# RCRA Closure Analysis of Tank Waste Residuals Impacts at Waste Management Area C, Hanford Site, Washington

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Abstract: This document provides the Resource Conservation and Recovery Act of 1976 (RCRA) Closure Analysis of hazardous chemical and dangerous waste constituent impacts from tank waste residuals left in Waste Management Area C tanks and ancillary equipment at closure. The RCRA Closure Analysis is required by the State of Washington for closing U.S. Department of Energy-operated facilities that will manage hazardous chemical and dangerous waste generated during departmental activities as low-level waste. The fundamental objective of this RCRA Closure Analysis is to support the closure of tanks and ancillary equipment within Waste Management Area C that will contain residual levels of hazardous chemical and dangerous wastes left at closure.

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APPROVED
By Lana Perry at 12:06 pm, Oct 04, 2016

Release Approval Date

DATE:
Oct 04, 2016
HANFORD RELEASE

Release Stamp

Approved For Public Release

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**To:** ^Information Clearance
**Cc:** Thursby, Christopher Y
**Subject:** RE: RPP-ENV-58806 Ready to Review
**Date:** Thursday, September 15, 2016 8:18:53 AM

Lana,
I have reviewed the photos and drawing contained in the documents that make up *" RPP-ENV-58806",* as requested, from an industrial safety point of view. Based on that review the documents that make up*"RPP-ENV-58806"* are **approved** for Public Release. Any question or comment, please ask.

Hugh Lawrence
WRPS Safety Programs

---

**From:** ^Information Clearance
**Sent:** Wednesday, September 14, 2016 3:03 PM
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**Cc:** Mesford, Timothy B <Timothy_B_Mesford@rl.gov>; Perry, Lana R <Lana_R_Perry@rl.gov>
**Subject:** RPP-ENV-58806 Ready to Review

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Good afternoon Hugh,

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In my haste to get this workflow initiated, I failed to include you on the required approvals. I recognized my error as I was finishing up the clearance process this morning.

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Thank you, Lana Perry
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**Cc:** ^Information Clearance <InformationClearance@rl.gov>
**Subject:** FW: RPP-ENV-58806 Ready to Review

Good afternoon,

Please approve RCRA Closure Analysis of Tank Waste Residuals Impacts at Waste Management Area C, Hanford Site, Washington, submitted by Tim Mesford for public release.

The Manager needs to approve first from IDMS, Personal and Assignments, before it will route to the WRPS Legal and External Affairs Reviewers. (Please note that only one person from the External Affairs and Legal User Groups can claim the task for review of the subject document.) After their reviews, the workflow will return to the owner/requestor for any comment incorporation and to Send On to the ORP Reviewer(s).

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RPP-ENV-58806 has been submitted in CDM and is ready for your review.

RPP-ENV-58806 can be found in the following folder:

**RPP-ENV-58806**
**Revision 0**

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| Rev. 0 | 30-Sep-2016 | S. Mehta et. al | Updates to Draft B in response to review comments provided by DOE-HQ through the Low-Level waste disposal facility Federal Review Group (LFRG) on companion document RPP-ENV-58782 and additional comments from WRPS. |

# EXECUTIVE SUMMARY

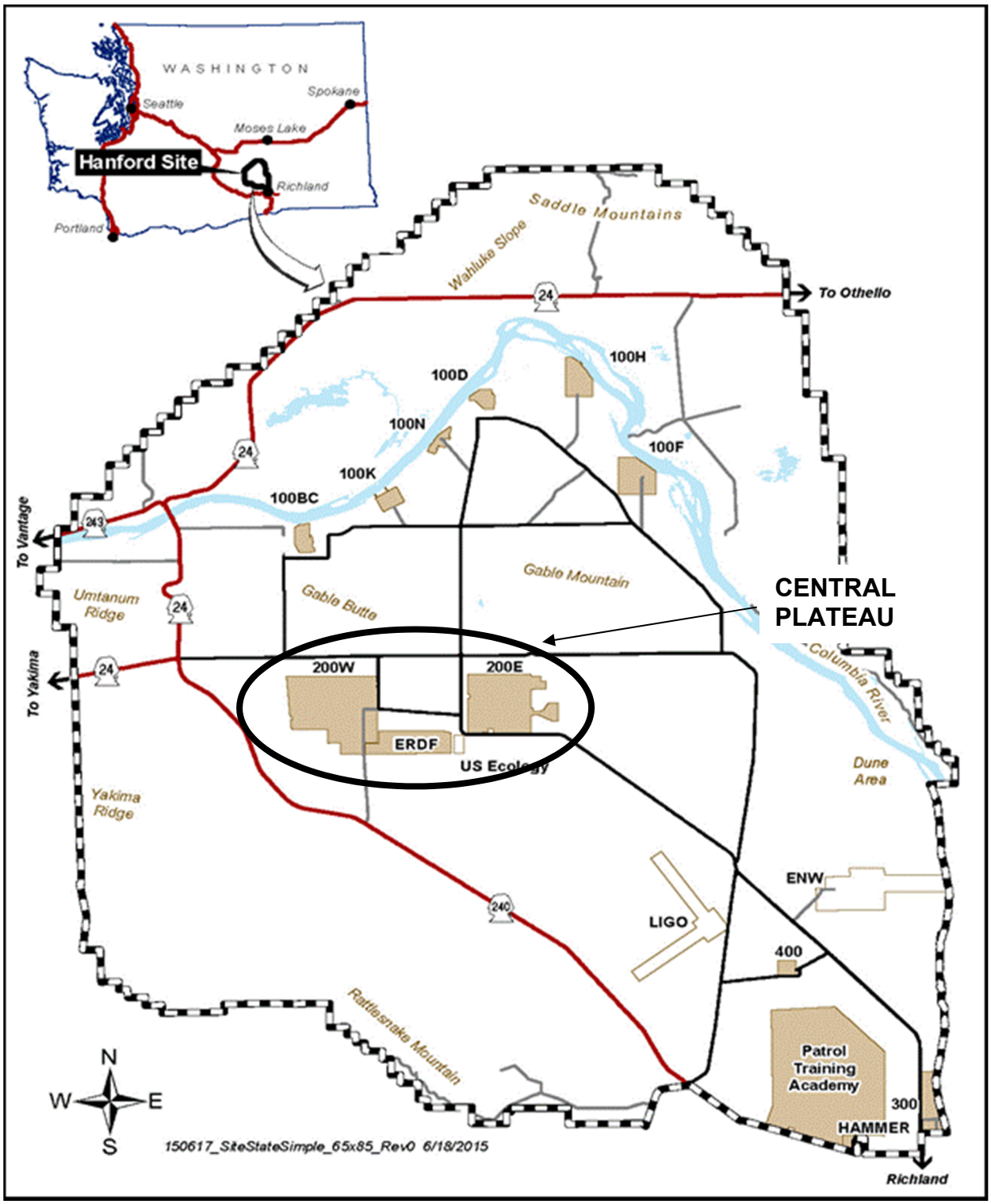
The U.S. Department of Energy, Office of River Protection (DOE-ORP) is pursuing closure on the single-shell tank (SST) Waste Management Area (WMA) C under Federal requirements and forthcoming State-approved closure plans and permits in accordance with the Hanford Federal Facility Agreement and Consent Order (HFFACO) (Ecology et al. 1989), Action Plan, Appendix I. Waste Management Area C is located in the 200 East Area of the Central Plateau at the Hanford Site in southcentral Washington (Figure ES-1) and is one of 12 tank farms grouped into 7 WMAs (A-AX, B-BX-BY, C, S-SX, T, TX-TY, and U) containing 149 SSTs and ancillary equipment built from 1943 to 1964 (see Figure ES-2).

This document provides the Resource Conservation and Recovery Act of 1976 (RCRA) Closure Analysis (RCA) of hazardous chemical and dangerous waste constituent impacts from tank waste residuals left in WMA C tanks and ancillary equipment at closure. The RCA is required by the State of Washington for closing U.S. Department of Energy (DOE)-operated facilities that will manage hazardous chemical and dangerous waste generated during departmental activities as low-level waste. The fundamental objective of this RCA is to support the closure of tanks and ancillary equipment within WMA C that will contain residual levels of hazardous chemical and dangerous wastes left at closure.

Waste Management Area C is located in the east central portion of the 200 East Area in land that is designated to be Industrial-Exclusive. In general, the WMA C boundary is represented by the fenceline surrounding the 241-C Tank Farm (C Farm) (Figure ES-3). The WMA C facility contains twelve 100-series tanks and four 200-series tanks (see Figure ES-3). The 100-series tanks are 23 m (75 ft) in diameter, with a maximum 5-m (16-ft) depth and 2,006,000-L (530,000-gal) design capacity. The 200-series tanks are 6 m (20 ft) in diameter with a maximum 7-m (24-ft) depth and 208,000-L (55,000-gal) design capacity. The tanks sit below grade with at least 2 m (7 ft) of soil cover to provide shielding from radiation exposure to operating personnel. Tank pits are located on top of the tanks and provide access to the tanks, pumps, and associated monitoring equipment. To support the transfer and storage of waste within WMA C SSTs, there is a complex waste transfer system of pipelines (transfer lines), diversion boxes, vaults, valve pits, and other miscellaneous structures. These miscellaneous features of the tank farm are referred to in this document by the general term “ancillary equipment and components.”

Closure of the individual SSTs and WMA C in its entirety occurs in three major steps: 1) SST waste retrieval, 2) filling the tanks with grout for stabilization, and 3) surface cover barrier placement. The final state of a tank farm that is considered in the RCA is therefore a set of grouted tanks with associated ancillary equipment containing residual wastes that remain at the end of retrieval, covered by a modified RCRA Subtitle C surface cover, residing in the native geological setting.

