) is a scripting language available on most Unix workstations and recently made available for Microsoft Windows-based machines.

Table 4-8. Parameter distributions used in the parameter uncertainty analysis.

Parameter	Distribution	Comments/Reference
Inventory scaling factor	Triangular: minimum 0.5, mode 1.0, maximum 2	Assumed to be $\pm$ a factor of 2 between deterministic value.
Engineered cover (cap) longevity (year)	Triangular: minimum 100 years, mode 500 years, maximum 1,000 years	Assumed. The minimum is equal to the end of institutional control (2118). The maximum was selected at the end of the compliance period (3018).
Engineered cover (cap) infiltration rate (m/yr)	Log-Uniform: minimum 0.0001, maximum 0.01	Assumed. The minimum is the deterministic value. The maximum was selected as the background infiltration rate (1 cm/yr).
Infiltration rate through engineered cover (cap) after failure (m/yr)	Triangular: minimum 0.005, mode 0.01, maximum 0.02	Assumed to be $\pm$ a factor of 2 from the deterministic value.
Longitudinal dispersivity in aquifer (m) ^a	Triangular: minimum 1.65, mode 3.31, maximum 6.62	Assumed to be $\pm$ a factor of 2 from the deterministic value.
Darcy velocity in aquifer (m/yr)	Triangular: minimum 10.9, mode 21.9, maximum 31.9	Based on variability of Darcy velocity in the INTEC area.
Iodine K_d (mL/g), alluvium and waste	Lognormal: GM 1.5, GSD 2.84	Based on range of values (0.04–8.7) in OU 3-14 RI/BRA (Cahn et al. 2006).
Iodine K_d (mL/g), clay	Lognormal: GM 1.0, GSD 1.7	GM value is the deterministic value; GSD is based on Sheppard and Thibault (1990).
Iodine K_d (mL/g), interbed	Lognormal: GM 0.7, GSD 2.3	Based on range of values (0.04 to 3 mL/g) in OU 3-14 RI/BRA (Cahn et al. 2006).
Technetium K_d (mL/g), alluvium, waste, and interbed	Exponential: $r = 27$	Based on range of values (-0.1 to 1.4 mL/g) in OU 3-14 RI/BRA (Cahn et al. 2006).
Technetium K_d (mL/g), clay	Lognormal: GM 1.0, GSD 1.03	GM value is the deterministic value; GSD is based on Sheppard and Thibault (1990).
Carbon K_d (mL/g), alluvium, waste, and interbed	Lognormal: GM 1.6, GSD 1.4	Based on range of values (0.5 to 2.8) in OU 3-14 RI/BRA (Cahn et al. 2006).
Carbon K_d (mL/g), clay	Lognormal: GM 1.0, GSD 2	GM value is the deterministic value. GSD not available in Sheppard and Thibault (1990) so assumed to be a value of 2.
Uranium K_d (mL/g), alluvium, waste, and interbed	Lognormal: GM 1.6, GSD 2.44	Based on range of values (0.12-12) in OU 3-14 RI/BRA (Cahn et al. 2006).
Uranium K_d (mL/g), clay	Lognormal: GM 63, GSD 3	GM value is the deterministic value; GSD is based on Sheppard and Thibault (1990).
Thorium K_d (mL/g), alluvium, waste, and interbed	Lognormal: GM 100, GSD 1.94	GM value is the deterministic value; GSD is based on Sheppard and Thibault (1990).
Thorium K_d (mL/g), clay	Lognormal: GM 1,700, GSD 3	GM value is the deterministic value; GSD is based on Sheppard and Thibault (1990).

Table 4-8. (continued).

Parameter	Distribution	Comments/Reference
Radium K_d (mL/g), alluvium, waste, and interbed	Lognormal: GM 100, GSD 6.3	GM value is the deterministic value; GSD is based on Sheppard and Thibault (1990).
Radium K_d (mL/g), clay	Lognormal: GM 9,100, GSD 1.6	GM value is the deterministic value; GSD is based on Sheppard and Thibault (1990).
Lead K_d (mL/g), alluvium, waste, and interbed	Lognormal: GM 550, GSD 3.8	GM value is the deterministic value; GSD is based on Sheppard and Thibault (1990).
Lead K_d (mL/g), clay	Lognormal: GM 700, GSD 2	GM value is the deterministic value. GSD not available in Sheppard and Thibault (1990) so assumed to be a value of 2.

a. The transverse and vertical dispersivities were correlated to the longitudinal dispersivity. The transverse dispersivity was $0.2 \times$ the longitudinal dispersivity. The vertical dispersivity was $0.00116 \times$ the longitudinal dispersivity. The factors for transverse and vertical dispersivities were based on Whelan, McDonald, and Sato (1996).

BRA baseline risk assessment
GM geometric mean
GSD geometric standard deviation
INTEC Idaho Nuclear Technology and Engineering Center
OU operable unit
RI remedial investigation

4.6.10.1.1 Inventory Scaling Factor—The ICDF inventory used in the base case represents a “best estimate” or central value of an unknown distribution of possible values. For this assessment, a multiplicative scaling factor was used to define the uncertainty in the source term. The scaling factor was nuclide-independent and was assigned an assumed triangular distribution where the mode was 1.0 and the minimum and maximum represented $\pm$ a factor of 2. A factor of 2 was chosen as a reasonable bound on the inventory uncertainty based on the fact the landfill is 60% full with known characterized waste, the projected inventory is relatively well defined, and a large change in the inventory projection is not expected. The product of the sampled scaling factor and the base case inventory provided an inventory estimate for a given realization. Activated metals were not included in the assessment because the release rate from activated metals is much lower compared to releases from radionuclides in soil.

4.6.10.1.2 Engineered Cover Longevity—Uncertainty was considered in the longevity of cover integrity. That is, the time in which the cover remains an effective infiltration barrier was considered to be an uncertain input parameter. The distribution used in the uncertainty analysis was assumed by the analyst. It was not based on engineering studies of the cover. The cover was assumed to degrade over a period equal to the longevity of the cover. For example, if the cover longevity is equal to 500 years, then the cover degraded to natural conditions in 1,000 years in the analysis. The minimum cover longevity (100 years) was assumed to be equal to the end of institutional control in 2118. The maximum cover longevity (1,000 years) was selected to include the compliance time of 1,000 years. A triangular distribution was assumed having a minimum of 100 years, a mode of 500 years, and a maximum of 1,000 years.

4.6.10.1.3 Infiltration After Cover Failure—After cover failure, the infiltration rate was assumed to return to background conditions. Background infiltration rates in undisturbed soils have been estimated to range between 0.4 and 1.2 cm/year (Cecil et al. 1992). A value of 1 cm/year was used

for the deterministic calculations. A factor of two uncertainty was assumed for the background infiltration rate, which approximately bounds the range of infiltration rates reported by Cecil et al. (1992).

4.6.10.1.4 Longitudinal Dispersivity in Aquifer—Dispersivity is a parameter that describes the spreading that occurs from mechanical mixing as a result of the tortuous path that fluid follows in a porous medium. For the 2003 ICDF PA, aquifer dispersivity was used as a means of calibrating the GWSCREEN model to STOMP output. In this PA, the calibrated value of 3.31 m was used as the deterministic value. A triangular distribution was assigned having a mode equal to the base case value, and a minimum and maximum of 1.65 m and 6.62 m, respectively (factor of two uncertainty). To keep the relative proportions of transverse and vertical-to-longitudinal dispersion constant, the ratios of these values for the base case condition ($\alpha_T/\alpha_L = 0.20$, $\alpha_V/\alpha_L = 0.00116$) were multiplied by the sampled α_L value to computed values for α_T and α_V .

4.6.10.1.5 Darcy Velocity in Aquifer—The Darcy velocity in the aquifer was assigned a deterministic value of 21.9 m/year. The OU 10-08 Site-wide groundwater model (DOE-ID 2008d) showed the Darcy velocity in the ICDF region to vary from 10.9 to 31.9 m/year. This range was used as the basis for assigning uncertainty to the Darcy velocity. A triangular distribution having a mode of 21.9 m/year, a minimum value of 10.9 m/year, and a maximum value of 31.9 m/year was used in the simulation.

4.6.10.1.6 Sorption Coefficients (K_d)—Distributions of sorption coefficients were assumed to be uncertain parameters for the waste soils, alluvium, and vadose zone interbeds. The sorption coefficient in unsaturated basalt and the aquifer was assumed to be zero for all radionuclides. Lognormal distributions were assigned in all cases except for Tc-99 in waste and interbed materials. Lognormal distributions are appropriate when the range of possible parameter values spans orders of magnitude, as is the case with most sorption coefficient data.

The geometric mean was assumed to be the deterministic value. The geometric standard deviation (GSD) was based on the distribution of measured K_d values either in the OU 3-14 RI/BRA (Cahn et al. 2006), or, if K_d s were not provided in this reference, the GSD was defined based on the GSD of the distribution reported in Sheppard and Thibault (1990) for a given lithology. Deterministic K_d values for clay were obtained from DOE-ID (2003a), which relied in part on Sheppard and Thibault (1990). Sorption coefficient distributions in alluvium and waste soil for Ra, Th, and Pb (all daughter products of U-238 and U-234) were also obtained from Sheppard and Thibault (1990).

The range of K_d values reported in Cahn et al. (2006) was assumed to represent the 1st and 99th percentile of a lognormal distribution. The central value was assumed to represent the geometric mean. The geometric standard deviation of this distribution can be estimated as follows:

$$GSD = \exp \left(\frac{\ln \left(\frac{99th}{1st} \right)}{2t} \right) \quad (4-9)$$

Where

- 99th = 99th percentile of the distribution
- 1st = 1st percentile of the distribution
- t = t-statistic for $\alpha = 0.01$, and $n = \infty$ (2.576).

In the case of Tc-99, the lower-bound K_d was less than zero, which is not compatible with the sorption model in MCM or GWSCREEN (i.e., the K_d value must be greater than or equal to zero). Furthermore, a K_d value less than or equal to zero cannot be simulated in a lognormal distribution. For this reason, an exponential distribution was assigned to Tc-99 in waste soils and interbeds. The exponential distribution is typically used to describe the time between occurrences of an event. However, its shape and properties work well in this particular application because the deterministic value represents the minimum of the distribution. In an exponential distribution, the highest probability density is skewed toward zero. The probability is defined by

$$p = 1 - \exp(-rx) \quad (4-10)$$

Where

r = rate constant
 x = the value of the variable.

The single parameter of the distribution is the rate constant r . It is assumed that the maximum of the range of K_d values ($x = 0.4$ mL/g) represents the 99.9th percentile ($p = 0.001$). Equation 4-10 was then solved for r , yielding a value of 17.27.

For clay materials and those radionuclides that did not have a K_d value provided in Cahn et al. (2006), the GSD of the distribution was defined by the distribution of values in Sheppard and Thibault (1990). Waste and interbed materials were assumed to be similar to sand. Sheppard and Thibault (1990) report the standard deviation of sorption coefficient logarithms in their results. This value can be converted to a GSD by taking its exponent. This GSD represents the GSD of the population. However, what is needed is the GSD of the estimate of the mean. The GSD of the geometric means is then given by:

$$GSD_{\mu} = \exp\left(\frac{\sigma}{\sqrt{n}}\right) \quad (4-11)$$

Where

σ = standard deviation of the natural logarithms
 n = number of observations.

If the K_d value was the same for waste and interbed, then the sampled value was correlated between these two lithologies. That is, the waste and interbed were assigned that same sampled value in a given realization of the model. Only iodine had different waste and interbed K_d values, and these values were treated independently in the sampling.

4.6.10.2 Parametric Uncertainty Analysis Results. The parameter uncertainty analysis output variable was the all-pathways EDE at specific times after 2018. Output distributions of individual radionuclide concentrations and individual radionuclide doses are available electronically.

Distributions of model output were developed from 1,000 model realizations. This was deemed to be a sufficient number of realizations to reflect the potential range of results. A confidence interval around percentiles of the output distribution was defined using a distribution-free approach developed in Hahn and Meeker (1991). The approach developed by Hahn and Meeker (1991) uses ordered statistics to define an interval where the true value of a given percentile lies at a specified level of confidence. In this way, confidence for any given percentile within the distribution could be defined. Of particular interest

are the tails of the distribution, because values at the tails (i.e., top and bottom) of the distribution change more with the number of model realizations; central values are more stable. The ordered statistics for the 5th and 95th percentiles for 1,000 model realizations are 50 and 950, respectively. That is, if the output values for 1,000 realizations are sorted in ascending order, the 5th percentile represents the 50th highest value; the 95th percentile represents the 950th highest value. The 95% confidence interval around the 5th percentile in terms of the ordered statistics is 37 and 64. The 95% confidence interval around the 95th percentile in terms of the ordered statistics is 936 and 963. This was interpreted to mean a 95% confidence that 90% of the model output lies between the ordered statistics 37 and 963.

A summary of the sampled parameters (Table 4-9) shows that mean and median values of the assigned distributions were well represented by the sampled distributions for log-normally distributed parameters. For unsymmetrical triangular distributions, the mean and median values tended to be slightly higher than the mode value. However, for symmetric triangular distributions, the mode was well represented by the mean value of the sampled distribution.

Table 4-9. Statistics of the sampled parameter distributions for 1,000 model realizations.

Parameter	Minimum	Maximum	Mean	Median
Inventory scaling factor ^a	0.52	1.96	1.16	1.13
Engineered cover (cap) longevity (year)	118	987	535	526
Engineered cover (cap) infiltration rate (m/year)	0.0001	0.0099	0.0022	0.00099
Infiltration rate through engineered cover (cap) after failure (m/year)	0.0053	0.0195	0.017	0.011
Longitudinal dispersivity in aquifer (m) ^a	1.74	6.57	3.87	3.78
Darcy velocity in aquifer (m/year)	9.14	34.7	22.0	22.1
Iodine K _d (mL/g), alluvium and waste	0.184	12.7	2.21	1.48
Iodine K _d (mL/g), clay	0.21	4.75	1.16	1.01
Iodine K _d (mL/g), interbed	0.11	4.77	0.91	0.70
Technetium K _d (mL/g), alluvium, waste, and interbed	5.7E-05	0.41	0.057	0.040
Technetium K _d (mL/g), clay	0.91	1.1	1.0	0.999
Carbon K _d (mL/g), alluvium, waste, and interbed	0.51	4.51	1.7	1.6
Carbon K _d (mL/g), clay	0.18	5.36	1.20	0.98
Uranium K _d (mL/g), alluvium, waste, and interbed	0.22	11.6	2.27	1.67
Uranium K _d (mL/g), clay	7.04	546	95.6	59.4
Thorium K _d (mL/g), alluvium, waste, and interbed	17.4	558	121	96.8
Thorium K _d (mL/g), clay	182	15,400	2,590	1,650
Radium K _d (mL/g), alluvium, waste, and interbed	5.33	1,890	243	103
Radium K _d (mL/g), clay	1,970	41,700	10,600	9,360
Lead K _d (mL/g), alluvium, waste, and interbed	48.3	6,250	908	516
Lead K _d (mL/g), clay	124	3,860	870	692

a. The inventory scaling factor was sampled independently for each radionuclide.

Histograms of several key parameters are illustrated in Figures 4-22 and 4-23.

Distributions of radionuclide concentrations at four output times (years 3018, 4018, 5018, and 7018) are summarized in terms of five percentile values: 5th, 25th, 50th, 75th, and 95th percentile (Tables 4-10 and 4-11). During the 1,000-year compliance timeframe, no model realizations had radionuclide concentrations exceeding MCLs. After the compliance period in calendar year 4018 (2000 years after closure), 70 out of the 1,000 model realizations had I-129 concentrations slightly exceeding the 1-pCi/L MCL. In calendar year 5018 (3000 years after closure), 140 out of the 1,000 model realizations had I-129 concentrations slightly exceeding the 1-pCi/L MCL.

The distribution of all-pathways EDE as a function of time is illustrated in Figure 4-24. The uncertainty bounds (the shaded area on Figure 4-24) span from the 2.5th percentile to the 97.5th percentile and thus represent 95% of the output distribution. The span of the distribution (from 2.5% to 97.5%) ranges from up to five orders of magnitude during the compliance period to about an order of magnitude from year 8,000 to year 12,000. This span increases to almost two orders of magnitude in about year 30,000. The span of the distribution is partially in response to cover failure times.

Maximum 97.5th percentile doses during the compliance period were less than 0.1 mrem/year. Deterministic dose during this time roughly followed the median (50th percentile) of the distribution of predicted doses and has a maximum dose of 5E-03. Tables 4-12 and 4-13 show percentiles of the all-pathways EDE by nuclide for selected output times. The results indicate the all-pathways dose objective is unlikely to be exceeded even when uncertainty in model inputs is considered. The total dose reported in Tables 4-12 and 4-13 for a given percentile is not the sum of the individual radionuclide doses at the given percentile. Rather, the total dose at a given percentile is derived from the distribution of total doses that was calculated for each model realization.

4.6.11 Sensitivity Analysis

A quantitative and qualitative sensitivity analysis was performed using the data generated during the uncertainty analysis. In the approach presented here, the Monte Carlo sampling techniques described earlier were used to propagate input parameter uncertainty into the predicted dose estimates. The quantitative analysis uses the rank correlation coefficient computed between each parameter and the corresponding predicted dose. Parameter sensitivities are then established by the degree of correlation between the parameter and the output variable (predicted all-pathways EDE). The qualitative approach uses scatter plots of sampled values of a given parameter and the total all-pathways dose at a specific output time to illustrate the relationship between the parameter and the output variable.

The methods used to quantitatively evaluate parameter sensitivity are described in the Crystal Ball software package (Decisioneering Inc. 2000). The rank correlation coefficients provide a quantitative measure of the sensitivity of the predicted dose to variations in the input parameters. Rank correlation replaces each input parameter and end point value pair with its ranking within the distribution. Linear correlation of the rankings is then performed. Consider a simulation of n Monte Carlo trials where the parameters a , b , and c are defined stochastically. The output variable defined as y is calculated n times during the simulation. The results may be tabulated as follows:

a_1	b_1	c_1	$\Rightarrow$	y_1
a_2	b_2	c_2	$\Rightarrow$	y_2
a_3	b_3	c_3	$\Rightarrow$	y_3
a_n	b_n	c_n	$\Rightarrow$	y_n

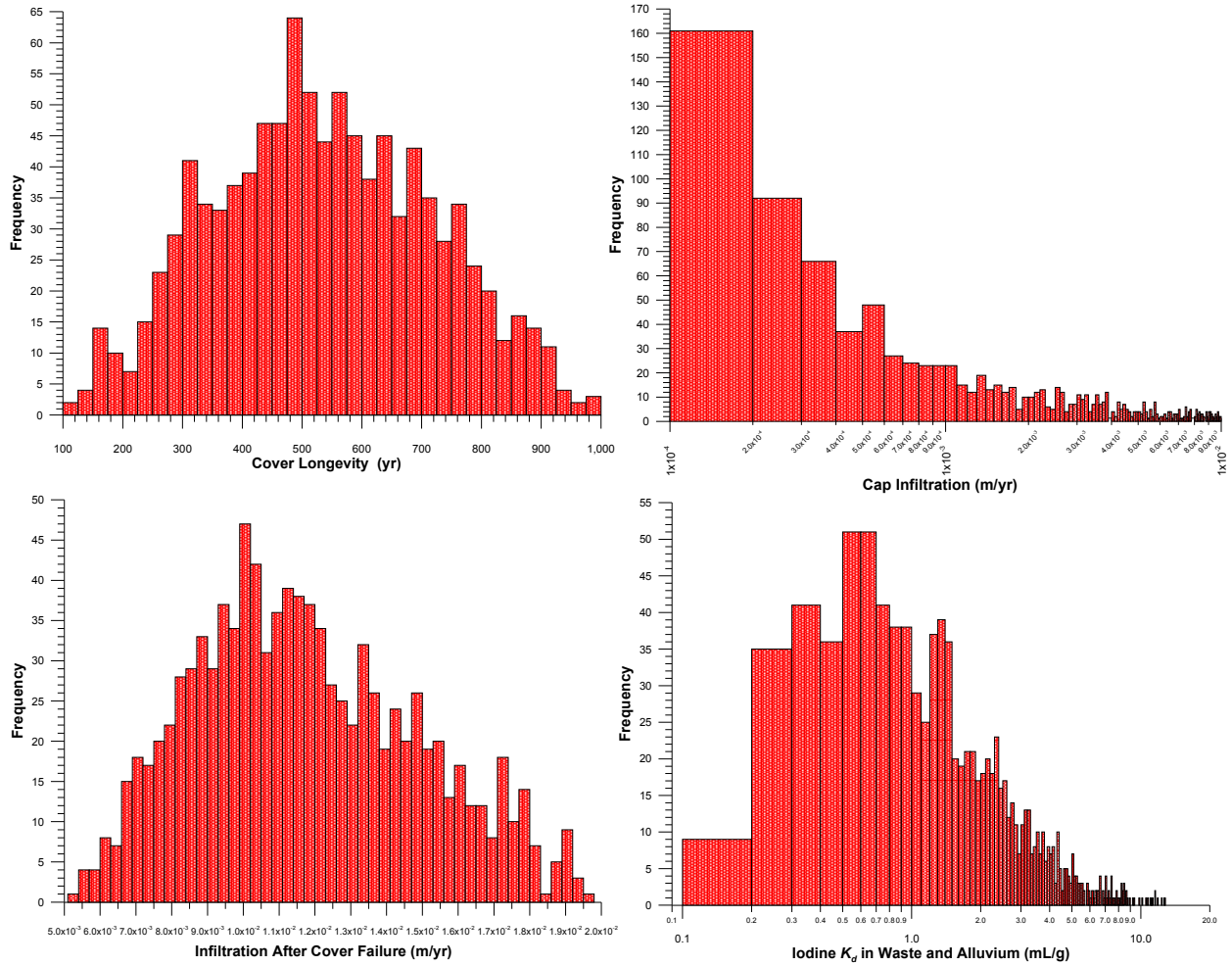


Figure 4-22. Histograms of sampled values for cover longevity, cap infiltration, infiltration after cap failure, and iodine K_d in waste and alluvium.

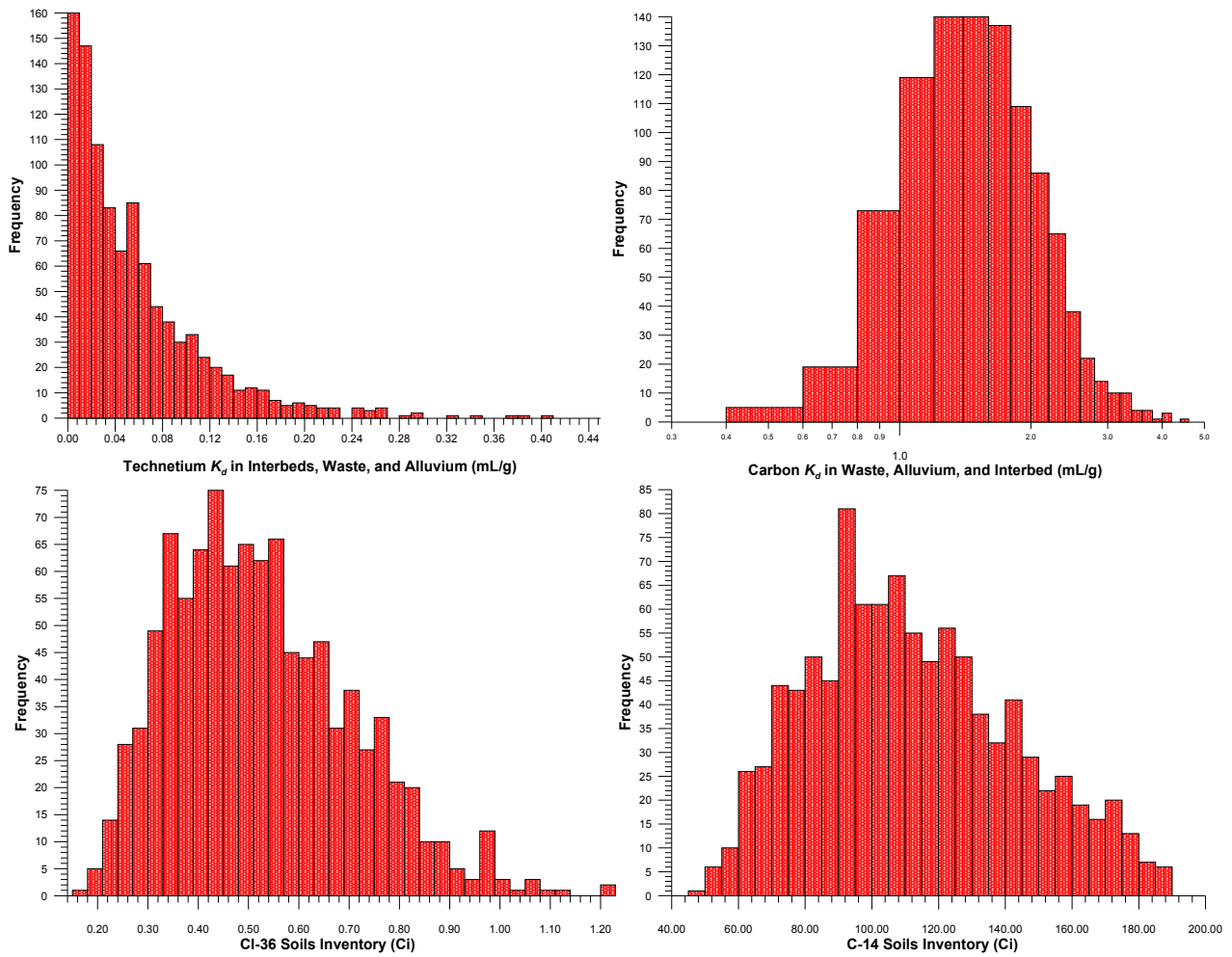


Figure 4-23. Histograms of sampled values for technetium K_d in waste, alluvium, and interbeds, carbon K_d in waste, alluvium, and interbeds, C1-36 soils inventory, and C-14 soils inventory.

Table 4-10. Percentiles of the distribution of groundwater concentrations for 1,000 and 2,000 years after landfill closure in 2018.

Radionuclide	Groundwater Concentration (pCi/L) 1,000 Years after Closure (Year 3018)					Groundwater Concentration (pCi/L) 2,000 Years after Closure (Year 4018)				
	Percentile					Percentile				
	5th	25th	50th	75th	95th	5th	25th	50th	75th	95th
C-14	4.35E-13	2.12E-09	4.93E-06	5.26E-04	6.83E-02	6.28E-04	3.68E-02	3.71E-01	3.28E+00	2.46E+01
Cl-36	7.36E-07	4.41E-04	1.43E-02	3.37E-02	6.19E-02	1.06E-06	4.32E-05	6.35E-04	4.86E-03	2.02E-02
I-129	5.98E-14	4.13E-10	1.23E-06	2.10E-04	1.80E-02	2.92E-05	2.43E-03	3.35E-02	2.27E-01	1.02E+00
Tc-99	1.18E-06	2.95E-03	6.92E-01	6.45E+00	1.53E+01	5.41E-02	7.50E-01	3.01E+00	6.50E+00	1.07E+01
U-234	5.69E-18	2.20E-13	5.52E-10	4.94E-07	2.82E-04	4.67E-09	1.89E-06	1.90E-04	6.67E-03	2.44E-01
Th-230	2.21E-21	3.20E-17	4.97E-14	3.70E-11	1.68E-08	5.40E-13	2.10E-10	1.61E-08	5.21E-07	1.64E-05
Ra-226	7.41E-23	4.06E-19	4.03E-16	2.11E-13	9.67E-11	1.50E-14	5.24E-12	3.40E-10	1.25E-08	5.13E-07
Pb-210	3.53E-23	1.50E-19	9.38E-17	4.58E-14	2.44E-11	6.79E-15	1.68E-12	1.03E-10	4.17E-09	1.68E-07
U-238	3.49E-18	1.42E-13	4.08E-10	3.01E-07	1.60E-04	2.85E-09	1.34E-06	1.32E-04	4.14E-03	1.10E-01
U-234	9.81E-21	3.98E-16	1.15E-12	8.76E-10	5.11E-07	1.60E-11	7.53E-09	7.41E-07	2.56E-05	7.47E-04
Th-230	4.41E-24	5.76E-20	9.81E-17	6.08E-14	2.57E-11	2.44E-15	7.77E-13	6.60E-11	1.82E-09	4.69E-08
Ra-226	1.37E-25	6.35E-22	6.81E-19	3.01E-16	1.24E-13	4.74E-17	1.76E-14	9.34E-13	4.26E-11	1.38E-09
Pb-210	5.34E-26	2.04E-22	1.54E-19	7.48E-17	2.85E-14	2.12E-17	6.31E-15	3.28E-13	1.35E-11	4.27E-10

Table 4-11. Percentiles of the distribution of groundwater concentrations for 3,000 and 5,000 years after landfill closure in 2018.

Radionuclide	Groundwater Concentration (pCi/L) 3,000 Years after Closure (Year 5018)					Groundwater Concentration (pCi/L) 5,000 Years after Disposal (Year 7018)				
	Percentile					Percentile				
	5th	25th	50th	75th	95th	5th	25th	50th	75th	95th
C-14	6.94E-02	1.68E+00	8.74E+00	4.17E+01	1.66E+02	2.56E+00	2.32E+01	5.66E+01	9.55E+01	1.56E+02
Cl-36	1.57E-12	7.69E-10	8.32E-08	3.47E-06	1.64E-04	1.89E-24	5.54E-20	3.28E-16	2.30E-13	4.52E-10
I-129	2.31E-03	5.33E-02	2.77E-01	7.18E-01	1.45E+00	1.90E-02	1.57E-01	3.27E-01	5.22E-01	9.04E-01
Tc-99	8.61E-06	8.59E-04	2.11E-02	2.87E-01	2.89E+00	1.03E-13	3.20E-10	1.12E-07	1.80E-05	6.18E-03
U-234	7.83E-07	2.13E-04	1.02E-02	1.47E-01	1.69E+00	6.50E-05	1.19E-02	2.06E-01	7.77E-01	2.23E+00
Th-230	1.63E-10	3.04E-08	1.19E-06	1.38E-05	1.57E-04	2.86E-08	3.10E-06	3.91E-05	1.55E-04	6.99E-04
Ra-226	9.16E-12	1.90E-09	5.78E-08	1.06E-06	2.73E-05	4.95E-09	4.20E-07	5.48E-06	3.70E-05	3.75E-04
Pb-210	4.48E-12	7.46E-10	2.08E-08	3.35E-07	6.65E-06	2.33E-09	2.16E-07	2.27E-06	1.45E-05	9.69E-05
U-238	5.24E-07	1.35E-04	6.86E-03	8.50E-02	9.69E-01	5.42E-05	8.49E-03	1.40E-01	4.93E-01	1.63E+00
U-234	4.41E-09	1.14E-06	5.83E-05	8.19E-04	9.07E-03	7.58E-07	1.19E-04	1.99E-03	7.15E-03	2.29E-02
Th-230	8.39E-13	1.66E-10	6.14E-09	7.39E-08	7.58E-07	2.55E-10	2.85E-08	3.28E-07	1.31E-06	5.25E-06
Ra-226	5.54E-14	9.92E-12	2.65E-10	4.90E-09	9.64E-08	4.02E-11	3.32E-09	4.02E-08	2.84E-07	2.41E-06
Pb-210	2.54E-14	3.56E-12	9.80E-11	1.64E-09	2.71E-08	1.99E-11	1.59E-09	1.75E-08	1.05E-07	6.27E-07

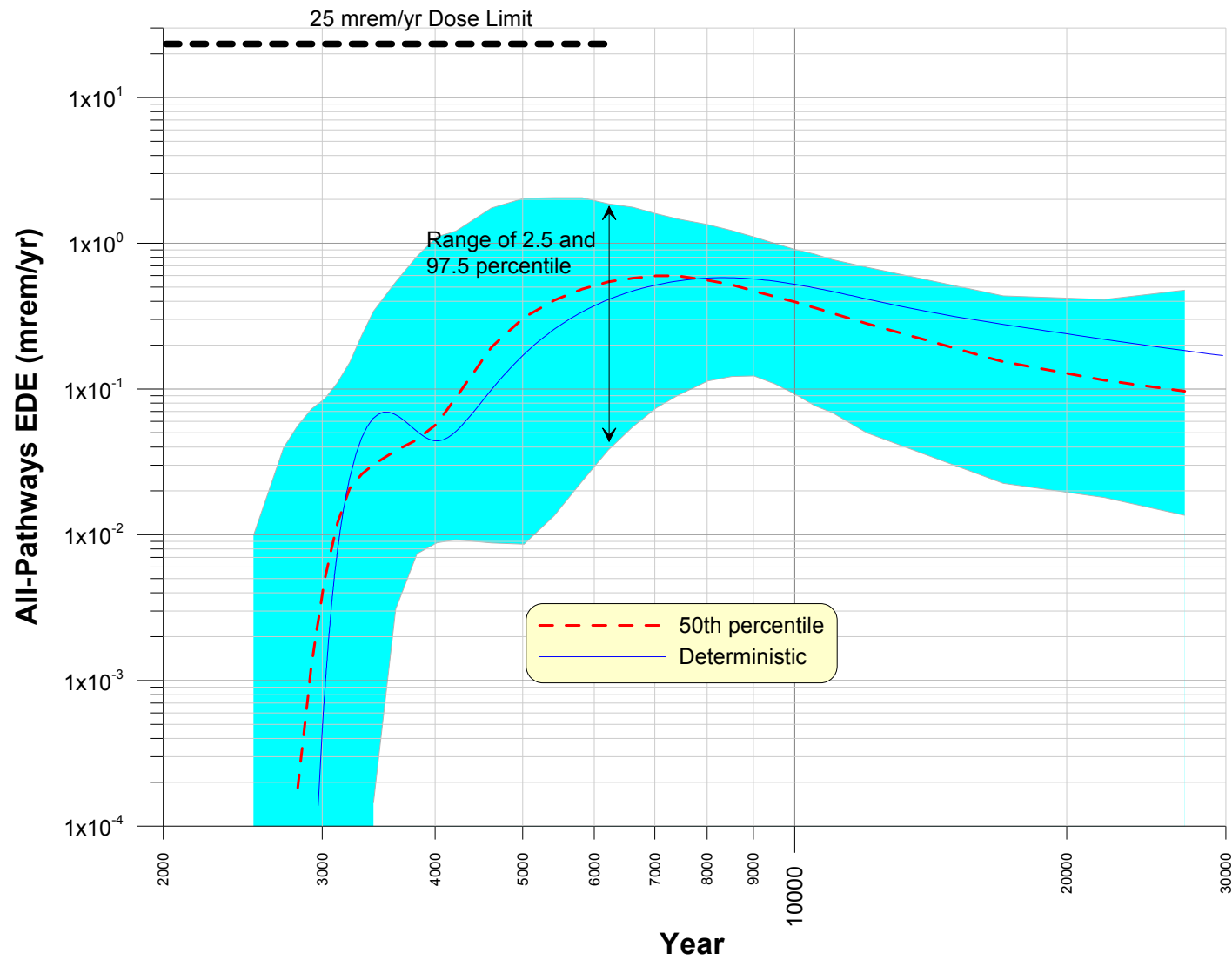


Figure 4-24. Stochastic simulation of the all-pathways effective dose equivalent as a function of calendar year 100 m downgradient from the Idaho CERCLA Disposal Facility Landfill.

Table 4-12. Percentiles of the distribution of all-pathways effective dose equivalent for 1,000 and 2,000 years after disposal in year 2018.

Radionuclide	All-Pathways Effective Dose Equivalent (mrem/year) 1,000 Years after Closure (Year 3018)					All-Pathways Effective Dose Equivalent (mrem/year) 2,000 Years after Closure (Year 4018)				
	Percentile					Percentile				
	5th	25th	50th	75th	95th	5th	25th	50th	75th	95th
C-14	2.42E-15	1.18E-11	2.73E-08	2.92E-06	3.79E-04	3.48E-06	2.04E-04	2.06E-03	1.82E-02	2.12E-01
Cl-36	9.13E-08	5.46E-05	1.77E-03	4.18E-03	7.68E-03	1.31E-07	5.36E-06	7.87E-05	6.02E-04	3.05E-03
I-129	2.72E-14	1.87E-10	5.59E-07	9.55E-05	8.18E-03	1.32E-05	1.10E-03	1.52E-02	1.03E-01	5.78E-01
Tc-99	3.97E-09	9.93E-06	2.33E-03	2.17E-02	5.17E-02	1.82E-04	2.53E-03	1.01E-02	2.19E-02	3.96E-02
U-234	8.31E-19	3.21E-14	8.05E-11	7.21E-08	4.11E-05	6.82E-10	2.76E-07	2.77E-05	9.73E-04	5.41E-02
Th-230	1.33E-21	1.94E-17	3.01E-14	2.24E-11	1.02E-08	3.27E-13	1.27E-10	9.73E-09	3.15E-07	1.46E-05
Ra-226	6.12E-23	3.35E-19	3.33E-16	1.75E-13	7.99E-11	1.24E-14	4.33E-12	2.81E-10	1.03E-08	8.54E-07
Pb-210	2.59E-21	1.10E-17	6.89E-15	3.37E-12	1.79E-09	4.99E-13	1.23E-10	7.58E-09	3.06E-07	2.22E-05
U-238	5.06E-19	2.05E-14	5.91E-11	4.37E-08	2.32E-05	4.13E-10	1.94E-07	1.91E-05	6.00E-04	2.46E-02
U-234	1.43E-21	5.81E-17	1.67E-13	1.28E-10	7.46E-08	2.34E-12	1.10E-09	1.08E-07	3.74E-06	1.57E-04
Th-230	2.67E-24	3.48E-20	5.94E-17	3.68E-14	1.55E-11	1.48E-15	4.70E-13	4.00E-11	1.10E-09	3.97E-08
Ra-226	1.13E-25	5.25E-22	5.63E-19	2.48E-16	1.03E-13	3.91E-17	1.46E-14	7.71E-13	3.52E-11	2.43E-09
Pb-210	3.93E-24	1.50E-20	1.13E-17	5.50E-15	2.09E-12	1.56E-15	4.64E-13	2.41E-11	9.92E-10	5.52E-08
Total	1.22E-07	9.14E-05	5.01E-03	2.84E-02	7.02E-02	1.20E-02	2.76E-02	5.78E-02	1.90E-01	7.48E-01

Table 4-13. Percentiles of the distribution of all-pathways effective dose equivalent for 3,000 and 5,000 years after disposal in year 2018.

Radionuclide	All-Pathways Effective Dose Equivalent (mrem/year) 3,000 Years after Closure (Year 5018)					All-Pathways Effective Dose Equivalent (mrem/year) 5,000 Years after Closure (Year 7018)				
	Percentile					Percentile				
	5th	25th	50th	75th	95th	5th	25th	50th	75th	95th
C-14	3.85E-04	9.32E-03	4.85E-02	2.32E-01	9.19E-01	1.42E-02	1.29E-01	3.14E-01	5.30E-01	8.66E-01
Cl-36	1.95E-13	9.53E-11	1.03E-08	4.30E-07	2.04E-05	2.34E-25	6.87E-21	4.07E-17	2.86E-14	5.60E-11
I-129	1.05E-03	2.42E-02	1.26E-01	3.26E-01	6.59E-01	8.63E-03	7.13E-02	1.48E-01	2.37E-01	4.11E-01
Tc-99	2.90E-08	2.89E-06	7.11E-05	9.68E-04	9.76E-03	3.46E-16	1.08E-12	3.78E-10	6.05E-08	2.08E-05
U-234	1.14E-07	3.11E-05	1.49E-03	2.14E-02	2.46E-01	9.49E-06	1.74E-03	3.01E-02	1.14E-01	3.25E-01
Th-230	9.87E-11	1.84E-08	7.19E-07	8.35E-06	9.53E-05	1.73E-08	1.88E-06	2.37E-05	9.38E-05	4.23E-04
Ra-226	7.56E-12	1.57E-09	4.78E-08	8.72E-07	2.25E-05	4.09E-09	3.47E-07	4.52E-06	3.06E-05	3.10E-04
Pb-210	3.29E-10	5.48E-08	1.53E-06	2.46E-05	4.89E-04	1.71E-07	1.59E-05	1.67E-04	1.06E-03	7.12E-03
U-238	7.59E-08	1.96E-05	9.95E-04	1.23E-02	1.41E-01	7.86E-06	1.23E-03	2.03E-02	7.15E-02	2.37E-01
U-234	6.44E-10	1.66E-07	8.51E-06	1.20E-04	1.32E-03	1.11E-07	1.73E-05	2.90E-04	1.04E-03	3.34E-03
Th-230	5.08E-13	1.01E-10	3.71E-09	4.47E-08	4.58E-07	1.54E-10	1.72E-08	1.99E-07	7.90E-07	3.18E-06
Ra-226	4.58E-14	8.19E-12	2.19E-10	4.05E-09	7.97E-08	3.32E-11	2.74E-09	3.32E-08	2.34E-07	1.99E-06
Pb-210	1.86E-12	2.62E-10	7.20E-09	1.20E-07	1.99E-06	1.46E-09	1.17E-07	1.28E-06	7.71E-06	4.61E-05
Total	1.52E-02	9.82E-02	3.10E-01	6.72E-01	1.55E+00	1.24E-01	3.67E-01	5.98E-01	8.90E-01	1.41E+00

The subscript 1, 2, 3, ... n refer to the Monte Carlo trial number. To calculate the rank correlation coefficient, the values of a_i , b_i , c_i , and y_i are replaced by their ranking within the distribution of values. For example, suppose for the third Monte Carlo trial, the values a_3 , b_3 , c_3 , are selected yielding an output value of y_3 . Suppose 500 trials are performed and the value of a_3 was ranked at 23; that is, it is the 23rd highest value within the distribution 500 values of a . The value of a_3 is replaced by 23. Likewise, the values of b_3 , c_3 , and y_3 are replaced by their respective ranks. Linear correlation is then performed between the ranks of each of the parameters and output variable, y .