**Figure ES-1. Hanford Site and its Location in Washington State.**




ENW = Energy Northwest
ERDF = Environmental Restoration Disposal Facility
HAMMER = Volpentest Hazardous Materials Management and Emergency Response (HAMMER) Federal Training Center
LIGO = Laser Interferometer Gravitational Wave Observatory

**Figure ES-2. Hanford Site Tank Farms.**

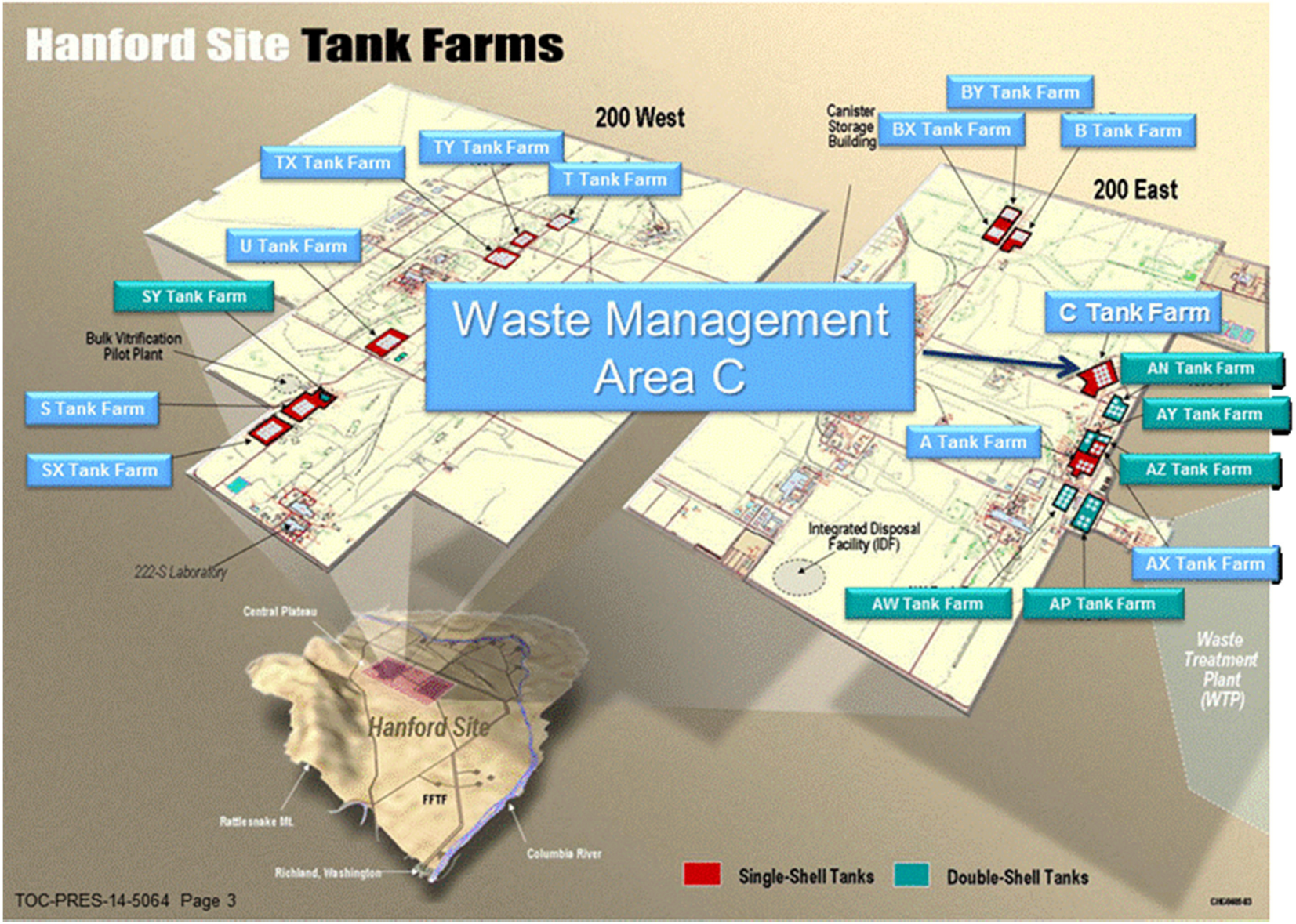
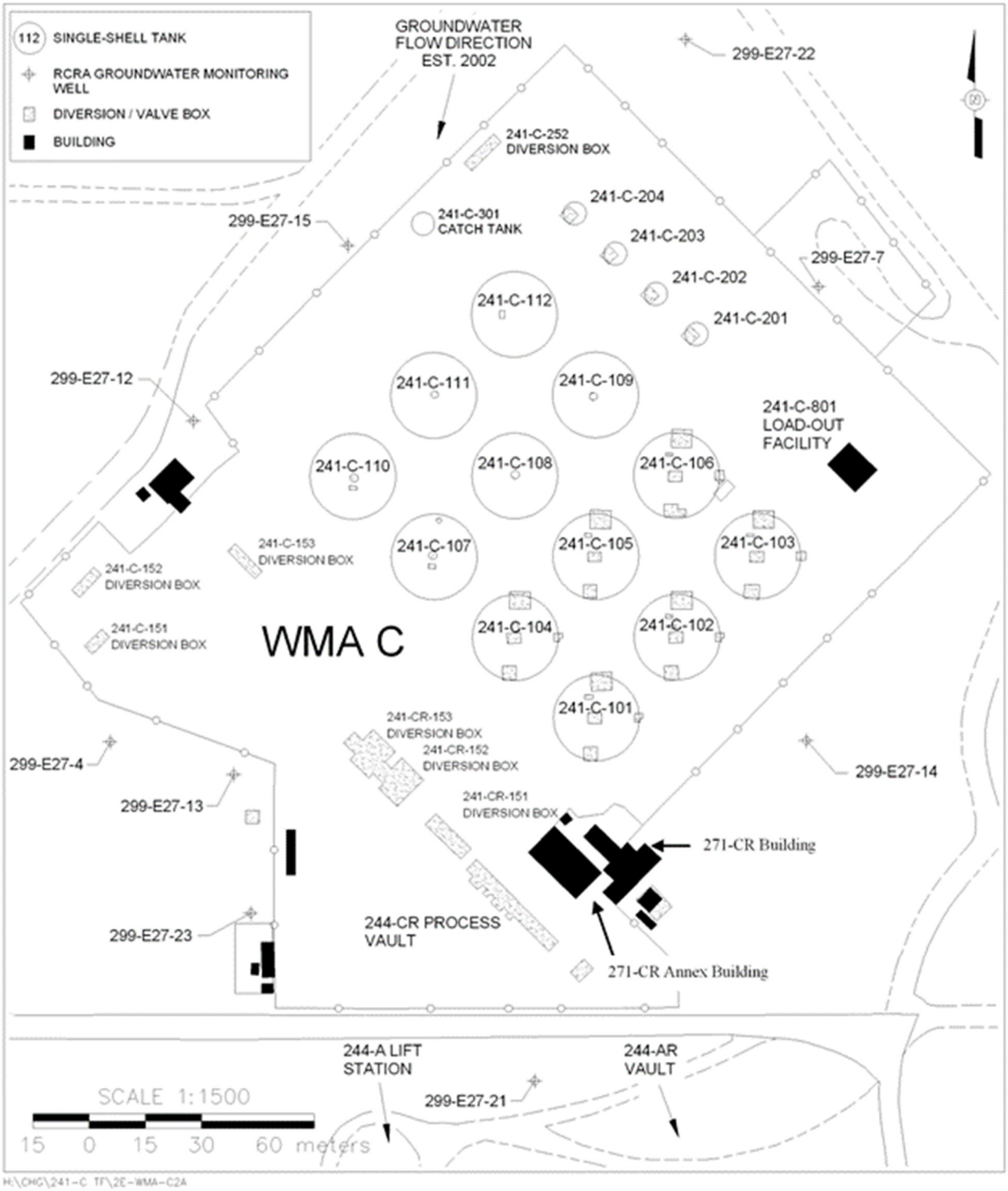


**Figure ES-3. Location of Facilities at Waste Management Area C and Surrounding Area.**




RCRA = Resource Conservation and Recovery Act of 1976 WMA = Waste Management Area

The safety concept for this system is composed of a set of safety functions of manmade as well as natural components that act together to provide the long-term performance of a closed facility required in closure regulations. The safety functions represent multiple and redundant barriers, so that the loss of one or some of the safety functions continues to result in adequate performance of the overall system. A schematic depiction of these safety functions for the closed WMA C is provided in Figure ES-4. The manmade components of the system that influence contaminant migration include a closure surface barrier, grouted tanks, and the distribution of waste in the subsurface tanks and ancillary equipment. The natural components of the system that influence contaminant migration are the several underlying, nearly-horizontal stratigraphic layers within the vadose zone and the unconfined aquifer.

The WMA C RCA has been structured to evaluate the behavior of the closed tank farm under a variety of potential future conditions. An analysis case has been defined in which the safety functions evolve in an expected manner without unusual behavior or unanticipated disruption: this is termed the "base case." The base case is the main analysis used to compare against the performance objectives, but is not the sole analysis for such comparisons. In addition, a set of deterministic sensitivity analyses have been conducted that show the effects when the safety functions are degraded compared to their expected behavior as defined in the base case. The specific safety functions examined in this way relate to the various physical components of the disposal system that included model evaluations of groundwater impacts with the following:

- Higher than expected infiltration rates; these may be the result of a number of potential effects, ranging from unexpectedly poor performance of the cover, through changes in land use with irrigation on top of the facility

- Changes in the effectiveness of the tanks and infill grout to act as barriers, by assuming that the hydraulic conductivity of the tanks increases at times earlier than expected

- Changes in the leachability of the residual wastes, by assuming that the material would dissolve instantly and completely upon contact with water

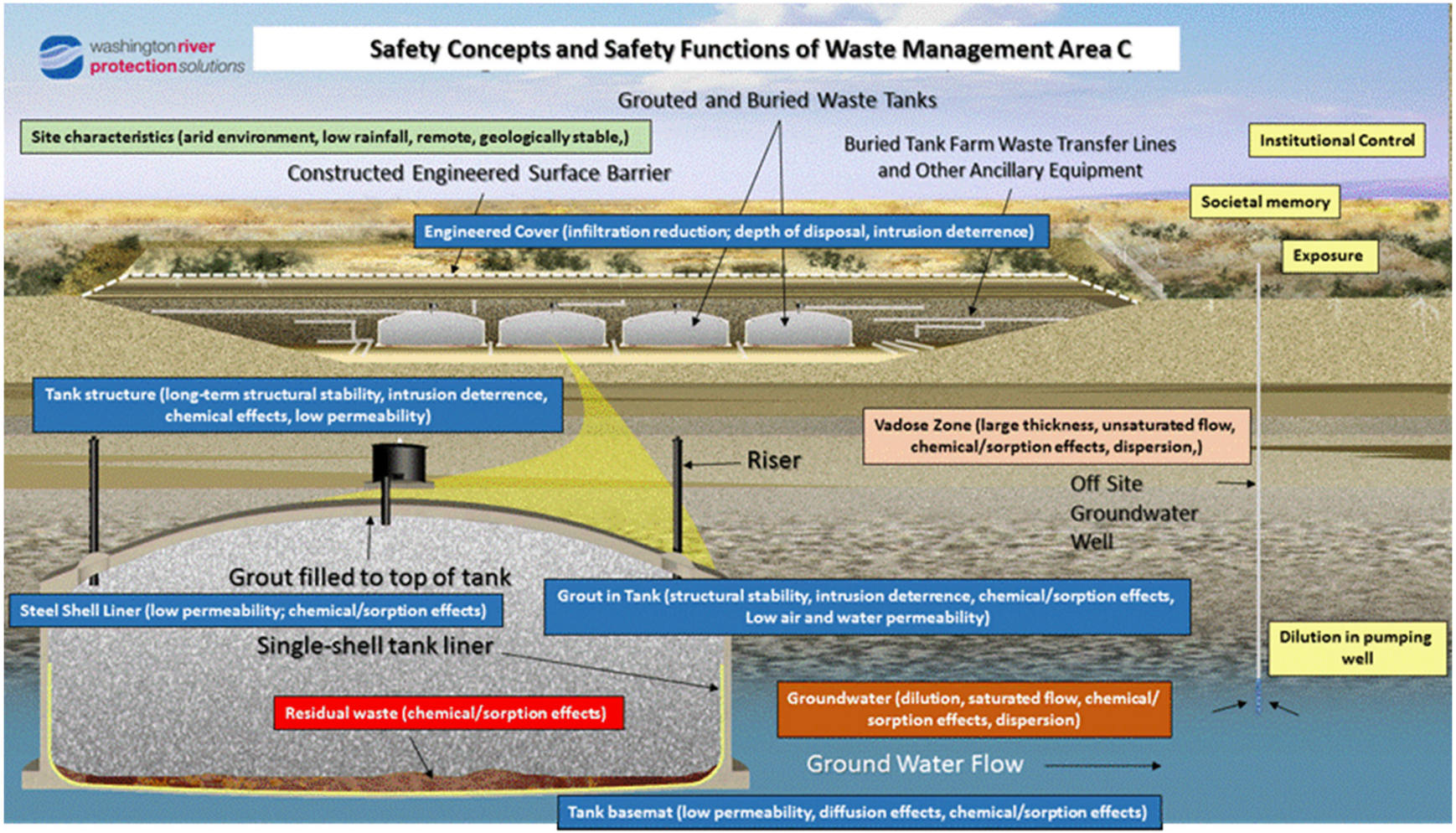
- Bounding inventories for unretrieved tanks

- Alternative conceptualizations of the stratigraphy of the vadose zone

- Alternative assumptions about dilution in the aquifer.

Consequently, the RCA includes a base case representing the expected behavior of the disposal system and alternative cases representing degraded safety functions. These two elements of the RCA represent the uncertainties in the post-closure performance of the closed WMA C that will support closure decisions.

**Figure ES-4. A Schematic Depiction of the Safety Functions for a Closed Waste Management Area C.**



A closure date of year 2020 has been assumed for the WMA C RCA. In the post-closure assessment, four time periods have been considered: (1) a 100-year institutional control period when the engineered surface cover works to its design capability resulting in effectively 0.5 mm/yr recharge rate under the base of surface cover system; (2) a 400-year post-institutional control period (from 100 years to 500 years after closure) within which the surface cover remains intact; (3) the time period from 500 years after closure up to 1,000 years after closure, during which the surface cover barrier function is assumed to be fully degraded at the start of the time period (assuming a design life of 500 years after closure); and (4) the period beyond 1,000 years up to 10,000 years after closure.

Residual inventory estimates used in this RCA were determined based on information and conditions as of September 2014. Inventory estimates were developed for 1) residuals in retrieved tanks with post-retrieval sampling, 2) residuals in retrieved tanks without post-retrieval sampling, 3) residuals in tanks undergoing retrieval and 4) post-retrieval residual inventory estimates for ancillary equipment, including C-301 catch tank, 244-CR vault tanks, and sumps, pits, diversion boxes, and waste transfer pipelines. All hazardous chemical and dangerous waste constituents left in tanks and ancillary equipment at WMA C at closure with non-negligible inventories were included in the RCA. A total of 12 constituents are identified for additional evaluation in the WMA C RCA.

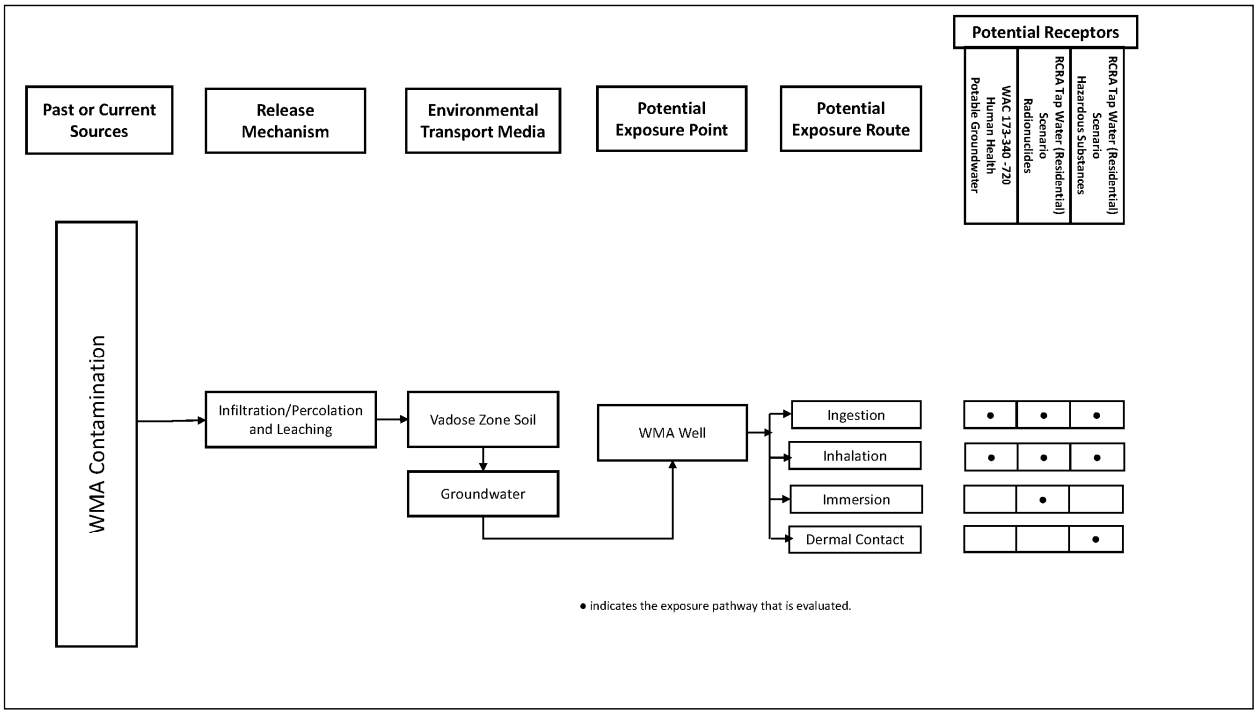
Hazardous chemical contaminant releases from the grout inside the tanks and 244-CR vault are controlled by diffusion processes while the grout is assumed to remain intact. In the base case, the tank structure and infill grout placed into the tanks were assumed to be intact for the entire period of analysis. This assumption is supported by an evaluation of the degradation rate of cementitious materials under shallow burial conditions at Hanford. Because all waste transfer lines will likely be disposed in place without the emplacement of infill grout within individual pipelines, the RCA considered contaminant release from wastes within the pipelines using a combination of advection and diffusion release mechanisms.

The various pathways of possible exposure evaluated in the WMA C RCA are illustrated in Figure ES-5. To meet RCRA requirements, risk-based calculations are performed using the tap water (resident) scenario. This scenario is used to estimate exposure to both radionuclides and chemicals to a resident receptor who uses the contaminated water from the well located at the point of calculation for domestic purposes. Exposure parameters and toxicity values that are used in the equations are obtained from U.S. Environmental Protection Agency (EPA) guidance. The receptor is assumed to be exposed to radionuclides and chemicals in groundwater from the following exposure routes:

- Ingestion of tap water
- Inhalation of volatiles (chemicals and radionuclides) while showering and other domestic purposes
- External exposure to immersion in tap water

- Dermal contact with skin while showering and using groundwater for other domestic purposes (such as washing dishes).

**Figure ES-5. Conceptual Exposure Model for the EPA Tap Water (Residential) Scenario and the 2007 MTCA Potable Groundwater Cleanup Levels.**




EPA = U.S. Environmental Protection Agency
RCRA = Resource Conservation and Recovery Act of 1976
MTCA = Model Toxics Control Act
WMA = Waste Management Area

Reference: WAC 173-340-720, "Groundwater Cleanup Standards," Washington Administrative Code, as amended.

During the compliance and post-compliance periods, the receptor is assumed to reside 100 m downgradient of the WMA C fenceline. The surface water pathway is not a possible exposure pathway for the disposal facility because surface water is not present near WMA C, and is too limited on the Hanford Site Central Plateau in quantity to be used domestically.

Excess lifetime cancer risks for carcinogens and non-cancer hazards for noncarcinogens are calculated. Estimation of intake is based on age-specific ingestion, inhalation and dermal contact rates for children and adults assuming 6-year exposure duration for children and 20-year exposure duration for adults.

To evaluate protection of water resources, chemical concentrations in groundwater 100 m downgradient from WMA C fenceline are compared to 2007 MTCA Method B groundwater cleanup levels. The cleanup levels are based on equations and exposure assumptions presented in 2007 MTCA WAC 173-340-720, "Groundwater Cleanup Standards" using a target risk level of $1 \times 10^{-6}$ for carcinogens or a hazard quotient of 1 for noncarcinogens.

The groundwater protection pathway analysis included the following.

(a) An initial three-dimensional screening analysis to identify contaminants that cannot provide calculable groundwater contamination over the duration of the simulation and thus can be screened out from further calculations. Using conservative recharge rates and hydraulic properties it was determined that radionuclides with a $K_d > 0.1$ mL/g require no detailed analysis for the 1,000-year compliance time frame, and contaminants with a $K_d > 1.5$ mL/g require no detailed analysis for the 10,000-year post-compliance period. As a result of the screening, contaminants with $K_d > 1.5$ mL/g are excluded from further consideration in the groundwater pathway calculations.

(b) A three-dimensional flow and transport analysis for the base case with the parameter values set at their expected values. This involved determining the appropriate boundary conditions under steady-state conditions that are expected in the future.

(c) A suite of sensitivity analyses to evaluate the performance of the system when the safety functions are degraded compared to their expected behavior.

The RCA results are shown in Table ES-1 for the 10,000-year post-closure period of analysis. Releases to groundwater were evaluated against regulatory standards (i.e., target risk, hazard quotients, and hazard indices associated with EPA Tap Water [Residential] Scenario and Federal and State maximum contaminant levels and 2007 MTCA Potable Cleanup Levels for groundwater).

Peak cumulative chemical cancer risk is not discussed because carcinogenic chemicals were not measured at any point of calculation during the entire period of analysis.

The cumulative radiological cancer risk results for all radionuclides that produced a nonzero cancer risk result within 10,000 years shows that the peak radiological cancer risk summed over all radionuclides is $1.58 \times 10^{-6}$, which occurs around 1,500 years after closure. This risk estimate is outside the acceptable risk range of $1 \times 10^{-4}$ to $1 \times 10^{-6}$. The highest radiological cancer risk within the 1,000-year time period is $6.20 \times 10^{-9}$, which occurs at 1,000 years after closure. This risk estimate is less than the lower end of the acceptable risk range of $1 \times 10^{-4}$ to $1 \times 10^{-6}$. The key contributing radionuclide at all times is $^{99}$Tc. Minor contributors to the total radiological cancer risk at times beyond the 1,000-year post-closure period are $^{79}$Se, $^{129}$I, $^{126}$Sn, and uranium isotopes.

RCA results at the 100-m distance downgradient of the WMA C fenceline show that the peak chemical non-cancer hazard index summed over all chemicals is 0.069 at 1,440 years after closure. This hazard index is less than the target hazard index of 1. The highest chemical non-cancer hazard index within the 1,000-year period is 0.061, which occurs at 1,000 years after closure. This hazard index is also less than the target hazard index of 1. The key contributing chemicals at all times are fluoride (27% contribution), nitrite (54% contribution), nitrate (11% contribution), and cyanide (8% contribution).

Peak groundwater concentrations for all points of calculation along the 100-m distance were compared to available Federal and State maximum contaminant levels and to the 2007 MTCA Method B groundwater cleanup levels.