The advantage of rank correlation over simple linear correlation is that it is nonparametric. That is, it is not dependent on the underlying distribution of either the input or output variables. The rank correlation coefficient is given by Press et al. (1992):

$$r_s = \frac{\sum_i (R_i - \bar{R})(S_i - \bar{S})}{\sqrt{\sum_i (R_i - \bar{R})^2} \sqrt{\sum_i (S_i - \bar{S})^2}} \quad (4-12)$$

Where

- r_s = the rank correlation coefficient
- R_i = the rank of the input parameter value
- S_i = the rank of the corresponding output value.

The significance of the correlation can also be estimated. A given variable may show a relatively high rank correlation coefficient, but the significance level, as measured by the number of standard deviations from the null hypothesis (i.e., *rank correlation coefficient* = 0), provides a measure of the significance of the correlation. A nonzero correlation was defined as significant if the number of standard deviations from zero exceeds 2. The advantage of using Monte Carlo techniques over that of a one-at-a-time approach is that interactions between parameters are included in the analysis. For example, the sensitivity of the dose due to parameter Y may depend on the value chosen for parameter X . Rank correlation coefficients provide a meaningful measure of the degree to which parameters and the end point (all-pathways dose) *change together*. The rank correlation coefficient takes on a value between -1 and +1. Perfect correlation is achieved when the absolute value of the correlation coefficient equals 1. Degree of correlation (and thereby degree of sensitivity) decreases with a decrease in the absolute value of the correlation coefficient. A positive correlation coefficient indicates that an increase in the value of the parameter results in an increase in the computational end point. A negative correlation coefficient indicates that an increase in the value of the parameter results in a decrease in the computational end point.

Another way to visualize the sensitivity analysis results is to compute the percent contribution each parameter has to the total variance. The contribution to the total variance was *approximated* using a simple technique described in the Crystal Ball® software (Decisioneering Inc. 2000), where the rank correlation coefficient for each parameter is squared and normalized to 100%. The output variable for this analysis is total (all nuclides) all-pathways dose at specific times. Based on the results of the uncertainty analysis, seven periods were chosen: years 3018, 4018, 5018, 5418, 7018, 7518, and 12,018.

For presentation of the sensitivity results, the sensitivity parameters have been divided into the following five categories:

- Infiltration through the cover – This category contains the parameters defining the engineering cover longevity, infiltration rate while the engineered cover is intact, and the infiltration rate after the engineered cover has fully failed.
- Aquifer transport – This category contains the parameters defining the Darcy velocity in the aquifer and the longitudinal dispersivity in the aquifer.
- Contaminant mobility in the alluvium, waste, and interbeds – This category includes mobility for carbon, iodine, technetium, uranium, thorium, radium, and lead.
- Contaminant mobility in the clay layer – This category includes mobility for carbon, iodine, technetium, uranium, thorium, radium, and lead.
- Inventory scaling factors – This category includes inventory scaling factors for C-14, Cl-36, I-129, Tc-99, U-234, and U-238.

Results of the quantitative sensitivity analysis (Tables 4-14 and 4-15) indicate that the sensitivity of a given parameter is time-dependent. Table 4-14 shows the rank correlation coefficient, with coefficients that were not significant marked in parenthesis. Table 4-15 shows the percent contribution to variance. The most sensitive input parameters to the all-pathways EDE results are different depending on the time period of interest:

- At the end of the compliance period (year 3018), the total all-pathways EDE was most sensitive to the infiltration-related parameters, in particular, the engineered cover longevity and the cover infiltration rate while the cover is intact. There is also some sensitivity to the Tc-99 K_d in the alluvium, waste, and interbeds which does not continue in the later years.
- In year 4018, the total all-pathways EDE continues to be sensitive to the infiltration parameters but is also sensitive to the K_d values in the alluvium, waste, and interbeds, primarily for iodine and carbon. By year 4018, the Darcy velocity and the K_d value for uranium in alluvium, waste, and interbeds are becoming contributors to the all-pathways dose. These will become more significant with time.
- In year 5018, the total all-pathways EDE is sensitive to the infiltration after failure of the cover and the K_d values in the alluvium, waste, and interbeds, primarily for iodine and carbon. Other parameters are minor contributors. The Darcy velocity and uranium K_d in alluvium, waste, and interbeds continue to contribute to the all-pathways EDE.
- In year 5418, the total all-pathways EDE is sensitive to basically the same parameters as in 5018.
- In year 7018, the total all-pathways EDE is sensitive to the infiltration after failure of the cover and also sensitive to the K_d values in the alluvium, waste, and interbeds, primarily for carbon and uranium. The EDE is sensitive to the Darcy velocity in the aquifer and the C-14 inventory scaling factor.
- In year 7518, the total all-pathways EDE is sensitive to basically the same parameters as in 7018.
- In year 12,018, the total all-pathways EDE is primarily sensitive to the Darcy velocity in the aquifer; uranium K_d in the clay; iodine, carbon, and uranium K_d in the alluvium, waste, and interbeds; and the inventory scaling factor for C-14 and U-234.

Table 4-14. Rank correlation coefficients for seven output times. Rank correlation coefficients in parenthesis are less than two standard deviations from the null hypothesis and are deemed not significant.

Parameter	Year 3018	Year 4018	Year 5018	Year 5418	Year 7018	Year 7518	Year 12,018
Engineered cover (cap) longevity	-0.669	-0.184	-0.135	-0.097	(0.038)	0.066	0.078
Engineered cover (cap) infiltration rate	0.503	0.120	0.107	0.090	(0.014)	(-0.007)	-0.081
Infiltration rate through engineered cover (cap) after failure	0.276	0.482	0.620	0.627	0.541	0.481	-0.084
Longitudinal dispersivity in aquifer	(-0.037)	(0.033)	(0.022)	(0.017)	(0.002)	(-0.001)	(0.038)
Darcy velocity in aquifer	(-0.051)	-0.182	-0.192	-0.216	-0.331	-0.355	-0.319
Carbon K_d in alluvium, waste, and interbed	(0.008)	-0.194	-0.352	-0.413	-0.429	-0.360	0.237
Iodine K_d in alluvium and waste	(-0.041)	-0.349	-0.341	-0.297	-0.109	-0.066	0.229
Iodine K_d in interbed	(0.005)	-0.429	-0.270	-0.189	(0.020)	(0.048)	0.139
Technetium K_d in alluvium, waste, and interbed	-0.161	0.066	(0.024)	(0.018)	(0.023)	(0.025)	(-0.018)
Uranium K_d in alluvium, waste, and interbed	(0.034)	-0.126	-0.169	-0.193	-0.305	-0.334	-0.234
Thorium K_d in alluvium, waste, and interbed	(-0.037)	(0.024)	(0.019)	(0.014)	(0.012)	(0.010)	(-0.002)
Radium K_d in alluvium, waste, and interbed	(0.001)	(0.015)	(0.017)	(0.017)	(0.018)	(0.018)	(-0.024)
Lead K_d in alluvium, waste, and interbed	(-0.020)	(0.032)	(0.032)	(0.034)	(0.041)	(0.043)	(0.016)
Iodine K_d in clay	(0.001)	(-0.049)	(-0.018)	(-0.003)	(0.015)	(0.015)	(0.034)
Technetium K_d in clay	(0.027)	(0.032)	(0.005)	(0.006)	(0.004)	(-0.000)	(-0.041)
Carbon K_d in clay	(0.019)	(-0.040)	-0.079	-0.089	-0.081	-0.066	(0.055)
Uranium K_d in clay	(0.039)	(-0.028)	(-0.050)	(-0.058)	-0.149	-0.185	-0.361
Thorium K_d in clay	(0.007)	(-0.023)	(0.003)	(0.007)	(0.003)	(0.000)	(0.017)
Radium K_d in clay	(-0.053)	(-0.023)	(-0.024)	(-0.022)	(-0.014)	(-0.014)	(-0.049)
Lead K_d in clay	(0.042)	(-0.020)	(-0.028)	(-0.025)	(-0.006)	(-0.008)	(-0.047)
Inventory scaling factor, C-14	(-0.026)	(0.059)	0.096	0.120	0.232	0.254	0.164
Inventory scaling factor, Cl-36	0.095	(-0.005)	(-0.004)	(-0.007)	(-0.014)	(-0.013)	(0.013)
Inventory scaling factor, I-129	(-0.029)	0.070	0.090	0.101	0.090	0.080	(0.035)
Inventory scaling factor, Tc-99	(0.053)	0.083	(-0.018)	(-0.029)	(-0.025)	(-0.017)	(0.055)
Inventory scaling factor, U-234	(0.011)	(0.017)	(0.026)	(0.032)	(0.052)	(0.058)	0.167
Inventory scaling factor, U-238	(-0.010)	(-0.024)	(-0.024)	(-0.016)	(0.011)	(0.015)	0.097

Table 4-15. Percent contribution to variance for the seven output times. Higher values indicate greater parameter sensitivity to the output variable (total all-pathways dose).

Parameter	Year 3018	Year 4018	Year 5018	Year 5418	Year 7018	Year 7518	Year 12,018
Engineered cover (cap) longevity	53.78%	4.81%	2.21%	1.13%	0.18%	0.60%	1.18%
Engineered cover (cap) infiltration rate	30.40%	2.05%	1.39%	0.98%	0.02%	0.01%	1.27%
Infiltration rate through engineered cover (cap) after failure	9.15%	33.01%	46.61%	47.33%	37.01%	31.84%	1.37%
Longitudinal dispersivity in aquifer	0.16%	0.15%	0.06%	0.03%	0.00%	0.00%	0.28%
Darcy velocity in aquifer	0.31%	4.71%	4.47%	5.62%	13.86%	17.35%	19.70%
Carbon K_d in alluvium, waste, and interbed	0.01%	5.35%	15.02%	20.54%	23.27%	17.84%	10.88%
Iodine K_d in alluvium and waste	0.20%	17.31%	14.10%	10.62%	1.50%	0.60%	10.15%
Iodine K_d in interbed	0.00%	26.15%	8.84%	4.30%	0.05%	0.32%	3.74%
Technetium K_d in alluvium, waste, and interbed	3.11%	0.62%	0.07%	0.04%	0.07%	0.09%	0.06%
Uranium K_d in alluvium, waste, and interbed	0.14%	2.26%	3.46%	4.48%	11.76%	15.35%	10.60%
Thorium K_d in alluvium, waste, and interbed	0.16%	0.08%	0.04%	0.02%	0.02%	0.01%	0.00%
Radium K_d in alluvium, waste, and interbed	0.00%	0.03%	0.04%	0.03%	0.04%	0.04%	0.11%
Lead K_d in alluvium, waste, and interbed	0.05%	0.15%	0.12%	0.14%	0.21%	0.25%	0.05%
Iodine K_d in clay	0.00%	0.34%	0.04%	0.00%	0.03%	0.03%	0.22%
Technetium K_d in clay	0.09%	0.15%	0.00%	0.00%	0.00%	0.00%	0.33%
Carbon K_d in clay	0.04%	0.23%	0.76%	0.95%	0.83%	0.60%	0.59%
Uranium K_d in clay	0.18%	0.11%	0.30%	0.41%	2.81%	4.71%	25.23%
Thorium K_d in clay	0.01%	0.08%	0.00%	0.01%	0.00%	0.00%	0.06%
Radium K_d in clay	0.34%	0.08%	0.07%	0.06%	0.02%	0.03%	0.46%
Lead K_d in clay	0.21%	0.06%	0.10%	0.08%	0.00%	0.01%	0.43%
Inventory scaling factor, C-14	0.08%	0.49%	1.12%	1.73%	6.81%	8.88%	5.21%
Inventory scaling factor, Cl-36	1.08%	0.00%	0.00%	0.01%	0.02%	0.02%	0.03%
Inventory scaling factor, I-129	0.10%	0.70%	0.98%	1.23%	1.02%	0.88%	0.24%
Inventory scaling factor, Tc-99	0.34%	0.98%	0.04%	0.10%	0.08%	0.04%	0.59%
Inventory scaling factor, U-234	0.01%	0.08%	0.07%	0.03%	0.02%	0.03%	1.82%
Inventory scaling factor, U-238	0.01%	0.04%	0.08%	0.12%	0.34%	0.46%	5.40%

Results of the quantitative sensitivity analysis (Tables 4-14 and 4-15) indicated that the all-pathways EDE results are more sensitive to the parameters in some categories and less in others:

- For all time periods up to year 7518, the total all-pathways EDE is largely sensitive to the parameters related to the infiltration through the cover. The total all-pathways EDE is most sensitive to the cover longevity and the infiltration rate through the cover before failure in year 3018 and much less sensitive in the future. The all-pathways EDE is progressively more sensitive to the infiltration rate through the cover after failure through year 7518 but drops off by year 12,018.
- The total all-pathways EDE is insensitive to the aquifer Darcy velocity in the earlier times and much more sensitive in the later times. The total all-pathways EDE has no significant sensitivity to the longitudinal dispersivity in the aquifer over all time.
- The total all-pathways EDE is relatively sensitive to the K_d values in the alluvium, waste, and interbeds for iodine, carbon, and uranium (after the first 1,000 years). The total all-pathways EDE is only sensitive to the technetium K_d early in time and is never sensitive to the thorium, radium, or lead K_d values during the 10,000 years evaluated.
- The total all-pathways EDE is sensitive to the K_d values in the clay layer for uranium after year 5418 and increases with time. The total all-pathways EDE is not sensitive to the K_d values in the clay layer for the other radionuclides.
- The total all-pathways EDE is relatively insensitive to the inventory scaling factors. Carbon-14 is a minor contributor in the later time periods.

Based on the sampled parameter distributions used for the quantitative sensitivity analysis, at the end of the compliance period (year 3018), the all-pathways EDE is sensitive to the infiltration-related parameters and relatively insensitive to all other parameters. As time goes on, the EDE becomes more sensitive to the Darcy velocity and K_d values in the alluvium, waste, and interbeds for iodine, carbon, and uranium. Late in time, the EDE becomes sensitive to the uranium K_d value in the clay layer and the C-14 inventory scaling factor. The all-pathways EDE is relatively insensitive to the other parameters.

For the qualitative sensitivity analysis, scatter plots of sampled parameter values versus the output variable are shown in Figures 4-25 through 4-30. The two most sensitive parameters in year 3018, as indicated by the rank correlation coefficient, were the engineered cover longevity and the cover infiltration rate (Figures 4-25 and 4-26). Figure 4-25 shows that the total all-pathways dose in year 3018 has a clear negative correlation for cap lives less than about 500 years and no correlation for longer cap lifetimes. For cap lives less than 400 years, the spread of the all-pathways dose is over two orders of magnitude, but, for longer cap lifetimes, the spread is over six orders of magnitude.

Figure 4-26 shows that the total all-pathway dose in year 3018 is positively correlated with cap infiltration rate for cap infiltration rates greater than about 0.1 cm/year. It does not appear correlated to cap infiltration rate for cap infiltration rates less than 0.1 cm/year. For cap infiltration rates over about 0.6 cm/year, the spread of the all-pathways dose is about one order of magnitude. However, for infiltration rates less than 0.1 cm/year, the spread of the all-pathways dose is about six orders of magnitude. Therefore, the cap infiltration rate has a domain of applicability where, if the cap infiltration rate is below 0.1 cm/year, then the all-pathways dose at year 3018 is insensitive to the cap infiltration rate.

In year 4018, rank correlation determined the total all-pathways dose was sensitive to the infiltration rate through the cap after failure, and the C-14 and I-129 K_d values. Scatter plots of the C-14 K_d value in waste, alluvium, and interbed (Figure 4-27) indicate a slight negative correlation, which indicates that the higher the K_d value the lower the all-pathways dose. All-pathways dose in this plot has

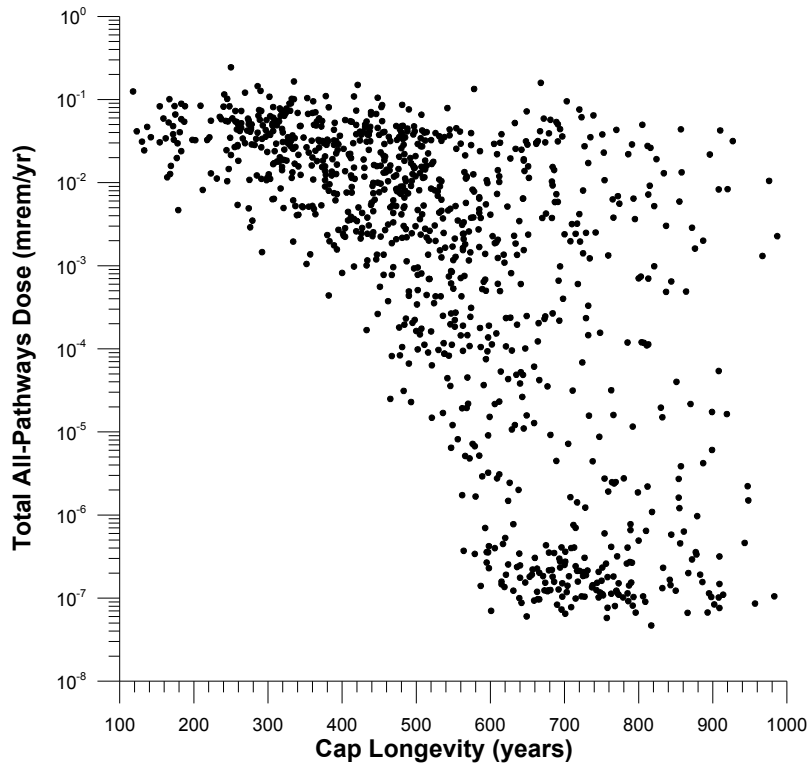


Figure 4-25. Scatter plot of cap longevity versus total all-pathways dose in year 3018 for 1,000 Monte Carlo realizations.

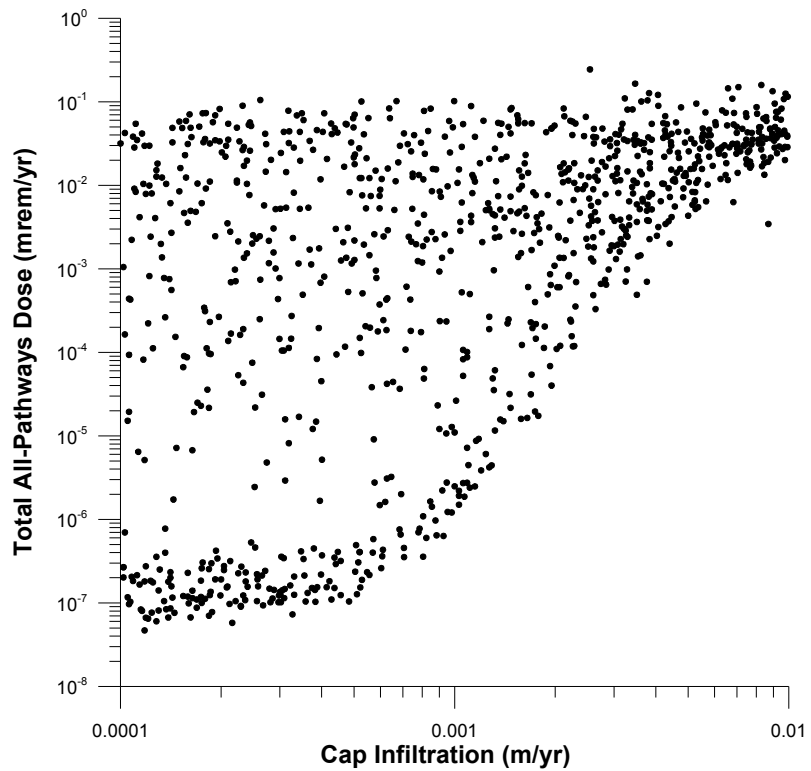


Figure 4-26. Scatter plot of cap infiltration versus total all-pathways dose in year 3018 for 1,000 Monte Carlo realizations.

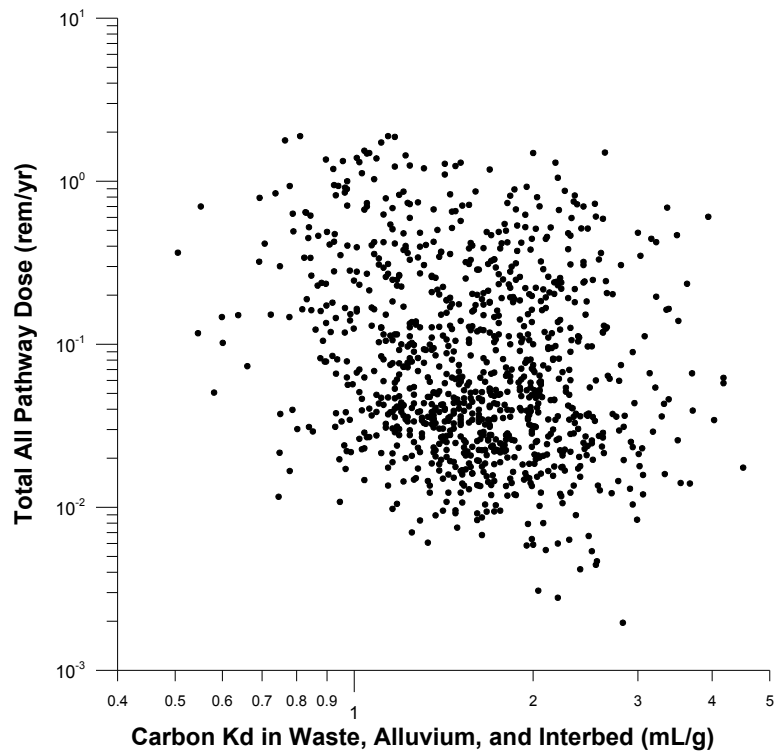


Figure 4-27. Scatter plot of carbon (C-14) K_d value versus total all-pathways dose in year 4018 for 1,000 Monte Carlo realizations.

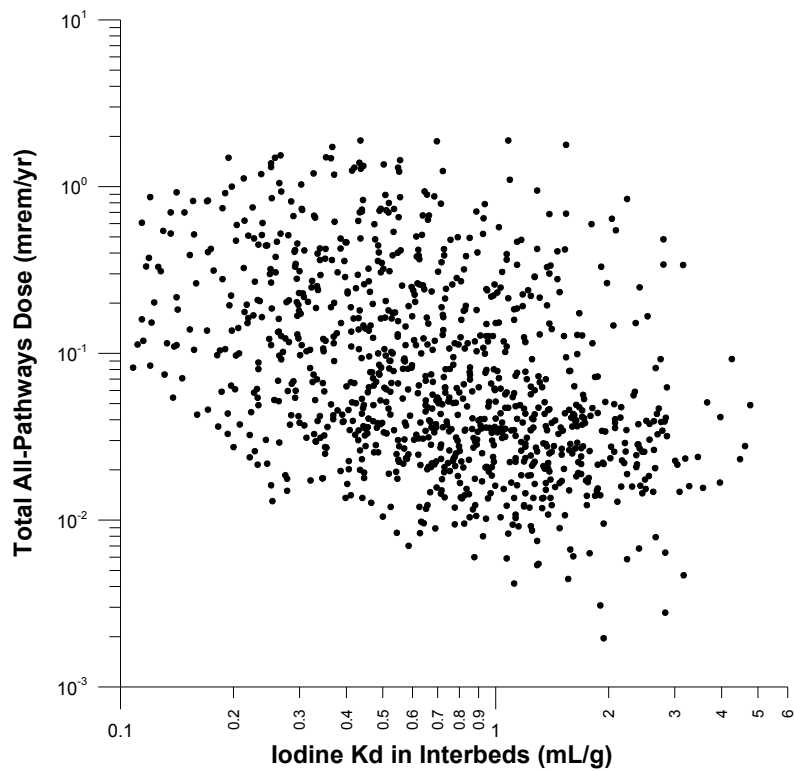


Figure 4-28. Scatter plot of iodine (I-129) K_d value versus total all-pathways dose in year 4018 for 1,000 Monte Carlo realizations.

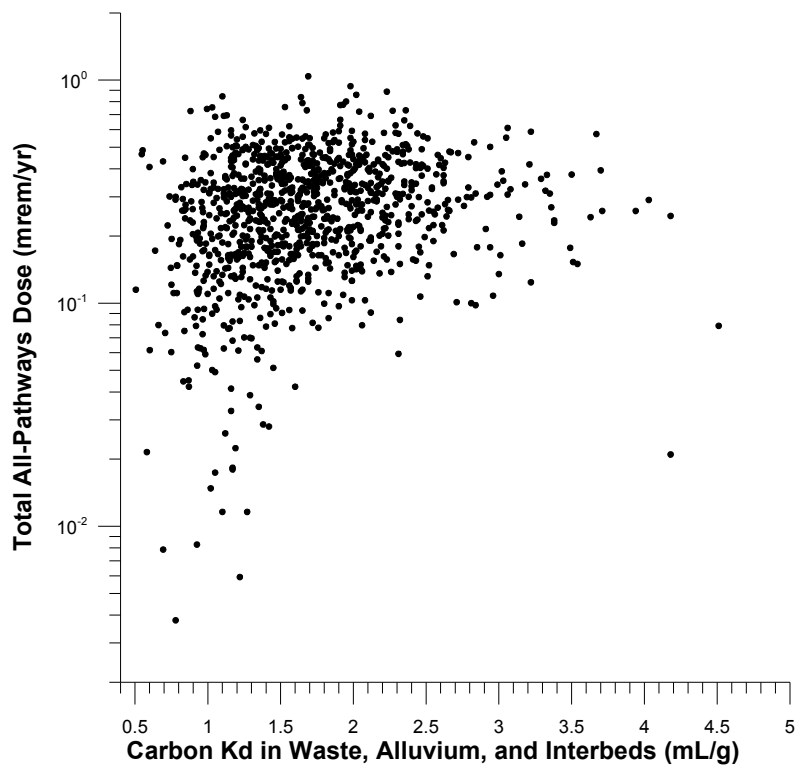


Figure 4-29. Scatter plot of carbon (C-14) K_d value versus total all-pathways dose in year 12,018 for 1,000 Monte Carlo realizations.

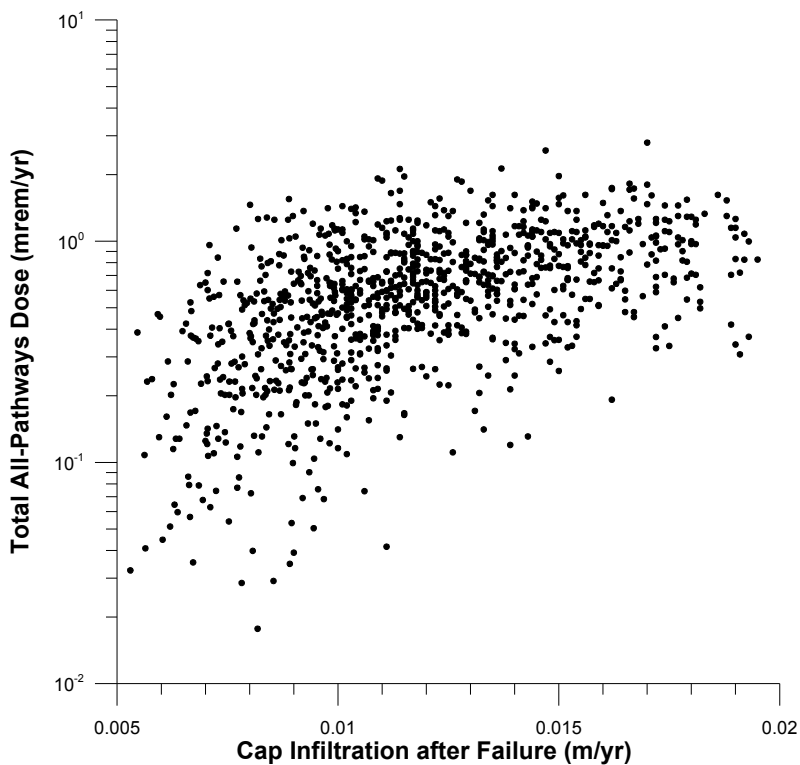


Figure 4-30. Scatter plot of cap infiltration after failure versus total all-pathways dose in year 7018 for 1,000 Monte Carlo realizations.

a spread of over two orders of magnitude. Scatter plots of the I-129 K_d value in interbeds (Figure 4-28) also indicates a slight negative correlation, which indicates that the higher the K_d value the lower the all-pathways dose. All-pathways dose in this plot has a spread of over two orders of magnitude.

Figure 4-29 shows a scatter plot of the C-14 K_d in waste, alluvium, and interbed versus the total all-pathways dose in year 12,018. In this case, the slope of the line is slightly positive, indicating that higher C-14 K_d values tend to produce higher all-pathways doses at this output time. The change in slope is because the higher K_d value results in longer radionuclide travel times such that C-14 arrives at the receptor at later times, resulting in a greater dose 10,000 years from now. Most of the all-pathways doses are clustered in the 0.1- to 1.0-mrem/year range. However, for C-14 K_d values less than about 1.5 mL/g, the spread of the all-pathways dose is much greater.

The quantitative sensitivity analysis also indicated the total all-pathways dose was sensitive to the infiltration rate after cap failure in year 7018. Figure 4-30 shows a scatter plot of these data. The slope of the data is positive, indicating higher cap infiltration rates tend to produce higher all-pathways doses. The spread of the all-pathways dose is about one order of magnitude for infiltration rates greater than 1 cm/year and roughly two orders of magnitude for infiltration rates less than 1 cm/year.

The conclusion that can be drawn from these plots is that the sensitivity of the total all-pathways dose to a given parameter is complex, and no global statement can be made concerning the sensitivity of the output variable to variability in a given input parameter. The sensitivity not only depends on the output time, but also the parameter may be only sensitive over a limited domain of the sampled population; and the total all-pathways dose is insensitive to parameter values that lie outside this domain of sensitivity.

5. INADVERTENT INTRUDER ANALYSIS

This section presents the analyses of the doses to a hypothetical individual who inadvertently intrudes into the ICDF Landfill, assuming a temporary lapse of institutional control. The performance measures apply after hypothetical loss of active institutional control at 100 years after facility closure and specify:

- An EDE of 100 mrem/year from all exposure pathways for scenarios involving continuous exposure
- An EDE of 500 mrem from all exposure pathways for scenarios involving a single, acute exposure.

Exposure scenarios were evaluated that involve direct intrusion into LLW buried in the landfill. The intruder dose assessment assumes that hypothetical inadvertent intruders at the ICDF could be exposed in accordance with two defined scenarios. The first scenario involves acute (i.e., short-term) exposure during an assumed initial contact with radioactive waste, and the second scenario involves chronic (i.e., long-term) exposure to waste after an intruder is assumed to take up permanent residence on the disposal site. The assumed scenarios are identified as an acute drilling scenario and a chronic post-drilling agriculture scenario.

This section documents the inadvertent intruder analysis and contains the following subsections:

- Inadvertent Intruder Radionuclide Screening – This subsection documents the screening methodology used to determine the primary inadvertent intruder contaminants of concern.
- Inadvertent Intruder Exposure Scenarios – This subsection describes the acute and chronic intruder scenarios evaluated in this PA.
- Inadvertent Intruder Analysis Results – This subsection provides the results of the inadvertent intruder analysis.
- Inadvertent Intruder Uncertainty Discussion – This subsection is a qualitative discussion of the uncertainty associated with the inadvertent intruder analysis.

5.1 Inadvertent Intruder Radionuclide Screening

The inventory for the ICDF Landfill consists of 115 individual radionuclides (see Table 2-6). The large number of radionuclides presents difficulties in estimating future dose impacts and distracts resources from those nuclides that are most important. Therefore, contaminant screening for ground burial was performed (similar to the screening performed for groundwater in Section 2.4) to reduce the number of nuclides to a manageable level and focus resources on those nuclides that are most important. EDF-9874 includes details of the screening analysis for the inadvertent intruder calculations.

5.1.1 Screening Procedure

The screening procedure consisted of (1) screening radionuclides based on their half-lives and (2) using screening factors developed by the National Council on Radiation Protection (NCRP) for ground burial to further eliminate radionuclides from the list. The methods presented in NCRP (1996) for ground burial screening were used.

5.1.1.1 Screening of Short-lived Radionuclides. Some nuclides can be eliminated from consideration early in the screening process based on their half-lives. Nuclides with half-lives less than 5 years were eliminated from further consideration, assuming the same screening cutoff the NCRP has

implemented in its ground burial screening models. Many of the nuclides removed from consideration were radioactive progeny of longer-lived parents (e.g., Ac-228). This screening only eliminated these nuclides from the disposed inventory; however, they are still considered in the decay chains of longer-lived parents. Table 2-7 presents the results of the screening of short-lived radionuclides.

5.1.1.2 Screening Dose Calculations. The NCRP provides a series of simple SFs that can be used to demonstrate compliance with environmental standards or other administratively set reference levels for releases of radionuclides to the atmosphere, surface water, or ground. The SF is essentially a dose conversion factor having units of total EDE per unit of activity (Sv/Bq). These factors incorporate radionuclide fate and transport processes and an assumed exposure scenario to calculate the annual total EDE to a hypothetical receptor per unit of activity in the radionuclide inventory. A complete discussion of the assumptions used in the screening dose calculations for ground disposal may be found in NCRP (1996).

The SFs provided for the ground burial screening include direct irradiation, inhalation of resuspended soil, and ingestion of soil, groundwater, and produce. For the purpose of selecting radionuclides for intruder analyses, the SFs used in this assessment included the surface pathways (direct, inhalation, soil, and vegetables).

The effective screening value for each radionuclide is calculated using the formula:

$$D_i = M_{0,i} \times SF_i \quad (5-1)$$

Where

- D_i = screening value for radionuclide i (Sv)
- $M_{0,i}$ = disposed inventory decayed for 100 years (Bq)
- SF_i = screening factor for ground burial for radionuclide i and all progeny for the period of maximum exposure (Sv/Bq).

The NCRP method decays the initial inventory for 10 years, representing the administrative control period. Because the intruder scenarios do not begin until after 100 years of institutional control, the inventory was decayed for an additional 90 years for this screening assessment.

Nuclides with an NCRP screening dose of less than 1 mrem (1E-05 Sv) were removed from further consideration. These nuclides are identified in Table 5-1 along with their NCRP screening dose values. The NCRP screening dose is calculated by multiplying the radionuclide inventory by the NCRP ground burial screening dose factor. (see EDF-9874)

5.1.2 Screening Results

Of the 67 nuclides remaining from the short-lived radionuclides screening presented in Section 2.4.1, 18 nuclides were screened using the NCRP screening methodology described above, leaving 49 nuclides. These 49 nuclides were then included in the inventory used for intruder analyses.

Table 5-1. Screening results for nuclides with half-lives >5 years using the NCRP screening factors.

Radionuclide	Ground Burial Surface Pathways NCRP Screening Factor (Sv/Bq) ^a	Screening Dose (Sv)	Is Screening Dose <1 mrem (1E-05 Sv)?	Radionuclide	Ground Burial Surface Pathways NCRP Screening Factor (Sv/Bq)	Screening Dose (Sv)	Is Screening Dose <1 mrem (1E-05 Sv)?
Ac-227	5.7E-11	5.7E-07	Yes	Ni-59	1.9E-14	4.1E-01	No
Ag-108m	1.6E-11	7.5E-01	No	Ni-63	4.0E-14	8.2E+01	No
Am-241	7.8E-12	4.7E-01	No	Np-237	6.0E-11	1.7E-01	No
Am-242m	5.0E-11	3.6E-03	No	Pa-231	1.6E-10	4.0E-05	No
Am-243	1.0E-11	9.0E-03	No	Pb-205	1.6E-14	2.5E-10	Yes
Ba-133	2.2E-12	7.1E-05	No	Pb-210	1.6E-11	8.7E-04	No
Be-10	4.2E-14	2.5E-03	No	Pm-145	2.0E-13	4.6E-08	Yes
C-14	1.7E-11	6.9E+01	No	Pu-238	6.2E-12	2.1E+00	No
Ca-41	5.8E-13	3.1E-05	No	Pu-239	7.5E-12	5.3E+00	No
Cf-249	1.2E-11	1.4E-04	No	Pu-240	7.4E-12	2.8E+00	No
Cf-250	2.5E-12	3.1E-06	Yes	Pu-241	2.3E-13	3.2E-03	No
Cf-251	1.0E-11	2.6E-05	No	Pu-242	7.1E-12	1.7E-04	No
Cl-36	7.0E-11	1.9E+00	No	Pu-244	2.9E-11	6.7E-09	Yes
Cm-243	5.4E-12	6.6E-04	No	Ra-226	7.5E-11	2.7E+00	No
Cm-244	2.9E-12	4.9E-03	No	Ra-228	2.9E-11	3.0E-08	Yes
Cm-245	1.6E-11	4.5E-04	No	Se-79	7.0E-13	4.4E-06	Yes
Cm-246	7.8E-12	2.9E-03	No	Si-32	1.1E-11	4.4E-12	Yes
Cm-247	1.5E-11	5.5E-06	Yes	Sm-146	8.2E-13	1.6E-12	Yes
Cm-248	2.9E-11	2.9E-03	No	Sm-151	2.0E-15	8.0E-06	Yes
Cm-250	1.8E-10	1.8E-11	Yes	Sn-121m	9.9E-13	1.3E-05	No
Co-60	6.5E-12	3.0E-02	No	Sr-90	3.3E-11	2.7E+02	No
Cs-135	1.7E-12	6.0E-08	Yes	Tb-158	7.9E-12	1.3E-04	No

Table 5-1. (continued).

Radionuclide	Ground Burial Surface Pathways NCRP Screening Factor (Sv/Bq) ^a	Screening Dose (Sv)	Is Screening Dose <1 mrem (1E-05 Sv)?	Radionuclide	Ground Burial Surface Pathways NCRP Screening Factor (Sv/Bq)	Screening Dose (Sv)	Is Screening Dose <1 mrem (1E-05 Sv)?
Cs-137	1.4E-11	5.4E+02	No	Tc-99	9.8E-12	2.4E-01	No
Eu-152	6.6E-12	5.4E-01	No	Th-229	3.2E-11	6.6E-06	Yes
Eu-154	5.4E-12	2.4E-02	No	Th-230	4.2E-11	1.6E-01	No
H-3	2.5E-13	7.3E+00	No	Th-232	9.9E-11	3.4E-01	No
Ho-166m	1.6E-11	2.0E-02	No	U-232	3.4E-11	3.6E-04	No
I-129	1.0E-11	5.6E-02	No	U-233	4.0E-12	1.8E-02	No
K-40	8.1E-12	2.9E-01	No	U-234	1.6E-12	4.1E-02	No
Kr-85	6.9E-15	2.0E-10	Yes	U-235	6.0E-12	3.4E-02	No
Mn-53	4.4E-14	1.4E-06	Yes	U-236	1.3E-12	1.9E-04	No
Mo-93	1.8E-13	8.8E-04	No	U-238	3.0E-11	5.5E-01	No
Nb-93m	1.2E-14	5.2E-09	Yes	Zr-93	2.4E-14	9.3E-09	Yes
Nb-94	1.7E-11	7.9E+00	No				

a. Includes inhalation, direct exposure, and ingestion of soil and produce. Does not include the groundwater pathway. Values listed in Table 3-2 of NCRP (1996), Volume 2, were used for “total” and subtracted column for “water.”

NCRP National Council on Radiation Protection

5.2 Inadvertent Intruder Exposure Scenarios

The inadvertent intruder dose assessment assumes that exposures of hypothetical inadvertent intruders at the ICDF Landfill involve acute (i.e., short-term) exposure during an initial contact with radioactive waste and chronic (i.e., long-term) exposure during contact with radioactive waste while residing on top of the closed facility. In the assumed drilling scenarios, the entire inventory is available for intrusion; therefore, no depletion due to leaching was assumed. Therefore, changes in radionuclide concentrations in waste containers over time are assumed to occur only by decay and subsequent in-growth and decay of radioactive progeny (if any). The inadvertent intruder scenarios are summarized in Table 5-2.

Table 5-2. Summary of exposure scenarios for inadvertent intrusion into low-level radioactive solid waste at the ICDF Landfill.

Assumed Scenario	Discussion
<i>Acute exposure</i>	
Drilling	Assumed to occur at 100 years or the time of the maximum between 100 and 1,000 years for each radionuclide, after disposal ceases. Dose is a result of drilling through disposal units. Assumed exposure pathways include external, inhalation, and soil ingestion for a short period of time.
<i>Chronic exposure</i>	
Post-drilling agriculture	Assumed to occur at 100 years or the time of the maximum between 100 and 1,000 years for each radionuclide after disposal ceases. Dose is a result of drilling a well through the waste and mixing of exhumed waste with garden soil. Assumed exposure pathways include ingestion of vegetables grown in contaminated garden soil, ingestion of contaminated beef and milk, ingestion of contaminated garden soil, external, and inhalation.