**Table ES-1. Comparison of Waste Management Area C RCRA Closure Analysis with Regulatory Standards (Target Risk, Hazard Index/Quotient, and Federal and State Maximum Contaminant Levels/2007 MTCA Method B Groundwater Cleanup Levels) for Period of Analysis. (2 sheets)**

| Exposure Scenario | Regulatory Standards | | | Period of Analysis (0 to 10,000 years post-closure) |
|---|---|---|---|---|
| Tap Water (Resident) Scenario | **Hazardous Chemicals** | | | |
| | Target Risk Level[b] | 1E-06 | | — |
| | Hazardous Quotient | 1 | | 3.7E-02 (Nitrite)<br>1.8E-02 (Fluoride)<br>7.6E-3 (Nitrate) |
| | Cumulative Risk Level[b] | 1E-05 | | — |
| | Hazard Index | 1 | | 0.069 |
| | **Radionuclides** | | | |
| | Target Risk Range | 1E-06 to 1E-04 | | 1.58E-06 (primarily for $^{99}$Tc)[c] |
| Groundwater Protection | **Federal and State Maximum Contaminant Levels<br>2007 Model Toxics Control Act (MTCA) Groundwater Cleanup Levels** | | | |
| | **Constituent of Potential Concern** | **Federal and State[d] Maximum Contaminant Level (µg/L)** | **2007 MTCA Method B Groundwater Cleanup Levels[e] (µg/L)** | **Concentration[a] (µg/L)** |
| | **Chromium, Total** | 100 | 24,000 | 4.9E-01 |
| | **Chromium VI** | — | 48 | 4.9E-01 |
| | **Cobalt** | — | 4.8 | 4.7E-05 |
| | **Cyanide** | 200 | 4.8 | 1.4E-02 |
| | **Fluoride** | 4,000 | 960 | 2.3E+01 |
| | **Nitrate** | 45,000 | 113,600 | 2.4E+02 |
| | **Nitrite** | 4,500 | 4,800 | 7.5E+01 |
| | **Selenium** | 50 | 80 | 1.8E-03 |
| | **Tin** | — | 9,600 | 1.3E-06 |
| | **Uranium, Total** | 30[f] | 48 | 4.9E-02 |

**Table ES-1. Comparison of Waste Management Area C RCRA Closure Analysis with Regulatory Standards (Target Risk, Hazard Index/Quotient, and Federal and State Maximum Contaminant Levels/2007 MTCA Method B Groundwater Cleanup Levels) for Period of Analysis. (2 sheets)**

[a] The point of highest projected concentration beyond a 100-meter buffer zone surrounding the disposed waste.

[b] Peak target and cumulative chemical cancer risk is not presented because carcinogenic chemicals were not found to arrive at any of the points of calculation during the 10,000-year period of analysis.

[c] Peak total risk is primarily from $^{99}$Tc; peak risk from all other individual radionuclides evaluated were found to be less than 2.4E-08 during the 10,000-year period of analysis.

[d] Washington Administrative Code 246-290-310, "Maximum Contaminant Levels (MCLs) and Maximum Residual Disinfectant Levels (MRDLs)."

[e] ECF-100NPL-10-0462, "Calculation of Standard Method B Groundwater Cleanup Levels for Potable Groundwater for the 100 Areas and 300 Area Remedial Investigation/ Feasibility Study Reports."

[f] 40 CFR 141, "National Primary Drinking Water Regulations."

MTCA = Washington State Model Toxics Control Act RCRA = Resource Conservation and Recovery Act of 1976

Similar to the EPA tap water (residential) scenario evaluation, the groundwater concentrations are calculated according to the methodology presented in Section 7. Groundwater cleanup levels were calculated using the equations and inputs described in the 2007 MTCA (WAC 173-340-720). Peak groundwater concentrations were not within the 1,000-year period; therefore, the entire 10,000-year modeling time frame was used for comparison purposes.

For each constituent of potential concern, the Federal and State maximum contaminant level, the 2007 MTCA Method B groundwater cleanup levels, peak groundwater concentration (within 10,000-year modeling time frame), and corresponding peak year indicate that all concentrations of constituents of potential concern evaluated (chromium [total], chromium VI, cobalt, cyanide, fluoride, nitrate, nitrite, selenium, tin, and total uranium) are less than the maximum contaminant level (if available) and the 2007 MTCA Method B groundwater cleanup levels. Boron, iron, manganese, mercury, nickel, lead, strontium, and tributyl phosphate do not reach groundwater within the 10,000-year time frame.

The RCA results indicate that regulatory standards (i.e., target risk, hazard quotients/indices, and Federal maximum contaminant levels/2007 MTCA Method B groundwater cleanup levels) were not exceeded for the entire period of analysis. For all of the sensitivity analyses evaluated, the disposal system also did not exceed these same standards. This result demonstrates the robustness of the landfill-closed WMA C to alternative assumptions with respect to the behavior of the safety functions and input parameters.

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# LIST OF TERMS

**Acronym or Abbreviation**

| | |
|---|---|
| 1-D | one-dimensional |
| 2-D | two-dimensional |
| 3-D | three-dimensional |
| AEA | Atomic Energy Act of 1954 |
| ALARA | As Low As Reasonably Achievable |
| ARAR | Applicable or relevant and appropriate requirement |
| ASR | alkali-silica reaction |
| BBI | Best-Basis Inventory |
| bgs | below ground surface |
| BP | before present |
| BRA | Baseline Risk Assessment |
| CAD | computer-aided design |
| CAS | Closure Authorization Statement |
| CCMS | camera/CAD modeling system |
| CCU | Cold Creek unit |
| CERCLA | Comprehensive Environmental Response, Compensation, and Liability Act of 1980 |
| CFR | Code of Federal Regulations |
| CHPRC | CH2M HILL Plateau Remediation Company |
| COPC | constituent of potential concern |
| CPGWM | Central Plateau Groundwater Model |
| CRBG | Columbia River Basalt Group |
| C-S-H | calcium silicate hydrate |

| | |
|---|---|
| CUL | cleanup level |
| DAS | Disposal Authorization Statement |
| DCF | dose conversion factor |
| DDI | distilled de-ionized |
| DF | dilution factor |
| DI | deionized |
| DKPRO | Radioactive Decay (DK) and Processing (PRO) (code) |
| DOE | U.S. Department of Energy |
| DOE-ORP | U.S. Department of Energy, Office of River Protection |
| DNFSB | Defense Nuclear Facilities Safety Board |
| DQO | data quality objectives |
| DST | double-shell tank |
| DWS | drinking water standard |
| Ecology | State of Washington Department of Ecology |
| EDS | energy dispersive spectroscopy |
| EHM | equivalent homogeneous media |
| EIS | Environmental Impact Statement |
| EMCF | Environmental Model Calculation File |
| EMMA | Environmental Model Management Archive |
| EMSL | Environmental and Molecular Sciences Laboratory |
| ENW | Energy Northwest Columbia Generating Station |
| EPA | U.S. Environmental Protection Agency |
| ERDF | Environmental Restoration Disposal Facility |
| ETF | Effluent Treatment Facility |
| FEPs | Features, Events, and Processes |

| | |
|---|---|
| FFTF | Fast Flux Test Facility |
| FLTF | Field Lysimeter Test Facility |
| FR | Federal Register |
| H3/CCu/RF | H3, CCU and Ringold Formation |
| HCP | Final Hanford Comprehensive Land-Use Plan |
| HDPE | high-density polyethylene |
| HDW | Hanford Defined Waste (Model) |
| Hf | Hanford formation |
| HEIS | Hanford Environmental Information System |
| HFFACO | Hanford Federal Facility Agreement and Consent Order |
| HFSUWG | Hanford Future Site Uses Working Group |
| HI | hazard index |
| HISI | Hanford Information Systems Inventory |
| HLAN | Hanford local area network |
| HLW | high-level waste |
| HMS | Hanford Meteorological Station |
| HQ | hazard quotient |
| HSU | hydrostratigraphic unit |
| HTWOS | Hanford Tank Waste Operations Simulator |
| HWIS | Hanford Well Information System |
| HWMA | Hazardous Waste Management Act |
| ICP | inductively coupled plasma |
| ICRP | International Commission on Radiological Protection |
| IDF | Integrated Disposal Facility |
| IHLW | immobilized high-level waste |

| | |
|---|---|
| ILAW | immobilized low-activity waste |
| IPA | Appendix I Performance Assessment |
| K-U-T | potassium, uranium, thorium |
| LAW | low-activity waste |
| LERF | Liquid Effluent Retention Facility |
| LFRG | Low-Level Waste Disposal Facility Federal Review Group |
| LHS | Latin hypercube sampling |
| LIGO | Laser Interferometer Gravitational Wave Observatory |
| LLW | low-level waste |
| MCL | maximum contaminant level |
| MMI | Modified Mercalli Intensity (scale) |
| MS | mass spectrometry |
| MTCA | Model Toxics Control Act |
| NAVD88 | North American Vertical Datum of 1988 |
| NEPA | National Environmental Policy Act of 1969 |
| NRC | U.S. Nuclear Regulatory Commission |
| NRIZ | normal residential intrusion zone |
| OECD | Organisation for Economic Co-operation and Development |
| OES | optical emission spectroscopy |
| OFM | Office of Financial Management |
| ORIGEN2 | Oak Ridge Isotope Generation and Depletion Code 2 |
| OU | operable unit |
| PA | performance assessment |
| PFP | Plutonium Finishing Plant |
| PHB | Prototype Hanford Barrier |

| | |
|---|---|
| PNNL | Pacific Northwest National Laboratory |
| PoCal | Point of Calculation |
| PUREX | Plutonium Uranium Extraction (facility) |
| RCA | RCRA Closure Analysis |
| RCC | Retrieval Completion Certification |
| RCRA | Resource Conservation and Recovery Act of 1976 |
| RCW | Revised Code of Washington |
| REDOX | Reduction-Oxidation (facility) |
| RETC | RETention Curve |
| RFD | Reference dose |
| RFI/CMS | RCRA facility investigation/corrective measures study |
| RI/FS | remedial investigations/feasibility study |
| RME | reasonable maximum exposure |
| ROD | Record of Decision |
| RSD | relative standard deviation |
| SALDS | State-Approved Land Disposal Site |
| SD | standard deviation |
| SEM | scanning electron microscopy |
| SEPA | State Environmental Policy Act of 1971 |
| SI | saturation index |
| SNF | spent nuclear fuel |
| SPFT | single-pass flow-through test |
| SST | Single-Shell Tank |
| SSTIP | Single-Shell Tank Integrity Project |
| SST PA | DOE/ORP-2005-01, Initial Single-Shell Tank System Performance Assessment for the Hanford Site |

| | |
|---|---|
| STOMP | Subsurface Transport Over Multiple Phases (computer code) |
| TC&WM | Tank Closure and Waste Management |
| TCE | Trichloroethylene |
| TEDF | Treated Effluent Disposal Facility |
| TIC | Total inorganic carbon |
| TOC | Total organic carbon |
| TSD | treatment, storage or disposal |
| TWINS | Tank Waste Information Network System |
| TWRS | Tank Waste Remediation System |
| UCL | upper confidence limit |
| UPR | unplanned release |
| USACE | U.S. Army Corps of Engineers |
| UST | underground storage tank |
| WAC | Washington Administrative Code |
| WMA | Waste Management Area |
| WRPS | Washington River Protection Solutions, LLC |
| WTP | Waste Treatment Plant |