5.2.1 Acute Exposure Scenario

The acute drilling scenario assumes that an inadvertent intruder drills a large-diameter (56 cm [22 in.]) irrigation well directly into the buried waste at the ICDF Landfill. The intruder is assumed to be exposed to contaminated drill cuttings brought to the surface and spread over the ground. The exposure pathways for this acute drilling scenario include external exposure to drill cuttings, inhalation of drill cuttings suspended in air, and ingestion of contaminated soil.

The intruder is assumed to be exposed to an average radionuclide concentration in all of the contaminated cuttings for 160 hours, which is the time local Idaho Falls well drilling contractors state it would take to drill and develop a 56-cm (22-in.) -diameter irrigation well (Seitz et al. 1991). Assuming the driller is standing in the middle of the dust cloud for the entire time is very conservative. Typically, drill cuttings are discharged from an exhaust tube some distance downwind from the drill rig. Exposure to a concentration averaged over all the cuttings is assumed to overpredict the exposure because, for the vast majority of the time, the driller would be primarily exposed to relatively clean cuttings from below the waste.

Based on a waste thickness of 10.4 m (34 ft) for the ICDF Landfill, the 56-cm (22-in.) well results in 2.5 m³ (88 ft³) of contaminated waste being brought to the surface during the acute drilling scenario. The total volume of cuttings brought to the surface for a 56-cm (22-in.) -diameter well drilled to a depth of 134 m (440 ft) (average depth to the water table below the ICDF) is 33 m³ (1,165 ft³). The cuttings are assumed to be spread over a 2,200-m² (24,000-ft²) area and, therefore, to an average depth of 0.02 m (~3/4 in.). The exposure pathways for this acute drilling scenario include inhalation of drill cuttings suspended in air, ingestion of drill cuttings, and external exposure to drill cuttings on the ground surface. Inhalation of suspended drill cuttings was modeled using an atmospheric mass-loading factor of 1 mg/m³ representative of construction activities (Maheras et al. 1997). Soil ingestion was modeled assuming an occupational ingestion rate of 50 mg/day for an 8-hr workday (EPA 1997b). The intruder is assumed to ingest a total of 1,000 mg of contaminated soil (drill cuttings) during the 160 hr or 20 days of exposure. The acute drilling scenario is subject to the 500-mrem performance measure for inadvertent intrusion scenarios per DOE M 435.1-1 Chg 1. The acute intruder scenario is illustrated in Figure 5-1.

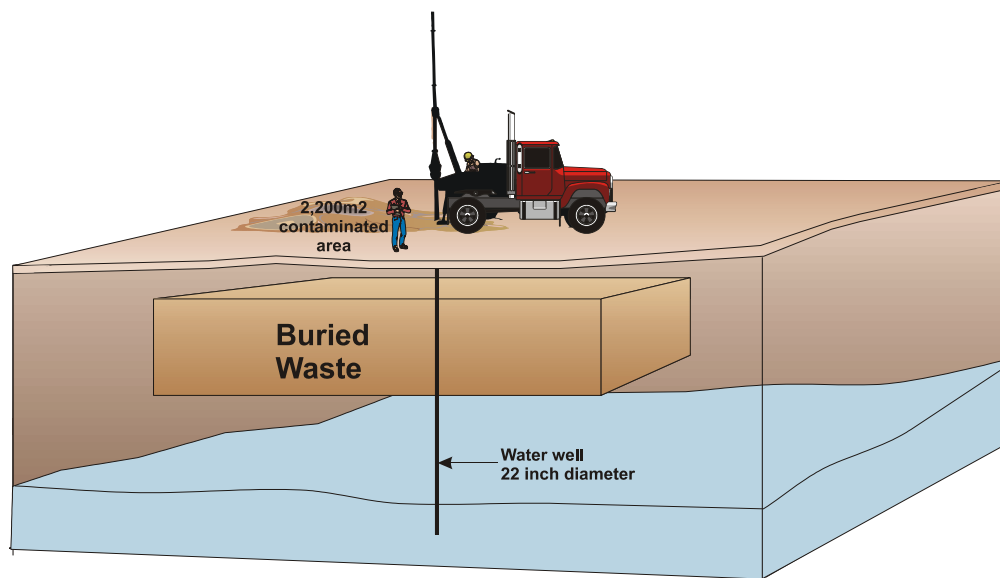


Figure 5-1. Graphical representation of the acute-intruder drilling scenario.

5.2.2 Chronic Exposure Scenario

The chronic post-drilling agriculture scenario assumes that an inadvertent intruder moves onto the closed facility and drills a residential well into the waste. The drilling portion of the scenario evaluates a 20-cm (8-in.) residential well. This well serves a single residence and provides enough additional water for a family garden and small quantities of livestock. As described in the acute drilling scenario, large-diameter wells are drilled to serve irrigation systems (i.e., hundreds of acres) that are located in the middle of farm fields, not near a farmer's residence. Therefore, in the chronic post-drilling scenario, the residence/home garden is evaluated using the traditional drinking water well diameter of 20 cm (8 in.). The drill cuttings that are brought to the surface are assumed to be spread over 2,200 m² (24,000 ft²) or approximately 1/2 acre of land surface. The exhumed waste is mixed or tilled with the garden soil to a depth of 61 cm (24 in.). The mixing depth was based on using a deep tilling plow to increase the depth of the root zone and to break up soil compaction. These plows are used in areas of southeast Idaho with highly erodible soils to minimize erosion. Deep tilling plows have shanks that till to a depth of 61 cm (24 in.). Based on a waste thickness of 10.4 m (34 ft) for the ICDF Landfill, the 20-cm (8-in.) -diameter well results in 0.32 m³ of contaminated waste being brought to the surface. The well cuttings are spread over a 2,200-m² area and tilled to a depth of 61 cm (24 in.); therefore, the total volume of soil is 1,342 m³.

The chronic post-drilling agriculture scenario assumes that the intruder is exposed to the exhumed waste during plowing and cultivation (i.e., dust inhalation) of his garden. The mass loading for inhalation is 0.0535 mg/m^3 . In addition, the intruder is assumed to ingest contaminated food products from the garden and from beef and milk cattle that consume contaminated forage. The intake of contaminated forage by the cattle was adjusted according to the fraction of feed grown on contaminated cuttings and the necessary remaining feed obtained from uncontaminated ground. The exposure time for this scenario was 1 year (8,760 hr). The chronic intruder post-drilling agriculture scenario is limited by a maximum dose of 100 mrem/year per DOE O 435.1 Chg 1. The chronic intruder post-drilling agriculture scenario is illustrated in Figure 5-2.

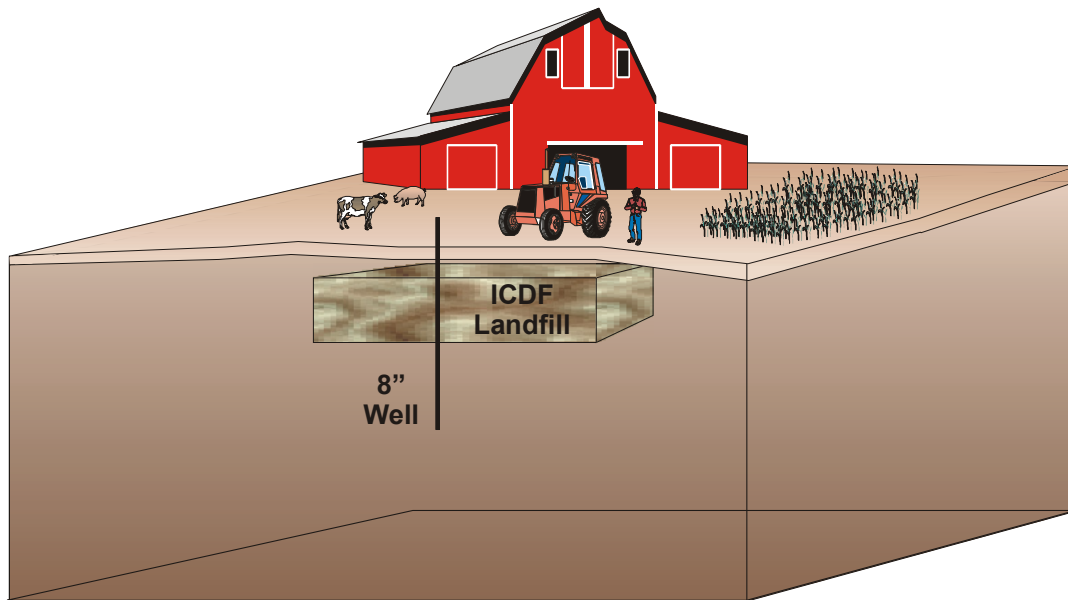


Figure 5-2. Graphical representation of the chronic intruder post-drilling agriculture scenario (figure does not depict actual landfill site with final cover and steep side slopes that would deter family from taking up residence).

Intruder doses were calculated starting at 100 years following site closure in the year 2018. The average activity concentration of radionuclides in the disposal facility was determined as follows:

$$C_{s,i} = \frac{C_{w,i}}{V\rho} (1 \times 10^{12} \frac{pCi}{Ci}) \quad (5-2)$$

Where

- $C_{s,i}$ = average waste activity concentration of radionuclide i in source zone (disposal facility) (pCi/g)
- $C_{w,i}$ = waste activity concentration of radionuclide i at the time of intrusion based on the total inventory in the disposal facility (Ci/m^3)
- V = total volume of the disposal facility
- ρ = bulk density of the source zone (disposal facility) (g/m^3).

Using this equation, the radionuclide concentration in the soil will be the same for any given well radius, but the total amount of contaminated soil will vary with the well radius. The radionuclide activity

in the waste is mixed with the soil in the drill cuttings. Changes in radionuclide concentrations in waste containers over time are assumed to occur only by decay and subsequent ingrowth and decay of radioactive progeny (if any); no depletion due to leaching was assumed.

The RESRAD code (Yu et al. 2001) was selected to calculate the doses from inadvertent intrusion into the waste because it has a recognized history of use for similar applications and specifically models the exposure of a receptor to buried waste via inhalation, external exposure, and ingestion (soil and food). RESRAD keeps track of ingrowth of progeny and includes the progeny in the dose calculations. RESRAD also meets the software quality assurance requirements for analysis software at the ICP.

The RESRAD code (Yu et al. 2001) was used to calculate the dose per unit concentration in the contaminated zone caused by drill cuttings at the time of exposure (including radioactive decay and ingrowth of progeny, as applicable) or DSRs using the input parameters shown in Tables 5-3 and 5-4 for the acute and chronic inadvertent intruder scenarios. Table 5-5 presents the food transfer factors used in the chronic agriculture scenario (Baes et al. 1984).

The dose to the hypothetical inadvertent intruder is then calculated as follows:

$$Dose = C_{s,i} \times DSR \times (V_w/V_T) \quad (5-3)$$

Where

<i>Dose</i>	=	dose to inadvertent intruder (mrem/year)
<i>C_{s,i}</i>	=	average waste activity concentration of radionuclide i in source zone (disposal facility) (pCi/g)
<i>DSR</i>	=	dose-to-source ratio calculated by RESRAD (mrem/year per pCi/g)
<i>V_w</i>	=	contaminated waste volume brought to the surface (m ³)
<i>V_T</i>	=	total volume of soil brought to the surface (m ³).

Intruder doses were calculated at various times after site closure in the year 2018. The three periods of concern are:

- Institutional control (100 years following facility closure). During this period, maintenance and surveillance monitoring of the disposal facility would deter inadvertent intruder access.
- Compliance period (100 to 1,000 years following facility closure). During this period, an inadvertent intruder may have limited access that would allow for acute and chronic intruder scenarios. However, long-term institutional controls would prevent such intrusions.
- Post-compliance period (beyond 1,000 years). The maximum time of compliance for DOE O 435.1 Chg 1 is 1,000 years; however, calculations may be extended beyond this time if doses appear to increase due to progeny ingrowth.

5.3 Inadvertent Intruder Analysis Results

This section presents the doses to hypothetical inadvertent intruders for the acute and chronic intruder drilling scenarios, based on a maximum time of compliance of 1,000 years. Calculations are provided beyond 1,000 years up to 10,000 years to detect potential increasing trends in doses due to ingrowth of radioactive daughters. The entire radionuclide inventory is assumed to be uniformly distributed in the overall soil and waste volume of the landfill.

Table 5-3. RESRAD input parameters used in acute intruder drilling scenario.

Parameter	Value	Comments
Soil concentration	1 pCi/g	—
Calculation times	0; 100; 500; 1,000; 5,000; and 10,000 yr	—
Contaminated zone		
Area	2,200 m ²	Maheras et al. (1997)
Thickness	0.02 m	a
Cover and contaminated zone hydrology		
Cover depth	0 m	—
Density of contaminated zone	1.946 g/cm ³	b
Contaminated zone erosion rate	0 m/yr	—
Average annual wind speed	3.35 m/sec	Clawson, Start, and Ricks (1989)
Humidity in air	3.5 g/m ³	Clawson, Start, and Ricks (1989)
Precipitation	0.22 m/yr	Clawson, Start, and Ricks (1989)
Occupancy, ingestion, inhalation, and external gamma data		
Soil ingestion rate	54.65 g/yr	c
Inhalation rate	8,400 m ³ /yr	Default
Mass loading for inhalation	0.001 g/m ³	Maheras et al. (1997)
Exposure duration	1 yr	—
Indoor time fraction	0	—
Outdoor time fraction	0.0183	160 hr/yr (Maheras et al. 1997)
Shape of contaminated zone	Circular	Default
a. The contaminated zone depth of 0.02 m is obtained by dividing the total volume of soil (33 m³) brought to the surface via the 56-cm (22-in.) well drilled to depth of 134 m (440 ft) by the area (2,200 m²) the drill cuttings are spread over. b. Source zone bulk density is 1.946 g/cm³ (Table 4 of EDF-ER-275). Bulk density of contaminated zone caused from well drill cuttings and surface soil is assumed to be the same as the source zone (disposal facility) bulk density because the drill cuttings are directly taken from the drill stem and spread on the ground surface. c. A total of 1,000 mg of soil is assumed to be ingested (20 days [8 hr each] × 50 mg/d, assuming a total of 160 hr of exposure). A value of 54.65 g/yr was used as the soil ingestion rate in RESRAD, because 54.65 g/yr × 0.0183 × 1 yr = 1,000 mg. 0.0183 is the outdoor time fraction.		

Table 5-4. Input parameters used in chronic intruder post-drilling scenario.

Parameter	Value	Comments
Soil concentration	1 pCi/g	—
Calculation times	0; 100; 500; 1,000; 5,000; and 10,000 yrs	—
Food transfer factors	(see Table 5-5)	Baes et al. (1984)
Contaminated zone from drill cuttings tilled into surface soil		
Area	2,200 m ²	Maheras et al. (1997)
Thickness	0.61 m (24 in.)	a
Cover and contaminated zone hydrology		
Cover depth	0 m	—
Density of contaminated zone	1.5 g/cm ³	b
Contaminated zone erosion rate	0 m/yr	—
Average annual wind speed	3.35 m/s	Clawson, Start, and Ricks (1989)
Humidity in air	3.5 g/m ³	Clawson, Start, and Ricks (1989)
Precipitation	0.22 m/yr	Clawson, Start, and Ricks (1989)
Occupancy, inhalation, and external gamma data		
Inhalation rate	8,400 m ³ /yr	Default
Mass loading for inhalation	5.53E-05 g/m ³	Maheras et al. (1997)
Exposure duration	1 yr	Case et al. (2000)
Shielding factor inhalation	0.4	Default
Shielding factor external gamma	0.7	Default
Indoor time fraction	0.5	Default
Outdoor time fraction	0.25	Default
Shape of contaminated zone	Circular	Default
Ingestion pathway, dietary data		
Fruit, vegetable, and grain consumption	94 kg/yr	Case et al. (2000)
Leafy vegetable consumption	17 kg/yr	Case et al. (2000)
Milk consumption	89 L/yr	Case et al. (2000)
Meat and poultry consumption	55 kg/yr	Case et al. (2000)
Soil ingestion	36.5 g/yr	Default
Ingestion pathway, nondietary data		
Livestock fodder intake for meat	5.4 kg/day	Case et al. (2000)
Livestock fodder intake for milk	7.2 kg/day	Case et al. (2000)
Livestock water intake for meat	50 L/day	Default
Livestock water intake for milk	160 L/day	Default
Livestock soil intake	0.5 kg/day	Default
Mass loading for foliar deposition	0.0001 g/m ³	Default
Depth of soil mixing layer	0.61 m (24 in.)	Maheras et al. (1997)
Depth of roots	0.15 m (6 in.)	Maheras et al. (1997)

a. Plow depth.

b. Bulk density of well drill cuttings tilled into surface soil is assumed to be 1.5 g/cm³ (RESRAD default value).

Table 5-5. Food transfer factors (Baes et al. [1984] unless otherwise specified).

Radionuclide	Plant ^a	Milk (d/L)	Beef (d/kg)
Ag	4.3E-02	2.0E-02	3.0E-03
Am	1.1E-04	4.0E-07	3.5E-06
Ba	6.4E-03	3.5E-04	1.5E-04
Be	6.4E-04	9.0E-07	1.0E-03
C	5.6E-01 ^b	1.2E-02 ^c	3.1E-02 ^c
Ca	1.5E-01	1.0E-02	7.0E-04
Cd	6.4E-02	1.0E-03	5.5E-04
Cf ^c	1.0E-03	7.5E-07	6.0E-05
Cl	3.0E+01	1.5E-02	8.0E-02
Cm	6.4E-06	2.0E-05	3.5E-06
Co	3.0E-03	2.0E-03	2.0E-02
Cs	1.3E-02	7.0E-03	2.0E-02
Eu	1.7E-03	2.0E-05	5.0E-03
H-3 ^c	4.8E+00	1.0E-02	1.2E-02
Ho	1.7E-03	2.0E-05	4.5E-03
I	2.1E-02	1.0E-02	7.0E-03
K	2.4E-01	7.0E-03	2.0E-02
Mo	2.6E-02	1.5E-03	6.0E-03
Nb	2.1E-03	2.0E-02	2.5E-01
Ni	2.6E-02	1.0E-03	6.0E-03
Np	4.3E-03	5.0E-06	5.5E-05
Pa	1.1E-04	5.0E-06	1.0E-05
Pb	3.9E-03	2.5E-04	3.0E-04
Pu	1.9E-05	1.0E-07	5.0E-07
Ra	6.4E-04	4.5E-04	2.5E-04
Re	1.5E-01	1.5E-03	8.0E-03
Sm	1.7E-03	2.0E-05	5.0E-03
Sn	2.6E-03	1.0E-03	8.0E-02
Sr	1.1E-01	1.5E-03	3.0E-04
Tb	1.7E-03	2.0E-05	4.5E-03
Tc	6.4E-01	1.0E-02	8.5E-03
Th	3.6E-05	5.0E-06	6.0E-06
U	1.7E-03	6.0E-04	2.0E-04

a. Plant/soil concentration ratio wet weight.

b. Value from Sheppard, Sheppard, and Amiro (1991) multiplied by factor of 0.43 to convert to fresh wet weight of vegetation.

c. RESRAD default.

The dose results for the acute intruder drilling scenario are presented in Table 5-6. The acute intruder drilling scenario yielded a peak dose of 1.7 mrem in 2118, the end of institutional control and beginning of the compliance period. Cs-137 was the dominant radionuclide, accounting for 1.6 mrem of the total dose with external exposure as the dominant pathway. Nb-94 was the next dominant radionuclide, accounting for 0.07 mrem of the total dose with external exposure as the dominant pathway. The total dose declined beyond 100 years. The total dose of 1.7 mrem is well below the DOE O 435.1 Chg 1 acute intruder performance measure of 500 mrem.

The dose results for the chronic intruder post-drilling scenario are presented in Table 5-7. The chronic intruder drilling scenario yielded a peak dose of 0.7 mrem/year in 2118, the end of institutional control and beginning of the compliance period. Cs-137 was the dominant radionuclide, accounting for 0.6 mrem/year of the total dose with external exposure as the dominant pathway. Sr-90 was the next dominant radionuclide, accounting for 0.06 mrem/year of the total dose with plant ingestion as the dominant pathway. The total dose declined beyond 100 years. The total dose of 0.7 mrem/year is well below the DOE O 435.1 Chg 1 chronic intruder performance measure of 100 mrem/year.

All calculations and parameter values associated with the inadvertent intruder analysis are documented in EDF-9874. Interpretation of the inadvertent intruder analysis results is provided in Section 6.6. Application of the inadvertent intruder results in the form of waste concentration limits based on the acute and chronic scenarios described above is discussed in Section 7.2.1.

5.4 Inadvertent Intruder Uncertainty Discussion

This section discusses the uncertainty associated with the inadvertent intruder analyses. Per the guidance of DOE M 435.1-1 Chg 1, the evaluation is limited to qualitative arguments. First, it should be acknowledged that the inadvertent intrusion is considered a hypothetical event. Thus, the selected intrusion scenarios are intended to reasonably bound the potential exposures using technologies and practices that are in use today. Nevertheless, to address the uncertainties, additional conservatism was added to the intruder analyses through the following assumptions:

1. A 56-cm (22-in.) irrigation well, instead of a 15- to 20-cm (6- to 8-in.) residential well, was selected for the acute drilling scenario to ensure that more waste material was brought to the surface.
2. A 20-cm (8-in.) residential well was selected over a more typical 15-cm (6-in.) well in the chronic post-drilling scenario to maximize the volume of waste brought to the surface.
3. In the acute drilling scenario, the material was spread over the surface of a 1/2-acre lot, rather than in a mud pit, so that the intruder directly contacts the waste and the waste is not diluted. The driller is also assumed to stand directly in the dust cloud rather than upwind as would typically be the case.
4. The drill cuttings from the waste zone were not diluted with other subsurface media acquired in the cuttings, and drill cuttings obtained from cover above grade were also not included.

Uncertainty exists in the selection of the model used to quantify the selected scenarios. Uncertainty in the model selected, RESRAD, can only be evaluated through model validation. Model validation answers the question “Does the model accurately simulate the behavior of the system?” While it is beyond the scope of this analysis to perform model validation, several features of the RESRAD model provided confidence that it was appropriate to model the performance of the ICDF Landfill. These features include the following:

1. RESRAD was developed for DOE to calculate radiation doses and excess lifetime cancer risk to an acute and/or chronic intruder, as well as to provide residual radioactive material guidelines.
2. Nine environmental pathways are considered: direct exposure, inhalation of particulates and radon, and ingestion of plant foods, meat, milk, aquatic foods, water, and soil.
3. The RESRAD code has been verified, has undergone several benchmarking analyses, and has been included in the International Atomic Energy Agency's VAMP and BIOMOVs II projects to compare environmental transport models.
4. RESRAD can incorporate site-specific data, which enables more realistic dose assessments.

Many uncertainties are associated with the parameter values selected for the model. Typically, parametric uncertainty is assessed through an uncertainty analysis, which involves quantifying the uncertainty of model output, based on the uncertainty of parameter values input into the model. Uncertainty analysis of the intruder scenarios was not conducted. Instead, to help ensure that the conclusions of the PA are reasonable, conservative values were selected, when appropriate, particularly for sensitive parameters.

Table 5-6. Acute drilling scenario dose results.

Radionuclide	Half-life ^a (yr)	PA Total Inventory ^b 2003–2018 (Ci)	Average Landfill Concentration ^c (pCi/g)	DSR at 100 yr ^d (mrem/yr per pCi/g)	Dose at 100 yr ^e (mrem)	DSR at 500 yr ^d (mrem/yr per pCi/g)	Dose at 500 yr ^e (mrem)	DSR at 1,000 yr ^d (mrem/yr per pCi/g)	Dose at 1,000 yr ^e (mrem)
Ag-108m	4.18E+02	1.47E+00	2.35E+00	2.61E-02	4.64E-03	2.94E-03	5.23E-04	1.92E-04	3.41E-05
Am-241	4.32E+02	1.89E+00	3.01E+00	9.75E-03	2.22E-03	5.13E-03	1.17E-03	2.30E-03	5.25E-04
Am-242m	1.41E+02	2.99E-03	4.76E-03	1.06E-02	3.80E-06	2.72E-03	9.80E-07	3.10E-04	1.12E-07
Am-243	7.37E+03	2.46E-02	3.92E-02	1.67E-02	4.96E-05	1.62E-02	4.81E-05	1.56E-02	4.64E-05
Ba-133	1.05E+01	3.23E-01	5.13E-01	1.62E-05	6.29E-07	9.94E-17	3.87E-18	9.61E-31	3.74E-32
Be-10	1.51E+06	1.58E+00	2.52E+00	1.85E-05	3.52E-06	1.85E-05	3.52E-06	1.85E-05	3.52E-06
C-14	5.70E+03	1.10E+02	1.76E+02	0.00E+00 ^f	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ca-41	1.03E+05	1.46E-03	2.33E-03	1.27E-06	2.24E-10	1.27E-06	2.24E-10	1.27E-06	2.23E-10
Cf-249	3.51E+02	3.88E-04	6.18E-04	1.95E-02	9.13E-07	9.25E-03	4.33E-07	3.98E-03	1.86E-07
Cf-251	8.98E+02	7.60E-05	1.21E-04	1.65E-02	1.51E-07	1.21E-02	1.11E-07	8.25E-03	7.56E-08
Cl-36	3.01E+05	7.19E-01	1.14E+00	1.84E-05	1.59E-06	1.83E-05	1.59E-06	1.83E-05	1.59E-06
Cm-243	2.91E+01	2.84E-02	4.51E-02	9.70E-04	3.32E-06	1.24E-05	4.25E-08	1.22E-05	4.17E-08
Cm-244	1.81E+01	1.43E+00	2.27E+00	1.59E-04	2.74E-05	2.79E-05	4.81E-06	2.65E-05	4.56E-06
Cm-245	8.50E+03	7.67E-04	1.22E-03	1.51E-02	1.39E-06	1.93E-02	1.78E-06	2.14E-02	1.97E-06
Cm-246	4.76E+03	1.02E-02	1.62E-02	4.08E-02	1.33E-05	4.07E-02	1.33E-05	4.07E-02	1.33E-05
Cm-248	3.48E+05	2.71E-03	4.31E-03	4.08E-02	1.33E-05	4.07E-02	1.33E-05	4.07E-02	1.33E-05
Co-60	5.27E+00	1.69E+04	2.70E+04	1.19E-07	2.44E-04	1.71E-30	3.49E-27	0.00E+00	0.00E+00
Cs-137	3.01E+01	8.32E+03	1.32E+04	1.54E-03	1.55E+00	1.49E-07	1.50E-04	1.44E-12	1.44E-09
Eu-152	1.35E+01	2.24E+02	3.57E+02	1.66E-04	4.49E-03	1.54E-13	4.16E-12	1.44E-16	3.90E-15
Eu-154	8.59E+00	1.68E+02	2.68E+02	1.22E-05	2.48E-04	2.53E-19	5.14E-18	1.99E-36	4.04E-35
H-3	1.23E+01	1.25E+05	1.99E+05	2.24E-10	3.37E-06	3.98E-20	5.98E-16	2.58E-32	3.89E-28
Ho-166m	1.20E+03	3.63E-02	5.77E-02	4.51E-02	1.97E-04	3.58E-02	1.57E-04	2.68E-02	1.17E-04

Table 5-6. (continued).

Radionuclide	Half-life ^a (yr)	PA Total Inventory ^b 2003–2018 (Ci)	Average Landfill Concentration ^c (pCi/g)	DSR at 100 yr ^d (mrem/yr per pCi/g)	Dose at 100 yr ^e (mrem)	DSR at 500 yr ^d (mrem/yr per pCi/g)	Dose at 500 yr ^e (mrem)	DSR at 1,000 yr ^d (mrem/yr per pCi/g)	Dose at 1,000 yr ^e (mrem)
I-129	1.57E+07	1.50E-01	2.39E-01	4.90E-04	8.89E-06	4.90E-04	8.89E-06	4.90E-04	8.89E-06
K-40	1.27E+09	9.68E-01	1.54E+00	4.10E-03	4.78E-04	4.10E-03	4.78E-04	4.10E-03	4.78E-04
Mo-93	4.00E+03	1.34E-01	2.13E-01	1.50E-05	2.41E-07	1.39E-05	2.23E-07	1.25E-05	2.02E-07
Nb-94	2.03E+04	1.26E+01	2.00E+01	4.29E-02	6.52E-02	4.23E-02	6.43E-02	4.16E-02	6.32E-02
Ni-59	7.60E+04	5.89E+02	9.37E+02	2.51E-07	1.78E-05	2.50E-07	1.78E-05	2.49E-07	1.77E-05
Ni-63	1.00E+02	1.03E+05	1.65E+05	3.25E-07	4.05E-03	1.81E-08	2.26E-04	4.90E-10	6.11E-06
Np-237	2.14E+06	7.68E-02	1.22E-01	1.95E-02	1.81E-04	1.95E-02	1.81E-04	1.95E-02	1.81E-04
Pa-231 ^g	3.28E+04	6.81E-06	1.08E-05	1.64E-01	1.35E-07	1.68E-01	1.38E-07	1.66E-01	1.37E-07
Pb-210	2.23E+01	2.42E-02	3.85E-02	3.34E-04	9.75E-07	1.33E-09	3.88E-12	2.37E-16	6.91E-19
Pu-238	8.77E+01	1.89E+01	3.00E+01	4.37E-03	9.93E-03	1.86E-04	4.23E-04	4.49E-06	1.02E-05
Pu-239	2.41E+04	1.93E+01	3.07E+01	1.06E-02	2.46E-02	1.05E-02	2.43E-02	1.03E-02	2.39E-02
Pu-240	6.56E+03	1.04E+01	1.66E+01	1.05E-02	1.32E-02	1.01E-02	1.26E-02	9.54E-03	1.20E-02
Pu-241	1.43E+01	2.95E+01	4.70E+01	3.34E-04	1.19E-03	1.77E-04	6.30E-04	7.94E-05	2.83E-04
Pu-242	3.73E+05	6.40E-04	1.02E-03	1.01E-02	7.81E-07	1.01E-02	7.81E-07	1.01E-02	7.80E-07
Ra-226	1.60E+03	1.01E+00	1.60E+00	5.31E-02	6.45E-03	4.50E-02	5.46E-03	3.62E-02	4.40E-03
Sn-121m	5.50E+01	1.06E-03	1.68E-03	1.03E-05	1.31E-09	6.65E-08	8.49E-12	1.22E-10	1.56E-14
Sr-90	2.88E+01	1.90E+03	3.03E+03	2.83E-05	6.48E-03	2.07E-09	4.75E-07	1.40E-14	3.22E-12
Tb-158	1.80E+02	6.45E-04	1.03E-03	1.32E-02	1.03E-06	2.09E-03	1.62E-07	2.07E-04	1.61E-08
Tc-99	2.11E+05	6.59E-01	1.05E+00	2.75E-06	2.18E-07	2.74E-06	2.18E-07	2.74E-06	2.18E-07
Th-230 ^g	7.54E+04	1.04E-01	1.65E-01	8.23E-03	1.03E-04	1.67E-02	2.09E-04	2.54E-02	3.17E-04
Th-232	1.41E+10	9.33E-02	1.49E-01	1.04E-01	1.17E-03	1.04E-01	1.17E-03	1.04E-01	1.17E-03
U-232	6.89E+01	7.12E-04	1.13E-03	2.27E-02	1.95E-06	4.82E-04	4.14E-08	3.92E-06	3.36E-10
U-233 ^g	1.59E+05	1.19E-01	1.90E-01	2.99E-03	4.29E-05	4.77E-03	6.85E-05	6.90E-03	9.90E-05

Table 5-6. (continued).

Radionuclide	Half-life ^a (yr)	PA Total Inventory ^b 2003–2018 (Ci)	Average Landfill Concentration ^c (pCi/g)	DSR at 100 yr ^d (mrem/yr per pCi/g)	Dose at 100 yr ^e (mrem)	DSR at 500 yr ^d (mrem/yr per pCi/g)	Dose at 500 yr ^e (mrem)	DSR at 1,000 yr ^d (mrem/yr per pCi/g)	Dose at 1,000 yr ^e (mrem)
U-234 ^g	2.46E+05	6.91E-01	1.10E+00	2.48E-03	2.06E-04	2.52E-03	2.10E-04	2.61E-03	2.18E-04
U-235 ^g	7.04E+08	1.55E-01	2.46E-01	7.21E-03	1.34E-04	8.63E-03	1.61E-04	1.04E-02	1.94E-04
U-236	2.34E+07	3.94E-03	6.27E-03	2.34E-03	1.11E-06	2.34E-03	1.11E-06	2.34E-03	1.11E-06
U-238	4.47E+09	4.97E-01	7.91E-01	3.01E-03	1.80E-04	3.02E-03	1.81E-04	3.02E-03	1.81E-04
Total dose					1.69E+00		1.13E-01		1.07E-01

a. Radionuclide half-lives obtained from the Integrated Waste Tracking System database with its data source the National Nuclear Data Center, Brookhaven Laboratory.
 b. Total inventory from Table 2-6.
 c. Waste activity concentration of radionuclide calculated by Equation 2 where disposal facility volume = 322,816 m³ and density of source zone (disposal facility) = 1.946 g/cm³.
 d. Dose-to-source ratio calculated by RESRAD at designated time (yr).
 e. Dose at designated time (yr) calculated using Equation 3 where volume of waste = 2.5 m³ and volume of total cuttings = 33 m³.
 f. The DSR for C-14, a volatile radionuclide, are zero beyond the institutional control period and therefore were not included in the RESRAD runs.
 g. The DSR for these radionuclides is increasing beyond 100 yr; therefore, the largest DSR at 1,000 yr is used in the dose calculation (with the exception of Pa-231 which occurs at 500 yr).

DSR dose-to-source ratio
 PA performance assessment

Table 5-7. Chronic drilling scenario dose results.

Radionuclide	Half-life ^a (yr)	PA Total Inventory 2003– 2018 ^b (Ci)	Average Landfill Concentration ^c (pCi/g)	DSR at 100 yr ^d (mrem/yr per pCi/g)	Dose 100 yr ^e (mrem)	DSR at 500 yr ^d (mrem/yr per pCi/g)	Dose 500 yr ^e (mrem)	DSR at 1,000 yr ^d (mrem/yr per pCi/g)	Dose at 1,000 yr ^e (mrem)
Ag-108m	4.18E+02	1.47E+00	2.35E+00	3.027	1.69E-03	0.3411	1.91E-04	2.23E-02	1.25E-05
Am-241	4.32E+02	1.89E+00	3.01E+00	1.34E-01	9.58E-05	7.05E-02	5.06E-05	3.18E-02	2.28E-05
Am-242m	1.41E+02	2.99E-03	4.76E-03	1.42E-01	1.61E-07	3.35E-02	3.80E-08	3.77E-03	4.27E-09
Am-243	7.37E+03	2.46E-02	3.92E-02	6.23E-01	5.82E-06	6.01E-01	5.62E-06	5.75E-01	5.37E-06
Ba-133	1.05E+01	3.23E-01	5.13E-01	1.66E-03	2.03E-07	1.02E-14	1.25E-18	9.86E-29	1.21E-32
Be-10	1.51E+06	1.58E+00	2.52E+00	9.11E-04	5.47E-07	9.10E-04	5.46E-07	9.10E-04	5.46E-07
C-14	5.70E+03	1.10E+02	1.76E+02	0.00E+00 ^f	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ca-41	1.03E+05	1.46E-03	2.33E-03	1.08E-02	6.00E-09	1.08E-02	5.99E-09	1.08E-02	5.98E-09
Cf-249	3.51E+02	3.88E-04	6.18E-04	1.17E+00	1.72E-07	5.38E-01	7.92E-08	2.10E-01	3.10E-08
Cf-251	8.98E+02	7.60E-05	1.21E-04	6.57E-01	1.90E-08	4.82E-01	1.39E-08	3.28E-01	9.46E-09
Cl-36	3.01E+05	7.19E-01	1.14E+00	5.38E+00	1.47E-03	5.38E+00	1.47E-03	5.37E+00	1.47E-03
Cm-243	2.91E+01	2.84E-02	4.51E-02	3.48E-02	3.75E-07	1.31E-04	1.41E-09	1.27E-04	1.37E-09
Cm-244	1.81E+01	1.43E+00	2.27E+00	1.62E-03	8.78E-07	2.92E-04	1.58E-07	2.77E-04	1.50E-07
Cm-245	8.50E+03	7.67E-04	1.22E-03	3.23E-01	9.40E-08	3.77E-01	1.10E-07	4.01E-01	1.17E-07
Cm-246	4.76E+03	1.02E-02	1.62E-02	1.12E-01	4.31E-07	1.05E-01	4.05E-07	9.74E-02	3.75E-07
Cm-248	3.48E+05	2.71E-03	4.31E-03	4.17E-01	4.29E-07	4.16E-01	4.28E-07	4.16E-01	4.28E-07
Co-60	5.27E+00	1.69E+04	2.70E+04	1.61E-05	1.04E-04	2.30E-28	1.48E-27	0.00E+00	0.00E+00
Cs-137	3.01E+01	8.32E+03	1.32E+04	1.85E-01	5.84E-01	1.79E-05	5.66E-05	1.72E-10	5.44E-10
Eu-152	1.35E+01	2.24E+02	3.57E+02	2.05E-02	1.74E-03	1.90E-11	1.62E-12	9.28E-16	7.89E-17
Eu-154	8.59E+00	1.68E+02	2.68E+02	1.53E-03	9.76E-05	3.17E-17	2.02E-18	2.49E-34	1.59E-35
H-3	1.23E+01	1.25E+05	1.99E+05	6.23E-09	2.95E-07	1.11E-18	5.25E-17	7.20E-31	3.41E-29
Ho-166m	1.20E+03	3.63E-02	5.77E-02	5.26E+00	7.24E-05	4.18E+00	5.75E-05	3.13E+00	4.31E-05

Table 5-7. (continued).

Radionuclide	Half-life ^a (yr)	PA Total Inventory 2003– 2018 ^b (Ci)	Average Landfill Concentration ^c (pCi/g)	DSR at 100 yr ^d (mrem/yr per pCi/g)	Dose 100 yr ^e (mrem)	DSR at 500 yr ^d (mrem/yr per pCi/g)	Dose 500 yr ^e (mrem)	DSR at 1,000 yr ^d (mrem/yr per pCi/g)	Dose at 1,000 yr ^e (mrem)
I-129	1.57E+07	1.50E-01	2.39E-01	3.62E-01	2.07E-05	3.62E-01	2.06E-05	3.62E-01	2.06E-05
K-40	1.27E+09	9.68E-01	1.54E+00	8.21E-01	3.02E-04	8.21E-01	3.02E-04	8.21E-01	3.02E-04
Mo-93	4.00E+03	1.34E-01	2.13E-01	2.92E-03	1.48E-07	2.70E-03	1.37E-07	2.45E-03	1.24E-07
Nb-94	2.03E+04	1.26E+01	2.00E+01	5.23E+00	2.50E-02	5.16E+00	2.47E-02	5.08E+00	2.43E-02
Ni-59	7.60E+04	5.89E+02	9.37E+02	3.15E-04	7.04E-05	3.14E-04	7.01E-05	3.12E-04	6.98E-05
Ni-63	1.00E+02	1.03E+05	1.65E+05	4.19E-04	1.64E-02	2.33E-05	9.16E-04	6.31E-07	2.48E-05
Np-237	2.14E+06	7.68E-02	1.22E-01	1.80E+00	5.25E-05	1.80E+00	5.25E-05	1.80E+00	5.25E-05
Pa-231 ^g	3.28E+04	6.81E-06	1.08E-05	2.20E+00	5.69E-09	2.26E+00	5.84E-09	2.24E+00	5.78E-09
Pb-210	2.23E+01	2.42E-02	3.85E-02	7.90E-02	7.25E-07	3.15E-07	2.89E-12	5.60E-14	5.14E-19
Pu-238	8.77E+01	1.89E+01	3.00E+01	4.53E-02	3.24E-04	1.94E-03	1.39E-05	5.47E-05	3.92E-07
Pu-239	2.41E+04	1.93E+01	3.07E+01	1.11E-01	8.12E-04	1.09E-01	7.99E-04	1.08E-01	7.87E-04
Pu-240	6.56E+03	1.04E+01	1.66E+01	1.10E-01	4.36E-04	1.05E-01	4.16E-04	9.96E-02	3.95E-04
Pu-241	1.43E+01	2.95E+01	4.70E+01	4.58E-03	5.14E-05	2.43E-03	2.72E-05	1.10E-03	1.23E-05
Pu-242	3.73E+05	6.40E-04	1.02E-03	1.05E-01	2.55E-08	1.05E-01	2.55E-08	1.05E-01	2.55E-08
Ra-226	1.60E+03	1.01E+00	1.60E+00	7.58E+00	2.90E-03	6.44E+00	2.46E-03	5.19E+00	1.98E-03
Sn-121m	5.50E+01	1.06E-03	1.68E-03	6.17E-04	2.48E-10	3.99E-06	1.60E-12	7.31E-09	2.94E-15
Sr-90	2.88E+01	1.90E+03	3.03E+03	8.72E-02	6.29E-02	6.39E-06	4.61E-06	4.33E-11	3.13E-11
Tb-158	1.80E+02	6.45E-04	1.03E-03	1.62E+00	3.96E-07	2.55E-01	6.23E-08	2.53E-02	6.18E-09
Tc-99	2.11E+05	6.59E-01	1.05E+00	5.30E-02	1.33E-05	5.29E-02	1.32E-05	5.28E-02	1.32E-05
Th-230 ^g	7.54E+04	1.04E-01	1.65E-01	2.80E+00	1.10E-04	1.55E+00	6.11E-05	2.80E+00	1.10E-04
Th-232	1.41E+10	9.33E-02	1.49E-01	9.06E+00	3.21E-04	9.06E+00	3.21E-04	9.06E+00	3.21E-04
U-232	6.89E+01	7.12E-04	1.13E-03	2.25E+00	6.08E-07	4.79E-02	1.29E-08	3.89E-04	1.05E-10

Table 5-7. (continued).

Radionuclide	Half-life ^a (yr)	PA Total Inventory 2003– 2018 ^b (Ci)	Average Landfill Concentration ^c (pCi/g)	DSR at 100 yr ^d (mrem/yr per pCi/g)	Dose 100 yr ^e (mrem)	DSR at 500 yr ^d (mrem/yr per pCi/g)	Dose 500 yr ^e (mrem)	DSR at 1,000 yr ^d (mrem/yr per pCi/g)	Dose at 1,000 yr ^e (mrem)
U-233 ^g	1.59E+05	1.19E-01	1.90E-01	1.34E-01	6.06E-06	8.82E-02	3.98E-06	1.34E-01	6.05E-06
U-234 ^g	2.46E+05	6.91E-01	1.10E+00	5.22E-02	1.37E-05	4.23E-02	1.11E-05	5.22E-02	1.37E-05
U-235 ^g	7.04E+08	1.55E-01	2.46E-01	5.03E-01	2.95E-05	4.80E-01	2.81E-05	5.03E-01	2.95E-05
U-236	2.34E+07	3.94E-03	6.27E-03	3.67E-02	5.49E-08	3.67E-02	5.49E-08	3.67E-02	5.49E-08
U-238	4.47E+09	4.97E-01	7.91E-01	1.19E-01	2.24E-05	1.19E-01	2.25E-05	1.19E-01	2.25E-05
Total dose					6.99E-01		3.21E-02		3.00E-02

a. Radionuclide half-lives obtained from the Integrated Waste Tracking System database with its data source the National Nuclear Data Center, Brookhaven Laboratory.

b. Total inventory from Table 2-6.

c. Waste activity concentration of radionuclide calculated by Equation 2 where disposal facility volume = 322,816 m³ and density of source zone (disposal facility) = 1.946 g/cm³.

d. Dose-to-source ratio calculated by RESRAD at designated time (yr).

e. Dose at designated time (yr) calculated using Equation 3 where volume of waste = 0.32 m³ and volume of total cuttings = 1,342 m³.

f. The DSR for C-14, a volatile radionuclide, are zero beyond the institutional control period and therefore were not included in the RESRAD runs.

g. The DSR for these radionuclides is increasing beyond 100 yr; therefore, the largest DSR at 1,000 yr is used in the dose calculation (with the exception of Pa-231 which occurs at 500 yr).

DSR dose-to-source ratio
PA performance assessment

6. INTERPRETATION OF RESULTS

In this section, the results presented in Sections 4 and 5 are consolidated to provide the basis for evaluating the performance of the ICDF Landfill. The goals of the interpretation of results are to:

- Address the findings of the sensitivity and uncertainty analyses to provide an overall estimate of the expected performance of the ICDF Landfill that is defensible for each of the performance criteria for the time of compliance at the points of compliance
- Provide a rational basis to conclude that the performance of the ICDF Landfill has been completely addressed
- Provide a rational basis to conclude that the analysis is logically interpreted
- Provide a rational basis to conclude that the results are correct representations of the ICDF Landfill performance
- Provide a rational basis to conclude that the results are sufficiently rigorous.

The interpretation of the results includes the findings for the:

- All-pathways analysis
- Radon flux analysis
- Air pathway analysis
- Groundwater resource protection analysis
- Inadvertent intruder analysis.

6.1 All-Pathways Dose

All-pathways doses were predicted to be well below the 25-mrem/year standard for all timeframes considered in the PA (Table 6-1). As presented in Section 4.5, the predicted peak all-pathways dose during the 1,000-year compliance time was 8.1E-04 mrem/year, dominated by Tc-99 and Cl-36 in year 3018 at the end of the compliance period (Figure 4-10 and Table 4-3). Two additional all-pathways dose peaks occurred after the 1,000-year compliance time: a peak of 0.07 mrem/year dominated by Tc-99 and Cl-36 around year 3518 and another peak of 0.58 mrem/year dominated by C-14 and I-129 around year 8368 (see Figures 4-10 and 4-11 and Table 4-3). Although these peaks were greater than the peak during the compliance period, both are still well below the 25-mrem/year all-pathways dose objective. Based on the curves illustrated in Figures 4-10 and 4-11, there is high confidence that the all-pathways peak doses for the assumptions in the base case calculations were captured over the 300,000-year simulation. The following paragraphs provide details regarding sensitivity and uncertainty analyses that were conducted to build confidence in the conclusions from the base case assessment.

Table 6-1. Summary of peak all-pathways doses during three time periods for the base case.

All-Pathways EDE (primary nuclide, year of peak)		
Institutional Control 2018–2118 (INL Site boundary) (mrem/yr)	Compliance Period 2119–3018 (100 m downgradient) (mrem/yr)	Post-Compliance 3019–Time of Peak Concentration (100 m downgradient) (mrem/yr)
0	8.1E-04 mrem/yr (Tc-99 and Cl-36, year 3018)	0.6 mrem/yr (C-14 and I-129, year 8368)
EDE effective dose equivalent		
INL Idaho National Laboratory		

Eight sensitivity cases were run in order to test different conceptual models and the results were compared with the base case results (Table 4-7 and Figures 4-14 to 4-21). Sensitivity Cases 1 and 2 assumed constant infiltration rates through a cover that lasts forever (0.1 cm/year for Case 1 and 1 cm/year for Case 2). Sensitivity Cases 3, 6, 7, and 8 assumed different failure scenarios for the HDPE liner and the cover. In Case 3, the cover performs as designed but the HDPE liner fails while the leachate collection system is operating. In Case 6, the cover operates as designed for 100 years, then fails. The HDPE liner does not fail until the facility fills with water in year 230. In Case 7, the cover operates as designed; the HDPE liner does not fail until the facility fills with water in year 850. In Case 8, the cover operates as designed; the HDPE liner never fails. The facility fills with water by year 850 and then overflows. The water moves through the vadose zone to the aquifer outside the boundaries of the ICDF Landfill. In Sensitivity Cases 4 and 5, the subsurface layers are changed. In Case 4, the bentonite clay layer is replaced with an alluvium layer and in Case 5 an interbed is eliminated from the simulation.

During the compliance period, relative to the base case, the peak all-pathways dose is smaller for Sensitivity Case 1 and larger for all other cases. For Sensitivity Case 1, the infiltration rate after year 500 is less than the base case, resulting in the smaller peak doses. For all other cases, the water in the waste moves quicker to the aquifer, resulting in higher fluxes from the ICDF Landfill and/or shorter travel times to the aquifer. The largest peak dose during the compliance period is for Sensitivity Case 8 in which the facility fills with water, overflowing and then moving much more quickly to the aquifer, and does not move through the bentonite clay layer. Doses are all well below the performance objective during the compliance period.

During the post-compliance period, there is relatively little difference in the peak all-pathways dose between the base case and the sensitivity cases, with the exception of Sensitivity Cases 1 and 8. In Sensitivity Case 1, the long-term infiltration rate is 10% of the base case infiltration rate and the peak all-pathways dose is almost 10 times smaller than the base case peak dose. In Case 8, the HDPE liner never fails, the facility fills with water and overflows. The infiltrating water moves through a much smaller area to the aquifer and avoids the bentonite clay layer (which slows the transport). The resulting peak all-pathways dose is more than 10 times the base case dose. For Sensitivity Cases 1-7, peak doses are all well below the performance objective during the post-compliance period. For Sensitivity Case 8, the peak dose is one-third the performance objective.

Monte Carlo uncertainty and sensitivity analyses provide a means to evaluate the influence of the uncertainty associated with a number of different parameters on the range of possible all-pathways dose results and also to develop an estimate of the relative importance of different parameters. The range of all-pathways dose results from the Monte Carlo uncertainty analysis is presented in Figure 4-24. The complete range of results (through 97.5th percentile) presented in Figure 4-24 is well under the 25-mrem/year objective for all times. This provides confidence that, for foreseeable conditions, few circumstances would arise leading to a dose in excess of the all-pathways dose objective.

Monte Carlo analysis results can also be used for sensitivity analysis to identify the parameters that have the largest influence on the results. Rank correlation coefficients and the percent contribution of each parameter to the variance in the all-pathways dose were provided for several different times in Tables 4-14 and 4-15 and are summarized in Table 6-2. The statistics of the sampled parameter distributions are provided in Table 4-9. Based on the sampled parameter distributions used for the quantitative sensitivity analysis, at the end of the compliance period (year 3018), the all-pathways EDE is sensitive to the infiltration-related parameters and relatively insensitive to all other parameters. As time goes on, the EDE becomes more sensitive to the Darcy velocity and K_d values in the alluvium, waste, and interbeds for iodine, carbon, and uranium. Late in time, the EDE becomes sensitive to the uranium K_d value in the clay layer and the C-14 inventory scaling factor. The all-pathways EDE is relatively insensitive to the other parameters.

Table 6-2. Summary of most-sensitive input parameters to the all-pathways dose output 100 m downgradient from the ICDF Landfill. (All parameters with greater than 5% contribution to variance in the rank correlation coefficient results are included here for the times of maximum dose during the compliance time [3018] and post-compliance time [5418]).

End of Compliance Time (year 3018)	Rank Correlation Coefficient	Percent Variance (%)	Post-Compliance Time (year 5418)	Rank Correlation Coefficient	Percent Variance (%)
Engineered cover longevity	-0.67	54	Infiltration rate after cover failure	0.63	47
Engineered cover infiltration rate	0.5	30	Carbon K_d in alluvium, waste, and interbed	-0.41	21
Infiltration rate after cover failure	0.28	9.1	Iodine K_d in alluvium and waste	-0.30	11
			Darcy velocity in aquifer	-0.22	5.6

The importance of different input parameters is often directly related to the radionuclides that lead to the greatest contribution to the dose. Thus, key parameters can have a significant influence at one or two times and minimal influence at others.

During the compliance time, only mobile (i.e., $K_d = 0$) radionuclides with sufficiently long half-lives were important. Consequently, only Tc-99 and Cl-36 were important in terms of all-pathways dose during the compliance time, accounting for over 99% of the total dose. Therefore, only parameters that influence the flux and dilution of Tc-99 and Cl-36 during this time period were important. These parameters were infiltration rates and cover longevity.

After the compliance period, C-14 and I-129 become the key contributors to the all-pathways dose. Important parameters then included the C-14 and I-129 K_d values, infiltration through the failed cover, and, to a lesser extent, the Darcy velocity in the aquifer.

6.2 Radon Flux Results

As described in Section 4.3, the projected waste inventory is not a significant radon source. Radium-226 concentrations in the ICDF waste (1.6 pCi/g) are near background concentrations found in INL Site soils (0.75 to 1.4 pCi/g) assuming secular equilibrium with Th-230 (Rood, Harris, and White 1996). In spite of this observation, a very conservative radon flux calculation was performed.

The peak radon flux within the 1,000-year compliance period, $0.6 \text{ pCi} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, is well below the performance objective of $20 \text{ pCi} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$. Of the radionuclides disposed of in the waste, the major dose contributor is Ra-226. The result, given the conservative nature of the calculations, provides confidence in the long-term performance of the facility from the perspective of the radon flux performance objective.

6.3 Biotic Pathways Results

Biointrusion at the ICDF Landfill is not expected because of the depth of the proposed final cover for the facility and the incorporation of a biobarrier component (EDF-ER-279). However, as discussed in Sections 3.5 and 4.4, a biointrusion analysis was performed.

Biointrusion by plant roots and harvester ants is assessed as a mechanism to move radioactive material to the land surface. Big sagebrush roots and harvester ants are assumed to penetrate to depths of 2.25 and 2.7 m (7.4 and 9 ft), respectively, during the compliance period and contact the disposed waste (under 2 m [6.6 ft] of cover). This will provide a biotic pathway for radionuclide migration to the surface. The contamination was assumed to remain on the surface where a hypothetical resident is exposed through the all-pathways scenario.

The maximum screening doses occurred at the end of institutional control. They were estimated to be 0.0022 mrem/year and 0.0019 mrem/year for biointrusion by harvester ants and plant roots, respectively. The dominant dose contributor is Cs-137 for biointrusion via harvester ants and Cl-36 for biointrusion via plant roots. Both these doses are well below the DOE O 435.1 Chg 1 all-pathways dose limit of 25 mrem/year. Given the conservative assumptions regarding the potential for flora or fauna to actually contact the waste, the low doses projected in this biotic intrusion screening analysis provide a solid basis to conclude that biotic intrusion will not significantly contribute to the all-pathways dose associated with the ICDF Landfill.

6.4 Air Pathway Results

The atmospheric pathway transport calculations are presented in Section 3.3.2, and the results are presented in Section 4.5.4. The air pathway results are presented in Table 6-3. Doses during the institutional control period and compliance period were well below the 10-mrem/year dose limit. Doses during the institutional control period were calculated at the site boundary, and the maximum dose (2.7E-05 mrem/year) occurred in year 2018, with H-3 as the major dose contributor. Maximum doses during the compliance time were dominated by C-14 and I-129, and the total maximum dose (5.8E-03 mrem/year) occurred in the year 2380.

Table 6-3. Volatile radionuclide doses via the air pathway during institutional control and compliance periods.

Radionuclide	Institutional Control Period at the INL Site Boundary		Compliance Period 100 m from the ICDF Landfill	
	Time of Maximum (calendar year)	Maximum Air Pathway EDE (mrem/yr)	Time of Maximum (calendar year)	Maximum Air Pathway EDE (mrem/yr)
C-14	2118	9.5E-07	2380	5.3E-03
H-3	2018	2.7E-05	2118	9.3E-05
I-129	2118	2.6E-07	2274	5.3E-04
Total	2018	2.7E-05	2380	5.8E-03

EDE effective dose equivalent
ICDF Idaho CERCLA Disposal Facility
INL Idaho National Laboratory

6.5 Groundwater Protection Results

Groundwater protection is evaluated by comparing predicted concentrations in groundwater 100 m downgradient from the ICDF Landfill during institutional control with the State of Idaho Ground Water Quality Rule (IDAPA 58.01.11) (see Table 4-4). The beta-gamma drinking water EDE was well below the 4-mrem/year EDE limit (1.7E-09 mrem/year). The gross alpha activity and the Ra-226/Ra-228

concentrations are essentially zero during this time period. The maximum H-3 concentration was $1.4\text{E-}06$ pCi/L.

Groundwater protection was also evaluated by comparing predicted concentrations in groundwater at the INL Site boundary during institutional control (2018–2118) and 100 m downgradient from the ICDF Landfill after institutional control with the State of Idaho Rules for Public Drinking Water Systems (IDAPA 58.01.08) (see Table 4-5).

For beta-gamma-emitting radionuclides (C-14, Cl-36, H-3, I-129, and Tc-99), an assessment of compliance with the radionuclides' respective MCLs was conducted by computing the dose equivalent and comparing the sum of the dose over time to the 4-mrem/year dose equivalent limit. The peak dose equivalent was zero during the institutional control period at the INL Site boundary. The peak dose equivalent was $7.4\text{E-}04$ mrem/year, which occurred at year 3018 at the end of the compliance period 100 m downgradient from the ICDF Landfill boundary (Figure 4-12). The peak dose equivalent during the post-compliance period (after year 3018) was 2.2 mrem/year and was dominated by I-129 (Figure 4-12). This dose is below the 4-mrem/year dose equivalent limit.

During the compliance period, the peak gross alpha activity is projected to be less than $1\text{E-}10$ pCi/L or essentially zero. The peak gross alpha activity for the entire simulation was 0.082 pCi/L in approximately year 13,500. This is a factor of 180 less than the 15-pCi/L standard, even substantially past the compliance period. The peak total uranium concentration during the compliance period was less than $1\text{E-}10$ $\mu\text{g/L}$ and the overall peak was $3.4\text{E-}04$ $\mu\text{g/L}$ in roughly year 20,500. These concentrations are both orders of magnitude below the total uranium concentration performance objective of 30 $\mu\text{g/L}$. The peak Ra-226/Ra-228 concentration during the compliance period was essentially zero (less than $1\text{E-}10$) and the overall peak was $1.5\text{E-}03$ pCi/L in year 37,800, which is orders of magnitude less than the performance objective of 5 pCi/L. The H-3 peak concentration was $9.3\text{E-}07$ pCi/L during the compliance period, which is well below the 20,000-pCi/L MCL. Sr-90 was screened and was not considered in the detailed analysis.

All of the groundwater protection performance objectives are well below the standards, which provide confidence that a reasonable expectation of compliance with the groundwater protection performance objectives can be achieved.

6.6 Inadvertent Intruder Analysis Results

The inadvertent intruder analysis was presented in Section 5. For the ICDF Landfill, the acute intruder drilling scenario yielded a peak dose of 1.7 mrem in 2118, the end of institutional control. Cs-137 was the dominant radionuclide, accounting for 1.6 mrem of the total dose, with external exposure as the dominant pathway. Nb-94 was the next dominant radionuclide, accounting for 0.07 mrem of the total dose with external exposure as the dominant pathway. Doses declined beyond 100 years. The total dose, 1.7 mrem, is well below the DOE O 435.1 Chg 1 acute exposure standard of 500 mrem.

The chronic intruder drilling scenario yielded a peak dose of 0.7 mrem/year in 2118, the end of institutional control and beginning of the compliance period. Cs-137 was the dominant radionuclide, accounting for 0.6 mrem/year of the total dose, with external exposure as the dominant pathway. Sr-90 was the next dominant radionuclide, accounting for 0.06 mrem/year of the total dose, with plant ingestion as the dominant pathway. The total dose declined beyond 100 years. The total dose of 0.7 mrem/year is well below the DOE O 435.1 Chg 1 chronic intruder performance measure of 100 mrem/year.

7. PERFORMANCE EVALUATION

This PA documents the projected radiological impacts associated with the disposal of LLW at the ICDF Landfill. The projected impacts are used to demonstrate compliance with applicable radiological dose criteria of DOE and EPA for protection of the public and the environment. This section compares PA results to applicable performance objectives and measures in the context of compliance. Additionally, it addresses the application of the results of the PA for development of WAC and action levels.

7.1 Comparison of Results to Performance Objectives

Table 7-1 presents the results of the ICDF PA and compare them to the applicable performance objectives and measures. The dose to a hypothetical member of the general public was assessed through reasonable, yet conservative, scenarios. These scenarios reflect the site-specific conditions at the ICDF Landfill. The PA results indicate the performance objectives and measures are met for both the compliance time period (1,000 years from site closure or year 3018) and any time afterward. Therefore, there is a reasonable expectation that performance objectives and measures established for the long-term protection of the public and the environment will not be exceeded following closure of the ICDF Landfill.

7.2 Use of Performance Assessment Results

This section uses the inadvertent intruder and groundwater calculations to support the generally applied radionuclide concentration thresholds for disposal of wastes at the ICDF Landfill. The hypothetical inadvertent intruder scenario is used to establish disposal thresholds for waste concentrations, and the all-pathways groundwater dose assessment is used to establish total inventories of radionuclides disposed of in the landfill.

7.2.1 Inadvertent Intruder Waste Concentration Disposal Thresholds

The intruder dose assessment described in Section 5 is used, together with the performance measures for inadvertent intruders (500 mrem for an acute exposure and 100 mrem/year for a chronic exposure), to derive generally applicable radionuclide concentration thresholds for waste packages to be disposed of in the landfill. Waste concentration thresholds are the maximum concentrations of individual radionuclides within a waste container that lead to a dose equivalent to the performance measure for an inadvertent intrusion scenario. The most limiting of the concentration thresholds from the acute or chronic scenarios are used to define the inadvertent intruder waste concentration disposal thresholds.

7.2.1.1 Derivation of Inadvertent Intruder Waste Concentration Thresholds. The following approach (Rood 2003b) is used to derive thresholds on the concentration of radionuclides in waste containers destined for disposal in the ICDF Landfill. Given a borehole of diameter d and length l , the volume of material extracted while drilling (V_T) is

$$V_T = \pi \left(\frac{d}{2} \right)^2 l . \quad (7-1)$$

Table 7-1. Comparison of performance objectives and the ICDF Landfill performance assessment results for the institutional control and compliance period.

Performance Objective and/or Measure	Standard	Performance Assessment Results		
		Institutional Control Period (2018–2118)		Compliance Period (2119–3018)
		(100 m downgradient of ICDF Landfill)	(12.7 km downgradient at southern INL Site boundary)	(100 m downgradient of ICDF Landfill)
All pathways (DOE O 435.1 Chg 1)	25 mrem/yr EDE	NA	0 mrem/yr	8.1E-04 mrem/yr
Atmospheric (40 CFR 61, Subpart H)	10 mrem/yr EDE (entire INL Site)	NA	2.7E-05 mrem/yr	5.8E-03 mrem/yr
Atmospheric (40 CFR 61, Subpart Q)	20 pCi·m ⁻² ·s ⁻¹ radon flux (at surface of disposal facility)	NA	NA	0.6 pCi·m ⁻² ·s ⁻¹
Acute inadvertent intruder (DOE O 435.1 Chg 1)	500 mrem EDE	NA	NA	1.7 mrem @ ICDF Landfill
Chronic inadvertent intruder (DOE O 435.1 Chg 1)	100 mrem/yr EDE	NA	NA	0.7 mrem/yr @ ICDF Landfill
Groundwater protection (40 CFR 141) (IDAPA 58.01.11 and IDAPA 58.01.08)	Beta-gamma dose equivalent ≤4 mrem/yr (based on federal MCL)	1.7E-09 ^a mrem/yr	0 mrem/yr	7.4E-04 ^b mrem/yr
	Gross alpha activity concentration ≤15 pCi/L	<1E-10 ^c pCi/L	0 pCi/L	<1E-10 ^c pCi/L
	Ra-226/Ra-228 concentration ≤5 pCi/L	<1E-10 ^c pCi/L	0 pCi/L	<1E-10 ^c pCi/L
	Uranium concentration ≤30 µg/L	NA ^d	0 µg/L	<1E-10 ^c µg/L
	Sr-90 concentration ≤8 pCi/L ^e	NA	NA	NA
	H-3 concentration ≤20,000 pCi/L	1.4E-06 pCi/L	0 pCi/L	9.3E-07 pCi/L

a. Beta-gamma effective dose equivalent ≤4 mrem/yr (IDAPA 58.01.11, State of Idaho Ground Water Quality Rule).

b. Beta-gamma dose equivalent ≤4 mrem/yr (based on federal MCL) (IDAPA 58.01.08, State of Idaho Rules for Public Drinking Water Systems).

c. Concentrations less than 1E-10 are essentially zero.

d. Not applicable, uranium not evaluated for IDAPA 58.01.11 State of Idaho Ground Water Quality Rule.

e. Not applicable; Sr-90 was screened out during evaluation of the groundwater pathway due to its relatively short half-life and its low mobility in the subsurface.

EDE effective dose equivalent
ICDF Idaho CERCLA Disposal Facility
INL Idaho National Laboratory
MCL maximum contaminant level
NA not applicable

The borehole intersects buried waste of thickness, T , the volume of waste brought to the surface (V_W) is then

$$V_W = \pi \left(\frac{d}{2} \right)^2 T . \quad (7-2)$$

The average radionuclide concentration in the borehole cuttings (C) is

$$C = \frac{C_W V_W}{V_T} \quad (7-3)$$

Where

C_W = the concentration in waste (Ci/m³).

For the acute drilling scenario, the volume of cuttings is assumed to be spread over 2,200 m² (24,000 ft²) and not mixed with the surface soil. For the chronic post-drilling scenario, the volume of cuttings is assumed to be spread over the same area, but mixed with the surface soil through tilling.

The dose-per-unit concentration in the source at the time of exposure (including radioactive decay and ingrowth of progeny, as applicable) or DSR (DSR in mrem/year per pCi/g) is used to calculate the maximum concentration *in the surface soil* that will yield a dose equal to the performance measure for the acute or chronic intruder scenario, D_L . This relationship is expressed as

$$C_s = \frac{D_L}{DSR} \quad (7-4)$$

Where

C_s = the concentration in the surface soil that yields a dose equal to the performance measure.

Note the C_s is not the concentration in the waste. The concentration in the waste is calculated by substituting C_s from Equation 7-4 for C in Equation 7-3 and solving for C_W . The waste concentration threshold for each radionuclide is then given by

$$\frac{D_L}{DSR} = \frac{C_W V_W}{V_T} \Rightarrow \text{solve for } C_W \Rightarrow C_W = \frac{D_L}{DSR} \frac{V_T}{V_W} . \quad (7-5)$$

Waste concentration disposal thresholds calculated in this manner are subject to sum-of-ratios or sum-of-fractions considerations when applied to a waste stream with multiple radionuclides. Note that this will involve conservatively summing the contributions for radionuclides with peak doses that occur at different times (i.e., some radionuclides have peak DSRs calculated at 100 years and others at 1,000 years). Also, it is worth noting that activated metals and other miscellaneous waste are treated the same for the purposes of this analysis. NRC (10 CFR 61.55) includes a factor of 10 increase in concentration limits for specific radionuclides in activated metal.

7.2.1.2 Inadvertent Intruder Results and Conclusions. Table 7-2 presents the acute drilling scenario peak calculated DSRs from RESRAD (which include decay and ingrowth of progeny) and the radionuclide concentration thresholds for the landfill, respectively. Table 7-3 provides the DSRs by pathway for the acute drilling scenario. Table 7-4 presents the chronic post-drilling peak calculated DSRs

from RESRAD (which include decay and ingrowth of progeny) and the radionuclide concentration thresholds for the landfill. Table 7-5 provides the DSRs by pathway for the chronic post-drilling scenario.

These are generally applicable thresholds for which sum-of-ratios considerations must be observed when evaluating a mixture of radionuclides, because the threshold for each radionuclide is obtained for a dose equivalent to the performance measure for inadvertent intrusion. Disposal of radionuclides with higher concentrations can be justified, if a special PA is conducted to demonstrate that special packaging or other considerations can ensure that the performance measure for inadvertent intrusion can be met. Before disposal of a given container, compliance with radionuclide-specific total inventory disposal limits must also be confirmed.

An administrative threshold of 0.01 Ci/m^3 is established for all other nontransuranic radionuclides (excluding noble gases) with half-lives greater than 5 years not considered in the RESRAD calculations and not listed in Tables 7-2 through 7-5. Transuranic radionuclides with half-lives greater than 20 years are limited to a maximum concentration of 10 nCi/g in LLW per the ICDF WAC (DOE-ID 2010b). An administrative threshold of 10 nCi/g is established for all transuranic radionuclides with half-lives greater than 5 years not listed in Tables 7-2 through 7-5. If concentrations of radionuclides not listed in Tables 7-2 through 7-5 are less than 0.01 Ci/m^3 (less than 10 nCi/g for transuranic radionuclides) or the half-life is less than 5 years, then it is not necessary to consider the radionuclides in the sum-of-ratios calculation. The administrative thresholds are less than the most restrictive thresholds in Tables 7-2 and 7-4, and 100 years of institutional control is enough time for at least 20 half-lives of decay for radionuclides with a half-life less than 5 years. For cases where concentrations are greater than 0.01 Ci/m^3 (10 nCi/g for transuranics) for a radionuclide with a half-life greater than 5 years not listed in Tables 7-2 and 7-4, a special analysis must be conducted to justify disposal, and concurrence for disposal must be received from DOE-ID.

Table 7-2. Calculated radionuclide concentration thresholds for waste disposal in the ICDF Landfill based on the acute drilling scenario (compliance with thresholds for waste streams with multiple radionuclides must be demonstrated using sum-of-fractions).

Radionuclide	DSR (mrem/yr per pCi/g)	C_w (pCi/g)	C_w (nCi/g)	C_w (Ci/m^3)	Dominant Pathway
Ag-108m	2.6E-02	2.5E+05	2.5E+02	4.9E-01	External
Am-241	9.8E-03	6.8E+05	<10 ^a (6.8E+02)	NA	Inhalation
Am-242m	1.1E-02	6.3E+05	<10 ^a (6.3E+02)	NA	Inhalation
Am-243	1.7E-02	4.0E+05	<10 ^a (4.0E+02)	NA	Inhalation
Ba-133	1.6E-05	4.1E+08	4.1E+05	7.9E+02	External
Be-10	1.9E-05	3.6E+08	3.6E+05	7.0E+02	External
C-14	0.0E+00	NL	NL	NL	NA
Ca-41	1.3E-06	5.2E+09	5.2E+06	1.0E+04	Ingestion
Cf-249	2.0E-02	3.4E+05	<10 ^a (3.4E+02)	6.6E-01	Inhalation
Cf-251	1.7E-02	4.0E+05	<10 ^a (4.0E+02)	7.8E-01	Inhalation
Cl-36	1.9E-05	3.6E+08	3.6E+05	7.0E+02	External
Cm-243	9.7E-04	6.8E+06	<10 ^a (6.8E+03)	NA	Inhalation
Cm-244	1.6E-04	4.2E+07	4.2E+04	8.1E+01	Inhalation
Cm-245 ^b	2.1E-02	3.1E+05	<10 ^a (4.4E+02)	NA	Inhalation
Cm-246	1.1E-02	6.0E+05	<10 ^a (6.0E+02)	NA	Inhalation
Cm-248	4.1E-02	1.6E+05	<10 ^a (1.6E+02)	NA	Inhalation

Table 7-2. (continued).

Radionuclide	DSR (mrem/yr per pCi/g)	C _w (pCi/g)	C _w (nCi/g)	C _w (Ci/m ³)	Dominant Pathway
Co-60	1.2E-07	5.5E+10	5.5E+07	1.1E+05	External
Cs-137	1.5E-03	4.3E+06	4.3E+03	8.3E+00	External
Eu-152	1.6E-04	4.0E+07	4.0E+04	7.7E+01	External
Eu-154	1.2E-05	5.4E+08	5.4E+05	1.1E+03	External
H-3	2.2E-10	3.0E+13	3.0E+10	5.7E+07	Ingestion
Ho-166m	4.5E-02	1.5E+05	1.5E+02	2.9E-01	External
I-129	4.9E-04	1.4E+07	1.4E+04	2.6E+01	Ingestion
K-40	4.1E-03	1.6E+06	1.6E+03	3.1E+00	External
Mo-93	1.5E-05	4.4E+08	4.4E+05	8.6E+02	External
Nb-94	4.3E-02	1.5E+05	1.5E+02	3.0E-01	External
Ni-59	2.5E-07	2.6E+10	2.6E+07	5.1E+04	Ingestion
Ni-63	3.3E-07	2.0E+10	2.0E+07	4.0E+04	Ingestion
Np-237	2.0E-02	3.4E+05	<10 ^a (3.4E+02)	NA	Inhalation
Pa-231	1.6E-01	4.0E+04	4.0E+01	7.8E-02	Inhalation
Pb-210	3.3E-04	2.0E+07	2.0E+04	3.8E+01	Ingestion
Pu-238	4.4E-03	1.5E+06	<10 ^a (1.5E+03)	NA	Inhalation
Pu-239	1.1E-02	6.2E+05	<10 ^a (6.2E+02)	NA	Inhalation
Pu-240	1.1E-02	6.3E+05	<10 ^a (6.3E+02)	NA	Inhalation
Pu-241	3.3E-04	2.0E+07	2.0E+04	3.8E+01	Inhalation
Pu-242	1.0E-02	6.5E+05	<10 ^a (6.5E+02)	NA	Inhalation
Ra-226	5.3E-02	1.2E+05	1.2E+02	2.4E-01	External
Sn-121m	1.0E-05	6.4E+08	6.4E+05	1.3E+03	External
Sr-90	2.8E-05	2.3E+08	2.3E+05	4.5E+02	Ingestion
Tb-158	1.3E-04	5.0E+07	5.0E+04	9.7E+01	External
Tc-99	2.8E-06	2.4E+09	2.4E+06	4.7E+03	Ingestion
Th-230 ^b	2.5E-02	2.6E+05	2.6E+02	5.1E-01	External
Th-232	1.0E-01	6.4E+04	6.4E+01	1.2E-01	External
U-232	2.3E-02	2.9E+05	2.9E+02	5.7E-01	External
U-233 ^b	6.9E-03	9.6E+05	9.6E+02	1.9E+00	Inhalation
U-234 ^b	2.6E-03	2.5E+06	2.5E+03	4.9E+00	Inhalation
U-235 ^b	1.0E-02	6.3E+05	6.3E+02	1.2E+00	External
U-236	2.3E-03	2.8E+06	2.8E+03	5.5E+00	Inhalation
U-238	3.0E-03	2.2E+06	2.2E+03	4.3E+00	Inhalation

a. Although calculated thresholds are higher, transuranic radionuclides (elements with atomic number >92) with half-lives greater than 20 years are subject to a limit of <10 nCi/g (1E+04 pCi/g) in low-level waste per ICDF WAC (DOE-ID 2010b).

b. Peak DSR is at 1,000 years; others are at 100 years.

Note: The DSR from the RESRAD computer code is the calculated peak dose per unit concentration in the source at the time of exposure that includes radioactive decay and contributions from ingrown progeny.

DSR dose-to-source ratio

ICDF Idaho CERCLA Disposal Facility

NA not applicable

NL No limit. The DSR for C-14, a volatile radionuclide, is zero after the institutional control period; therefore the concentration threshold is unlimited for the intruder scenarios.

WAC waste acceptance criteria

Table 7-3. Dose-to-source ratios by pathway for the acute drilling scenario from RESRAD output.

Radionuclide	External DSR (mrem/yr per pCi/g)	Inhalation DSR (mrem/yr per pCi/g)	Ingestion DSR (mrem/yr per pCi/g)
Ag-108m	2.6E-02	2.7E-06	4.3E-06
Am-241	4.3E-04	6.3E-03	3.0E-03
Am-242m	2.9E-04	6.9E-03	3.4E-03
Am-243	6.0E-03	7.3E-03	3.5E-03
Ba-133	1.6E-05	2.0E-10	5.1E-09
Be-10	8.2E-06	5.9E-06	4.6E-06
C-14	0.0E+00	0.0E+00	0.0E+00
Ca-41	0.0E+00	2.2E-08	1.2E-06
Cf-249	7.8E-03	7.9E-03	3.9E-03
Cf-251	3.1E-03	9.0E-03	4.4E-03
Cl-36	1.5E-05	3.6E-07	3.0E-06
Cm-243	3.0E-04	4.5E-04	2.2E-04
Cm-244	5.4E-08	1.1E-04	5.1E-05
Cm-245	2.4E-03	8.5E-03	4.1E-03
Cm-246	2.0E-06	7.4E-03	3.6E-03
Cm-248	1.6E-06	2.7E-02	1.3E-02
Co-60	1.2E-07	6.6E-12	4.8E-11
Cs-137	1.5E-03	5.2E-08	4.8E-06
Eu-152	1.7E-04	2.0E-08	3.4E-08
Eu-154	1.2E-05	1.7E-09	3.4E-09
H-3	0.0E+00	0.0E+00	2.2E-10
Ho-166m	4.5E-02	1.2E-05	7.5E-06
I-129	2.2E-04	2.9E-06	2.7E-04
K-40	4.1E-03	2.1E-07	1.8E-05
Mo-93	1.2E-05	9.4E-07	1.8E-06
Nb-94	4.3E-02	6.9E-06	7.0E-06
Ni-59	0.0E+00	4.5E-08	2.1E-07
Ni-63	0.0E+00	5.1E-08	2.7E-07
Np-237	6.2E-03	9.0E-03	4.4E-03
Pa-231	1.2E-02	1.3E-01	2.4E-02
Pb-210	2.6E-06	1.7E-05	3.1E-04
Pu-238	1.0E-06	2.9E-03	1.4E-03
Pu-239	2.2E-06	7.1E-03	3.5E-03
Pu-240	2.2E-06	7.1E-03	3.4E-03
Pu-241	1.5E-05	2.2E-04	1.0E-04
Pu-242	1.8E-06	6.8E-03	3.3E-03
Ra-226	4.5E-02	4.9E-04	7.9E-03
Sn-121m	9.6E-06	5.6E-08	6.2E-07
Sr-90	1.3E-05	2.0E-06	1.4E-05

Table 7-3. (continued).

Radionuclide	External DSR (mrem/yr per pCi/g)	Inhalation DSR (mrem/yr per pCi/g)	Ingestion DSR (mrem/yr per pCi/g)
Tb-158	1.3E-02	2.7E-06	2.7E-06
Tc-99	1.2E-06	1.4E-07	1.4E-06
Th-230 ^a	1.6E-02	5.5E-03	3.4E-03
Th-232	6.6E-02	3.3E-02	4.9E-03
U-232	1.5E-02	6.4E-03	8.0E-04
U-233 ^a	7.9E-04	5.5E-03	6.4E-04
U-234 ^a	8.3E-05	2.2E-03	3.0E-04
U-235 ^a	4.9E-03	4.8E-03	7.8E-04
U-236	2.5E-06	2.1E-03	2.6E-04
U-238	7.9E-04	2.0E-03	2.6E-04

a. Peak DSR is at 1,000 years; others are at 100 years.

Note: The DSR from the RESRAD computer code is the calculated peak dose per unit concentration in the source at the time of exposure that includes radioactive decay and contributions from ingrown progeny.

DSR dose-to-source ratio

Table 7-4. Calculated radionuclide concentration thresholds for waste disposal in the ICDF Landfill based on the chronic post-drilling scenario (compliance with thresholds for waste streams with multiple radionuclides must be demonstrated using sum-of-fractions).

Radionuclide	DSR (mrem/yr per pCi/g)	C _w (pCi/g)	C _w (nCi/g)	C _w (Ci/m ³)	Dominant Pathway
Ag-108m	3.0E+00	1.4E+05	1.4E+02	2.1E-01	External
Am-241	1.3E-01	3.1E+06	<10 ^a (3.1E+03)	NA	Soil ingestion
Am-242m	1.4E-01	3.0E+06	<10 ^a (3.0E+03)	NA	Soil ingestion
Am-243	6.2E-01	6.7E+05	<10 ^a (6.7E+02)	NA	External
Ba-133	1.7E-03	2.5E+08	2.5E+05	3.8E+02	External
Be-10	9.1E-04	4.6E+08	4.6E+05	6.9E+02	External
C-14	0.0E+00	NL	NL	NL	NA
Ca-41	1.1E-02	3.9E+07	3.9E+04	5.8E+01	Plant ingestion
Cf-249	1.2E+00	3.6E+05	<10 ^a (3.6E+02)	5.4E-01	External
Cf-251	6.6E-01	6.4E+05	<10 ^a (6.4E+02)	9.6E-01	External
Cl-36	5.4E+00	7.8E+04	7.8E+01	1.2E-01	Plant ingestion
Cm-243	3.5E-02	1.2E+07	<10 ^a (1.2E+04)	NA	External
Cm-244	1.6E-03	2.6E+08	2.6E+05	3.9E+02	Soil ingestion
Cm-245 ^b	3.2E-01	1.3E+06	<10 ^a (1.3E+03)	NA	External
Cm-246	1.1E-01	4.0E+06	<10 ^a (4.0E+03)	NA	Soil ingestion
Cm-248	4.2E-01	1.0E+06	<10 ^a 1.0E+03	1.5E+00	Soil ingestion
Co-60	1.6E-05	2.6E+10	2.6E+07	3.9E+04	External
Cs-137	1.9E-01	2.3E+06	2.3E+03	3.4E+00	External
Eu-152 ^b	2.1E-02	2.0E+07	2.0E+04	3.1E+01	External
Eu-154 ^b	1.5E-03	2.8E+08	2.8E+05	4.1E+02	External
H-3	6.2E-09	6.7E+13	6.7E+10	1.0E+08	Soil ingestion

Table 7-4. (continued).