**Waste Types**

| | |
|---|---|
| 1C | First cycle BiPO4 decontamination waste |
| 1CFeCN | Ferrocyanide sludge from in-plant scavenging of T-Plant 1C waste (without coating waste) |
| 2C | Second cycle BiPO4 decontamination waste |
| AR | Water washed PUREX sludge (1967-1976) |
| BiPO4 | bismuth phosphate |
| BL | B Plant strontium processing wastes and miscellaneous wastes |

| | |
|---|---|
| BNW | research waste from Battelle Northwest |
| CW | cladding (coating) waste from Plutonium Uranium Extraction (PUREX) or Reduction Oxidation (REDOX) Plants |
| CWP1 | PUREX aluminum cladding waste (1956-1960) |
| CWP2 | PUREX aluminum cladding waste (1961-1972) |
| CWR1 | Reduction-Oxidation (S Plant) aluminum cladding waste |
| CWZr1 | PUREX/REDOX zirconium cladding waste (1968-1972) |
| HS | 201-C Hot Semiworks waste (1961-1968) |
| IX | cesium denuded waste from ion exchange process in B Plant |
| MW1 | BiPO4 Metal Waste (1944-1949) |
| OWW3 | PUREX organic wash waste (1968-1972) |
| PFeCN | Ferrocyanide sludge from tributyl phosphate (TBP) in-plant scavenged supernate and co-disposed TBP sludge |
| PSN | PUREX high-level waste (HLW) supernate |
| PSS | PUREX Sludge Supernate derived from washing PUREX HLW sludges in 244-AR Vault or 241-A and 241-AX tanks |
| RSN | REDOX HLW Supernate |
| SRR | Strontium recovery waste (1969-1985) |
| TBP | tributyl phosphate |
| TBP (UR) | Tributyl phosphate/Uranium Recovery Waste (1952-1957) |
| TCE | Trichloroethylene |
| TFeCN | Ferrocyanide waste from 244-CR vault treatment of TBP waste |
| TH | Thorium process waste from PUREX Plant |
| TH1 | Thoria process waste (1966) |
| TH2 | Thoria process waste (1970) |

# PREFACE

This document is volume one of four volumes being written to support the performance assessment (PA) required under Section 2.5 of the Hanford Federal Facility Agreement and Consent Order (Ecology et al. 1989, hereinafter referred to as HFFACO) Appendix I for closure of Hanford Tank Farms. The first single-shell tank (SST) farm being closed is Waste Management Area (WMA) C. This particular volume contains an evaluation of impacts from hazardous chemicals and dangerous waste residual contaminants in tanks and ancillary equipment at WMA C, which is needed by the Washington State Department of Ecology (Ecology) for closure of WMA C SSTs per Washington Administrative Code (WAC) 173-303-610, "Closure and Post-Closure." The other three volumes are: 1) **DOE O 435.1 Performance Assessment** (RPP-ENV-58782, "Performance Assessment of Waste Management Area C, Hanford Site, Washington") – An evaluation of impacts from radioactive residual waste contaminants in tanks and ancillary equipment at a closed WMA C, which is needed by the U.S. Department of Energy (DOE) for closure of WMA C SSTs per DOE O 435.1, Radioactive Waste Management; 2) **Baseline Risk Assessment** (RPP-RPT-58329, "Baseline Risk Assessment for Waste Management Area C"), which is an evaluation of impacts to human and ecological receptors from both non-radiological and radiological contaminants in soils at WMA C under current condition, in the absence of actions to control or mitigate releases; and 3) **Analysis of Past Leaks** (RPP-RPT-59197, "Analysis of Past Tank Waste Leaks and Losses in the Vicinity of Waste Management Area C at the Hanford Site, Southeast Washington") – An evaluation of future impacts to human and ecological receptors from both non-radiological and radiological contaminants in soils at the closed WMA C. A more complete description of each of these documents is given in Section 1.2 General Approach to Waste Management Area C Hanford Federal Facility Agreement and Consent Order Performance Assessment.

# 1.0 INTRODUCTION

The Hanford Site, a facility in the DOE nuclear waste complex, encompasses ~1,500 $km^2$ (~586 $mi^2$) northwest of the city of Richland along the Columbia River in southeastern Washington State, as shown in Figure 1-1. The Federal government acquired the Site in 1943 for the production of plutonium. Production of special nuclear materials continued until the 1980s. Since the 1990s, DOE has focused on environmental remediation of the Hanford Site.

Ecology, the U.S. Environmental Protection Agency (EPA), and DOE entered into an agreement and consent order, the HFFACO, as provided for under the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) and the Resource Conservation and Recovery Act of 1976 (RCRA), to clean up the Hanford Site. The HFFACO, an enforceable agreement, includes provisions for closing the SST system.

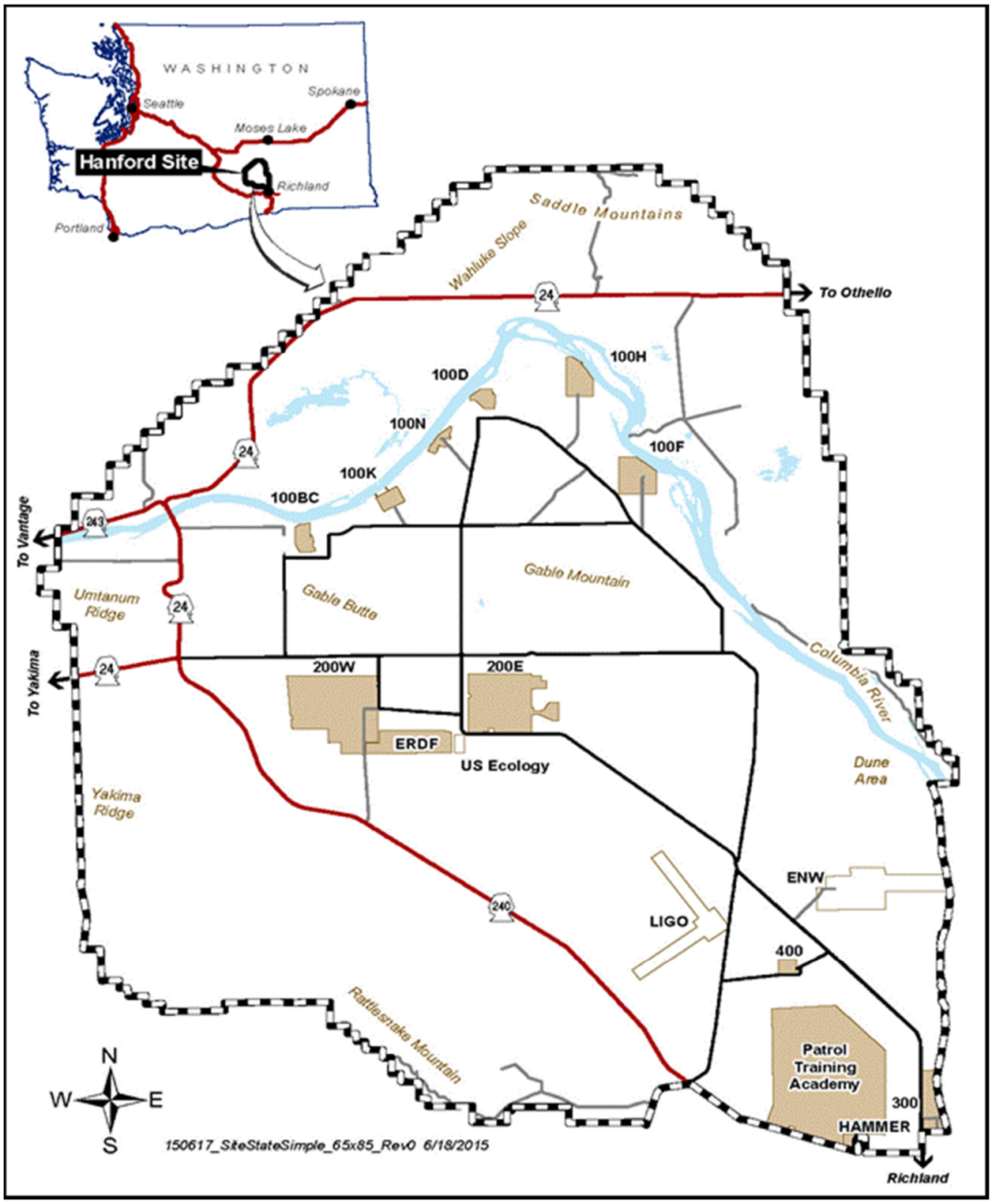
The HFFACO Action Plan Milestone M-045-00 states that closure of the SST system is to occur in accordance with the RCRA-authorized Washington State dangerous waste regulations contained in WAC 173-303-610. This specific milestone requires the following:

> "Complete Closure of All Single-Shell Tank Farms.
>
> Closure will follow retrieval of as much tank waste as technically possible, with tank waste residues not to exceed 360 cubic feet (Cu. Ft.) in each of the 100 Series tanks, 30 Cu. Ft. in each of the 200 Series tanks, or the limit of waste retrieval technology capability, whichever is less.
> …
> For the purposes of this agreement all units located within the boundary of each tank farm will be closed in accordance with WAC 173-303-610. This includes contaminated soil and ancillary equipment that were previously designated as RCRA past practice units. Adopting this approach will ensure efficient use of funding and will reduce potential duplication of effort via application of different regulatory requirements: WAC 173-303-610 for Closure of the TSD Units and RCRA Section 3004(U) for remediation of RCRA past practice units."

The two primary options for closure under WAC 173-303-610 call for a closed WMA that meets all regulatory requirements for 1) clean closure or 2) a landfill closure. However, 78 FR 75913, "Record of Decision: Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington," the Record of Decision (ROD) for DOE/EIS-0391, "Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington" (TC&WM EIS) states that the SST system will be landfill closed under the WAC regulations (Section 1.1.1).

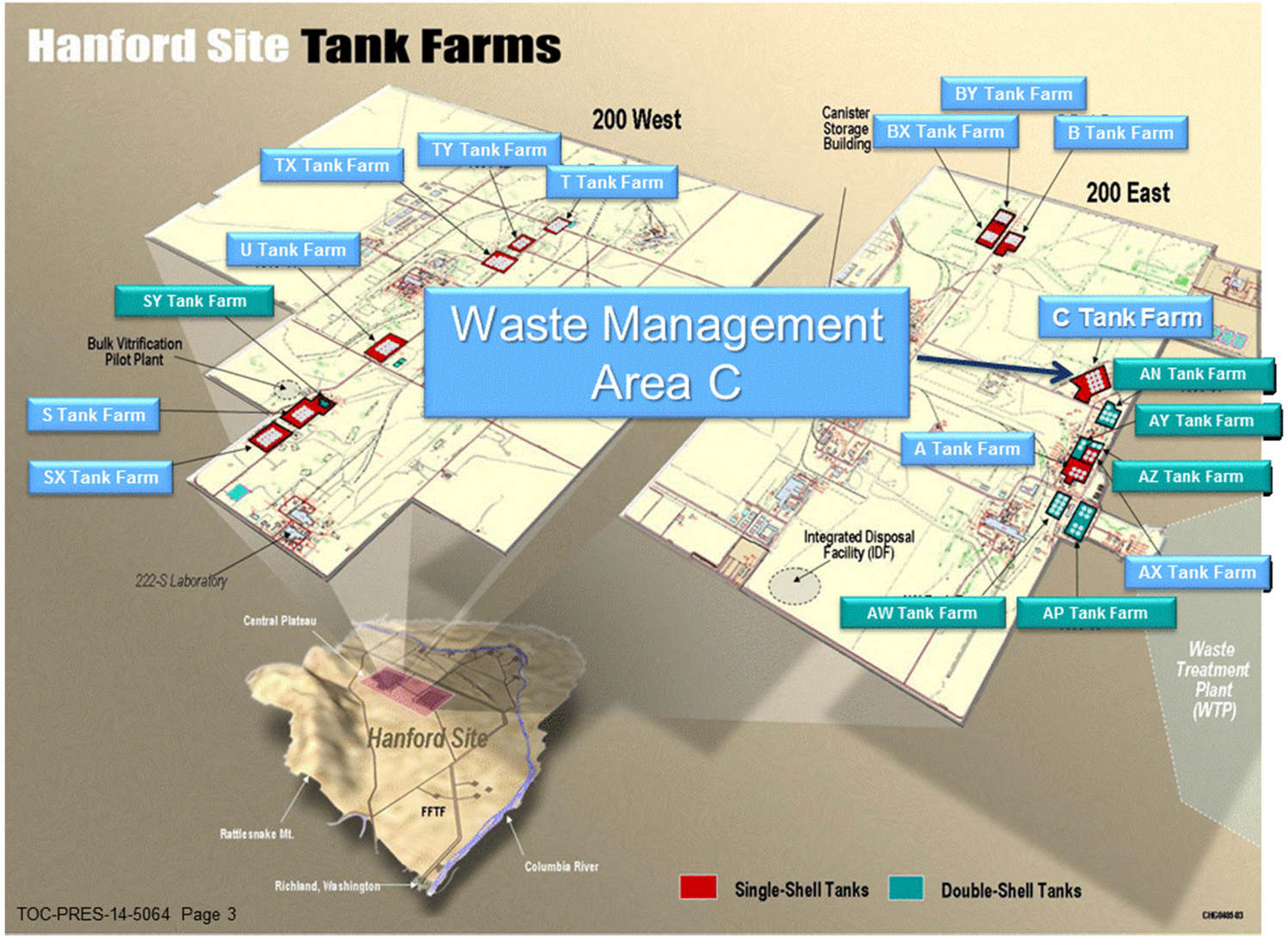
Furthermore, HFFACO requires that all work completed under the Milestone M-45 series be conducted in compliance with HFFACO Action Plan Appendix I, "Single-Shell Tank System Waste Retrieval and Closure Process." Appendix I of the HFFACO Action Plan describes the waste retrieval and closure process that is to be implemented for Hanford Site SST systems, and Section 2.5 of Appendix I identifies that an individual PA shall be developed for each WMA. Under DOE O 435.1, a PA is an analysis of a radioactive waste disposal facility conducted to demonstrate that 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. Under HFFACO Action Plan Appendix I, the PA has been expanded to included non-radionuclides (Section 1.1.2). The intent is for each WMA PA to include the information and analyses necessary to develop credible estimates of impacts to human health and the environment related to the planned closure and post-closure conditions for the WMA of interest. The DOE-Office of River Protection (DOE-ORP) is pursuing closure of WMA C. This WMA is located in the 200 East Area of the Central Plateau at the Hanford Site and is one of 12 SST farms grouped into 7 WMAs (A-AX, B-BX-BY, C, S-SX, T, TX-TY, and U) that contain 149 SSTs and ancillary equipment (see Figure 1-2).

**Figure 1-1. Hanford Site and its Location in Washington State.**




ENW = Energy Northwest Columbia Generating Station LIGO = Laser Interferometer Gravitational Wave Observatory
ERDF = Environmental Restoration Disposal Facility

**Figure 1-2. Hanford Site Tank Farms.**




FFTF = Fast Flux Test Facility

Reference: TOC-PRES-14-5064-VA, "Waste Management Area C Performance Assessment (PA) Current Status."

The HFFACO Action Plan Appendix I PA process for WMA C was initiated in 2009 and various interagency working sessions have been held and documents have been produced over the years to support this effort. This document of the HFFACO Action Plan Appendix I PA provides the impacts related to DOE-generated hazardous chemicals and dangerous waste within the WMA. DOE has elected to call this impact assessment the RCRA Closure Analysis (RCA). The RCA fulfills a request by Ecology during the interagency working sessions to present a comparison of concentration of hazardous chemicals and dangerous chemicals remaining at WMA C after closure against the WAC 173-340, "Model Toxics Control Act – Cleanup" Cleanup Levels. Additionally, it provides long-term evaluation on the release of these contaminants from the closed facility, the subsequent transport of contamination through the environment, and the potential impacts to human and ecological receptors. The RCA furnishes the technical basis for subsequent decision documents (i.e., RCRA Closure Plans and Permit Modifications) in order for these documents to assure compliance with WAC 173-303-610; WAC 173-303-640, "Tank Systems," subsection (8) "Closure and post-closure care"; and WAC 173-303-665, "Landfills" subsection (6) "Closure and post-closure care."

An example of a closure decision that could be included in the decision documents would be the length of post-closure care time. Under RCRA, post-closure care is usually on the order of 30 years [WAC 173-303-610, subsection (7) "Post-closure care and use of property," item (a)]; however, Ecology may elect to shorten the post-closure care period [WAC 173-303-610 (7)(b)(i)] if the reduced period is sufficient to protect human health and the environment or lengthen it [WAC 173-303-610 (7)(b)(ii)] if it finds an extended care period is necessary to protect human health and the environment. In order to provide both DOE and Ecology information necessary to make a decision on the length of post-closure care time, the RCA contains a long-term evaluation of contaminants remaining in the tanks and ancillary equipment because it may take hundreds to thousands of years for these contaminants to leach from the tank sources and travel through the vadose zone and unconfined aquifer to reach a potential receptor.

The starting point for this long-term evaluation assumes the closure conditions given in the TC&WM EIS ROD, which calls for grouting of the SSTs and the placement of a modified RCRA Subtitle C barrier over the top of the WMA (Section 1.1.1).

Although the RCA follows the general outline and content guidelines that are identified in the Draft Radioactive Waste Management Disposal Authorization Statement Technical Basis Documentation (DOE-STD-XXX) and those presented in the June 2014 working session, modifications have been made to ensure that the RCA meets requests made by Ecology during the working sessions.

The purpose of this section, Section 1 Introduction, is to provide a general overview of the HFFACO Action Plan Appendix I PA process for WMA C including high-level assumptions, the relationship of this RCA with previous PA documents, and background information on the WMA C facility and regulatory requirements. This information is presented in the following subsections:

- Regulatory Context (Section 1.1)
- General Approach to WMA C PA (Section 1.2)

- General WMA C Facility Description (Section 1.3)
- A Safety Concept and Safety Functions for a Closed WMA C (Section 1.4)
- Land Use and Institutional Control Assumptions (Section 1.5)
- WMA C History and Plan for Closure (Section 1.6)
- Previous Performance Assessments and Overlapping Analyses (Section 1.7)
- Summary of Key RCA Analysis Assumptions (Section 1.8).

The remainder of the document is comprised of the following sections:

- Assessment Context (Section 2)
- Site and Facility Characteristics (Section 3)
- Comparison of Tank Residuals with WAC 173-340 Soil Cleanup Levels (Section 4)
- Contaminant Identification for Use in Vadose/Zone Groundwater Model (Section 5)
- Waste Characteristics (Section 6)
- Analysis of Risk and Hazard Impacts (Section 7)
- Analysis of Results (Section 8)
- Sensitivity Analysis (Section 9)
- Performance Evaluation and Interpretation of Results (Section 10)
- Quality Assurance (Section 11)
- List of Preparers (Section 12)
- References (Section 13).

Additional information supporting this document is contained in Appendices A through H.

## 1.1 REGULATORY CONTEXT

The regulatory context for tank farm closure, including requirements for the protection of human health and the environment, is complex and regulated by multiple agencies, DOE, Ecology, and EPA. The primary laws and regulations that govern cleanup and closure processes include the following:

- National Environmental Policy Act of 1969 (NEPA)

- HFFACO

- RCRA/Hazardous Waste Management Act (HWMA) (Revised Code of Washington [RCW] 70.105, “Hazardous Waste Management”)

- Atomic Energy Act of 1954 (AEA)

- CERCLA.

In concert, these laws and regulations provide the overarching guidelines for the cleanup and closure processes. NEPA provides the decision-making structure for Federal agencies. The

HFFACO describes closure activities, which are driven by both the requirements of 1) the AEA, as amended, regulating the radioactive portion of mixed waste and 2) RCRA/HWMA as implemented through WAC 173-303, "Dangerous Waste Regulations," regulating the nonradioactive dangerous portion of mixed waste. It should be noted that the various laws and regulations for closure create redundant and possibly conflicting administrative requirements.

### 1.1.1 National Environmental Policy Act of 1969

In December 2012, DOE published a NEPA environmental impact statement (EIS) for the closure of Hanford Site tanks: DOE/EIS-0391, "Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington" (TC&WM EIS). The TC&WM EIS in part analyzes SST system closure alternatives, including clean, landfill, and hybrid clean/landfill closure. The summary to the TC&WM EIS states:

> "For closure of the SSTs, DOE prefers landfill closure…which may require soil removal or treatment of the vadose zone. Decisions on the extent of soil removal or treatment, if needed, will be made on a tank farm– or waste management area–basis through the RCRA closure permitting process."

The DOE issued the TC&WM EIS ROD in December 2013 (78 FR 75913). The ROD stated "The tanks will be grouted and contaminated soils may be removed. The SSTs will be landfill-closed, which means they will be stabilized, and an engineered modified RCRA Subtitle C barrier put in place followed by post-closure care." The Basis for the Decision states "DOE has determined landfill closure of the SST system, which would include corrective/mitigation actions that may require soil removal or treatment of the vadose zone, is a more appropriate approach for SST system closure than clean closure."

### 1.1.2 Hanford Federal Facility Agreement and Consent Order

The HFFACO, signed by DOE, Ecology, and EPA on May 15, 1989, is an enforceable agreement that requires DOE to clean up and dispose of radioactive and hazardous waste at the Hanford Site and close facilities that have been used to treat, store, or dispose of such waste. The HFFACO establishes work requirements (milestones), methods for resolving problems, and an action plan for cleanup that addresses priority activities. The HFFACO also recognizes the applicability of RCRA and its amendments to the Hanford Site. It incorporates a regulatory strategy that specifically places SST activities, including waste retrieval, facility cleanup, remediation, waste disposal, and closure under the HWMA.

An integrated regulatory closure process entitled "Single-Shell Tank System Waste Retrieval and Closure Process" has been developed in the HFFACO Action Plan Appendix I by DOE, in conjunction with Ecology and EPA, to streamline regulatory approval for Hanford Site tank farm closure. This integrated regulatory process uses the existing HFFACO process, action plan, and milestones; completes the HWMA closure process as negotiated by DOE and Ecology; and also recognizes that SST WMA closure and other waste site cleanup activities via compliance with

Federal and State requirements need integration[1]. The process also integrates the applicable requirements of the above regulations consistent with DOE M 435.1-1, Radioactive Waste Management Manual and the AEA. The agency responsible for the closure of all SST WMAs is DOE.