Radionuclide	DSR (mrem/yr per pCi/g)	C _w (pCi/g)	C _w (nCi/g)	C _w (Ci/m ³)	Dominant Pathway
Ho-166m	5.3E+00	8.0E+04	8.0E+01	1.2E-01	External
I-129	3.6E-01	1.2E+06	1.2E+03	1.7E+00	Plant ingestion
K-40	8.2E-01	5.1E+05	5.1E+02	7.7E-01	External
Mo-93	2.9E-03	1.4E+08	1.4E+05	2.2E+02	Plant ingestion
Nb-94	5.2E+00	8.0E+04	8.0E+01	1.2E-01	External
Ni-59	3.2E-04	1.3E+09	1.3E+06	2.0E+03	Plant ingestion
Ni-63	4.2E-04	1.0E+09	1.0E+06	1.5E+03	Plant ingestion
Np-237	1.8E+00	2.3E+05	<10 ^a (2.3E+02)	NA	Plant ingestion
Pa-231	2.2E+00	1.9E+05	1.9E+02	2.9E-01	External
Pb-210	7.9E-02	5.3E+06	5.3E+03	8.0E+00	Plant ingestion
Pu-238	4.5E-02	9.3E+06	<10 ^a (9.3E+03)	NA	Soil ingestion
Pu-239	1.1E-01	3.8E+06	<10 ^a (3.8E+03)	NA	Soil ingestion
Pu-240	1.1E-01	3.8E+06	<10 ^a (3.8E+03)	NA	Soil ingestion
Pu-241	4.6E-03	9.2E+07	9.2E+04	NA	Soil ingestion
Pu-242	1.1E-01	4.0E+06	<10 ^a (4.0E+03)	NA	Soil ingestion
Ra-226	7.6E+00	5.5E+04	5.5E+01	8.3E-02	External
Sn-121m	6.2E-04	6.8E+08	6.8E+05	1.0E+03	External
Sr-90	8.7E-02	4.8E+06	4.8E+03	7.2E+00	Plant ingestion
Tb-158	1.6E+00	2.6E+05	2.6E+02	3.9E-01	External
Tc-99	5.3E-02	7.9E+06	7.9E+03	1.2E+01	Plant ingestion
Th-230 ^b	2.8E+00	1.5E+05	1.5E+02	2.3E-01	External
Th-232	9.1E+00	4.6E+04	4.6E+01	6.9E-02	External
U-232	2.3E+00	1.9E+05	1.9E+02	2.8E-01	External
U-233 ^b	1.3E-01	3.1E+06	3.1E+03	4.7E+00	External
U-234 ^b	5.2E-02	8.0E+06	8.0E+03	1.2E+01	Plant ingestion
U-235 ^b	5.0E-01	8.3E+05	8.3E+02	1.3E+00	External
U-236	3.7E-02	1.1E+07	1.1E+04	1.7E+01	Plant ingestion
U-238	1.2E-01	3.5E+06	3.5E+03	5.3E+00	External

a. Although calculated thresholds are higher, transuranic radionuclides (elements with atomic number >92) with half-lives greater than 20 years are subject to a limit of <10 nCi/g (1E+04 pCi/g) in low-level waste per the ICDF WAC (DOE-ID 2010b).

b. Peak DSR is at 1,000 years; others are at 100 years.

Note: The DSR from the RESRAD computer code is the calculated peak dose per unit concentration in the source at the time of exposure that includes radioactive decay and contributions from ingrown progeny.

DSR dose-to-source ratio

ICDF Idaho CERCLA Disposal Facility

NA not applicable

NL No limit. The DSR for C-14, a volatile radionuclide, is zero after the institutional control period; therefore the concentration threshold is unlimited for the intruder scenarios.

WAC waste acceptance criteria

Table 7-5. Dose-to-source ratios by pathway for the chronic post-drilling agriculture scenario from RESRAD output.

Radionuclide	External DSR (mrem/yr per pCi/g)	Inhalation DSR (mrem/yr per pCi/g)	Plant Ingestion DSR (mrem/yr per pCi/g)	Meat Ingestion DSR (mrem/yr per pCi/g)	Milk Ingestion DSR (mrem/yr per pCi/g)	Soil Ingestion DSR (mrem/yr per pCi/g)
Ag-108m	3.0E+00	3.8E-06	1.1E-02	5.9E-05	7.0E-04	1.2E-04
Am-241	2.1E-02	8.7E-03	1.9E-02	3.3E-05	6.1E-06	8.5E-02
Am-242m	2.4E-02	9.6E-03	1.5E-02	2.6E-05	5.1E-06	9.3E-02
Am-243	4.9E-01	1.0E-02	2.2E-02	3.8E-05	7.0E-06	9.9E-02
Ba-133	1.7E-03	2.7E-10	1.8E-06	2.5E-09	9.7E-09	1.4E-07
Be-10	5.9E-04	8.1E-06	1.7E-04	1.4E-05	2.1E-08	1.3E-04
C-14	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Ca-41	0.0E+00	3.1E-08	1.1E-02	7.0E-06	2.0E-04	3.5E-05
Cf-249	8.3E-01	1.1E-02	2.2E-01	7.1E-04	1.7E-05	1.1E-01
Cf-251	2.7E-01	1.3E-02	2.5E-01	8.2E-04	1.7E-05	1.2E-01
Cl-36	1.3E-03	5.0E-07	5.0E+00	2.4E-01	9.6E-02	8.3E-05
Cm-243	2.8E-02	6.2E-04	9.3E-05	2.3E-06	2.1E-05	6.1E-03
Cm-244	1.8E-06	1.5E-04	2.8E-05	4.7E-07	4.2E-06	1.4E-03
Cm-245 ^a	1.9E-01	1.7E-02	1.9E-02	6.6E-05	3.4E-04	1.7E-01
Cm-246	6.8E-05	1.0E-02	1.5E-03	3.9E-05	3.6E-04	1.0E-01
Cm-248	5.3E-05	3.8E-02	5.5E-03	1.4E-04	1.3E-03	3.7E-01
Co-60	1.6E-05	9.2E-12	8.2E-09	3.1E-09	5.0E-10	1.3E-09
Cs-137	1.8E-01	7.2E-08	3.5E-03	3.4E-04	2.0E-04	1.3E-04
Eu-152	2.1E-02	2.7E-08	3.3E-06	5.4E-07	3.5E-09	9.5E-07
Eu-154	1.5E-03	2.4E-09	3.3E-07	5.4E-08	3.5E-10	9.5E-08
H-3	0.0E+00	0.0E+00	1.2E-11	0.0E+00	0.0E+00	6.2E-09
Ho-166m	5.3E+00	1.7E-05	7.2E-04	1.1E-04	7.7E-07	2.1E-04
I-129	7.4E-03	4.0E-06	3.2E-01	7.2E-03	1.8E-02	7.6E-03
K-40	5.7E-01	2.8E-07	2.5E-01	4.0E-03	2.8E-03	5.1E-04
Mo-93	4.1E-04	1.3E-06	2.0E-03	4.3E-04	6.5E-05	5.0E-05
Nb-94	5.2E+00	9.5E-06	8.3E-04	5.5E-03	7.2E-04	2.0E-04
Ni-59	0.0E+00	6.2E-08	3.0E-04	4.9E-06	1.4E-06	5.7E-06
Ni-63	0.0E+00	7.0E-08	4.0E-04	6.5E-06	1.9E-06	7.6E-06
Np-237	6.0E-01	1.2E-02	1.1E+00	7.7E-04	1.2E-04	1.2E-01
Pa-231	1.2E+00	1.8E-01	1.8E-01	1.2E-03	1.7E-03	6.8E-01
Pb-210	1.5E-04	2.3E-05	6.9E-02	3.0E-04	4.1E-04	8.8E-03
Pu-238	4.0E-05	4.1E-03	1.6E-03	2.2E-06	8.8E-07	4.0E-02
Pu-239	1.6E-04	9.8E-03	3.9E-03	5.3E-06	1.7E-06	9.7E-02
Pu-240	8.4E-05	9.7E-03	3.9E-03	5.3E-06	1.7E-06	9.6E-02
Pu-241	7.1E-04	3.0E-04	6.5E-04	1.1E-06	2.1E-07	2.9E-03
Pu-242	7.4E-05	9.4E-03	3.7E-03	5.1E-06	1.6E-06	9.2E-02
Ra-226	5.8E+00	6.8E-04	1.5E+00	7.3E-03	1.2E-02	2.2E-01
Sn-121m	3.5E-04	7.7E-08	9.2E-05	1.6E-04	3.2E-06	1.7E-05
Sr-90	1.2E-03	2.7E-06	8.5E-02	2.8E-05	2.7E-04	3.8E-04

Table 7-5. (continued).

Radionuclide	External DSR (mrem/yr per pCi/g)	Inhalation DSR (mrem/yr per pCi/g)	Plant Ingestion DSR (mrem/yr per pCi/g)	Meat Ingestion DSR (mrem/yr per pCi/g)	Milk Ingestion DSR (mrem/yr per pCi/g)	Soil Ingestion DSR (mrem/yr per pCi/g)
Tb-158	1.6E+00	3.7E-06	2.6E-04	3.8E-05	2.8E-05	7.6E-05
Tc-99	7.0E-05	1.9E-07	5.2E-02	3.0E-04	7.3E-04	4.0E-05
Th-230 ^a	2.1E+00	7.7E-03	5.0E-01	2.7E-03	4.2E-03	9.5E-02
Th-232	8.8E+00	4.6E-02	5.9E-02	1.2E-03	3.3E-03	1.4E-01
U-232	2.2E+00	8.8E-03	4.8E-02	3.2E-04	1.5E-03	2.2E-02
U-233 ^a	8.0E-02	7.6E-03	2.8E-02	1.8E-04	8.7E-04	1.8E-02
U-234 ^a	1.1E-02	3.1E-03	2.9E-02	1.9E-04	8.7E-04	8.2E-03
U-235 ^a	4.5E-01	6.6E-03	2.9E-02	1.9E-04	8.4E-04	2.2E-02
U-236	1.2E-04	2.9E-03	2.5E-02	1.7E-04	8.1E-04	7.4E-03
U-238	8.3E-02	2.7E-03	2.5E-02	1.7E-04	8.1E-04	7.4E-03

a. Peak DSR is at 1,000 years; others are at 100 years.

Note: The DSR from the RESRAD computer code is the calculated peak dose per unit concentration in the source at the time of exposure that includes radioactive decay and contributions from ingrown progeny.

DSR dose-to-source ratio

A comparison of the acute and chronic waste concentration thresholds developed in this PA with the ICDF WAC (DOE-ID 2010b) waste concentration thresholds is presented in Table 7-6. The radionuclides highlighted (Cs-137, Pa-231, Pb-210, Sr-90, and U-232) in this table indicate the waste concentration threshold developed in this PA is more restrictive than the ICDF WAC (DOE-ID 2010b) value.

Table 7-6. Comparison of ICDF PA waste concentration thresholds to ICDF WAC (DOE-ID 2010b) waste concentration thresholds.^a

Radionuclide	ICDF PA Acute C _w (pCi/g)	ICDF PA Chronic C _w (pCi/g)	ICDF WAC (DOE-ID 2010b) (pCi/g)
Ag-108m	2.5E+05	1.4E+05	8.0E+02
Am-241	6.8E+05	1.0E+04 ^a (3.1E+06)	1.0E+04
Am-242m	6.3E+05	1.0E+04 ^a (3.0E+06)	NM
Am-243	4.0E+05	1.0E+04 ^a (6.7E+05)	3.3E-01
Ba-133	4.1E+08	2.5E+08	NM
Be-10	3.6E+08	4.6E+08	1.5E+06
C-14	NL	NL	6.8E+05
Ca-41	5.2E+09	3.9E+07	NM
Cf-249	3.4E+05	1.0E+04 ^a (3.6E+05)	1.0E+04
Cf-251	4.0E+05	1.0E+04 ^a (6.4E+05)	1.0E+04
Cl-36	3.6E+08	7.8E+04	1.4E+01
Cm-243	6.8E+06	1.0E+04 ^a (1.2E+07)	8.4E+01
Cm-244	4.2E+07	2.6E+08	5.2E+05
Cm-245 ^b	3.1E+05	1.0E+04 ^a (1.3E+06)	1.0E+04
Cm-246	6.0E+05	1.0E+04 ^a (4.0E+06)	1.0E+04
Cm-248	1.6E+05	1.0E+04 ^a (1.0E+06)	1.0E+04
Co-60	5.5E+10	2.6E+10	1.9E+05

Table 7-6. (continued).

Radionuclide	ICDF PA Acute C _w (pCi/g)	ICDF PA Chronic C _w (pCi/g)	ICDF WAC (DOE-ID 2010b) (pCi/g)
Cs-137 ^c	4.3E+06	2.3E+06	2.3E+09
Eu-152	4.0E+07	2.0E+07	9.7E+05
Eu-154	5.4E+08	2.8E+08	8.2E+05
H-3	3.0E+13	6.7E+13	5.0E+04
Ho-166m	1.5E+05	8.0E+04	NM
I-129	1.4E+07	1.2E+06	3.1E+00
K-40	1.6E+06	5.1E+05	2.4E+02
Mo-93	4.4E+08	1.4E+08	2.8E+07
Nb-94	1.5E+05	8.0E+04	1.0E+05
Ni-59	2.6E+10	1.3E+09	9.5E+06
Ni-63	2.0E+10	1.0E+09	6.0E+07
Np-237	3.4E+05	1.0E+04 ^a (2.3E+05)	6.4E+02
Pa-231	4.0E+04	1.9E+05	2.1E+09
Pb-210	2.0E+07	5.3E+06	NL
Pu-238	1.5E+06	1.0E+04 ^a (9.3E+06)	1.0E+04
Pu-239	6.2E+05	1.0E+04 ^a (3.8E+06)	6.7E+03
Pu-240	6.3E+05	1.0E+04 ^a (3.8E+06)	1.5E+03
Pu-241	2.0E+07	9.2E+07	6.4E+04
Pu-242	6.5E+05	1.0E+04 ^a (4.0E+06)	3.2E+03
Ra-226	1.2E+05	5.5E+04	4.7E+02
Sn-121m	6.4E+08	6.8E+08	NM
Sr-90	2.3E+08	4.8E+06	3.5E+09
Tb-158	5.0E+07	2.6E+05	NM
Tc-99	2.4E+09	7.9E+06	5.8E+03
Th-230 ^b	2.6E+05	1.5E+05	1.4E+01
Th-232	6.4E+04	4.6E+04	1.7E+01
U-232	2.9E+05	1.9E+05	4.4E+21
U-233 ^b	9.6E+05	3.1E+06	1.6E+05
U-234 ^b	2.5E+06	8.0E+06	6.0E+03
U-235 ^b	6.3E+05	8.3E+05	1.1E+02
U-236	2.8E+06	1.1E+07	2.0E+02
U-238	2.2E+06	3.5E+06	2.0E+03

a. Although calculated thresholds (shown in parentheses) are higher, transuranic radionuclides (elements with atomic number >92) with half-lives greater than 20 years are subject to a limit of <10 nCi/g (1E+04 pCi/g) in low-level waste per the ICDF WAC (DOE-ID 2010b).

b. Peak DSR is at 1,000 years; others are at 100 years.

c. Radionuclides highlighted in yellow indicate the ICDF PA waste concentration thresholds are lower than the ICDF WAC (DOE-ID 2010b) values.

DSR dose-to-source ratio
ICDF Idaho CERCLA Disposal Facility
NL no limit
NM not modeled
PA performance assessment
WAC waste acceptance criteria

7.2.2 Groundwater Pathway Waste Acceptance Criteria

The groundwater pathway dose assessment results for the base case radionuclides are presented in Section 4. These results are used, together with the performance measures for groundwater pathway, to derive generally applicable total inventory thresholds for the ICDF Landfill. These total inventory guidelines are radionuclide-specific, and, in some cases, waste-form-specific. Most of the radionuclides are disposed of in multiple waste forms; however, relative to the total inventory thresholds, the waste forms are only an important consideration for the mobile nuclides (C-14, Cl-36, H-3, I-129, and Tc-99). All other radionuclides are conservatively assumed to be disposed of in only the miscellaneous waste form. The other waste form for the mobile radionuclides was activated metals. Activated metals must corrode to release radionuclides into waste soil matrix and subsequent subsurface transport to the aquifer.

The total inventory thresholds are determined for the following performance measures for maximum predicted all-pathways EDE and concentration:

- Calculated all-pathways EDE compared to the 25-mrem/year performance criteria for the compliance period (2119–3018) and post-compliance period (>3018)
- Calculated maximum concentration compared to the MCL for the compliance period (2119–3018) and post-compliance period (>3018).

The total inventory threshold calculation is an extension of the PA dose assessment results and is given by

$$I_T = \frac{P_O}{P_A/I} \quad (7-6)$$

Where

I_T	=	inventory threshold (Ci)
P_O	=	performance objective for dose (mrem/year) or concentration (pCi/L)
P_A	=	predicted radionuclide concentration (pCi/L) or all-pathway dose (mrem/year) from the PA
I	=	radionuclide inventory (Ci) in the PA.

The predicted concentration and dose come from the PA base case models and analysis. The thresholds are calculated during the compliance and post-compliance periods and used the maximum concentrations and doses predicted 100 m downgradient of the ICDF Landfill.

The performance objectives are:

1. All-pathways dose limit of less than 25 mrem/year
2. MCL not exceeded. MCLs include:
 - 4 mrem dose equivalent for beta-gamma emitters
 - 15 pCi/L gross alpha concentration
 - 5 pCi/L Ra-226 and -228 concentrations
 - 30 µg/L uranium mass concentration.

Because Ra-226 and Ra-228 were not considered as important parent nuclides in this analysis, thresholds based on these criteria were only addressed for decay chains that included Ra-226 or Ra-228. For example, the threshold for U-238 considered the all-pathways dose criteria of 25 mrem/year, the gross alpha concentration of 15 pCi/L for all alpha-emitting U-238 progeny (excluding U-238 and U-234), Ra-226/228 concentration of 5 pCi/L, and total uranium mass of 30 µg/L.

For convenience, the activity concentration for each uranium isotope that is equivalent to 30 µg/L was calculated and used in the inventory threshold determination. The activity concentration was calculated using

$$C = 30 \frac{\mu\text{g}}{\text{L}} \times \text{SpA} \times \frac{\text{g}}{1 \times 10^6 \mu\text{g}} \times \frac{10^{12} \text{ pCi}}{\text{Ci}} \quad (7-7)$$

Where

SpA = specific activity (Ci/g).

The specific activities were 3.36E-07 Ci/g, 2.16E-06 Ci/g, 6.22E-03 Ci/g, 6.47E-05 Ci/g, and 9.64E-03 Ci/g for U-238, U-235, U-234, U-236, and U-233, respectively. The corresponding activity concentrations were 10 pCi/L, 64.8 pCi/L, 1.866E+05 pCi/L, 1.94E+03 pCi/L, and 2.892E+05 pCi/L for U-238, U-235, U-234, U-236, and U-233, respectively. The compliance point was 100 m downgradient from the ICDF Landfill in all cases.

The total inventory threshold provides the maximum allowable inventory for a single radionuclide disposed of to the facility. For a mixture of radionuclides, the sum-of-ratios is computed to assure that dose limits are not exceeded. The sum-of-ratios is given by:

$$SOR = \sum_{i=1}^n \frac{I_i}{I_{Ti}} \quad (7-8)$$

Where

I_i = the actual inventory of radionuclide i

I_{Ti} = the total inventory threshold for radionuclide i .

7.2.2.1 Groundwater Pathway Total Inventory Threshold Results. The groundwater total inventory thresholds for the compliance time (2119–3018) and post-compliance time (>3018) for the ICDF Landfill are presented in Table 7-7. The thresholds are based on the predicted maximum aquifer concentrations and associated all-pathways dose.

For mobile radionuclides (C-14, Cl-36, H-3, I-129, and Tc-99), the inventory thresholds for activated metals are significantly different than those for waste soils. Therefore, separate threshold values were calculated for these waste forms.

For LLW management purposes, the most limiting threshold is selected. As shown in Table 7-7, the all-pathways dose and the beta-gamma dose are the primary performance measures determining the groundwater pathway total inventory thresholds. The thresholds calculated for the mobile radionuclides are limited by the beta-gamma performance measure. The other radionuclides are primarily limited by the all-pathways dose performance measure. The threshold for U-238 is limited by the uranium mass performance measure.

In addition to thresholds presented in Table 7-7, maximum concentrations and doses were evaluated against the State of Idaho groundwater protection measures, during the institutional control period, 100 m downgradient of the ICDF Landfill. Radionuclide concentrations in the aquifer during the institutional control period were essentially zero for all radionuclides. Therefore, this criterion would have no impact on the calculated inventory thresholds presented in Table 7-7.

A comparison of the groundwater pathway total inventory thresholds developed in this PA with the ICDF WAC (DOE-ID 2010b) groundwater pathway total inventory thresholds is presented in Table 7-8. The total inventory limit developed in this PA for Tc-99 is more restrictive than the ICDF WAC total inventory value (DOE-ID 2010b).

Table 7-8. Comparison of total inventory thresholds (based on the compliance time) for the ICDF Landfill developed in this PA compared to the ICDF WAC (DOE-ID 2010b) total inventory thresholds.

Radionuclide	ICDF PA Total Inventory Thresholds (Ci)	ICDF WAC (DOE-ID 2010b) Total Inventory Thresholds (Ci)
C-14	4.79E+11	5.1E+05
C-14 (activated metal)	3.08E+17	NA
Cl-36	1.81E+02	1.0E+01
Cl-36 (activated metal)	1.84E+05	NA
H-3	2.43E+11	3.8E+04
H-3 (activated metal)	1.13E+19	NA
I-129	1.08E+06	2.4E+00
I-129 (activated metal)	5.63E+11	NA
Np-237	7.21E+11	4.9E+02
Pu-239	1.44E+19	5.1E+03
Pu-240	4.95E+17	1.1E+03
Tc-99	2.44E+03	4.4E+03
Tc-99 (activated metal)	2.86E+06	NA
U-233	1.53E+12	1.2E+05
U-234	1.63E+12	2.6E+03
U-235	6.14E+11	8.3E+01
U-238	9.55E+10	1.5E+03
ICDF Idaho CERCLA Disposal Facility NA not applicable; the ICDF WAC is not waste-form-specific PA performance assessment WAC waste acceptance criteria		

7.2.3 As-Low-As-Reasonably-Achievable Analysis

Two key components form the basis for DOE's approach to radiation protection for LLW disposal. One component is the performance objectives and performance measures described in Section 1.5, which specify maximum doses for various exposure scenarios and pathways. The other component requires doses to be maintained ALARA.

The goal of the ALARA process is the lowest practical dose level after taking into account social, technical, economic, and public policy considerations. Therefore, in addition to providing a reasonable expectation that the performance objectives described in Section 1.5 will not be exceeded, the PA also needs to demonstrate that LLW disposal limits releases of radionuclides to the environment and potential exposures ALARA. This ALARA analysis presents the doses estimated in the ICDF and evaluates options to further reduce those doses.

The peak all-pathways dose for the base case during the compliance period was $8.1\text{E-}04$ mrem/year (year 3018), primarily due to Tc-99 and Cl-36. During the post-compliance period, the peak dose is 0.58 mrem/year, primarily due to C-14 and I-129. All of these doses are well below the 25-mrem/year all-pathways dose standard in DOE M 435.1-1 Chg 1. The doses were projected for a single-family subsistence farm located 100 m from the ICDF.

An advantage of the INL Site is the very remote location and sparse population in the region. As discussed in Section 2.1, no towns and/or residents of any kind are within 10 miles of the ICDF. The extreme depth to the water table and lack of reliable water supplies near the ICDF make it difficult to establish a residence in the future as well. However, consistent with the assumptions for the PA, for the purposes of the ALARA analysis, it is assumed that one or two families establish a residence 100 m downgradient of the ICDF. Given the typical family size, ranging from 2.78 to 4.28 people in the counties that surround the INL Site, it is conservatively assumed that the exposed population would be 10 people. Based on an individual dose of $8.1\text{E-}04$ mrem/year, this would yield an annual collective dose of $8.1\text{E-}06$ person-rem. For this same population, the annual collective dose from background radiation on the ESRP is 3.6 person-rem (McCarthy et al. 2000). Thus, the estimated ICDF annual collective dose is roughly 0.0002% of background levels.

Other potential options that have been considered include a larger buffer zone, more robust covers, or other engineered measures; but, given the very low collective doses currently estimated and the incremental cost associated with any of these options, it is hard to imagine any of these options being cost-effective from the ALARA perspective.

7.3 Further Work

DOE M 435.1-1 Chg 1 (IV.P.(4)) includes a requirement for PA/CA maintenance to evaluate the impact of design and operational changes and also to incorporate any new information regarding waste forms, site characteristics, etc. This PA was prepared to satisfy this requirement. The following items summarize the further work required to satisfy the requirements for a Disposal Authorization Statement:

- Prepare annual reviews and annual determination of continued adequacy of the PA/CA – Annual reviews and the annual determination are required to be prepared every year (except the year in which the PA is prepared) and submitted to DOE to continue disposals at the landfill.
- Continue to conduct special PAs as needed – A special PA is required if a waste to be disposed of at the ICDF contains nuclides with no specified WAC or if average radionuclide activities in the waste form are above the generally applied radionuclide concentration thresholds. The results of the special PA are the development of specific disposal measures to be taken to address the radiological hazards posed by a specific waste.
- Prepare a maintenance plan that documents the activities that are planned to maintain the PA/CA for the ICDF.
- Continue to monitor the performance of the facility through continued collection of environmental and operational samples. These samples will be compared against action levels and summarized in the annual report.

8. PREPARERS

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Ms. Koslow is an advisory scientist for the ICP with over 25 years of experience in the field of surface water and groundwater hydrology and hazardous waste management. She prepares surface-water storm evaluation studies for RCRA Part B permitting of hazardous waste storage facilities. She has performed hydrologic modeling of landfill cover designs for a mixed-waste landfill using the EPA code HELP. She has prepared several human health risk assessments in support of CERCLA/RCRA investigations. She is proficient in the use of the RESRAD computer model designed to estimate radiation doses and risks from residual radioactive materials. More recently, she has been focusing her efforts on PA/CA evaluations for the disposal of LLW per DOE O 435.1 Chg 1 at the INL Site. She has been involved with the subsequent development of PA and CA action levels and radionuclide waste concentration thresholds required by DOE O 435.1 Chg 1.

For this study, Ms. Koslow has been one of the principal investigators, performing the inadvertent intruder analyses, radon analysis, focusing on project coordination, reviews, and overall document preparation.

Arthur S. Rood

M.S., Health Physics/Radioecology, Colorado State University, Fort Collins, 1987

B.S., Geology, Mesa State College, Grand Junction Colorado, 1982

Mr. Rood is an environmental engineer and health physicist with over 20 years of experience in developing and applying models of contaminant fate and transport in the environment. He developed the groundwater model used in this performance assessment and also co-authored the food-chain model for the MACCS reactor consequence code. Mr. Rood has also been involved in numerous environmental assessments at the INL Site, including other performance assessments. In addition, he performed much of the environmental transport modeling for the Rocky Flats Historical Public Exposures Studies.

Currently, Mr. Rood is an advisory engineer/scientist for INL/ICP. His achievements over the past 2 years have included a detailed analysis of subsurface tritium migration at RWMC. Highly visible projects include PA/CA evaluations for the ICDF and RWMC and development of WAC required by DOE O 435.1 Chg 1.

For this study, Mr. Rood has been one of the principal investigators, focusing on groundwater fate and transport pathways and uncertainty analysis, and document preparation.

James M. McCarthy, Ph.D.

Ph.D., Civil Engineering, University of California, Los Angeles, 1988

M.S., Water Resource Systems, University of California, Los Angeles, 1984

B.S., Environmental Resources Engineering, California State University, Humboldt, 1981

Dr. McCarthy has over 25 years of experience related to groundwater hydrology, surface water hydrology, and water resource systems. During the last 20 years he has focused his efforts on performance assessment- and risk assessment-related projects. He has been the principal investigator on a number of environmental restoration- and waste management-related subsurface flow and transport studies, including, most recently, the PA/CA evaluation for two LLW disposal facilities at the INL Site.

For this study, Dr. McCarthy has been one of the principal investigators contributing to the project coordination, technical aspects, and document preparation.

Alva M. Parsons

M.S., Hydrology, New Mexico Institute of Mining and Technology, Socorro, NM, 1988

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Ms. Parsons is a groundwater hydrologist with expertise in vadose zone hydrology, subsurface flow and transport, and hydrogeological characterization and monitoring. She has over 15 years of professional experience working on performance assessment, risk assessment, and environmental restoration projects within the DOE complex, including Sandia National Laboratories, Savannah River Site, Los Alamos National Laboratory, and the West Valley site. In addition, Ms. Parsons assisted with the saturated zone numerical analysis for the Yucca Mountain Total System Performance Assessment. Ms. Parsons is currently a Staff Scientist for the ICP at the INL Site. Most recently, she has provided technical support for PA/CA projects at RWMC at the INL Site.

For this study, Ms. Parsons performed the screening analysis and participated in groundwater pathway and uncertainty analyses, and document preparation.

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Appendix A

Cover Design Life

Appendix A

Cover Design Life

This cover design life engineering analysis supported EPA, DEQ, and DOE-ID approval of the ICDF. Sections below discuss the following: potential postclosure impacts to cover systems (Section A-1), engineering analyses and DOE commitments (Section A-2), and long-term ICDF cover performance expectation (Section A-3).

A-1. POTENTIAL POST-CLOSURE IMPACTS TO COVER SYSTEMS

Water and wind erosion, lack of vegetation, excessive sunlight, disturbance by soil-dwelling animals (or by people), and freeze-thaw of compacted clay layers all are potential problems for landfill cover systems (EPA 1989). Each is discussed below.

A-1.1 Water and Wind Erosion

Heavy water and wind erosion of the top cover layer can lead to exposure of the waste itself. The potential for erosion depends on local weather patterns, soil type in the cover, and length and slope of the surface. Providing a deeper cover will compensate for erosion estimated over the cover service life (EPA 1989).

A-1.2 Lack of Vegetation

The top layer of the landfill cover is the vegetative layer. This layer prevents wind and water erosion, minimizes the percolation of surface water into the waste layer, and maximizes evapotranspiration (the loss of water from the soil by evaporation and transpiration) (EPA 1989). Long-term considerations in vegetation selection include periods of drought or fire and local plant species based upon vegetation studies for disturbed areas. Appropriate vegetation for the landfill cover will control transpiration and erosion control sufficiently.

A-1.3 Excessive Sunlight

Excessive sunlight (ultraviolet light and ozone) degrades flexible membrane liners. Adequately burying the cover's flexible membrane liners will minimize degradation. Typical soil depths of liners range from 3 to 6 ft (EPA 1989).

A-1.4 Disturbance by Soil-Dwelling Animals

Adequately burying the cover system will minimize the effects of animals. Adequate liner soil depths typically range from 3 to 6 ft. Large rocks can also thwart the intrusion of animals into the cover system. Biotic barriers can be used to prevent intrusion of burrowing animals into the cover system. Posting signs and/or erecting fences can usually prevent human intrusion (EPA 1989).

A-1.5 Freeze-Thaw of Compacted Clay Layers

The impact of freeze-thaw cycles on clay is still not known. Therefore,, clay liners should be placed below the frost penetration layer (EPA 1989).

A-2. COVER ENGINEERING DESIGN AND ANALYSIS ADDRESSING IMPACTS

This section summarizes the engineering analyses for the ICDF landfill cover system design (EDF-ER-281).

A-2.1 Record of Decision Design and Operating Objectives

The ICDF Complex must comply with the Record of Decision (ROD) design and operating objectives(DOE-ID 1999):

- Maintain the cover placed over the closed ICDF Landfill to prevent the release of leachate to underlying groundwater, which would result in exceeding a cumulative carcinogenic risk of 1E-04, a total hazard index (HI) of 1, or applicable State of Idaho groundwater quality standards (i.e., maximum contaminant levels [MCLs]) in the Snake River Plain Aquifer (SRPA).
- In 2095, and beyond, ensure that SRPA groundwater does not exceed a cumulative carcinogenic risk of 1E-04, a total HI of 1, or applicable State of Idaho groundwater quality standards (i.e., MCLs).
- Minimize precipitation run-on and maximize precipitation run-off to effectively reduce infiltration through the contaminated soils and debris.
- Minimize subsidence of the waste and landfill cap.
- Ensure that the design is protective of human and ecological receptors.
- Ensure that the final cover is designed to serve as an intrusion barrier for a period of at least 1,000 years.

The performance specifications for the ICDF Landfill and Evaporation Pond (SPC-332) describe the performance and other requirements for the liner and cover system. Specifically, the ICDF Landfill design must meet all applicable or relevant and appropriate requirements (ARARs), which include the substantive requirements listed below:

- Comply with the substantive requirements of the Resource Conservation and Recovery Act (RCRA) Subtitle C design standards specified in Idaho Administrative Procedures Act (IDAPA) 58.01.05.008 (40 CFR 264.301 and 40 CFR 264.302) and the polychlorinated biphenyls (PCBs) chemical waste landfill design requirements (40 CFR 761.75).
- Comply with the substantive requirements of RCRA Subtitle C closure requirements specified in IDAPA 58.01.05.008 (40 CFR 264.310), which include the following:
 - Provide long-term minimization of migration of liquids through the closed landfill.
 - Function with minimum maintenance.
 - Promote drainage and minimize erosion or abrasion of the cover.
 - Accommodate settling and subsidence so that integrity of the cover is maintained.
 - Have permeability less than or equal to the permeability of any bottom liner system or natural subsoils present.
 - Maintain the integrity and effectiveness of the final cover, including making repairs to the cover as necessary to correct the effects of settling, subsidence, erosion, or other events.

- Maintain and monitor the groundwater monitoring system.
- Prevent run-on and run-off from eroding or otherwise damaging the final cover.
- Protect and maintain surveyed benchmarks used in complying with 40 CFR 264.309.

A-2.2 Description of Cover System

The ICDF Landfill will be capped with a robust state-of-the practice cover barrier to minimize long-term infiltration. The cover system will vary from approximately 28 to 54 ft above ground surface. The sides of the cover system will be sloped 2.5 to 1 and will be covered with approximately 2 ft of basalt riprap (5- to 12-in. diameter). The height and covering the side slopes with riprap will make the cover a very predominate feature in a flat sagebrush plain. The ICDF Complex is sited in a sagebrush plain southwest of INTEC and is not near any other facilities. So the final state of ICDF will be a 54-ft-high mound with steep side slopes with a width and length of approximately 1,000 ft. The cover system will meet the remedial action objectives to minimize infiltration and maximize run-off and protect against inadvertent intrusion for minimum of 1,000 years and meet ARARs under the IDAPA and RCRA Subtitle C requirements for closure of a hazardous waste landfill.

The cover system will minimize infiltration and maximize run-off by maintaining a sloped surface, storing water for later release to the atmosphere, having lateral drainage, and providing a low-permeability composite liner barrier system. The cover can be divided by function into three main sections. Each section and its function are listed below:

- Upper section: The upper water storage component (top 9 ft of the cover) provides water storage during wet periods for later release into the atmosphere during dry periods.
- Middle section: The biointrusion component provides protection from burrowing animals and a capillary break. This layer is immediately below the upper section and is approximately 4.5 ft thick where the top of the section is at least 9 ft below the surface of the cover.
- Lower section: The lower section includes a composite liner system that has a permeability less than or equal to the permeability of the landfill bottom liner system that complies with IDAPA 58.01.05.008 [40 CFR 264.310]. Lateral drainage can occur above the composite liner system through a high-permeability drainage material in the middle section. This layer is immediately below the middle section and is a minimum of 4 ft thick and 13 ft below the surface of the cover.

Each component in the cover profile is shown in Figures A-1 and A-2.

A-2.3 Cover Surface Grade and Erosion Protection

The ICDF Landfill cover surface grade and erosion protection meets or exceeds the requirements of RCRA Subtitle C design standards specified in IDAPA 58.01.05.008 (40 CFR 264.301 and 40 CFR 264.302). It is designed to minimize long-term migration of liquids through the closed landfill, function with minimum maintenance, and minimize erosion.

The cover's surface promotes surface water drainage away from the waste, minimize erosion, and providing a medium for vegetation. The surface will be sloped so that surface water run-off is directed to the side slopes of the landfill lined with basalt riprap armoring. The riprap armor will dissipate eroding forces from stormwater until the stormwater reaches the existing ground surface (over 100 ft from the edge of the waste mass).

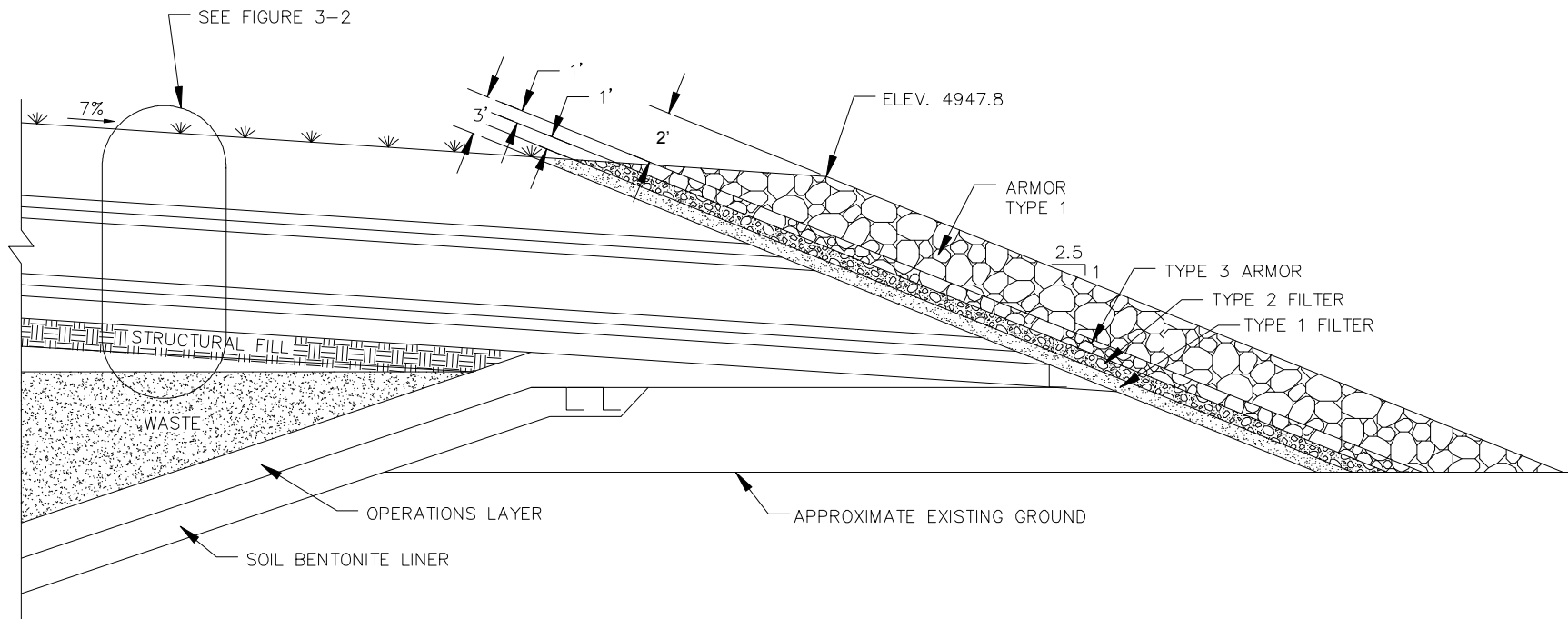


Figure A-1. Landfill cover section.

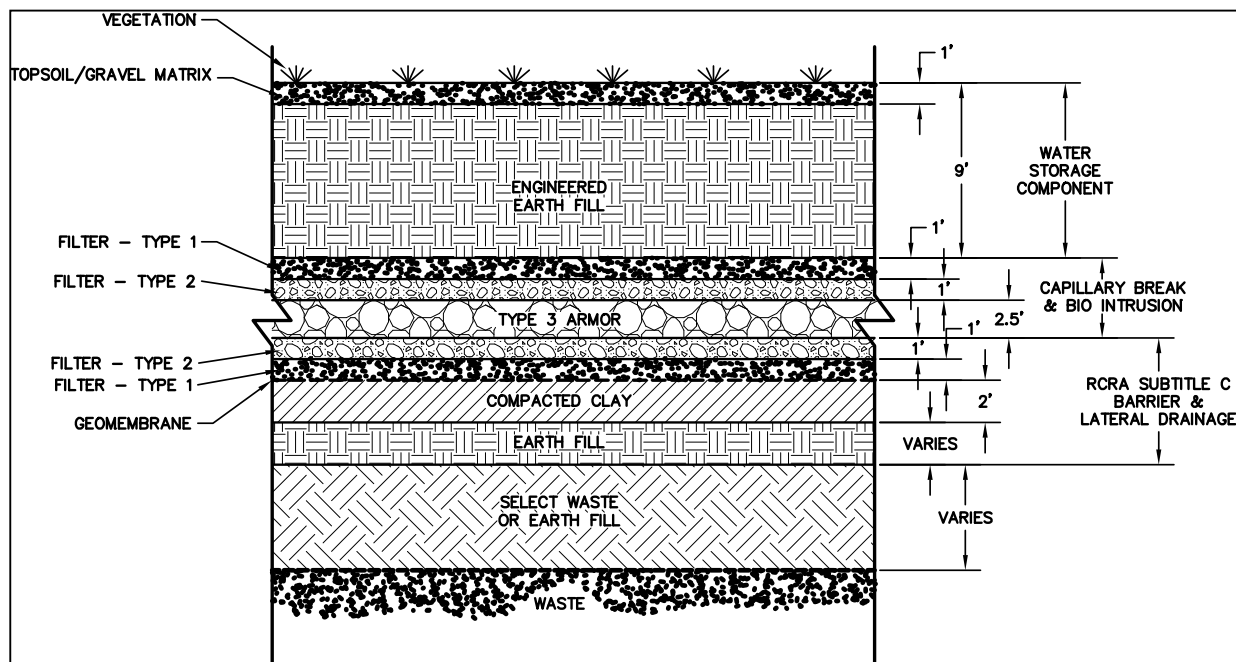


Figure A-2. Landfill cover profile.