The HFFACO Action Plan, Appendix I, Section 2.5 establishes the need for a single PA that will be approved by Ecology and by DOE pursuant to their authorities under RCRA and the AEA, respectively, and to ensure the actions taken for WMA closure will be protective of human health for all contaminants of concern, both radiological and non-radiological. The PA being developed per DOE O 435.1 will also undergo extensive internal DOE review and be reviewed by the U.S. Nuclear Regulatory Commission (NRC) under a consultation agreement.

### 1.1.3 Resource Conservation and Recovery Act of 1976/Hazardous Waste Management Act

The HFFACO designates Ecology as the lead regulatory agency for SST closure. Ecology regulates the SSTs as dangerous waste storage and treatment units under the HWMA and WAC 173-303, which implement RCRA.

The decision under the ROD for the TC &WM EIS is that the SST system will be landfill closed under the WAC regulations. Following the ROD, and in accordance with WAC 173-303-610 and WAC 173-303-640, DOE submitted DOE/ORP-2014-02, Clean Closure Practicability Demonstration for Single-Shell Tanks to Ecology via Letter 14-ECD-0030, "Transmittal of Clean Closure Practicability Demonstration for the Single-Shell Tanks DOE/ORP-2014-02," which demonstrated that clean closure of any portion of the SST system is impracticable. DOE will therefore close the WMAs and perform closure and post-closure care in accordance with applicable landfill closure and post-closure requirements set forth in WAC 173-303-665(6) and WAC 173-303-610.

### 1.1.4 Atomic Energy Act of 1954

Under its authority of the AEA, DOE regulates the closure of its facilities containing radioactive materials. The primary mechanism for this regulation is DOE O 435.1 and the associated documents (particularly DOE M 435.1-1).

Where information regarding treatment, management, and disposal of the radioactive source, byproduct material, special nuclear material (as defined by the AEA) and/or the radionuclide component of mixed waste has been incorporated into the Hanford Site-Wide RCRA Permit (WA7 89000 8967, "Hanford Facility Resource Conservation and Recovery Act Permit, Dangerous Waste Portion Revision 8C for the Treatment, Storage, and Disposal of Dangerous Waste"), it is not incorporated for the purpose of regulating the radiation hazards of such components under the authority of this closure plan or RCW 70.105.

[1] For the purpose of this document and HFFACO Appendix I, the terms "integrate" and "integration" mean "to coordinate for the purposes of efficiency and effectiveness." Such terms have no effect on respective agency authority, requirements, or responsibilities (see pp. I-1 of HFFACO Action Plan).

### 1.1.5 Comprehensive Environmental Response, Compensation, and Liability Act of 1980

Under Appendix I of HFFACO (Ecology et al. 1989), closure decisions for SST system soils will be made through the RCRA corrective action process pursuant to Agreement Milestones M-45-55 through M-45-62 and its established process for the development of interim measures where appropriate, RCRA facility investigation/corrective measures study (RFI/CMS) work plans, remedial field investigations, and corrective measures studies. Ecology will also seek the involvement of EPA for the purpose of ensuring that the work is consistent with future CERCLA remedial decisions, and to provide EPA and DOE a basis to evaluate the need for additional work that might be required if the closure activities were conducted under CERCLA remedial action authority. Note that the SST WMAs will be closed in close coordination with other closure and cleanup activities of the Hanford Site Central Plateau, including the CERCLA evaluations being conducted for the BP-5 and PO-1 groundwater operable units.

## 1.2 GENERAL APPROACH TO WASTE MANAGEMENT AREA C HANFORD FEDERAL FACILITY AGREEMENT AND CONSENT ORDER PERFORMANCE ASSESSMENT

Under DOE O 435.1, a PA is an analysis of a low-level radioactive waste disposal facility performance, used to address post-closure protection of human health. Appendix I of the HFFACO Action Plan contains language that broadens the scope of a "performance assessment." Section 2.5 of HFFACO Action Plan Appendix I states:

> "Ecology, as the lead agency for SST system closure, EPA, and DOE have elected to develop and maintain as part of the SST system closure plan <u>one performance assessment</u> for the purposes of evaluating whether SST system closure conditions are protective of human health and the environment for <u>all contaminants of concern</u>, both radiological and nonradiological. DOE intends that this performance assessment (PA) will document by reference relevant performance requirements defined by RCRA, HWMA, *Clean Water Act, Safe Drinking Water Act*, and the *Atomic Energy Act of 1954* (AEA) and any other performance requirements that might be ARARs under CERCLA. <u>The PA is of larger scope than a risk assessment</u> required solely for nonradiological contaminants. The PA is expected to provide a single source of information that DOE can use to satisfy potentially duplicative functional and/or documentation requirements. <u>A PA will be developed for each WMA</u> and will incorporate the latest information available. These PAs will be approved by Ecology and DOE pursuant to their respective authorities. For Ecology approval means incorporation by reference, into the Site-Wide Permit through the closure plans.
>
> As <u>individual components are retrieved or characterized</u>, or other component closure activities are completed, <u>the resulting component characterization information will be incorporated into the WMA PA</u> to <u>determine its relative risk compared to the entire WMA performance.</u> In doing this, the Parties will be able to make interim closure decisions for individual components. Initially, the WMAPA *[sic]* will be based on assumptions and available data describing

> component characterization information. As each WMA proceeds toward closure, its respective PA will be updated to address all pertinent new results and findings – and will, as a minimum, incorporate the following results as they become available: actual volumes of tank waste residuals left after retrieval, results of leak investigations, new geologic and ancillary equipment waste characterization information, and the results of new barrier and tank residual stabilization and fill performance studies and tests. Final WMA closure decisions will be made after all components are retrieved and/or characterized, and all other component closure activities have been completed and a final WMA PA is completed."

Note: Underlining is added to emphasize key points in the scope of the HFFACO Action Plan Appendix I "performance assessment."

To distinguish between the two terms and avoid confusion, the term "performance assessment" will be used in this document in the following manner:

- The broadened scope of the HFFACO Action Plan Appendix I analysis will be referred to as the "Appendix I Performance Assessment" (IPA)

- The simpler "performance assessment" (PA) will refer solely to the DOE O 435.1 definition of performance assessment.

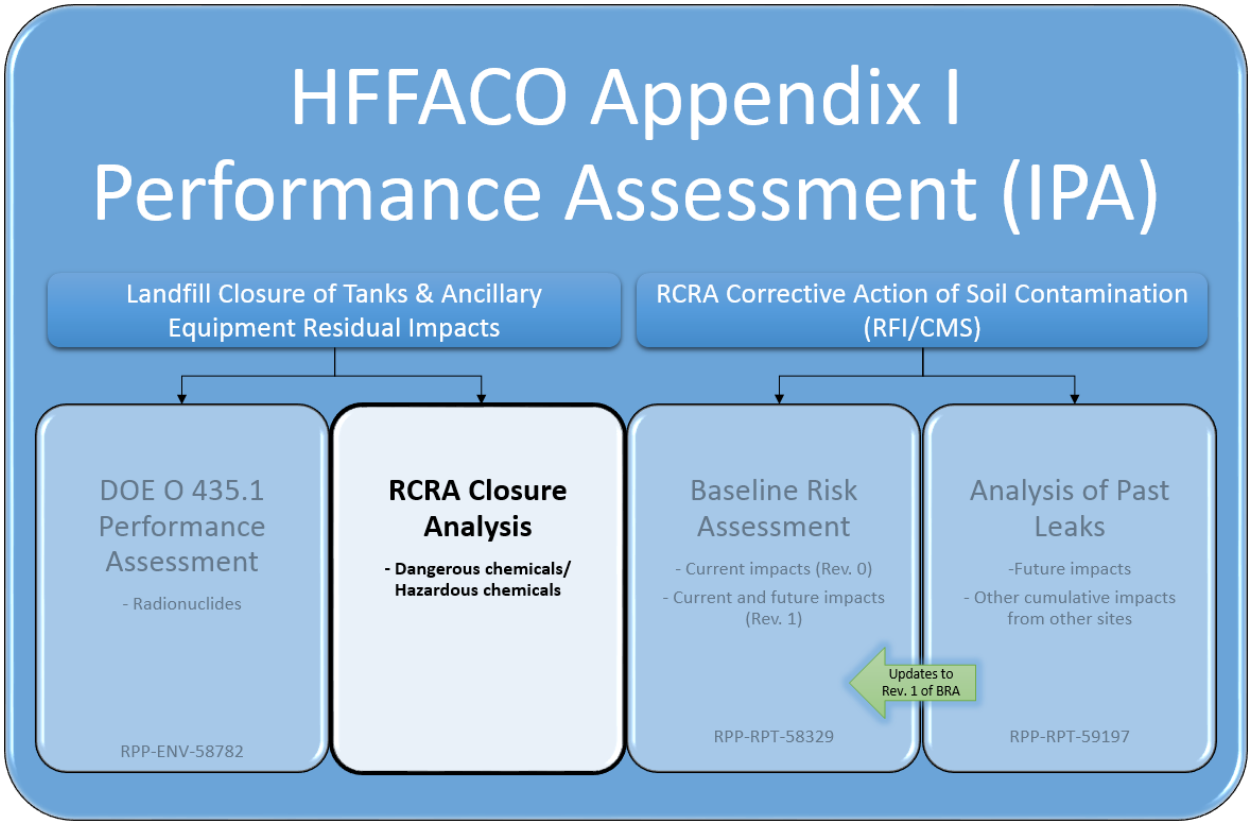
Appendix I of the HFFACO Action Plan describes the waste retrieval and closure process that is to be implemented for the Hanford Site SST system. The four components of the IPA are illustrated in Figure 1-3.

Closure decisions for the Hanford Site SST system soils are made through the RCRA corrective action process. The RCRA corrective action component of the IPA is documented in the RPP-RPT-58339, "Phase 2 RCRA Facility Investigation Report for Waste Management Area C," Draft A and will contain 1) a baseline risk assessment and 2) an analysis of past leaks.

- **Baseline Risk Assessment** – An evaluation of impacts to human and ecological receptors from both non-radiological and radiological contaminants in soils at WMA C under current condition, in the absence of actions to control or mitigate releases. Under the EPA, this is completed at contaminated waste sites prior to remediation activities to establish a need for action. An initial version of the baseline risk assessment, which addresses current human health and environmental impacts, has been prepared (RPP-RPT-58329, "Baseline Risk Assessment for Waste Management Area C"). Revision 1 of this document will address both current and future impacts to human health and the environment.

- **Analysis of Past Leaks** – An evaluation of future impacts to human receptors from both non-radiological and radiological contaminants in soils at the closed WMA C. This evaluation of future impacts will support updates to the anticipated Revision 1 of the baseline risk assessment (RPP-RPT-58329).

**Figure 1-3. The Components of the Appendix I Performance Assessment.**




BRA = Baseline Risk Assessment
HFFACO = Hanford Federal Facility Agreement and Consent Order
RCRA = Resource Conservation and Recovery Act of 1976
RFI/CMS = RCRA facility investigation/corrective measures study

References:
DOE O 435.1, Radioactive Waste Management.
RPP-ENV-58782, "Performance Assessment of Waste Management Area C, Hanford Site, Washington."
RPP-RPT-58329, "Baseline Risk Assessment for Waste Management Area C."

The evaluation of residual waste in tanks and ancillary equipment in support of landfill closure at WMA C is documented in two documents: 1) a RCRA Closure Analysis, and 2) a DOE O 435.1 PA.