The cover settlement has been evaluated in the “Landfill Compaction Subsidence Study” (EDF-ER-267). Based on the settlement determined in this study and the other design considerations (subsidence, erosion, and abrasion) provided herein, a final grade of 7% was determined for the cover. This will ensure that a minimum slope of 3% is maintained after consolidation to promote surface water drainage off the cover system through its life cycle.

Analyses of surface water and wind erosion determine soil loss from the cover due to sheet flow. the Modified Universal Soil Loss Equation (MUSLE) was used to analyze for erosion due to surface water, as recommended by the Nuclear Regulatory Commission (NRC) for long-term (i.e., 1,000-year) soil loss (NRC 1986). The surface of the cover was assumed to be fine-grained soils such as those found at the Rye Grass Flats area without accounting for the protection of the soil/gravel matrix. The analysis determined the probable maximum precipitation (PMP) event and calculated soil loss per year using the MUSLE equation. Approximately 2 ft of soil could erode from the surface of the cover over a 1,000-year time period. The minimum water storage layer thickness needed to maximize water storage is 6.5 ft based on the “Hydrologic Modeling of the Final Cover” (EDF-ER-279). The water storage layer will be constructed with an additional 2.5 ft of material to provide a sacrificial layer in the event that the surface would erode due to water erosion.

Extensive wind tunnel studies performed at the Hanford facility show that a mixture of fine-grained soil and pea gravel significantly reduced erosion due to wind forces. Soil/pea gravel armoring can reduce erosion rates from 96.5 to more than 99% at wind speeds of 45, 56, and 67 mph (Ligotke 1993). The average wind speed at the INL Site based on the period of record is 9 mph with peak gusts up to 82 mph (NOAA 2001). Based on these studies, a soil/pea gravel matrix will provide sufficient protection against wind and aeolian forces for the ICDf cover through its life cycle, and conceivably beyond.

The top surface of the cover will consist of a vegetated soil/gravel matrix system sloped to minimize infiltration and maximize run-off. Vegetation will enhance the evapotranspiration properties of the upper cover portion and provide erosion control. The soil/gravel matrix will prevent excessive soil

loss due to wind and surface water run-off. The design of the cover surface and erosion protection is a combination of ICDF site-specific studies and off-site studies performed at the Hanford facility to support the development of long-term protective covers.

A-2.3.1 DOE Commitments

Long-term performance of the cover is based upon the vegetation that will be well established. The cover will be periodically monitored as part of the ICP long term stewardship program and maintained as necessary.

Institutional controls anticipated to be implemented as part of long-term stewardship include the following:

- Access restrictions will prevent intrusions into the closed area, including the creation of a buffer zone surrounding the capped ICDF and supporting structures
- Access controls, monitoring, and maintenance will remain in place for as long as the contents of the landfill remain a threat to human health or the environment if uncontrolled.

The ICDF Landfill closure requirements will include access restrictions with a buffer zone that will be maintained around the landfill for as long as the landfill contents remain a threat to human health and the environment. The institutional controls are designed to prevent disturbance of closed areas and to maintain a cumulative carcinogenic risk of less than 1E-04 and a total HI of 1. The access restrictions are designed to prevent intrusion into a closed area and establish a buffer zone of protection. Access controls, monitoring, and maintenance will remain in place as long as the contents of landfill remain a threat to human health and environment (cumulative carcinogenic risk of greater than 1E-04 and a total HI greater than 1).

The DOE-ID is required to monitor the ICDF Complex after its operational life is completed. The institutional controls for this facility will include proper signage, security, and monitoring. The long-term management of the ICDF Complex and associated monitoring, maintenance, etc., will be transferred to ICP Long-Term Management and Control. DOE-ID will place easily visible permanent markers at all the corner boundaries for each cell of the landfill and identify the potential hazards. In addition, the DOE-ID will maintain all institutional controls until that responsibility is passed, along with management of the property, to another federal agency such as the Bureau of Land Management (BLM).

In the ROD, Table 11-1, the Agencies agreed to rely upon institutional controls as part of the selected remedy (DOE-ID 1999). In general, institutional controls will be designed to limit site access after closure of the ICDF. The institutional controls address two timeframes—current DOE operations and DOE control postoperations. The controls under current DOE operations include operating ICDF as an industrial Radiologically Controlled Area with visible access restrictions (warning signs, copies of surveyed maps, etc.). Activities such as drilling or excavating will be controlled. In addition, surveillance to ensure controls are in-place includes periodic inspections by DOE and IDEQ/EPA reviews. The frequency of the surveillance is determined in the ICDF Remedial Action Work Plan and includes a combination of daily and weekly inspections.

The institutional controls for post-operations include restricting access to the landfill such that there will be no unauthorized intrusion into the capped area; drilling and excavating will be controlled. Only Federal Facility Agreement and Consent Order (FFA/CO) -approved operations and maintenance (O&M) activities will be authorized. Controls under the post-operation's timeframe include visible access restrictions (warning signs), notice to affected stakeholders, and property lease requirements. Affected stakeholders (e.g., BLM, Fish and Wildlife Service, Sho Ban Tribal Council, local county governments,

State, and EPA) will be notified regarding notice of any change in land use designation, restriction, land users, or activities. Warning signs will be installed and maintained to warn intruders of the risks of remaining in the area. These warnings would be to unauthorized trespassers if current DOE radiological site controls were no longer used. DOE will control post-operations of the ICDF such that the landfill will have no unauthorized intrusion into the capped area. Also, DOE will maintain the integrity of the cap. The effectiveness of the institutional controls will be periodically evaluated during 5-year reviews. The 5-year reviews will continue until these reviews are no longer needed by the Agencies. Specifically, the 5-year reviews will continue as long as contaminants exist at levels that result in restricted access or limited site usage at ICDF. The remedy will be evaluated no less than every 5 years to ensure it is functioning as intended and remains effective in reducing risks and complying with applicable or relevant and appropriate requirements. These long-term requirements minimize the potential for cap degradation and inadvertent intrusion because DOE institutional controls will be maintained for a sufficiently adequate time period until restricted access is no longer necessary due to unacceptable levels of contamination.

A-2.4 Side Slope Erosion and Stability

The landfill cover side slopes will be sloped at 2.5H:1V (2.5 horizontal to 1 vertical) from the edge of the cover to the existing ground surface as shown in Figure A-1. The side slopes will be armored with durable basalt rock native to the INL area. The rock armor was designed to dissipate erosional forces from surface water run-off and protect the underlying cover layer and waste. The side slope erosion protection and stability analysis will ensure that the cover maintains its integrity over the long term.

The primary function of the side slope armor is to maintain the integrity of the cover system and waste mass. It will dissipate the energy from water run-off from the cover and protect the cover from an unlikely event of a flood. Its secondary function is to provide a biobarrier for the landfill. The side slope armor will be comprised of earthen materials sized to maintain the cover's integrity through the 1,000-year design life cycle. The rock armor size varies from 5 to 12 in. in diameter depending on the weight of the individual rock piece.

A-2.5 Evapotranspiration Component

The evapotranspiration component consists of silty loam-type soils that provide water storage during wet periods for later release into the atmosphere during dry periods. Coupled with a capillary break provided by the underlying sand and gravel layers, it will store moisture from long-term, low-probability precipitation events for later release to the atmosphere by evapotranspiration. The evapotranspiration layer in the cover is an integral component that provides long-term minimization of migration of liquids through the closed landfill while functioning for the long term with minimal maintenance.

The primary function of the evapotranspiration component is to store and release moisture and provide a medium for plant growth. It also provides a buffer zone between the waste and ecological receptors. Hydrologic modeling has shown that the evapotranspiration component can recover after cycles of extreme precipitation events and will continue to function through its 1,000-year design life and conceivably years beyond.

The thickness of the evapotranspiration layer was determined based on hydrologic modeling provided in the "Hydrologic Modeling of Final Cover" (EDF-ER-279). Sensitivity analysis was performed that determined an optimal layer thickness between 5 and 6.5 ft. The sensitivity analysis shows clearly that increasing the water storage thickness beyond the optimal thickness increases water storage capacity, but does not reduce the percolation rate. Insignificant changes in percolation occur for the water

storage layer thickness beyond 6.5 ft. Additional material was added to the water storage layer to address erosion protection described in Section A-2.3.

A-2.6 Biointrusion/Drainage

Small animals and insects such as badgers and ants have been known to burrow into landfills, bringing waste materials to the surface and leaving defects in the cover system. Past barrier studies at INL, Hanford, and other facilities have shown that a thin layer of gravel is effective in preventing animals and ants from penetrating underlying waste materials (Morris and Bleu 1997; Wing 1993). The ICDF Landfill cover will include a 2.5-ft-thick, Type 3 armor layer comprised of 2- to 5-in.-diameter gravel. This biointrusion layer is shown on Figure A-2. The Type 3 armor will also provide lateral drainage in the event breakthrough occurs through the upper cover layers. The primary function of the biointrusion layer is to prevent burrowing animals indigenous to the INL area from penetrating the underlying cover components and the waste material. It also provides a high-permeable drainage media if water were to percolate from the upper portions of the cover system.

The biointrusion design was primarily based on review of past studies performed at INL. The increase in infiltration due to holes left in the evapotranspiration component were evaluated in the “Hydrologic Modeling of Final Cover” (EDF-ER-279). The biointrusion design evaluated both plant and animal intrusion. Based on the total cover thickness varies from 17.5 to 21.5 ft below the cover surface, biointrusion will not be a concern because this depth is greater than known burrowing depths at the INL. The biointrusion material will consist of gravel screened from the local available alluvium at INL. The alluvium gravels at INL are composed of granite, quartz, and other durable minerals that make it ideally suited for long-term applications.

A-2.7 Barrier Layers

The primary mechanism for minimizing infiltration through the cover is the upper evapotranspiration cover layer. Barrier layers are included in the lower portions of the cover for redundancy and regulatory compliance. The barrier consists of a single high-density polyethylene (HDPE) geomembrane/soil-bentonite liner (SBL) composite system. Similar to the landfill liner system beneath the waste, the composite system will intercept water in the event breakthrough occurred from upper cover sections and divert it laterally through the overlying sand and gravel layers. The cover barrier layer complies with the substantive requirements of Subtitle C hazardous waste closure specified in IDAPA 58.01.05.008 (40 CFR 264.310) and will have a permeability less than or equal to the permeability of the ICDF bottom liner system. The function of the barrier layer is to provide a redundancy in the cover system and divert water away from the waste if it were to break through the upper cover sections. The earthen SBL is expected to perform through the 1,000-year design life of the cover.

Stresses will be induced in the cover SBL and geomembrane barrier components due to settlement in the foundation soils waste, and the cover itself. When the cover settles, the geomembranes will compress, resulting in a reduction in stress. However, the SBL could crack due to excessive settlement. The proposed cover surface will have a slope of 7%. The cover could accommodate an additional settlement (after surface consolidation, cover settlement, and the maximum strains are accounted for) of 13 ft. Approximately 54% (i.e., 6 ft) of the allowable settlement are predicted over the long term. Consequently, the strain in the SBL will not cause cracking and increased permeability.

Landfill covers must maintain a positive slope to promote surface water runoff (40 CFR 264.310). The EPA recommends a final top slope between 3 and 5%, after settlement has occurred. The proposed cover surface will have a slope of 7% (EDF-ER-281) and a length of 387 ft measured on its shortest side. The final top slope after settlement will be approximately 3%.

SBL can sustain irreversible damage caused by freeze-thaw cycles. Water added during construction for compaction can freeze, increasing the hydraulic permeability through formation of cracks, microcracks, and interconnected macro pores (Benson and Othman 1993). Extreme frost penetration at INL is estimated to be 3.75 ft. The ICDF Landfill SBL will be protected from frost by 15.5 ft of overlying soil layers in the cover.

A-2.8 Filter Layers

The cover will be comprised of two filter-type materials to prevent fine-grained material from migrating to other components of the cover system. The filter layers provide a smooth transition from one material to another while maintaining the capillary break and lateral drain between the sections. Filter layers also provide capillary breaks due to the contrast in unsaturated permeabilities. Filters are included between the upper soil storage layer and biointrusion, between the biointrusion and SBL, and beneath the side slope armor.

Filters allow water to pass while keeping soil particles in place. They are typically comprised of sand and gravel or manufactured from synthetic materials. The filter layers in the landfill cover system will be composed of graded sands and gravels screened from the alluvium material that exists at the INL. The gradation of each filter is designed to prevent fine materials from the overlying layer from migrating downward. The filter layers will perform their function through the 1,000-year design life cycle. A summary of rock armor and filter sizes is provided in Tables A-1 and A-2, respectively.

Table A-1. Summary of rock armor sizes.

Armor/Filter	D ₅₀ ^a (in.)	Percent Finer Than						
		12 in.	8 in.	6 in.	4 in.	3 in.	2 in.	1.5 in.
Type 1—Side slope armor	10–12	100	35–60	15–35	0–5			
Type 3—Armor biointrusion barrier	2.5–4			100	100–40	100–25	30–0	0–1

a. D₅₀ is the medium diameter of the material.

Table A-2. Summary of filter sizes.

Armor/ Filter	D ₅₀ ^a (in.)	Percent Finer Than											
		3 in.	2 in.	1.5 in.	3/4 in.	3/8 in.	#4	#10	#20	#40	#60	#100	#200
Type 2— Coarse filter material	0.15– 0.5	100	100– 85	100– 77	86–57	68–42	55– 30	40–15	23–0	10–0	3.0		
Type 1— Fine filter material							100	100– 80	90– 58	75– 43	65– 33	55– 25	40– 12

a. D₅₀ is the medium diameter of the material.

A-2.9 Vegetation

The landfill cover surface will be seeded and fertilized to promote plant growth. Vegetation will minimize erosion and accelerate removal of water from the water storage layer. Long-term considerations include periods of drought or fire so erosion and hydrologic modeling studies have assumed a poor stand of vegetation. The vegetation will consist of local plant species based on vegetation studies performed for

disturbed areas at INL (DOE-ID 1989). This should produce a healthier stand of vegetation than natural conditions, providing more transpiration and better erosion control.

Vegetation is expected to be present through the 1,000-year design life. Vegetation is expected to continue with periods of drought or fire. Vegetation based on native plant species will include the following:

- Secar bluebunch wheatgrass
- Bottlebrush squirreltail
- Sandberry bluegrass
- Sodar streambank wheatgrass
- Green rabbit brush.

The maximum allowable noxious weed percentage (by dry weight) will be 0.5%. The maximum allowable wet and other crop percentage will be 1.5%. The engineered seed mix will provide superior vegetation providing more transpiration and erosion control than the surrounding natural vegetation.

A-3. LONG-TERM COVER PERFORMANCE EXPECTATION

The only long-term performance consideration for the ICDF Landfill is potential of cover system degradation over the long-term service life. Material degradation could potentially change the physical properties that would impact the performance of the cover. The soil and rock materials used will not be problematic with respect to degradation if the current materials specified are used during cover construction. These materials have a long track record with respect to degradation based on extensive studies associated with geology. The physical characteristics of geologic materials, such as soil and rock, do change with time, but these changes take a very long time, usually on the order of millions of years.

The ICDF cover system will consist of natural and synthetic materials. A description of each material and its long-term performance characteristics is presented below to determine the viability of the performance requirements being met.

A-3.1 Natural Materials

The majority of the cover system will consist of the natural materials. These materials will include the following: soil, rock, and vegetation.

The engineering properties of these materials are well understood and have obvious longevity. They will be engineered to perform a specific function in the ICDF such as hydraulic barriers, water storage, transpiration, erosion control, filtration, and drainage. Descriptions of the materials' natural properties (e.g., low permeability, capillary potential, energy dissipation) that make them well suited for their function are provided in the subsections below. Long-term degradation issues are described such as desiccation and freeze-thaw issues in clay soil or erosion potential in rock.

SBLs have a natural low saturated permeability due to the clay mineral crystalline structure. Clay is found in abundance in nature as a result of the chemical and physical erosion of rock. Geologically (millions of years), clay will continue to change chemically and physically if exposed to the environment. The clay mineral used in the SBL (e.g., bentonite, montmorillonite) is electrically unbalanced and has an affinity for water. This results in a swelling effect when water is available. Conversely, moisture loss will

cause drying and shrinking, which results in cracking. Cracks or desiccation will increase permeability in SBLs. Clays are also subject to freeze-thaw cycles that can increase permeability.

The SBL used for the landfill cover will be protected by the overlying cover materials 15.5 ft thick. The frost depth at INL is approximately 3.75 ft below the ground surface. The SBL in the landfill bottom cover will be below the frost depths. Additionally, at this depth, the SBL will retain its moisture and maintain its low permeability characteristic.

Sands and gravel will be used in the cover system for filtration and drainage. There is an abundance of alluvial soils at INL that can be engineered to provide the required gradation and drainage properties for each layer in the landfill cover. The alluvium gravels at INL are comprised of granite, quartz, and other durable minerals that make it ideally suited for long-term applications.

The upper portion of the cover will be comprised of fine-grained soils that provide good water storage capabilities. These soils are also available at INL and have been shown to provide good water storage and release characteristics in engineered barrier studies performed at INL. Soil is a product of the decomposition of rock and will retain its properties for the long-term life of the cover. However, its fine-grained composition makes it vulnerable to erosional forces such as wind and water.

A soil/pea gravel mulch and vegetation providing armor against erosion will protect the upper portion of the cover. The cover will also be overbuilt as a contingency in the unlikely event that the soil/pea gravel is eroded, exposing the upper fine-grained water storage material to long-term erosional forces.

Rock armor will line the side slopes of the ICDF Landfill. Shallow formations of basalt underlie INL and can be easily mined for erosion protection. Basalt is a durable volcanic rock that provides excellent erosion protection, however, it may vary in its density and competency. Los Angeles Abrasion Tests (ASTM C535) will be performed on the rock armor selected for the ICDF cover prior to construction to determine its long-term durability. Based on the results of these tests, rock armor will be oversized if necessary to ensure that it performs its function for the life of the cover system.

A-3.2 Human Intrusion

To deter the inadvertent intrusion of humans into the waste, a marker system will be used to warn future generations of the dangers of the buried waste. DOE intends to maintain active control of INL (using fences, patrols, alarms, and monitoring instruments) for the foreseeable future (next 100 years). If these measures should cease, other passive-type measures will warn the inadvertent intruder from waste buried beneath the permanent cover barrier. The measures may include recognizable warning markers and other physical features. Site information will be provided on an Internet website, U.S. Geological Survey maps, libraries, and other information repositories that would be readily available to the public.

The ICDF Landfill will have a steep rocky side slope of basalt riprap. This feature clearly delineates the boundaries of the surface barrier by providing a distinct contrast with the surrounding flat terrain. These side slopes are engineered structures that will be obvious that humans had built the structure. These distinct riprap side slopes in combination with warning signs will minimize the risk of human intrusion.

If ownership of any portion of the land is ever proposed for transfer outside the federal government, the DOE-ID will fulfill the requirements of 42 USC 9620 (Comprehensive Environmental Response, Compensation and Liability Act [CERCLA] §120[h]) to provide the transferee with complete notification and warranty of completed RA. At such time, the federal government will establish, in

cooperation with local governments, appropriate land use restrictions, zoning restrictions, and deed restrictions on the ICDF Landfill and its adjacent buffer zone, which will preclude industrial, institutional, or residential development until unacceptable risk no longer exists. These documents will include disposal records and the marker locations. These conditions will be verified as part of the EPA, IDEQ, and DOE 5-year review.

A-3.3 Potentially Disruptive Natural Events

Potential disruptive events would include a high wind condition, earthquake, or massive flood event. The likelihood and magnitude of these events at the INL are discussed in the following paragraphs. How the cover would be affected by these catastrophic events is discussed below.

Tornado-type winds are expected to be extremely rare at the ICDF Complex. The side slope armor will consist of large heavy basalt riprap that will resist tornado-type winds. The surface of the permanent cover will consist of vegetation and soil/pea gravel matrix. The soil/pea gravel matrix has shown to be resistant to high wind forces generated in wind tunnel tests performed at the Hanford facility.

The ICDF Complex is situated outside the 100-year and 500-year Big Lost River floodplains predicted by the United States Geological Survey (Berenbrock and Kjelstrom 1998) and United States Bureau of Reclamation (BOR 1999), respectively. As a conservative check, the ICDF Landfill was analyzed for the effect of the 500-year flood event flowing past the side slopes. Floodwaters at the base of the cover were assumed to rise to an elevation of 4,925 or 4 ft below the crest of the landfill berm. At this level, the estimated flow velocity is approximately 2.5 ft per second. Even during active landfill operations, this flow velocity and potential erosion can be resisted using native vegetation on the slopes.

Although the permanent ICDF cover barrier has a design life of 1,000 years, it could conceivably perform beyond this time. Its earthen material composition allows the permanent cover to perform like a geological structure requiring many years to break down its outer shell of rock armor. Forces of a catastrophic nature would be required to compromise the 17.5-ft cover comprised of soil, gravels, rock, and clay. Consequently, there is a likely probability that the cover will continue to perform after its 1,000-year design life.

In summary the ICDF cover system addresses all potential postclosure impacts as follows:

- An additional 2.5 ft of soil and pea gravel are added to the water storage layer to address water and wind erosion for 1,000-year design life.
- A vegetative cover including native plant species is expected to continue during its 1,000-year design life with periods of drought and fire.
- All flexible membrane liners are adequately buried to avoid degradation and are expected to continue during its 1,000-year design life.
- Biointrusion layer is placed at a depth greater known burrowing depths and is expected to continue during its 1,000-year design life.
- The sloped sides of the cover will have rock armor to minimize intrusion and is expected to continue during its 1,000-year design life.
- The soil bentonite liner is protected from frost and is expected to continue during its 1,000-year design life.

A-4. INFILTRATION RATE THROUGH THE COVER

Several engineering analyses were completed to achieve approval of the *ICDF Remedial Design/Construction Work Plan* (DOE-ID 2002) by EPA, Region X; IDEQ; and DOE-ID. One of these engineering analyses focused upon hydrologic modeling of cover to determine the design infiltration rate. The first subsection will address proposed cover design and conceptual model used to determine the design infiltration rate through the ICDF Landfill cover. The next subsection will summarize the engineering design and modeling analyses to achieve approval of the cover infiltration rate. The third subsection will summarize the results of the sensitivity analyses. This section will be concluded with a discussion regarding the design infiltration rate through the ICDF cover. The complete modeling for the cover is presented in "Hydrologic Modeling of Final Cover," EDF-ER-279.

A-4.1 Cover Design

The ICDF Landfill will be capped with a robust, state-of-the practice cover to minimize long-term infiltration. The cover system must meet the remedial action objectives (RAOs) to minimize infiltration and maximize run-off and protect against inadvertent intrusion for greater than 1,000 years (DOE-ID 1999). The cover system must also meet applicable or relevant and appropriate requirements under the IDAPA and RCRA Subtitle C requirements for closure of a hazardous waste landfill.

The cover system will minimize infiltration and maximize run-off by maintaining a sloped surface, storing water for latter release to the atmosphere, lateral drainage, and providing a low-permeability composite liner barrier system. Each component in the cover profile is shown in Figure A-3.

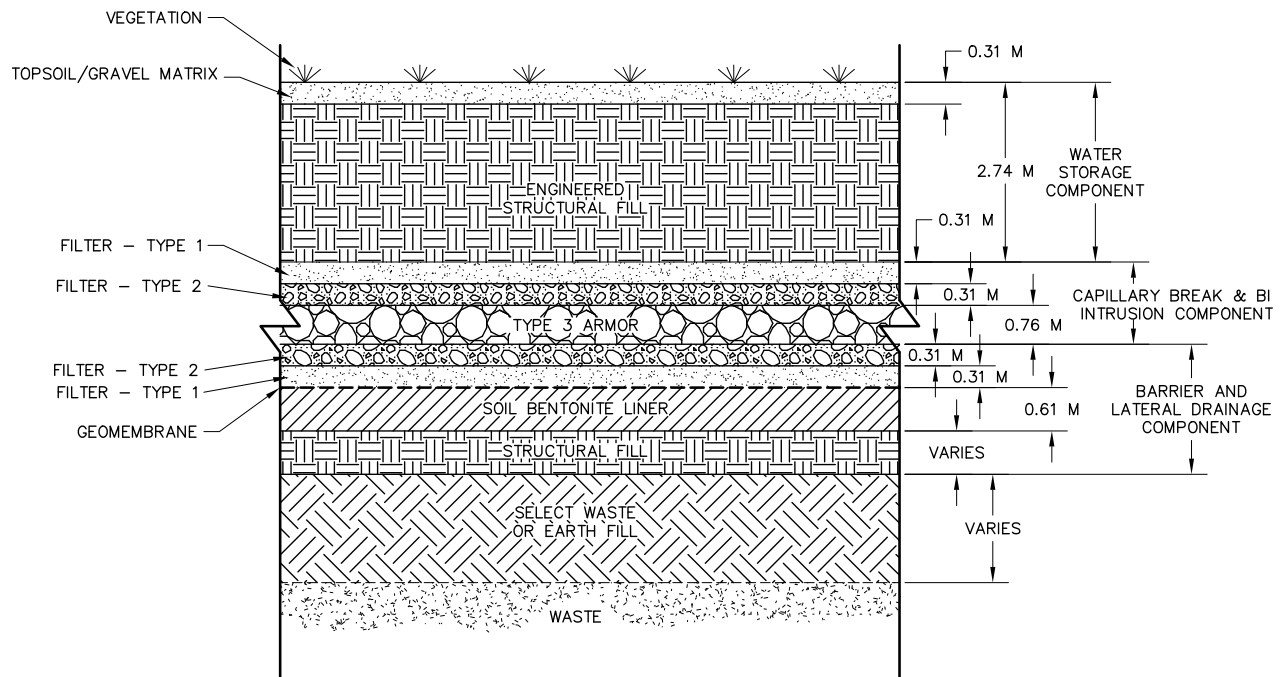


Figure A-3. Schematic of modeled cover section.

The cover can be divided by function into three main sections. Each section and its function are listed below:

- Upper section: The upper water storage component provides water storage during wet periods for latter release into the atmosphere during dry periods.
- Middle section: The biointrusion provides protection from burrowing animals and a capillary break to reduce infiltration.
- Lower section: The lower section includes a composite liner system that has a permeability less than or equal to the permeability of the landfill bottom liner system that complies with IDAPA 58.01.05.008 (40 CFR 264.310). Lateral drainage can occur above the lower section of the liner system through a high-permeability drainage material.

A-4.2 Conceptual Model

Figure A-4 shows the overall cover system model configuration. The arrows in Figure A-4 represent the layers that were evaluated to determine the ultimate percolation from the base of the SBL, Point F. The layers are represented by observation points and are referenced throughout this section to provide a point of reference for the analyses. Each point is described below:

- Point A: Precipitation on the cover surface
- Point B: Evapotranspiration from the cover surface
- Point C: Surface water run-off from the cover surface
- Point D: Breakthrough from the base of the water storage layer
- Point E: Lateral drainage
- Point F: Percolation from the base of the SBL.

NOTE: *Percolation was determined at the base of Layers D and F across the cover, not at a specific point.*

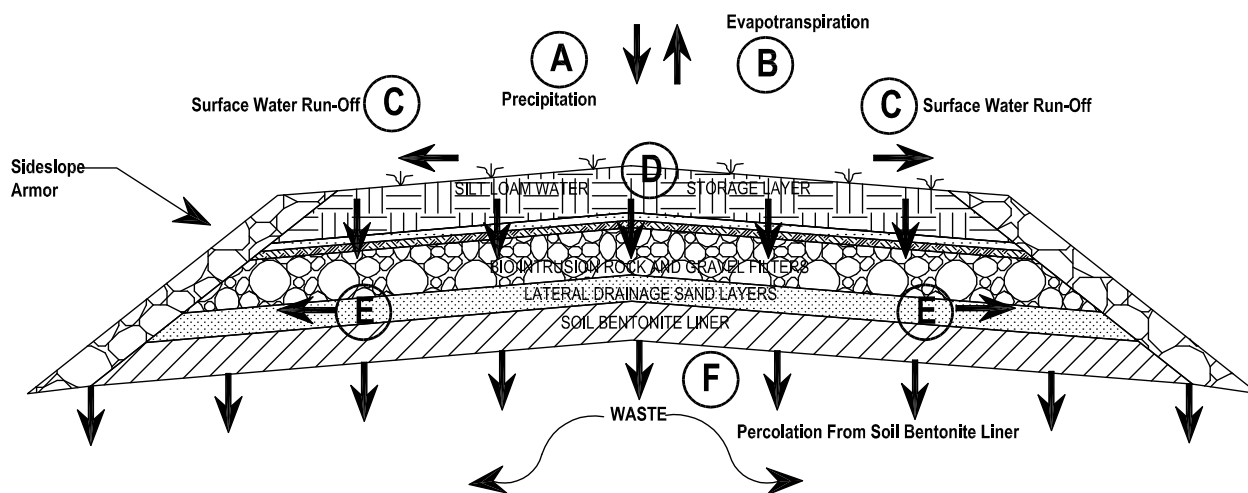


Figure A-4. Hydrologic model geometry and location of layers.

A-4.3 Design and Modeling Analyses

Climatological data, surface run-off, evapotranspiration, infiltration, biological intrusion, lateral drainage, and the modeled infiltration rate analyses and information from “Hydrologic Modeling of Final Cover” (EDF-ER-279) will be summarized in the following subsections.

A-4.3.1 Climatological Data

The hydrologic modeling of the final cover studies evaluated two climate scenarios that included a 10-year period having the conditions that most likely would break through the upper section at Point D shown in Figure A-4 and an extreme condition to address potential long-term climate changes. The extreme condition included back-to-back years that had precipitation amounts greater than the 90th percentile. Figure A-5 shows the period of climate data and the selected 10-year base case period. The 10-year period selected was from October 1, 1967, through September 30, 1976, with an average annual precipitation of 237 mm. This period provides the most likely chance of cover breakthrough from the upper section since the 10-year average annual precipitation (237 mm) is greater than the average annual precipitation (218 mm) for the period of record. Moreover, the selected 10-year period includes higher-than-normal precipitation events during the initial years that “load” the water storage cover layer with moisture, allowing the model to simulate the cover’s recovery capability after large precipitation events.

Figure A-6 shows the years selected for the extreme scenario. The 90th percentile for the period of record was 306 mm/year. As shown, the years with precipitation greater than the 90th percentile were 1957, 1963, 1964, 1968, and 1995. These years, back-to-back (with the exception of 1968, which was included in the average climatic scenario), were used to determine break through from the upper section for long-term, worst-case climate conditions.

Maximum and minimum daily temperatures for the simulated years were included in the input data sets for the unsaturated flow model, Soil Cover 2000. Daily precipitation, maximum and minimum relative humidity, and wind speed data from these years were also input to the model. As a result of the lack of relative humidity data for the years simulated (only 2 years of data were available), monthly averages for minimum and maximum relative humidity were used in the model.

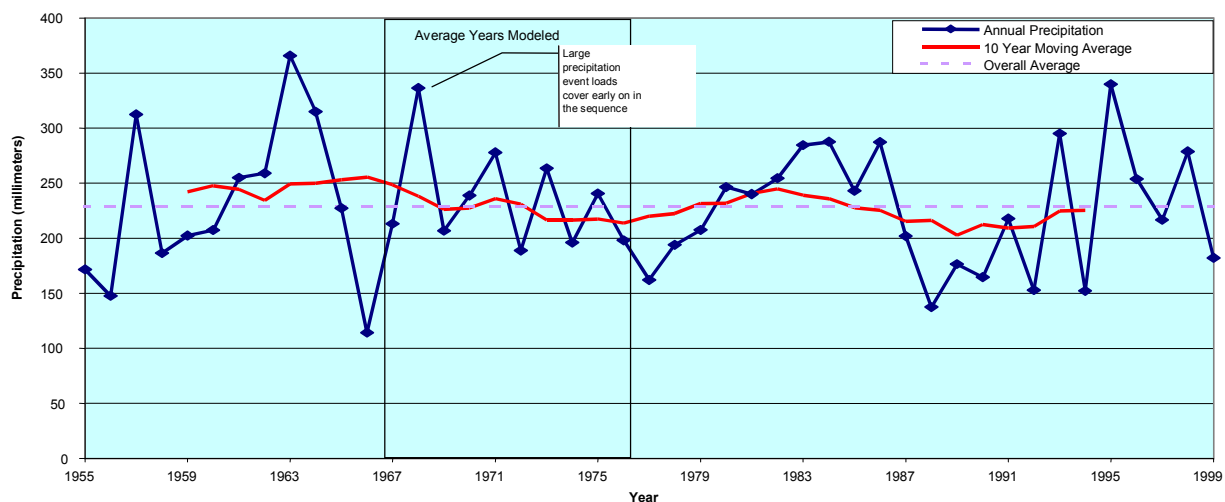


Figure A-5. Idaho National Laboratory Site annual precipitation.

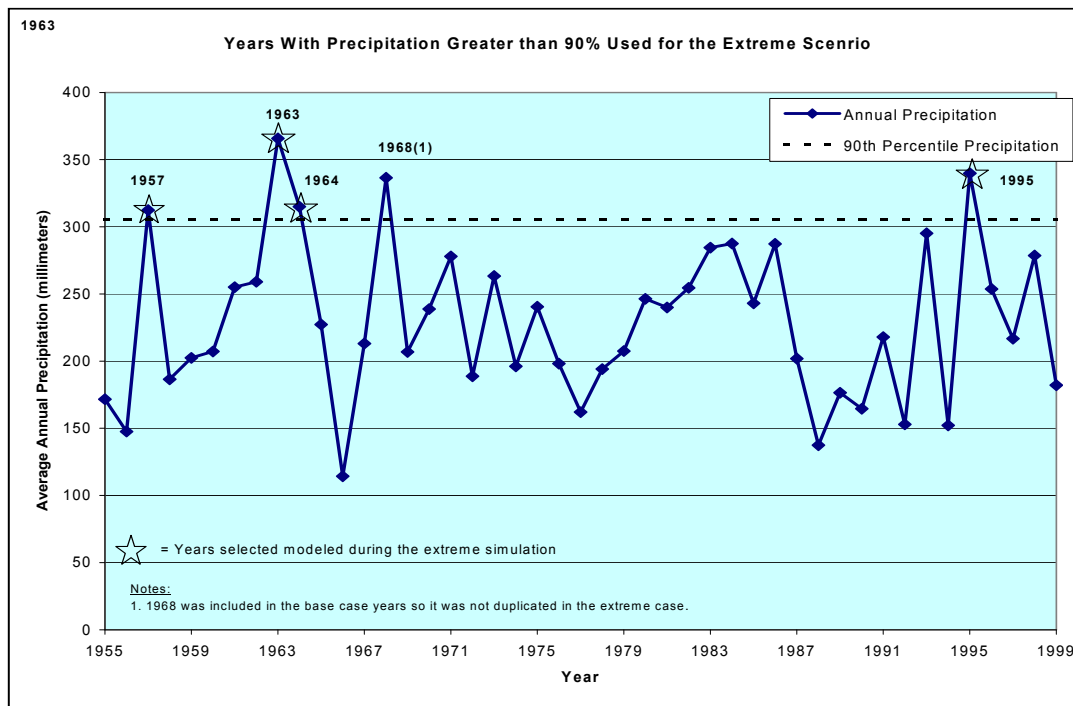


Figure A-6. Extreme precipitation events.

Global solar radiation data were synthetically generated using the Weather Generating Program (WGEN) computer code, which takes into account observed precipitation and temperature data (Martian 1995). These data were converted to net radiation using the method provided in the Handbook of Hydrology (Maidment 1993).

The climatological data for the extreme case were used in this study to determine the worst-case percolation through the base of the cover. Additionally, typical storms for Idaho Falls are of short duration (i.e., less than 6 hours) with high intensity resulting in run-off with little time for infiltration. Storm events for the hydrologic cover model were distributed over 12 hours, maximizing infiltration.

A-4.3.2 Surface Run-Off

The surface water run-off component of the model is shown as Point C in Figure A-4. Surface water run-off was calculated using the curve number method developed by the Soil Conservation Service (SCS). Total run-off during the base case simulation period was calculated using the SCS method as 1.3 mm/year, which represents approximately 0.6% of the total annual precipitation. The run-off for the extreme case simulation was 3.33 mm/year, which is approximately 1% of the total annual precipitation. To account for the run-off in the hydrologic model, the daily precipitation values were adjusted by subtracting the run-off from the recorded precipitation. The observation point location in the model for run-off is shown at Point C in Figure A-4.

A-4.3.3 Biological Intrusion

Studies performed at INL and the Hanford facility have shown that small mammals can burrow into the cover and in some cases potentially deep enough to reach waste materials. Waste can be transported upward and holes left behind can increase infiltration into the cover. Observed burrow depths based on biointrusion studies were 1.47 m for pocket gophers, 1.40 m for pocket mice, and 1.14 m for the

Townsend ground squirrel. A report cited in the Hanford study indicates that the great basin pocket mouse can burrow as deep as 1.93 m (CH2M HILL 2002). Biobarrier demonstration plots at INL showed that 1- to 2-in.-size cobbles were effective in preventing animals from burrowing to underlying soil layers (Laundre 1996).

Of the animals that may introduce penetrating burrows to engineered soil structures such as the ICDF final cover, mammals such as badgers (*Taxidea taxus*) and coyotes (*Canis latrans*) may produce the largest-diameter burrows. These animals, however, are not likely to present dense populations on a structure such as the ICDF cover. Badgers tend to be solitary and excavated coyote dens tend to not be closely spaced. Both badgers and coyotes may create substantial excavations when hunting for smaller mammalian prey (Audubon Society 1992).

Small mammals such as the Great Basin pocket mouse (*Perognathus parvus*) and the northern pocket gopher (*Thomomys talpoides*) are expected to be common residents of the INL and may be expected, over time, to establish residence within disturbed areas of the ICDF Complex (Audubon Society 1992). Studies conducted at the INL and at DOE's Hanford Site in Washington State confirmed the presence of both species on, and near, retired waste sites. One study reported a pocket mouse burrow frequency of 2.9 burrows per 100 meters (m) along study transects. Pocket gopher burrows were observed at a frequency of 1.9 borrows per 100 m along the same transects (Smallwood 1996). The same study also reported observation of harvester ant colonies at a frequency of 1.2 colonies per 100 m. Another study of a pocket gopher population on a retired waste site at Hanford reported an average gopher density of 25.3 gophers per hectare over a two-year study (Hedlund and Rogers 1976).

The characteristics and habits of common burrowing animals indicate that the potential exists for such animals to populate an unmaintained engineered soil structure. In addition, the nature of the burrows produced by these populations could possibly increase water infiltration through the ICDF final cover to an unacceptable rate. The increase in infiltration through the upper section water storage layer from a burrow was determined assuming a mammal left a hole that could be flooded during precipitation events. It was assumed that the animal created one hole in the cover with a diameter of 20 cm that went through the upper section of the cover to the bio-intrusion layer. This hole drained an area 10 times the diameter of the hole, 200 cm. All precipitation contacting this area was added to the infiltration at Point D of Figure A-4.

The infiltration through the water storage layer resulting from one hole through the upper portion of the cover was computed as 0.01 mm/year for the base case and 0.02 mm/year for the extreme case. The infiltration through the water storage layer due to a hole that partially penetrates the upper portion of the cover was computed as 0.005 mm/year for the base case and 0.01 mm/year for the extreme case. The infiltration at Point D shown in Figure A-4 through the water storage layer due to animal burrows was 0.015 mm/year and 0.03 mm/year for the base and extreme cases, respectively.

Considering the burrow density of the pocket mouse, the additional infiltration through the water storage layer would only be 0.16 mm/year. The pocket mouse density of 2.9 burrows per 100 m would produce a total number of burrow holes on the landfill of approximately 16. Based on an infiltration through each burrow hole of 0.01 mm/year, the total additional infiltration through the water storage layer would be 0.16 mm/year, which would provide a total infiltration rate of 0.62 mm/year through the water storage layer. This infiltration rate is less than the infiltration rate required to produce total breakthrough at the bottom of the clay barrier of 0.1 mm/year.

A-4.4 Lateral Drainage

Hydraulic head in the drainage layer was determined using the vertical downward infiltration at Point D shown in Figure A-4 determined by the SoilCover program plus the infiltration due to bio-intrusion. The volume of water that can be removed by the drainage layer is a function of its slope, length, and permeability. For the base and extreme climate scenarios, the drainage layer can remove approximately 112 and 136 m³/year of water given the amount of hydraulic head on the SBL. The water removal capacity of the drainage layer was compared to the infiltration rate from the upper cover section to determine potential infiltration into the compacted SBL and build-up of hydraulic head in the drainage layer. Spreading the volume of water that can be removed from the drainage layer over the area of the cover results in 894 and 1,094 mm/year water removal rate for the base and extreme climate scenarios, respectively. Comparing these values to the predicted infiltration from the upper cover section of 0.41 and 0.48 mm/year (including 0.01 mm/year due to defects caused by biointrusion) for the base and extreme climate scenarios, respectively, indicates that drainage will exceed infiltration, minimizing percolation from the base of the SBL.

A-4.5 Modeled Infiltration Rate

The percolation at the base of the cover in the lower cover section of the model is shown as Point F in Figure A-4. Infiltration at this point can enter the waste mass, potentially generating leachate and migration of contaminants in the waste. Hydrologic simulations of landfill bottom liner systems using EPA's HELP model have been performed to determine the effectiveness of bottom liner systems. Correlations between infiltration and percolation through landfill liner systems were developed to determine the minimum saturated permeability requirement of 1E-07 cm/sec. an average annual percolation rate of 0.1 mm/year is estimated to drain from the base of the ICDF Landfill cover and contact the underlying waste mass. Although a small value, the average annual percolation rate of 0.1 mm/year is conservative since it would require a near steady source of infiltrating water through the landfill cover system.

Two-dimensional finite element modeling was completed using SEEP/W to determine the percolation at the base of the lower cover section shown as Point F in Figure A-4. Steady-state simulations were performed using three inflow rates into the drainage layer in the range of the vertical downward infiltration at Point D shown in Figure A-4 determined by the SoilCover program plus the infiltration due to bio-intrusion. The volume of water exiting the based of the compacted SBL is a function of its slope, length, and permeability. The amount of water exiting the base of the compacted SBL was compared to the infiltration rate from the upper cover section to determine the percentage of the infiltration traveling vertically through the SBL base. Comparing these values to the predicted infiltration from the upper cover section of 0.40 and 0.46 mm/year, the percolation from the SBL is provided in Table A-3.

Based on the SEEP/W modeling, the SBL can reduce the unsaturated inflow by 99.9%. The in-percolation estimated using the HELP studies is approximately an order of magnitude higher, thereby simulating a conservatively larger volume of water to percolate through the SBL.

Table A-3. Lower cover section vertical drainage.

Input Weather	3% Slope		7% Slope	
	SBL Percolation (mm/yr)	Percent Reduction	SBL Percolation (mm/yr)	Percent Reduction
Base case weather	0.0002	99.9%	0.0003	99.9%
Extreme case weather	0.0003	99.9%	0.0003	99.9%

A-5. SENSITIVITY ANALYSIS

Sensitivity analyses were conducted to determine effects of changes in thickness of the silt loam layer, increased precipitation, and changing climatic conditions on the cover's performance. This subsection specifically addresses sensitivity of the cover to the variations mentioned above. Observation Point D was used as the point of interest for evaluating infiltration. A summary of the sensitivity analyses is provided below.

A-5.1 Water Storage Layer

Changes in thickness of the silt loam layer of the water storage section were evaluated using the base and extreme climate scenarios. The modeling methodology was the same as was used to determine the infiltration at Point D in previous models. The silt loam water storage layer thickness was varied from 0.25 to 3.5 m.

At a thickness of 0.25 m, average annual infiltration was reduced to approximately 18 mm/year. Increasing the cover thickness to 0.5 m reduced the average annual infiltration to approximately 10 mm/year. A cover thickness of 1.5 m reduced infiltration to less than 2 mm/year. Average annual infiltration was less than 1 mm/year for cover thickness of 2 m and greater.

The sensitivity analysis shows clearly that increasing the water storage thickness beyond the optimal thickness does not provide added water storage. Based on the analysis, the optimal water storage layer thickness is between 1.5 and 2 m. Insignificant changes in infiltration occur for the water storage layer thickness beyond 2 m. A minimum water storage layer thickness of 2 m is recommended for the ICDF Landfill cover. Additional material may be required to address erosion control and aeolian effects. A thicker water storage layer may be needed so that the minimum thickness is maintained after long-term erosion. This information was summarized in Section A-2.2 above.

A-5.2 Increased Precipitation

The effect of increased precipitation on infiltration through the water storage layer of the cover was analyzed using an average year of weather and multiples of the average year's precipitation. The weather data for the year were repeated until the soil profile reached a quasi-steady state. The year with total precipitation closest to average was 1975, which had 269 mm of precipitation including 51 mm of water-equivalent snowfall. The average precipitation for the period of record is 218 mm/year including 37 mm of water-equivalent snowfall.

The one-dimensional computer was run using one, two, three, and four times the 1975 precipitation. Twenty years were modeled for each precipitation interval using two 10-year simulations. Based on the analysis, the upper cover may become ineffective when exposed to an average annual precipitation of greater than 810 mm/year. This also assumes all other climate parameters remain constant. The resulting infiltration at the Point D layer is 0.17 mm/year at three times the average annual precipitation, which is less than the 0.46 mm/year infiltration based on the extreme climatological scenario. The four times precipitation resulted in significant breakthrough from the water storage cover.

A-5.3 Climate Change

The effect of decreased evaporation on infiltration through the water storage layer of the cover was analyzed using the Penman equation. The Penman equation determines potential evaporation from the soil surface based on temperature, net radiant energy, wind speed, and relative humidity. Changes in these climate conditions at the ICDF in the long term could potentially reduce evaporation from the surface of the cover increasing infiltration.

Based on the analysis, long-term climate changes could reduce evaporation from the cover between 14 to 28% of the potential evaporation determined from the hydrologic model. The resulting infiltration at the Point D layer would then increase between 14 and 28% from what was predicted by the hydrological model, conservatively assuming that a change in potential evaporation is directly proportional to the change in infiltration. For the base case climate scenario used in the hydrologic model, the infiltration could increase between 0.45 to 0.51 mm/year. For the extreme case climate scenario, the infiltration could increase between 0.52 to 0.60 mm/year.

A-6. DESIGN INFILTRATION RATE

Eight different steady-state models were run for this exercise using the SEEP/W. Four models were run with a cover slope of 3%, which is a worst-case cover slope scenario and 7%, which is the design cover slope. All the models utilized the same geometry and materials types with a range of inflow fluxes in the lateral drainage layer. The 3% cover (worst-case) model output indicates that a steady influx into the lateral drainage layer of approximately 0.85 mm/year or greater is required to obtain a percolation rate of more than 0.1 mm/year from the bottom of the SBL. The value of 0.1 mm/year is used as input into the fate and transport model.

Based on the results from the simulations for the ICDF Landfill cover, results from experimental studies at the INL, and experimental and modeling results from other sites in the western U.S., it is believed that the cover design proposed for the ICDF Landfill represents a state-of-the-practice design for a landfill cover that minimizes infiltration into the waste. Any leakage that occurs through the cover due to defects or extreme changes in climate is likely to be intercepted by the lateral drainage layers at the base of the cover. A conservative estimate of 0.1 mm/year of percolation from the base of the cover was determined based on the estimated break through from the upper section of the cover. Based on the results reported in this EDF, it is believed that the cover design, which incorporates a store and release soil cover underlain by a capillary break and composite liner system, represents the best technology for minimizing infiltration into the landfill given site-specific climatic conditions.

A-7. REASONABLY CONSERVATIVE ESTIMATE OF INFILTRATION

The above results indicate 0.1 mm/year of infiltration through the lower section of the soil cover into the waste. This is considered reasonably conservative for the reasons listed below:

- All snow was assumed to melt in a 22-day period each year, stressing the cover's water storage capacity.
- A poor stand of grass was assumed to simulate drought or post-fire conditions.
- The daily precipitation was distributed over 12 hours increasing infiltration into the cover.
- The years selected for the weather data included large precipitation events early on in the simulation to stress the recovery capacity of the cover.

- An extreme case was modeled that assumed four years of back-to-back precipitation events that were above the 90th percentile based on the period of record.
- Bio-intrusion does not account for increased evaporation from lower depths of the soil resulting from increased air circulation or for evaporation and dispersion resulting from precipitation moving through the soil.
- The 20% of the break through that percolates from the base of the SBL is an order of magnitude higher than two-dimensional modeling results using SEEP/W.
- The two-dimensional modeling was based on a steady-state inflow versus less conservative transient conditions.

The sensitivity results show that the cover will perform as modeled for precipitation up to three times the annual average. Increasing the water storage layer thickness greater than 2 m results in minimal improvement in hydraulic performance. Extreme changes in temperature, net solar radiation, wind speed, and humidity could increase influx into the lateral drainage layer, resulting in a percolation from the base of the SBL of less than 0.1 mm/year.

Water movement was calculated from the cover layer represented by the observation points shown in Figure A-7. The average annual percolation from the base of the cover is provided in Table A-4.

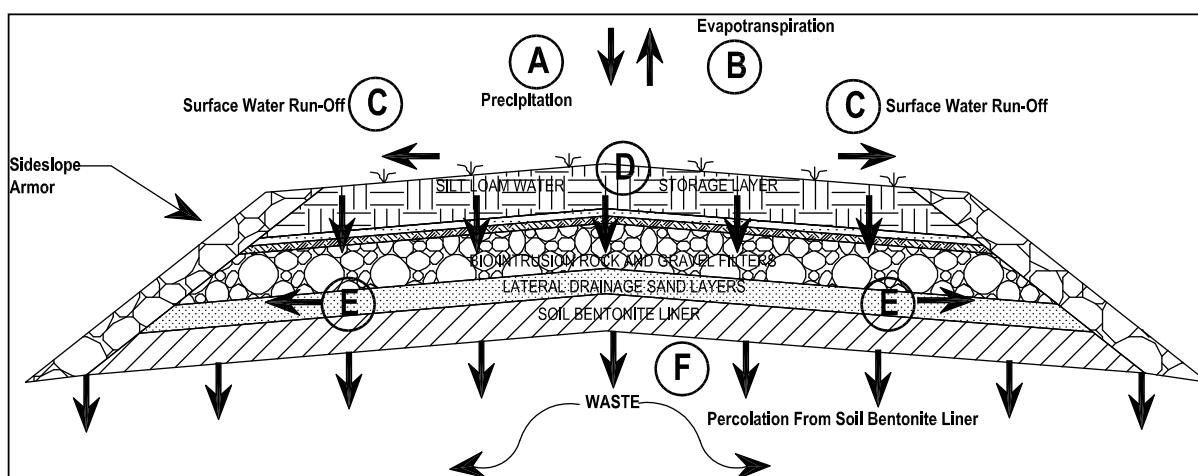


Figure A-7. Hydrologic model geometry and location of observation points.

The values listed in Table A-4 represent average annual flow from the main components of the cover system. The flux or break through from the water storage layer represented by Point D is assumed to be the same at the crest and downslope areas. The difference between the flux at the crest and downslope portion of the cover is expected to be small, since surface run-off is small and the lateral movement of water within the water storage layer will be minimal, due to its low saturated permeability and gradual slope. Using the conservative estimate of infiltration, the safety factors for the base and extreme cases are 3.0 and 2.6, respectively. With this infiltration due primarily from a depression in the SBL, these safety factors reflect a conservative viewpoint of cap degradation and performance.

Table A-4. Summary of water movement from base of cover.

Point	Description	Base Case		Extreme Case	
		Value	Direction	Value	Direction
D	Influx into lateral drainage layer (mm/yr)	0.42	Downward	0.49	Downward
E	Lateral drainage (mm/yr)	0.41	Lateral	0.40	Lateral
F	Percolation due to depression in SBL (mm/yr)	0.03	Downward	0.03	Downward
F	Percolation due to upper cover section influx (mm/yr)	0.003	Downward	0.009	Downward
Total Percolation from base of cover (mm/yr)		0.033	Downward	0.039	Downward

A-8. REFERENCES

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Appendix B

Numerical Experiments – Justify One-Dimensional Vadose Zone Model at the ICDF

Appendix B

Numerical Experiments – Justify One-Dimensional Vadose Zone Model at the ICDF

B-1. INTRODUCTION

This appendix, together with Section 2.1, Site Characteristics, provides the rationale for one-dimensional vadose zone conceptual and numerical models for the ICDF-PA. In particular, this appendix discusses numerical experiments that support the use of a one-dimensional model for the ICDF vadose zone simulations.

In order to choose the appropriate spatial dimensions for the vadose zone flow and transport modeling beneath the ICDF, characteristics of the subsurface and the water sources were evaluated. A combination of complex geology, multiple water sources, and large fluxes of water can overcome gravity and cause multi-dimensional flow and multi-modal mass fluxes to the aquifer. These situations could drive the need for a multi-dimensional model. Section 2.1, Site Characteristics, discusses site-specific conditions (such as arid environment and thick vadose zone) that support the assumption of one dimensional unsaturated flow in the vadose zone. This appendix focuses on the numerical experiments and related water sources.

The subsurface at the INL Site is heterogeneous with layers of basalt and sediments that vary in thickness; although they are generally horizontal, they may contain some slope. This geology can create a complex system for water flow and transport, in particular if large water fluxes from multiple water sources result in perched water. Multiple field studies and simulation modeling exercises at the INL Site have shown that flow and transport through the vadose zone are essentially one-dimensional and vertical if there is one water source driving flow and transport (like precipitation or a pond) unless the flux of water is significantly larger than the unsaturated hydraulic conductivity of an interbed. For these high-flux situations, portions of the vadose zone will become saturated, and horizontal transport in perched water could become a factor. For example, at INTEC has multiple anthropogenic sources of water, as well as sources of contaminants. These sources of water create significant perching within and on top of sedimentary interbeds, causing horizontal water spreading. Historically, the volume of anthropogenic water introduced to the subsurface could be as high as ~2 million gallons a day. The multiple sources of water, contaminants already present in the subsurface and dissolved in infiltrating water, and a subsurface comprising fractured basalt with sloping sedimentary interbeds results in interaction between water and contaminant sources and a complex transport problem that includes horizontal transport in perched water. The WAG 3 CERCLA program identified anthropogenic water as a major contaminant transport driving force; hence, they are actively identifying anthropogenic water sources and eliminating them. The percolation ponds south of INTEC and relatively close to the ICDF introduced about 1 million gallons of water a day to the subsurface from 1984–2002. This flux of water to the vadose zone resulted in perched water and significant horizontal spreading in the vadose zone. The percolation ponds were closed and moved 2 miles (3.2 km) (ICP 2009) to the west so that percolation water would no longer influence the vadose zone at the INTEC or the ICDF. Since the percolation ponds were removed from service, monitoring well data indicate the perched water has drained out in subsurface interbeds in the vicinity of the ICDF. Therefore, no anthropogenic water is anticipated in the vicinity of the ICDF. More recently, leaks in the industrial water systems at INTEC have been identified and repaired. Water releases from INTEC to the vadose zone are an ongoing issue, but these fluxes have been reduced significantly.

Natural water sources can also contribute to perched water in the vadose zone. For example, the subsurface in the immediate vicinity of the intermittently flowing Big Lost River can potentially create perched water and result in horizontal flow at the interbeds. As discussed in Section 2.1.5.1, when water is flowing in the Big Lost River, perched water levels have increased in wells in the northern part of INTEC. Well BLR-CH is 500 ft (150 m) from the Big Lost River and is the furthest well from the river that is clearly influenced by its flow. Perched water is also present in this area from anthropogenic water sources. If there is already perched water in the system, then the horizontal influence of the Big Lost River is much larger than if there is no perched water. The Big Lost River is about 3,600 ft (1,100 m) north of the ICDF. INTEC studies have shown that the Big Lost River influence is limited to less than 1,000 ft (300 m) from the channel, even in the presence of perched water (DOE-ID 2010a). Without perched water, the influence would probably be much smaller as gravity would be the dominant flow and transport driver.

INTEC has anthropogenic releases from industrial water leaks and french drains, but these sources are well to the north of the ICDF, and the vadose zone wells between the INTEC and ICDF indicate no perched water currently near ICDF. Because (a) there is no perched water at the ICDF, (b) the Big Lost River is relatively far (~0.7 miles [1.1 km]) from the ICDF, and (c) no anthropogenic water sources currently influence or are expected to influence the subsurface at the ICDF, the conceptual model of water flow and contaminant transport through the subsurface at the ICDF should be essentially one-dimensional. The subsurface flow and transport conceptual model and the INL Site subsurface field studies (DOE-ID 2006a, 2010a) support the rationale for a one-dimensional flow and transport model (see Section 2.1.5.1). In addition, numerical studies have evaluated the impacts of the one-dimensional versus two- and three-dimensional models at the ICDF and in the INTEC area. The following section summarizes the numerical studies and findings.

B-2. ICDF DESIGN AND 2003 PA NUMERICAL SIMULATIONS – 2-D VERTICAL VERSUS 1-D VERTICAL

Design of the ICDF Landfill included vadose zone fate and transport modeling (EDF-ER-275) using the STOMP model (PNNL 1996) in a two-dimensional vertical mode.

The model was configured such that the 150-m-long vertical slice of the vadose zone underlying the ICDF was modeled having three contiguous sedimentary interbeds with fractured basalt in between the interbeds. A constant water flux was applied to the top of the domain and no-flow boundary conditions were applied to the sides. Therefore, the model was essentially one-dimensional.

The use of a relatively complex two-dimensional numerical model to simulate a relatively simple one dimensional conceptual model resulted in long run times without providing additional information from what could be obtained from a simpler one-dimensional model. The long run times for the STOMP model made it impractical to simulate contaminant transport explicitly in a deterministic mode and to use in the thousands of computer runs needed for the Monte Carlo simulations for the 2003 PA uncertainty analysis. A simpler numerical code (GWSCREEN) was chosen for use in the ICDF-PA 2003 simulations. Some numerical experiments (DOE-ID 2003) were performed for the 2003 PA to show the equivalence of the STOMP and GWSCREEN results. The experiments showed that, for the same set of assumptions, the two-dimensional STOMP model and the one-dimensional GWSCREEN model produce similar results.

Figure B-1 is a copy of Figure 3-6 in DOE-ID (2003). It shows the results of the calibrations for four surrogate contaminants with different transport parameters. Very good agreement was reached between STOMP and GWSCREEN. This showed that the two-dimensional model simulated with STOMP was in fact a one-dimensional conceptual model and could be simulated with a one-dimensional model to address the ICDF PA compliance questions.

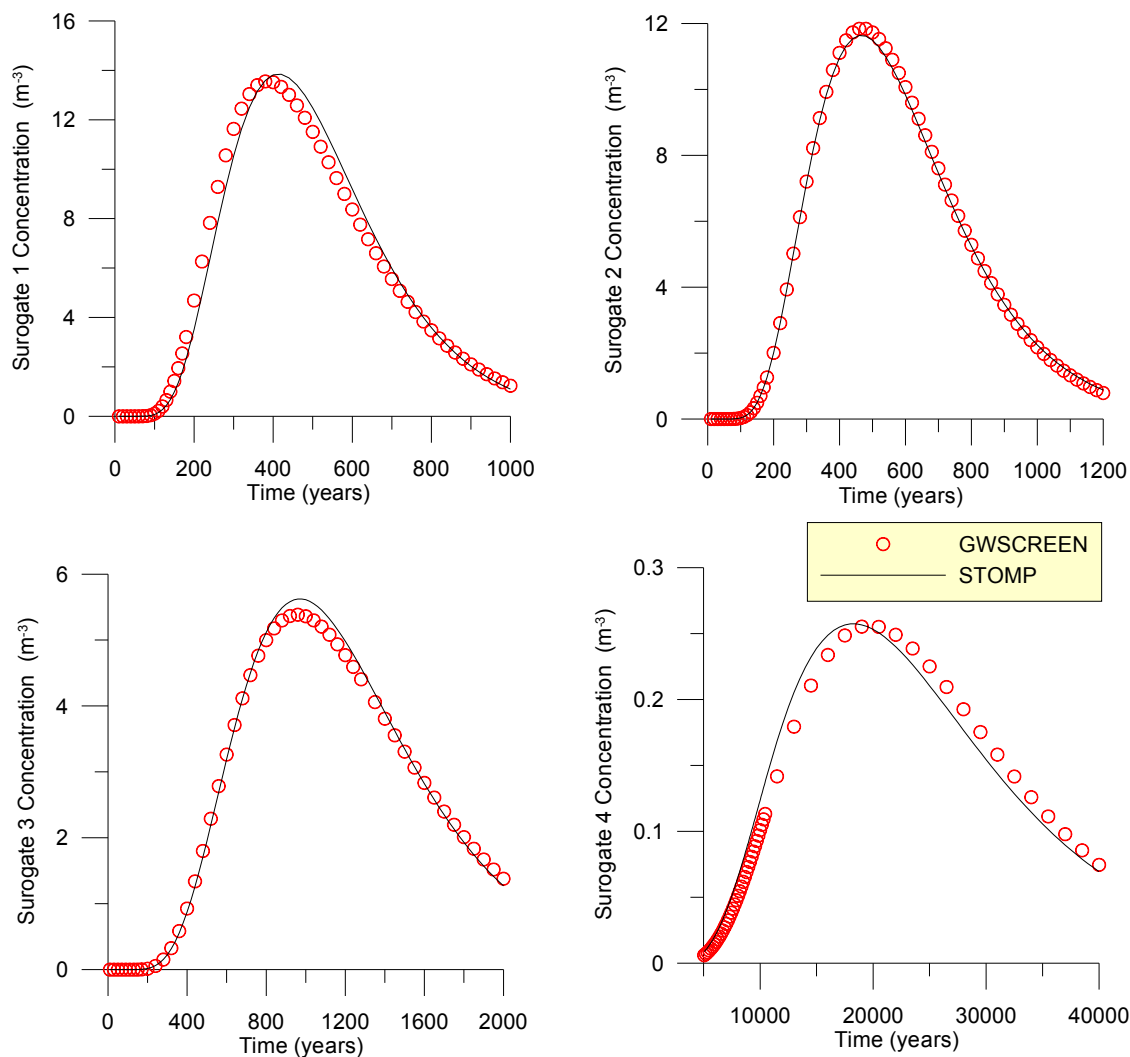


Figure B-1. Results of calibration of GWSCREEN to STOMP.

B-3. NUMERICAL SIMULATIONS – DEMONSTRATE AREA OF INFLUENCE OF BIG LOST RIVER IN THE VADOSE ZONE

Another numerical experiment uses a complex three-dimensional model and a response function model. The modeling demonstrates that the further a contaminant source is from the Big Lost River, the less effect the river has on flow and transport in the vadose zone and the more appropriate a one-dimensional model is (DOE-ID 2010a). This section's figures are taken directly from DOE-ID (2010b). The original work was performed as part of the High-Level-Waste Environmental Impact Statement (HLW-EIS) (Schafer 1998).

The OU 3-13 model (DOE-ID 1997) is a three-dimensional model that simulates multiple INTEC area waste sources and water sources. The three-dimensional model includes water from natural sources (precipitation and Big Lost River) as well as anthropogenic water sources (percolation ponds; sewage treatment ponds; french drains for steam from the heating system; and leaks from facility water piping, including pressurized fire water). The three-dimensional model includes contaminant sources from around the INTEC area. Calculation needs for Schafer (1998) necessitated a numerical model that could be simulated much faster than the three-dimensional OU 3-13 model. A response surface model was developed based on the OU 3-13 model and used for the HLW-EIS calculations (DOE 2002). The methods of superposition and convolution were used together with the response functions to generate a solution. A simplified version of this model was used for numerical experiments to evaluate the effect and area of influence of the Big Lost River on flow and transport in the subsurface and under what situation it is appropriate to model flow and transport in one dimension. This model was used for numerical experiments that demonstrate the effect of the Big Lost River on dissolved-phase transport at different distances from the river.

Figure B-2 shows the INTEC facility outline, facility locations, and the numerical grids defined in the OU 3-13 model. The Big Lost River is the line in the northwestern portion of the domain starting in grid block (10,5) and ending in grid block (3,1). ICDF would be positioned in about grid block (8,10) or (8,11). The dimensions of the numerical grids are 200 m $\times$ 200 m. The dimensions of the ICDF are similar (160 m $\times$ 194 m).

The response function approach was evaluated regarding the dimensionality of flow and transport and the effect of the Big Lost River on transport of contaminants by:

- Modifying the OU 3-13 response function model to eliminate all anthropogenic water sources and include only the Big Lost River and precipitation. Infiltration from precipitation was assumed to be the background infiltration rate and the Big Lost River was assumed to flow at a steady-state rate.
- Placing a unit mass of a tracer in a single grid cell at the surface at the start of the simulation. For this numerical experiment, three scenarios were simulated assuming the unit mass was placed in (1) grid block (6,5) about 350 m from the river, (2) grid block (5,6) about 630 m from the river, and (3) grid block (6,7) about 700 m from the river. In general, the source locations were collocated with clustered INTEC facility locations, with some locations selected simply based on distance from the Big Lost River. Distance from the river was evaluated because contaminants originating at locations closer to the river were expected to experience more horizontal spreading and faster travel times between land surface to the aquifer relative to those contaminants originating further from the Big Lost River.
- Tracking the output of the tracer at the vadose zone-aquifer interface that results from the tracer source in one of the three grid blocks at the top of the vadose zone. The mass flux from one grid block at the vadose zone-aquifer interface as a function of time is referred to as a mass flux response function. For example, if a unit mass is placed in grid block (5,6) at ground surface, then the mass flux from each grid block at the vadose zone-aquifer interface defines 150 (one for each grid block) mass flux response functions from grid block (5,6) to the grid blocks at the vadose zone-aquifer interface.
- Assessing the mass-flux variability across the vadose zone-aquifer interface by comparing the mass flux at many different grid blocks. In addition, the total mass flux derived from the fully three-dimensional fluxes is calculated and presented. The mass flux variability and the total mass flux are used as evidence for adopting a one-dimensional model for use in this ICDF PA.

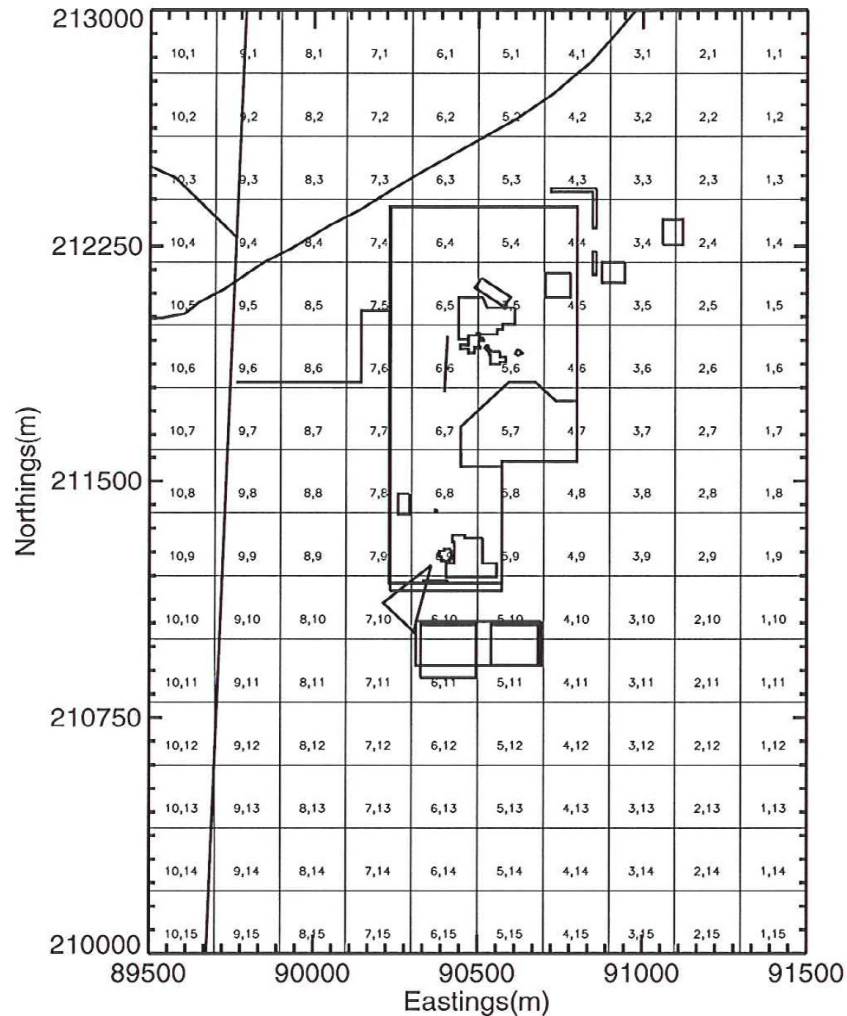


Figure B-2. Map showing the INTEC facility, primary facility locations, and numerical grid for the OU 3-13 model. Response surface simulations were simulated grid blocks (6,5), (5,6), and (6,7). (The Big Lost River is represented by the diagonal line across the north-west corner.)

A completely one-dimensional vertical system would result with all the contaminant mass exiting at the vadose zone-aquifer interface from the same numerical grid block (in plan view) as the mass was put in. If there were only dispersion impacts, then the mass flux would be primarily from the input grid, with lesser and uniform mass fluxes from the surrounding grids. If there is horizontal advection influencing flow and transport, then more mass flux will be from grid blocks in the direction of the horizontal advection. If there is advection influencing the vertical flow and transport, then the travel time to the vadose zone-aquifer interface would be shorter.

To extend the analysis to the ICDF, the analysis requires assessing anthropogenic water and the potential for formation of perched water with origins in the Big Lost River.

Based on the current assumptions, transport of contaminants from ICDF would occur well after the anthropogenic water sources at INTEC had been removed. Even now, there is no evidence of anthropogenic water sources influencing the vadose zone at the ICDF. Assuming a one-dimensional

vertical model and neglecting horizontal dispersion is conservative and will result in higher predicted aquifer concentrations than a three dimensional model with horizontal dispersion.

B-3.1 Impulse Response for a Source in Grid Blok (6,5)

The results of the first simulation, placing the mass in grid block (6,5), are given in Figures B-3 and B-4. Figure B-3 shows the mass flux at the vadose zone-aquifer interface for a 4-by-5 matrix of grid blocks, beginning with grid block (4,5) (upper right) and ending with grid block (7,9) (lower left), as shown in Figure B-2. Other grid blocks had a negligible mass flux and are not plotted.

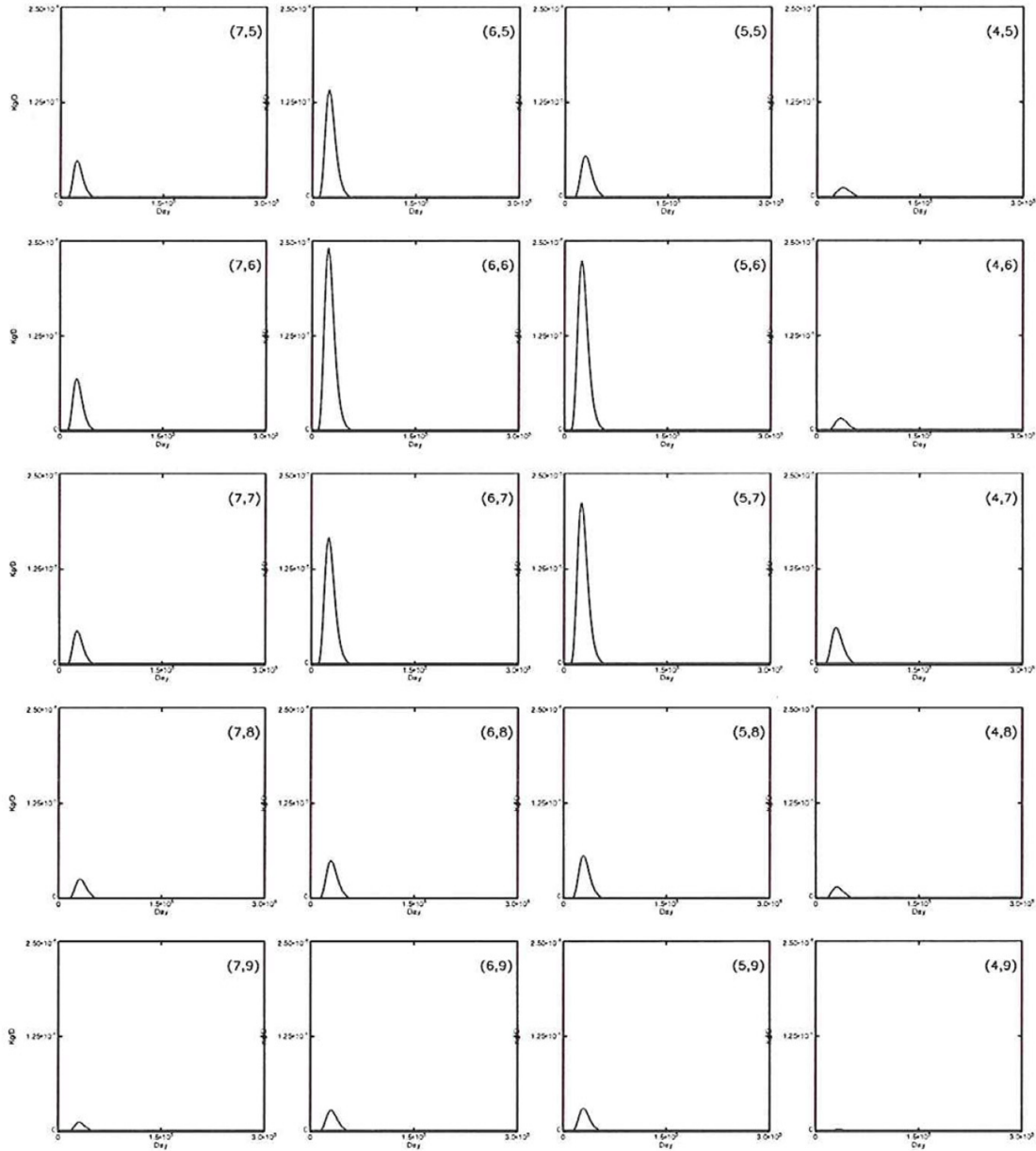


Figure B-3. Mass flux (kg/day) as a function of time (days) in each vadose zone-aquifer interface grid cell for a source mass placed in grid block (6,5) of the Operable Unit 3-13 model.

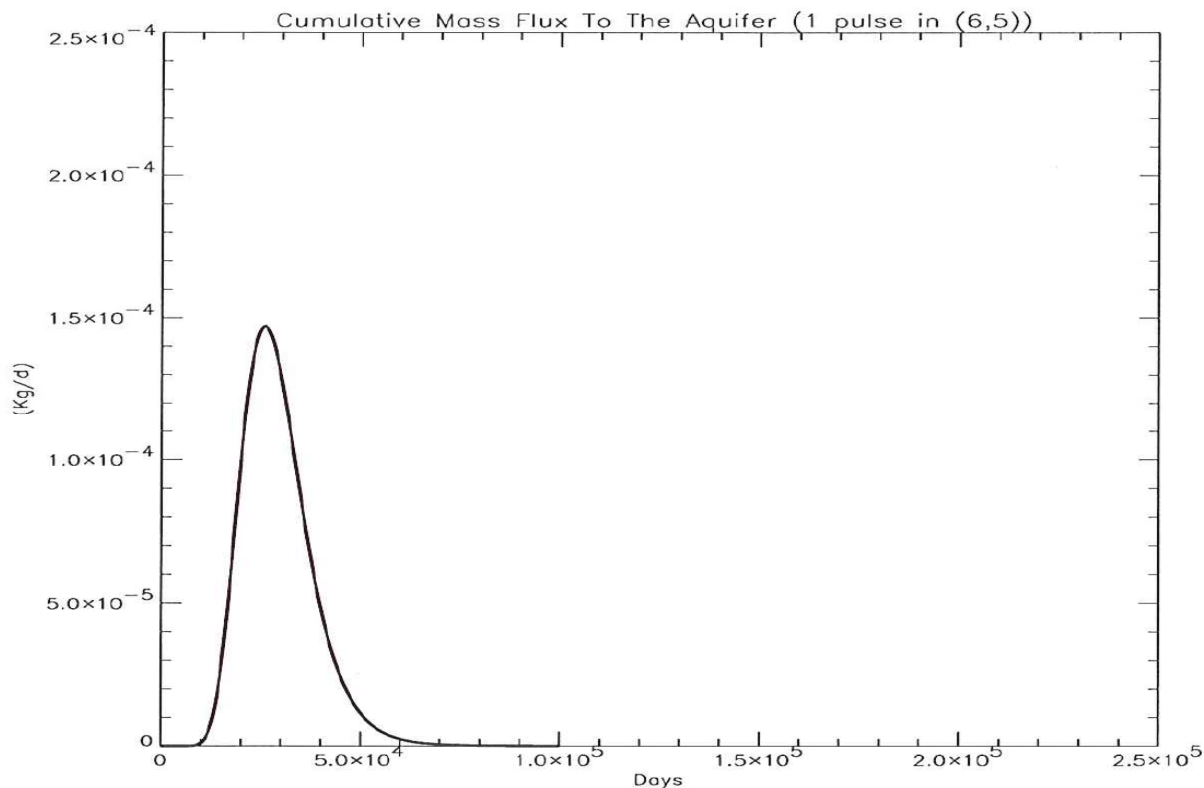


Figure B-4. Sum of the mass fluxes at the vadose zone-aquifer interface for the source mass placed in grid block (6,5) of the Operable Unit 3-13 model.

There is some variability between the mass flux curves for the various grid blocks, as expected. For example, the peak response is observed in grid block (6,6) even though the source was placed in the surface grid block at (6,5). The physical reason for this is a result of the interaction of spatially variable lithology (hydrologic properties and interbed slopes) and flow induced by the Big Lost River. The total distance impacted in the north-south direction is somewhat larger than in the east-west direction. Of particular interest in these individual mass flux curves is the relative uniformity in shape and arrival time. That is, the peak flux is approximately the same for each curve. Each of them could be represented by a single one-dimensional model because none of them exhibit multi-modal behavior indicative of the arrival of multiple flow paths.

When summed together, the total mass flux curve (Figure B-4) exhibits no multi-modal behavior, and the curve could be represented by a one-dimensional advection dispersion equation. Horizontal spreading while the tracer moves vertically through the vadose zone is a result of the advective flow from the Big Lost River and geologic heterogeneity introduced by the sedimentary interbed structure.

B-3.2 Impulse Response for a Source in Grid Block (5,6)

The results of the second simulation, placing the mass in grid block (5,6), are given in Figures B-5 and B-6. Figure B-5 shows the mass flux at the vadose zone-aquifer interface for the same 4-by-5 matrix of grid blocks given in Figure B-3.

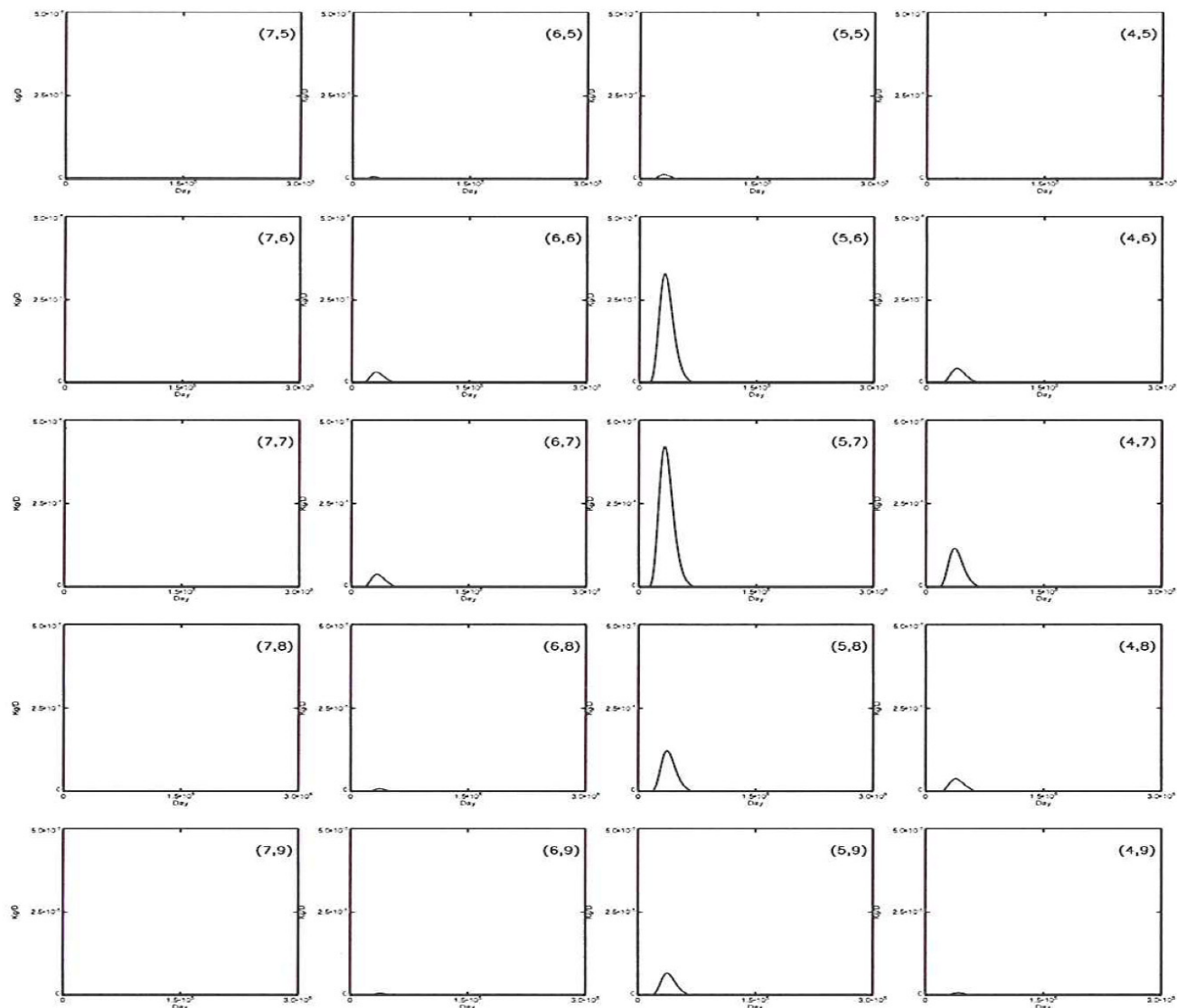


Figure B-5. Mass flux (kg/day) as a function of time (days) in each vadose zone-aquifer interface grid cell for a source mass placed in grid bock (5,6) of the Operable Unit 3-13 model.

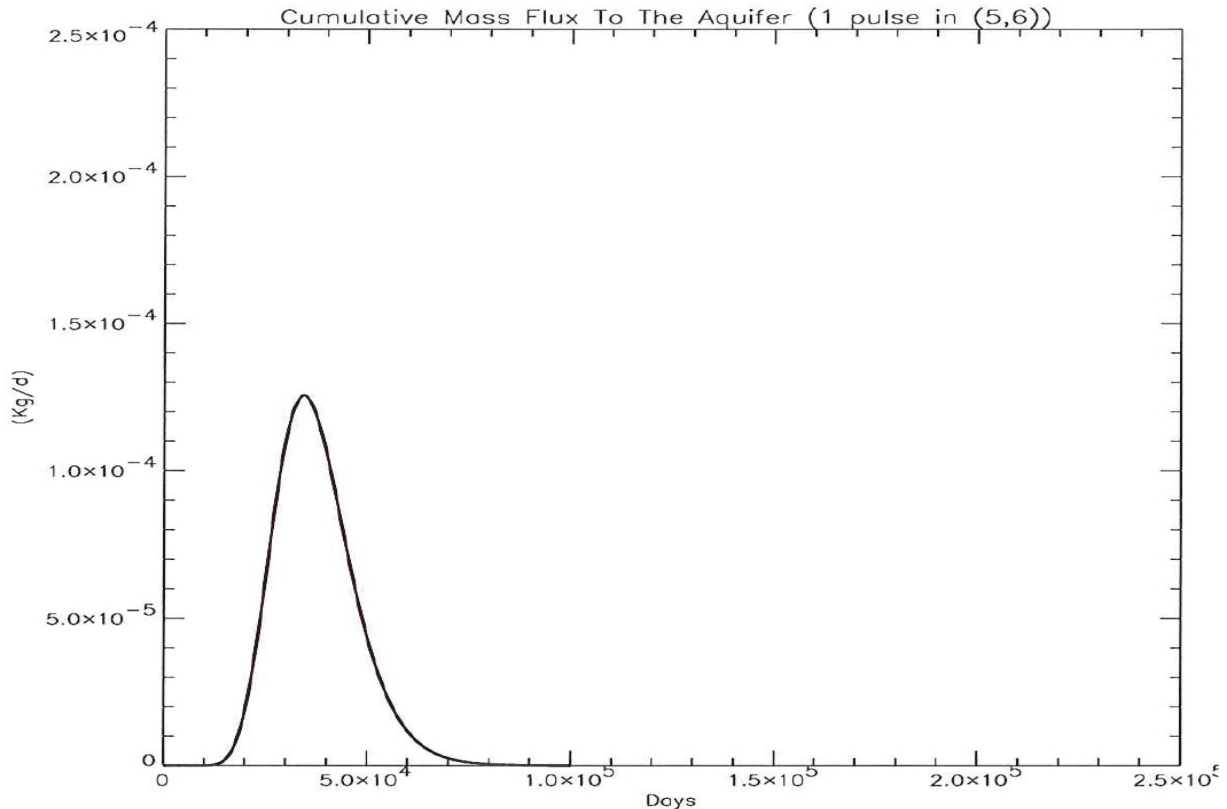


Figure B-6. Sum of the mass fluxes at the vadose zone-aquifer interface for the source mass placed in grid block (6,5) of the Operable Unit 3-13 model.

When mass is placed into grid block (5,6), variability between the mass flux curves (response functions) for the various grid blocks (Figure B-5) is less than for a source placed in grid block (6,5) (Figure B-3). The majority of the mass flux is from grid block (5,6) and the grid block to the immediate south (5,7). There is slightly less variability in the overall distribution across the response functions (Figure B-5 versus Figure B-3). That is, more of the mass leaving the bottom of the domain is near the grid block where it originated. The physical reason for this is primarily the increased distance from the Big Lost River so that the river has less influence on the horizontal movement of the tracer in the vadose zone. The shape of the individual mass flux curves is relatively uniform. Each could be represented by a single one-dimensional model because none of them exhibit multi-modal behavior indicative of the arrival of multiple flow paths.

The lack of multi-modal behavior is also observed in the total mass flux for this source location (Figure B-6). The time of the peak mass flux (Figure B-6) is later than the time in Figure B-4 because there is less influence from the Big Lost River at grid block (5,6) than at (6,5). The decreased influence of the Big Lost River water also results in the total flux to the aquifer being more spread out over time. This total mass-flux curve could be represented by an analytical solution to a one-dimensional advective dispersive equation.

B-3.3 Impulse Response for a Source in Grid Blok (6,7)

The results of the third simulation, placing the mass in grid block (6,7), are given in Figures B-7 and B-8. Figure B-7 shows the mass flux at the vadose zone-aquifer interface for the same 4-by-5 matrix of grid blocks given in Figures B-3 and B-5.

There is again a decrease in spreading between the mass flux curves among the various grid blocks for a source placed in grid block (6,7), which is further from the river than the other two scenarios. Increased distance from the Big Lost River results in primarily gravity-driven flow and transport. The shape of the individual mass flux curves is relatively uniform. Each could be represented by a single one-dimensional model because none of them exhibit multi-modal behavior indicative of the arrival of multiple flow paths.

The lack of multi-modal behavior is again observed in the total mass flux for this source location (Figure B-8). The time of the peak mass flux (Figure B-8) is again later than the time in Figures B-4 and B-6 because there is less influence from the Big Lost River at grid blocks (5,6) and (6,5) than at (6,7). The decreased influence of the Big Lost River water also results in the total flux to the aquifer being more spread out over time. As with the other two scenarios, this total mass-flux curve could also be represented by an analytical solution to a one-dimensional advective dispersive equation.

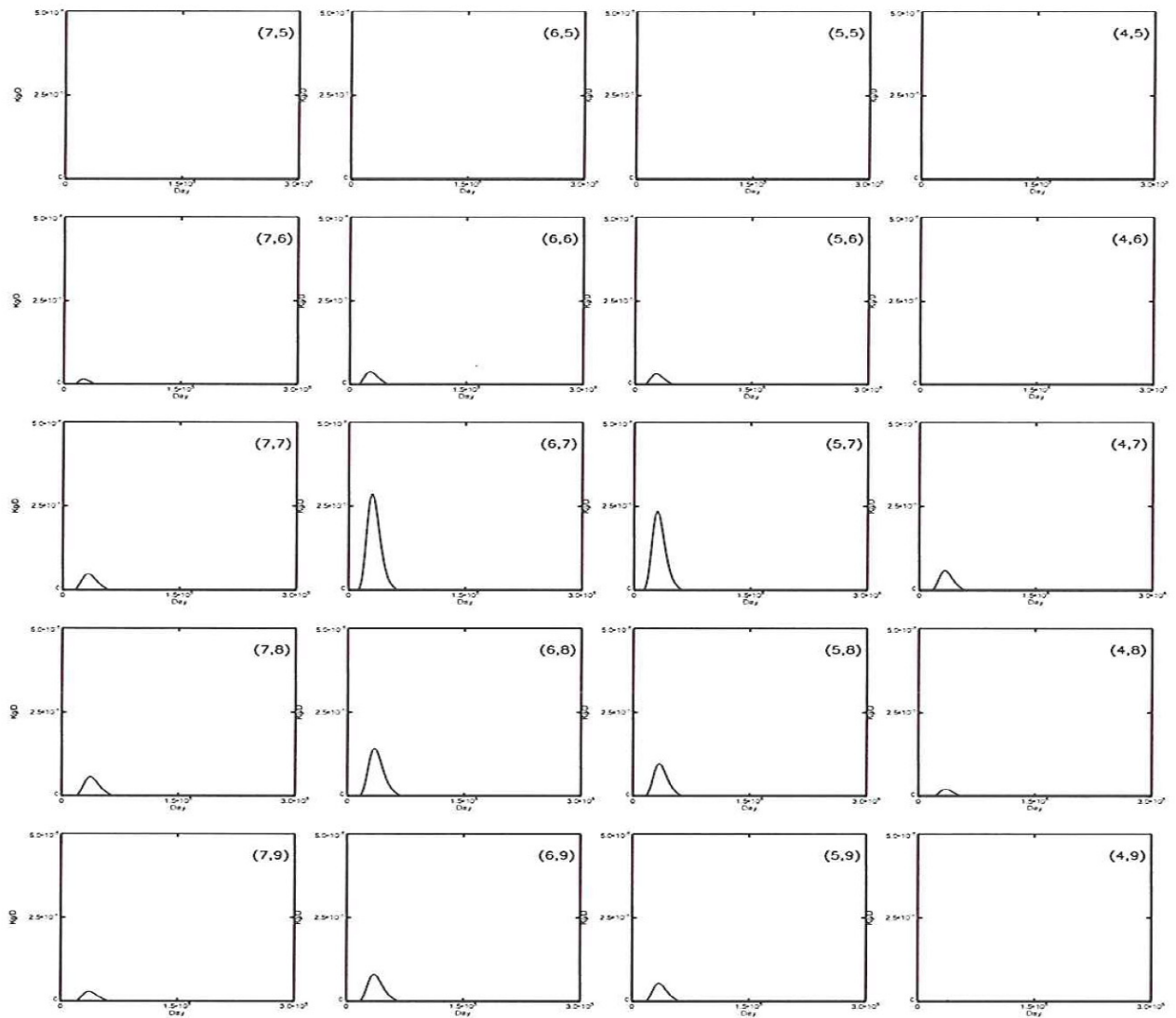


Figure B-7. Mass flux (kg/day) as a function of time (days) in each vadose zone-aquifer interface grid cell for a source mass placed in grid block (6,7) of the Operable Unit 3-13 model.

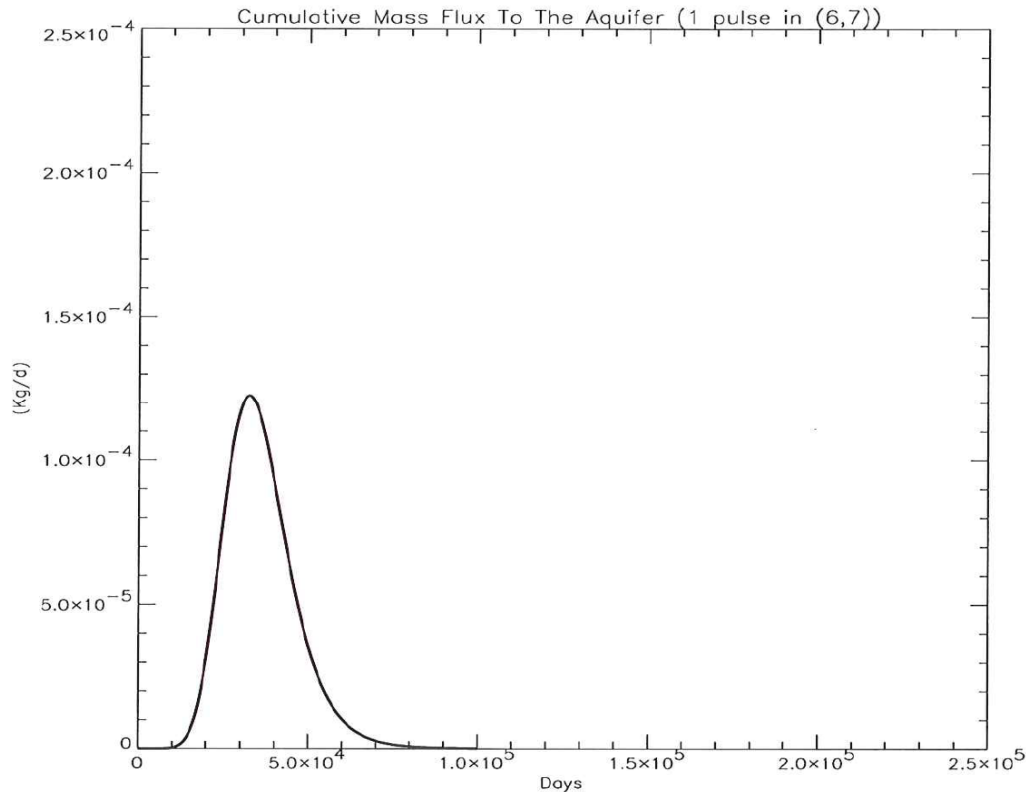


Figure B-8. Sum of the mass fluxes at the vadose zone-aquifer interface for the source mass placed in grid block (6,7) of the Operable Unit 3-13 model.

B-4. SUMMARY

The discussion in Section 2.1 and the information provided in this appendix support the choice for a one-dimensional model to simulate flow and transport in the vadose zone at the ICDF. Lack of current and future anthropogenic water sources in the vicinity of the ICDF results in primarily gravity-dominated unsaturated flow that is essentially vertical. The influence of surface water sources is shown by the graphical assessment of mass-flux as a function of distance from the Big Lost River (Section B-3). The numerical experiments shown in Section B-3 involve placing mass in one grid block that is similar in area to the ICDF area. The numerical experiments show that a one-dimensional model is an appropriate simulator for flow and transport through the vadose zone at the ICDF. The one-dimensional model will not allow the horizontal spreading shown in the three response surface numerical experiments (Figures B-3, B-5, and B-7). Restriction of the horizontal spreading by using a one-dimensional model results in a larger mass flux (conservative simulation) than would result from the use of the three-dimensional model. These results are consistent with the field observations of the response of perched water wells to flow in the Big Lost River (DOE-ID 2006b, 2010a).

Given these findings, one-dimensional flow and transport is a suitable vadose zone representation at the ICDF and sufficient to address the ICDF PA questions. Its simplicity allows for numerous model simulations that are necessary for the uncertainty analysis requirement of the ICDF PA.

B-5. REFERENCES

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Appendix C

Screening Thresholds for 274 Radionuclides Considered in the Performance Assessment Screening Analysis

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Screening Thresholds for 274 Radionuclides Considered in the Performance Assessment Screening Analysis

Screening thresholds for all 274 radionuclides considered in the ICDF PA screening analysis are shown in Table C-1. Table C-2 provides the distribution coefficient (K_d) values used in the calculations for the screening thresholds.

Table C-1. Screening thresholds for 274 radionuclides considered in the performance assessment screening analysis.

Radionuclide	Half-Life (Yr) ^a	Total Inventory 2003–2018 (Ci) ^b	Screening Dose with Unit Inventory (mrem) ^c	Screening Threshold (Ci) ^d	Notes
Ac-225	2.74E-02	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Ac-227	2.18E+01	4.73E-06	0.00E+00	NL	GWSCREEN screening threshold calculation, decays in the disposal facility and vadose zone due to short half-life.
Ac-228	7.02E-04	1.52E-02	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Ag-106	4.56E-05	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Ag-108	4.51E-06	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Ag-108m	4.18E+02	1.47E+00	1.40E-23	NL	GWSCREEN screening threshold calculation, maximum allowable inventory >1E+10 Ci.
Ag-109m	1.25E-06	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Ag-110	7.80E-07	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Ag-110m	6.84E-01	6.44E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Ag-111	2.04E-02	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Al-26	7.17E+05	0.00E+00	3.52E-03	1.1E+02	GWSCREEN screening threshold calculation.
Am-241	4.32E+02	1.89E+00	1.33E+01	1.5E+02	Simulated as Np-237. GWSCREEN screening threshold calculation.
Am-242	1.83E-03	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Am-242m	1.41E+02	2.99E-03	7.97E+00	9.3E+01	Simulated as U-234. GWSCREEN screening threshold calculation.
Am-243	7.37E+03	2.46E-02	3.90E-03	1.0E+02	GWSCREEN screening threshold calculation.
Am-245	2.34E-04	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).

Table C-1. (continued).

Radionuclide	Half-Life (Yr) ^a	Total Inventory 2003–2018 (Ci) ^b	Screening Dose with Unit Inventory (mrem) ^c	Screening Threshold (Ci) ^d	Notes
Am-246	7.42E-05	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Ar-39	2.69E+02	0.00E+00	0.00E+00	NL	Stable - noble gas.
As-76	2.95E-03	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
At-217	1.02E-09	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Ba-133	1.05E+01	3.23E-01	0.00E+00	NL	GWSCREEN screening threshold calculation, decays in the disposal facility and vadose zone due to short half-life.
Ba-136m	9.77E-09	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Ba-137m	4.85E-06	7.17E+03	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Ba-140	3.49E-02	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Be-10	1.51E+06	1.58E+00	1.18E-03	3.4E+02	GWSCREEN screening threshold calculation.
Be-7	1.46E-01	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Bi-207	3.29E+01	0.00E+00	0.00E+00	NL	GWSCREEN screening threshold calculation, decays in the disposal facility and vadose zone due to short half-life.
Bi-210	1.37E-02	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Bi-211	4.07E-06	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Bi-212	1.15E-04	1.20E-02	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Bi-213	8.67E-05	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Bi-214	3.78E-05	1.41E-02	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Bk-249	9.04E-01	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Bk-250	3.67E-04	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
C-14	5.73E+03	1.10E+02	7.94E-02	WAC	Included in PA groundwater pathway base case.
Ca-41	1.03E+05	1.46E-03	1.00E-02	4.0E+01	GWSCREEN screening threshold calculation.
Ca-45	4.45E-01	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Cd-104	1.10E-04	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Cd-109	1.26E+00	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Cd-113	7.70E+15	0.00E+00	1.07E+00	3.7E-01	GWSCREEN screening threshold calculation.
Cd-113m	1.41E+01	0.00E+00	0.00E+00	NL	GWSCREEN screening threshold calculation, decays in the disposal facility and vadose zone due to short half-life.
Cd-115m	1.22E-01	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).

Table C-1. (continued).

Radionuclide	Half-Life (Yr) ^a	Total Inventory 2003–2018 (Ci) ^b	Screening Dose with Unit Inventory (mrem) ^c	Screening Threshold (Ci) ^d	Notes
Ce-134	8.65E-03	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Ce-137	1.03E-03	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Ce-139	3.77E-01	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Ce-141	8.90E-02	4.09E-21	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Ce-142	5.00E+16	0.00E+00	0.00E+00	NL	Stable - long half-life (>5E+16 yr).
Ce-144	7.80E-01	1.08E-01	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Cf-249	3.51E+02	3.88E-04	1.33E+01	1.8E+02	Simulated as Np-237. GWSCREEN screening threshold calculation.
Cf-250	1.31E+01	3.91E-03	4.53E-01	8.8E-01	GWSCREEN screening threshold calculation.
Cf-251	8.98E+02	7.60E-05	3.96E-01	2.7E+01	Simulated as Pu-239. GWSCREEN screening threshold calculation.
Cf-252	2.65E+00	2.06E-03	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Cl-36	3.01E+05	7.19E-01	1.21E+00	WAC	Included in PA groundwater pathway base case.
Cm-241	8.98E-02	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Cm-242	4.46E-01	4.01E-03	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Cm-243	2.91E+01	2.84E-02	3.96E-01	8.4E+02	Simulated as Pu-239. GWSCREEN screening threshold calculation.
Cm-244	1.81E+01	1.43E+00	2.30E-01	6.3E+02	Simulated as Pu-240. GWSCREEN screening threshold calculation.
Cm-245	8.50E+03	7.67E-04	1.33E+01	7.6E+00	Simulated as Np-237. GWSCREEN screening threshold calculation.
Cm-246	4.76E+03	1.02E-02	4.53E-01	6.9E+01	Simulated as Pu-242. GWSCREEN screening threshold calculation.
Cm-247	1.56E+07	9.84E-06	4.37E-01	1.6E-03	Simulated as Pu-239. GWSCREEN screening threshold calculation.
Cm-248	3.48E+05	2.71E-03	2.05E-02	2.0E+01	GWSCREEN screening threshold calculation.
Cm-250	9.70E+03	2.65E-12	0.00E+00	NL	GWSCREEN screening threshold calculation. No dose due to high K _d (4,000 mL/g).
Co-57	7.44E-01	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Co-58	1.94E-01	1.28E-02	—	NL	Screened in Phase I screening analysis (half-life <5 yr).

Table C-1. (continued).

Radionuclide	Half-Life (Yr) ^a	Total Inventory 2003–2018 (Ci) ^b	Screening Dose with Unit Inventory (mrem) ^c	Screening Threshold (Ci) ^d	Notes
Co-60	5.27E+00	1.69E+04	0.00E+00	NL	GWSCREEN screening threshold calculation, decays in the disposal facility and vadose zone due to short half-life.
Cr-51	7.58E-02	4.61E-01	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Cs-132	1.77E-02	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Cs-134	2.07E+00	2.30E-01	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Cs-135	2.30E+06	9.51E-07	1.07E-02	3.7E+01	GWSCREEN screening threshold calculation.
Cs-136	3.60E-02	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Cs-137	3.01E+01	8.32E+03	0.00E+00	NL	GWSCREEN screening threshold calculation, decays in the disposal facility and vadose zone due to relatively short half-life.
Cs-144	3.20E-08	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Er-169	2.57E-02	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Eu-150	3.69E+01	0.00E+00	0.00E+00	NL	GWSCREEN screening threshold calculation, decays in the disposal facility and vadose zone due to short half-life.
Eu-152	1.35E+01	2.24E+02	0.00E+00	NL	GWSCREEN screening threshold calculation, decays in the disposal facility and vadose zone due to short half-life.
Eu-154	8.59E+00	1.68E+02	0.00E+00	NL	GWSCREEN screening threshold calculation, decays in the disposal facility and vadose zone due to short half-life.
Eu-155	4.76E+00	2.03E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Eu-156	4.16E-02	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Fe-55	2.74E+00	1.73E+03	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Fe-59	1.22E-01	3.31E-15	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Fr-221	9.32E-06	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Fr-223	4.18E-05	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Gd-152	1.08E+14	0.00E+00	4.57E-02	8.8E+00	GWSCREEN screening threshold calculation.
Gd-153	6.58E-01	1.56E-04	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
H-3	1.23E+01	1.25E+05	1.42E-03	WAC	Included in PA groundwater pathway base case.
Hf-175	1.92E-01	2.25E-14	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Hf-178m	1.27E-07	1.05E-01	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Hf-181	1.16E-01	3.72E-16	—	NL	Screened in Phase I screening analysis (half-life <5 yr).

Table C-1. (continued).

Radionuclide	Half-Life (Yr) ^a	Total Inventory 2003–2018 (Ci) ^b	Screening Dose with Unit Inventory (mrem) ^c	Screening Threshold (Ci) ^d	Notes
Hg-203	1.28E-01	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Ho-166m	1.20E+03	3.63E-02	2.10E-23	NL	GWSCREEN screening threshold calculation, maximum allowable inventory >1E+10 Ci.
I-124	1.14E-02	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
I-125	1.63E-01	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
I-129	1.57E+07	1.50E-01	1.39E+02	WAC	Included in PA groundwater pathway base case.
I-131	2.20E-02	9.82E-04	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
I-132	2.62E-04	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
I-133	2.37E-03	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
In-113m	1.89E-04	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
In-114	2.28E-06	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
In-114m	1.36E-01	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
In-115	4.41E+14	0.00E+00	2.25E-02	1.8E+01	GWSCREEN screening threshold calculation.
In-115m	5.12E-04	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
In-119m	3.42E-05	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Ir-192	2.02E-01	1.34E-09	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
K-40	1.27E+09	9.68E-01	1.11E-01	3.6E+00	GWSCREEN screening threshold calculation.
Kr-81	2.29E+05	0.00E+00	0.00E+00	NL	No DCF - noble gas.
Kr-85	1.08E+01	2.62E-04	0.00E+00	NL	No DCF - noble gas.
Kr-95	2.47E-08	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
La-138	1.05E+11	0.00E+00	2.44E-04	1.6E+03	GWSCREEN screening threshold calculation.
La-140	4.59E-03	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Mn-53	3.74E+06	8.41E-04	1.60E-04	2.5E+03	GWSCREEN screening threshold calculation.
Mn-54	8.55E-01	9.93E-01	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Mo-93	4.00E+03	1.34E-01	4.90E-02	8.2E+00	GWSCREEN screening threshold calculation.
Mo-99	7.52E-03	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Na-22	2.60E+00	8.14E-05	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Na-24	1.71E-03	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).

Table C-1. (continued).

Radionuclide	Half-Life (Yr) ^a	Total Inventory 2003–2018 (Ci) ^b	Screening Dose with Unit Inventory (mrem) ^c	Screening Threshold (Ci) ^d	Notes
Na-25	1.87E-06	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Nb-92	3.47E+07	0.00E+00	0.00E+00	NL	No DCF - x-ray emitter decays to stable isotope.
Nb-92m	2.78E-02	2.44E-07	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Nb-93m	1.61E+01	5.55E-04	0.00E+00	NL	GWSCREEN screening threshold calculation, decays in the disposal facility and vadose zone due to short half-life.
Nb-94	2.03E+04	1.26E+01	1.57E-03	2.5E+02	GWSCREEN screening threshold calculation.
Nb-95	9.58E-02	4.11E-03	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Nb-95m	9.88E-03	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Nd-144	2.29E+15	0.00E+00	0.00E+00	NL	No DCF - stable, long half-life.
Nd-147	3.01E-02	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Ni-59	7.60E+04	5.89E+02	1.25E-04	3.2E+03	GWSCREEN screening threshold calculation.
Ni-63	1.00E+02	1.03E+05	0.00E+00	NL	GWSCREEN screening threshold calculation, decays in the disposal facility and vadose zone due to combination of relatively short half-life and high K_d .
Np-235	1.08E+00	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Np-236	1.54E+05	0.00E+00	2.87E+01	1.4E-02	GWSCREEN screening threshold calculation.
Np-237	2.14E+06	7.68E-02	1.33E+01	WAC	Included in PA groundwater pathway base case.
Np-238	5.80E-03	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Np-239	6.45E-03	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Np-240	1.18E-04	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Np-240m	1.37E-05	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Os-194	6.00E+00	0.00E+00	0.00E+00	NL	GWSCREEN screening threshold calculation, decays in the disposal facility and vadose zone due to short half-life.
P-32	3.90E-02	9.03E-49	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Pa-231	3.28E+04	6.81E-06	9.79E-03	4.1E+01	GWSCREEN screening threshold calculation.
Pa-233	7.38E-02	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Pa-234	7.64E-04	3.27E-07	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Pa-234m	2.22E-06	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Pb-205	1.53E+07	4.15E-07	7.29E-04	5.5E+02	GWSCREEN screening threshold calculation.

Table C-1. (continued).

Radionuclide	Half-Life (Yr) ^a	Total Inventory 2003–2018 (Ci) ^b	Screening Dose with Unit Inventory (mrem) ^c	Screening Threshold (Ci) ^d	Notes
Pb-209	3.71E-04	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Pb-210	2.23E+01	2.42E-02	0.00E+00	NL	GWSCREEN screening threshold calculation, decays in the disposal facility and vadose zone due to short half-life.
Pb-211	6.86E-05	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Pb-212	1.21E-03	1.38E-02	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Pb-214	5.10E-05	1.52E-02	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Pd-107	6.50E+06	0.00E+00	1.85E-04	2.2E+03	GWSCREEN screening threshold calculation.
Pm-145	1.77E+01	2.10E-04	0.00E+00	NL	GWSCREEN screening threshold calculation, decays in the disposal facility and vadose zone due to short half-life.
Pm-146	5.53E+00	0.00E+00	0.00E+00	NL	GWSCREEN screening threshold calculation, decays in the disposal facility and vadose zone due to short half-life.
Pm-147	2.62E+00	4.10E+03	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Pm-148	1.47E-02	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Pm-148m	1.13E-01	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Po-210	3.79E-01	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Po-211	1.64E-08	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Po-212	9.47E-15	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Po-213	1.16E-13	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Po-214	5.21E-12	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Po-215	5.64E-14	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Po-216	4.60E-09	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Po-218	5.89E-06	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Pr-142	2.18E-03	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Pr-143	3.72E-02	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Pr-144	3.29E-05	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Pr-144m	1.37E-05	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Pu-236	2.86E+00	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Pu-237	1.24E-01	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).

Table C-1. (continued).

Radionuclide	Half-Life (Yr) ^a	Total Inventory 2003–2018 (Ci) ^b	Screening Dose with Unit Inventory (mrem) ^c	Screening Threshold (Ci) ^d	Notes
Pu-238	8.77E+01	1.89E+01	7.52E+00	1.5E+02	Simulated as U-234. GWSCREEN screening threshold calculation.
Pu-239	2.41E+04	1.93E+01	3.96E-01	WAC	Included in PA groundwater pathway base case.
Pu-240	6.56E+03	1.04E+01	2.30E-01	WAC	Included in PA groundwater pathway base case.
Pu-241	1.43E+01	2.95E+01	1.33E+01	4.5E+03	Simulated as Np-237. GWSCREEN screening threshold calculation.
Pu-242	3.73E+05	6.40E-04	4.53E-01	8.8E-01	GWSCREEN screening threshold calculation.
Pu-243	5.65E-04	1.97E-06	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Pu-244	8.00E+07	6.25E-09	1.98E+00	2.0E-01	GWSCREEN screening threshold calculation.
Pu-246	6.74E-01	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Ra-222	7.04E-06	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Ra-223	3.13E-02	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Ra-224	1.00E-02	1.80E-07	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Ra-225	4.08E-02	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Ra-226	1.60E+03	1.01E+00	2.60E-06	1.5E+05	GWSCREEN screening threshold calculation.
Ra-228	5.75E+00	1.45E-03	0.00E+00	NL	GWSCREEN screening threshold calculation, decays in the disposal facility and vadose zone due to short half-life.
Rb-86	5.10E-02	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Rb-87	4.75E+10	0.00E+00	7.28E-03	5.5E+01	GWSCREEN screening threshold calculation.
Re-186	1.02E-02	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Re-187	4.35E+10	0.00E+00	1.36E-04	2.9E+03	GWSCREEN screening threshold calculation.
Re-188	1.94E-03	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Rh-102	5.67E-01	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Rh-103m	1.07E-04	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Rh-105	4.03E-03	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Rh-106	9.44E-07	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Rn-218	6.91E-09	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Rn-219	1.25E-07	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Rn-220	1.76E-06	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).

Table C-1. (continued).

Radionuclide	Half-Life (Yr) ^a	Total Inventory 2003–2018 (Ci) ^b	Screening Dose with Unit Inventory (mrem) ^c	Screening Threshold (Ci) ^d	Notes
Rn-222	1.05E-02	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Ru-103	1.07E-01	6.06E-05	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Ru-105	5.07E-04	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Ru-106	1.02E+00	2.68E-01	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
S-35	2.40E-01	2.89E-08	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Sb-122	7.46E-03	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Sb-124	1.65E-01	8.15E-11	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Sb-125	2.76E+00	5.19E-01	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Sb-126	3.41E-02	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Sb-126m	3.64E-05	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Sc-44	4.53E-04	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Sc-46	2.29E-01	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Se-75	3.28E-01	8.24E-06	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Se-79	1.10E+06	1.70E-04	1.91E-01	2.1E+00	GWSCREEN screening threshold calculation.
Si-32	1.72E+02	1.55E-11	1.05E-22	NL	GWSCREEN screening threshold calculation, maximum allowable inventory >1E+10 Ci.
Sm-145	9.31E-01	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Sm-146	1.03E+08	5.24E-11	6.08E-02	6.6E+00	GWSCREEN screening threshold calculation.
Sm-147	1.06E+11	0.00E+00	5.48E-02	7.3E+00	GWSCREEN screening threshold calculation.
Sm-148	7.00E+15	0.00E+00	0.00E+00	NL	No DCF - stable, long half-life.
Sm-149	2.00E+15	0.00E+00	0.00E+00	NL	No DCF - stable.
Sm-151	9.00E+01	2.15E-01	0.00E+00	NL	GWSCREEN screening threshold calculation, decays in the disposal facility and vadose zone due to combination of relatively short half-life and high K _d .
Sn-113	3.15E-01	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Sn-117m	3.72E-02	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Sn-119m	8.02E-01	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).

Table C-1. (continued).

Radionuclide	Half-Life (Yr) ^a	Total Inventory 2003–2018 (Ci) ^b	Screening Dose with Unit Inventory (mrem) ^c	Screening Threshold (Ci) ^d	Notes
Sn-121m	5.50E+01	1.06E-03	0.00E+00	NL	GWSCREEN screening threshold calculation, decays in the disposal facility and vadose zone due to combination of relatively short half-life and high K_d .
Sn-123	3.54E-01	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Sn-125	2.64E-02	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Sn-126	1.00E+05	0.00E+00	7.58E-03	5.3E+01	GWSCREEN screening threshold calculation.
Sr-85	1.78E-01	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Sr-89	1.38E-01	6.80E-16	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Sr-90	2.88E+01	1.90E+03	1.78E-41	NL	GWSCREEN screening threshold calculation, maximum allowable inventory >1E+10 Ci.
Ta-182	3.13E-01	1.72E-10	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Tb-158	1.80E+02	6.45E-04	0.00E+00	NL	GWSCREEN screening threshold calculation, decays in the disposal facility and vadose zone due to combination of relatively short half-life and large K_d .
Tb-160	1.98E-01	1.55E-12	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Tb-161	1.88E-02	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Tc-98	4.20E+06	0.00E+00	2.61E+00	1.5E-01	GWSCREEN screening threshold calculation.
Tc-99	2.11E+05	6.59E-01	8.57E-01	WAC	Included in PA groundwater pathway base case.
Te-123	6.00E+14	0.00E+00	9.34E-03	4.3E+01	GWSCREEN screening threshold calculation.
Te-123m	3.28E-01	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Te-125m	1.57E-01	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Te-127	1.07E-03	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Te-127m	2.98E-01	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Te-129	1.32E-04	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Te-129m	9.20E-02	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Th-226	5.81E-05	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Th-227	5.13E-02	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Th-228	1.91E+00	9.87E-02	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Th-229	7.34E+03	5.64E-06	6.79E-02	5.9E+00	GWSCREEN screening threshold calculation.

Table C-1. (continued).

Radionuclide	Half-Life (Yr) ^a	Total Inventory 2003–2018 (Ci) ^b	Screening Dose with Unit Inventory (mrem) ^c	Screening Threshold (Ci) ^d	Notes
Th-230	7.54E+04	1.04E-01	2.43E+00	1.6E-01	GWSCREEN screening threshold calculation.
Th-231	2.91E-03	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Th-232	1.41E+10	9.33E-02	2.71E+00	1.5E-01	GWSCREEN screening threshold calculation.
Th-234	6.60E-02	8.93E-03	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Tl-204	3.78E+00	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Tl-207	9.07E-06	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Tl-208	5.80E-06	3.89E-03	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Tl-209	4.11E-06	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Tm-170	3.53E-01	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Tm-171	1.92E+00	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
U-228	1.73E-05	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
U-230	5.69E-02	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
U-232	6.89E+01	7.12E-04	2.11E-01	1.9E+00	GWSCREEN screening threshold calculation.
U-233	1.59E+05	1.19E-01	1.16E+01	WAC	Included in PA groundwater pathway base case.
U-234	2.46E+05	6.91E-01	7.52E+00	WAC	Included in PA groundwater pathway base case.
U-235	7.04E+08	1.55E-01	8.28E+00	WAC	Included in PA groundwater pathway base case.
U-236	2.34E+07	3.94E-03	6.88E+00	5.8E-02	GWSCREEN screening threshold calculation.
U-237	1.85E-02	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
U-238	4.47E+09	4.97E-01	6.49E+00	WAC	Included in PA groundwater pathway base case.
U-239	4.46E-05	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
U-240	1.61E-03	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Xe-127	9.97E-02	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Xe-129m	2.43E-02	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Xe-131m	3.27E-02	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Xe-133	1.44E-02	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
V-49	9.04E-01	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
W-185	2.06E-01	4.57E-09	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
W-187	2.71E-03	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).

Table C-1. (continued).

Radionuclide	Half-Life (Yr) ^a	Total Inventory 2003–2018 (Ci) ^b	Screening Dose with Unit Inventory (mrem) ^c	Screening Threshold (Ci) ^d	Notes
Y-88	2.92E-01	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Y-90	7.30E-03	1.63E+03	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Y-91	1.60E-01	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Zn-65	6.69E-01	1.30E-02	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Zr-88	2.28E-01	0.00E+00	—	NL	Screened in Phase I screening analysis (half-life <5 yr).
Zr-93	1.53E+06	1.05E-05	4.58E-04	8.7E+02	GWSCREEN screening threshold calculation.
Zr-95	1.75E-01	2.01E-03	—	NL	Screened in Phase I screening analysis (half-life <5 yr).

a. Radionuclide half-lives obtained from the Integrated Waste Tracking System database with its data source the National Nuclear Data Center, Brookhaven Laboratory.

b. From Table 4, EDF-9463.

c. Modified from Table 2-10 of this report. Maximum screening dose with unit inventory is equal to maximum screening dose reported in Table 2-10 of this report divided by the total inventory. Listed as “—” if radionuclide half-life is less than 5 years.

d. Screening threshold calculation conducted if half-life greater than 5 years.

DCF dose conversion factor
NL no limit
PA performance assessment
WAC waste acceptance criteria

Table C-2. Distribution coefficient (K_d) values used for screening calculations.

Element Name	Symbol	K_d Unsaturated			Reference
		K_d Source (mL/g) ^a	Zone (mL/g) ^b	K_d Aquifer (mL/g) ^c	
Actinium	Ac	450	450	0	Jenkins (2001)
Aluminum	Al	250	250	0	Jenkins (2001)
Americium ^d	Am	340	340	0	Jenkins (2001)
Argon	Ar	0	0	0	Jenkins (2001)
Barium	Ba	50	50	0	Jenkins (2001)
Beryllium	Be	250	250	0	Jenkins (2001)
Bismuth	Bi	100	100	0	Jenkins (2001)
Cadmium	Cd	6	6	0	Jenkins (2001)
Calcium	Ca	5	5	0	Jenkins (2001)
Californium	Cf	510	510	0	Jenkins (2001)
Carbon ^d	C	1.6	1.6	0	Cahn et al. (2006)
Cerium	Ce	500	500	0	Jenkins (2001)
Cesium ^d	Cs	50	50	0	Cahn et al. (2006)
Chlorine	Cl	0	0	0	Jenkins (2001)
Cobalt	Co	10	10	0	Jenkins (2001)
Curium	Cm	4,000	4,000	0	Jenkins (2001)
Europium ^d	Eu	340	340	0	Jenkins (2001)
Gadolinium	Gd	240	240	0	Jenkins (2001)
Holmium	Ho	250	250	0	Jenkins (2001)
Hydrogen ^d	H	0	0	0	Jenkins (2001)
Indium	In	390	390	0	Jenkins (2001)
Iodine ^d	I	0	0	0	Jenkins (2001)
Krypton	Kr	0	0	0	Jenkins (2001)
Lanthanum	La	1,200	1,200	0	Jenkins (2001)
Lead	Pb	100	100	0	Jenkins (2001)
Manganese	Mn	50	50	0	Jenkins (2001)
Molybdenum	Mo	10	10	0	Jenkins (2001)
Neodymium	Nd	240	240	0	Jenkins (2001)
Neptunium ^d	Np	2	2	0	Cahn et al. (2006)
Nickel	Ni	100	100	0	Jenkins (2001)
Niobium	Nb	100	100	0	Jenkins (2001)
Osmium	Os	190	190	0	Jenkins (2001)
Palladium	Pd	55	55	0	Jenkins (2001)
Plutonium ^d	Pu	140	22	0	Jenkins (2001)
Potassium	K	15	15	0	Jenkins (2001)

Table C-2. (continued).

Element Name	Symbol	K _d Unsaturated			Reference
		K _d Source (mL/g) ^a	Zone (mL/g) ^b	K _d Aquifer (mL/g) ^c	
Promethium	Pm	240	240	0	Jenkins (2001)
Protactinium	Pa	550	550	0	Jenkins (2001)
Radium	Ra	100	100	0	Jenkins (2001)
Rubidium	Rb	55	55	0	Jenkins (2001)
Rhenium	Re	10	10	0	Jenkins (2001)
Samarium	Sm	240	240	0	Jenkins (2001)
Selenium	Se	4	4	0	Jenkins (2001)
Silicon	Si	35	35	0	Jenkins (2001)
Silver	Ag	90	90	0	Jenkins (2001)
Strontium ^d	Sr	12	12	0	Jenkins (2001)
Technetium ^d	Tc	0	0	0	Cahn et al. (2006)
Tellurium	Te	125	125	0	Jenkins (2001)
Terbium	Tb	240	240	0	Jenkins (2001)
Thorium	Th	100	100	0	Jenkins (2001)
Tin	Sn	130	130	0	Jenkins (2001)
Uranium ^d	U	1.6	1.6	0	Cahn et al. (2006)
Zirconium ^d	Zr	600	600	0	Jenkins (2001)

a. Waste soil designation from Jenkins (2001) unless otherwise noted.

b. Interbed designation from Jenkins (2001) unless otherwise noted.

c. Basalt K_d in aquifer assumed to be zero.

d. Radionuclide listed in both Jenkins (2001) and Cahn et al. (2006). For screening, assumed the most conservative value (i.e., smallest K_d between the two reports).