- **RCRA Closure Analysis** – An evaluation of impacts from hazardous chemicals and dangerous waste residual contaminants in tanks and ancillary equipment at a closed WMA C. This component of the IPA is the sole focus of this current document.

- **DOE O 435.1 Performance Assessment** – An evaluation of impacts from radioactive residual waste contaminants in tanks and ancillary equipment at a closed WMA C. This component of the IPA is documented in a companion report, RPP-ENV-58782, "Performance Assessment of the Waste Management Area C, Hanford Site."

The RCA portion of the IPA, which is covered by this document, will satisfy part of the requirements outlined in Appendix I of the HFFACO Action Plan by providing a comparison of residual contaminant concentration to Washington State Cleanup Standards as defined in WAC 173-340 and assessing the long-term fate and transport of nonradioactive components of the residual waste in the environment.

### 1.2.1 Waste Management Area C Appendix I Performance Assessment Scoping Process

The foundation of the WMA C IPA meeting the analysis requirements of the HFFACO Action Plan Appendix I was established in a scoping process that was conducted with regulatory agencies and stakeholders between 2009 and 2011. As a part of the scoping process, a series of working sessions were conducted that addressed the following technical topic areas:

- Residual Inventory (Detailed conceptual models and data related to residual waste inventories left in WMA C tanks and ancillary equipment at closure) (May 5-7, 2009)
- Assessment Context/General Conceptual Models (September 1-3, 2009)
- Soil Inventory (Detailed conceptual models and data on waste inventories released to the environment from historical releases during operations) (October 27-29, 2009)
- Engineered System #1 (Detailed conceptual models and data on natural recharge and waste release) (January 26-28, 2010)
- Natural System (Detailed conceptual models and data on vadose zone and groundwater flow and transport) (May 25-27, 2010)
- Engineered System #2 (Continuation discussion of detailed conceptual models, data, and characteristics of the engineered systems) (July 27-29, 2010)
- Exposure Scenarios (Detailed conceptual models and data on human health exposure scenarios) (September 28-30, 2010)
- Vadose Zone and Groundwater Flow and Transport Modeling (Use of numerical and system-level codes and models to support the PA) (January 25-27, 2011)
- Ecological Risk Assessment (Detailed conceptual models and data related to ecosystem risk assessments) (May 17-19, 2011).

Regulatory agency members who participated in the scoping process included representatives from DOE, EPA, NRC, and Ecology as well as their contractors. Other participants in the working sessions included representatives of the tribal nations, other stakeholders groups, and members of the interested public.

Prior to each working session, a data package was prepared for the working session. That data package provided the working material which would be presented at the working session. The

data packages were distributed to all participants in the working session 30 days prior to the working session. After the working session was over, Ecology provided review comments for the data packages. These comments were addressed and the data packages were revised. Each revised data package contains an appendix titled "Review Comment Record" which documents the comments from Ecology along with how each comment was addressed. The purpose of the working sessions was to obtain a common understanding concerning the scope, methods, and data to be used in the IPA for WMA C, and to solicit input from the working session participants. The listing of the current versions of each data package produced in each of the working sessions is summarized in Table 1-1.

**Table 1-1. Data Packages Produced as a Part of the Scoping Process for the Waste Management Area C Hanford Federal Facility Agreement and Consent Order Action Plan Appendix I Performance Assessment.**

| Working Session Topical Area | Report Number (Year Published) | Current Revision No. | Title |
|---|---|---|---|
| **Residual Inventory** | RPP-RPT-42323 (2015) | 3 | Hanford C-Farm Tank and Ancillary Equipment Residual Waste Inventory Estimates |
| **Assessment Context** | RPP-RPT-41918 (2010) | 0 | Assessment Context for Performance Assessment for Waste in C Tank Farm Facilities after Closure |
| **Soil Inventory** | RPP-RPT-42294 (2016) | 2 | Hanford Waste Management Area C Soil Contamination Inventory Estimates |
| **Engineered System #1** | RPP-RPT-44042 (2010) | 0 | Recharge and Waste Release within Engineered System in Waste Management Area C |
| **Engineered System #2** | RPP-RPT-46879 (2011) | 2 | Corrosion and Structural Degradation within Engineered System in Waste Management Area C |
| **Natural System** | RPP-RPT-46088 (2010) | 1 | Flow and Transport in the Natural System at Waste Management Area C |
| **Exposure Scenarios** | RPP-RPT-47479 (2011) | 1 | Exposure Scenarios for the Waste Management Area C Performance Assessment |
| **Numerical Codes** | RPP-RPT-48490 (2011) | 1 | Technical Approach and Scope for Flow and Contaminant Transport Analysis in the Initial Performance Assessment of Waste Management Area C |
| **Ecosystem Risk** | RPP-RPT-49425 (2011) | 1 | Ecological Risk Assessment Approach for Hanford Waste Management Area C |

After development of the data packages, updated information became available for some of the inputs and new conceptualizations and interpretations of data were realized. Also, communications from stakeholders led the project team to develop additional conceptual models and sensitivity analysis cases.

Specific areas in which deviations or updates from the prior data packages occurred include the following:

1) Tank inventories have been updated for retrieved tanks based on post-retrieval samples and volume measurements

2) Data on the contaminant-specific release behavior of waste residuals has been used to develop empirical approaches from modeling dissolution of the tank residuals

3) Data and modeling have been conducted on degradation of the engineered barrier system to provide an improved basis for the analysis

4) Two alternative models of the site stratigraphy have been implemented in collaboration with stakeholders

5) Vadose zone flow properties have been updated to better represent site-specific data

6) Aquifer flow properties have been updated to reflect new data and interpretations.

### 1.2.2 Residual Contaminant Concentration Comparison to Washington State Cleanup Standards

During the "Assessment Context" and "Exposure Scenarios" working sessions, DOE made a commitment to Ecology to provide a residual contaminant concentration comparison against the WAC 173-340 Cleanup Standards (see Section 7 in RPP-RPT-41918, "Assessment Context for Performance Assessment for Waste in C Tank Farm Facilities after Closure" and Section 3 in RPP-RPT-47479, "Exposure Scenarios for the Waste Management Area C Performance Assessment"). The results of these comparisons are given in Section 4 of this document. At the present time, waste retrieval has been completed on 13 of 16 tanks. For 10 of the retrieved tanks, a sample of the residual waste was obtained after retrieval and a chemical analysis of the residual waste is available for this comparison. The 6 remaining tanks will use a concentration based on current Best-Basis Inventory (BBI) or a modeled concentration (see Section 4). This analysis was completed for the residuals remaining in pipelines in RPP-PLAN-47559, "Single-Shell Tank Waste Management Area C Pipeline Feasibility Evaluation."

### 1.2.3 Model Development and Implementation Process

The long term assessment of tank residuals and ancillary equipment uses alternative fate and transport models which are allowed under WAC 173-340-747, "Deriving Soil Concentrations for Groundwater Protection," subsection (8) "Alternative fate and transport models." The process to use alternative fate and transport models on the Hanford Site is given in DOE/RL-2011-50, Regulatory Basis and Implementation of a Graded Approach to Evaluation of Groundwater Protection. All signatories of HFFACO concurred on the use of this document on January 17, 2012.

While there is no guidance in WAC-173-303-610, WAC-173-303-640(8), or WAC 173-303-665(6) as to what a long-term RCA should contain, relevant guidance that may be applicable to this effort can be found in WAC 173-303-665, subsection (2) "Design and operating requirements," item (b) which allows Ecology to exempt the owner or operator from the requirement for a landfill liner [WAC 173-303-665(2)(a)]. The exemption under WAC 173-303-665(2)(b) is

> "…based on a demonstration by the owner or operator, that alternative design and operating practices, together with location characteristics, will prevent the migration of any dangerous constituents into the groundwater or surface water at any future time. In deciding whether to grant an exemption, the department will consider:
>
> (i) The nature and quantity of waste;
> (ii) The proposed alternate design and operation;
> (iii) The hydrogeologic setting of the facility, including the attenuative capacity and thickness of the liners and soils present between the landfill and groundwater or surface water; and
> (iv) All other factors which would influence the quality and mobility of the leachate produced and the potential for it to migrate to groundwater or surface water."

Although WAC 173-303-665(2)(b) does not apply to tank systems, but because WMA C does not have a liner and/or leachate collection system, it is being brought forward to assist in determining what information/data Ecology might need to support closure decisions. The RCA puts together the information requested in WAC 173-303-665(2)(b)(i) through (iv) in a variety of modeling approaches to understand contaminant levels in the leachate migrating out of the tank and ancillary equipment as a result of the residual contamination left behind, and its subsequent transport through the vadose zone into the unconfined aquifer in order to make better closure and post-closure care decisions.

The modeling approaches used in the WMA C PA are shown in Figure 1-4. These approaches include a range of process-specific models that address particular transport mechanisms and alternative conceptual models. While the RCA modeling approach considers a wide range of processes that contribute to contaminant transport and exposure pathways, the description of the general technical approach focuses on the hydrogeological aspects of flow and contaminant transport; specifically, the transport in porous media at the site, including consideration of water, and solid phases of engineered media (e.g., grout) and environmental media (e.g., unsaturated and saturated geologic strata).

As shown in Figure 1-4, the modeling performed for the RCA portion of the IPA makes use of a combination of process and systems models. The Subsurface Transport Over Multiple Phases (STOMP©)[2] computer code-based process model is used in the analysis of post-closure flow for both the unsaturated and saturated systems. These groundwater flow analyses are used in

[2] Subsurface Transport Over Multiple Phases (STOMP©) is copyrighted by Battelle Memorial Institute, 1996.

subsequent groundwater transport analyses in both STOMP© and GoldSim©[3]. The STOMP©-based process models are used deterministically to examine a range of model parameters through sensitivity analyses. The GoldSim©-based system-level model is used to calculate releases for wastes (see Section 6.3.1), to calculate risk and hazard impacts (see Section 6.3.3), and to perform selected additional sensitivity analyses (see Section 8) for comparison with the performance (i.e., risk, hazard, and groundwater protection) measures related to the RCA. The GoldSim©-based system-level model was used to perform uncertainty analyses and additional sensitivity analyses to support the basis for comparisons with performance objectives and measures under DOE O 435.1. Details of the basis and results of these analyses are presented in Section 8 of RPP-ENV-58782.

The groundwater part of analyses in this RCA is focused on the local-scale impacts at WMA C and not on a regional scale. The groundwater impacts are evaluated at 100 m (328 ft) downgradient of the WMA C fenceline to be consistent with the comparable analysis of radiological impacts being conducted to meet the requirements in DOE O 435.1. Additional information of potential groundwater impacts at the WMA C fenceline and other selected downgradient locations is also provided. The STOMP©-based process models are used deterministically to examine a range of model parameters through sensitivity analyses.

The scope of the sensitivity analysis cases used in the RCA consists of the use of safety functions linked to a formal review of Features, Events, and Processes (FEPs) (refer to Section 1.4 for further overview). Additionally, agreements from the 2009 through 2011 working sessions were combined with this information to produce a suite of sensitivity analyses that represent the basis for comparisons with risk and hazard impact measures. This overall approach leads to the identification of specific modeling analyses that will test the robustness of the WMA C closure assumptions.

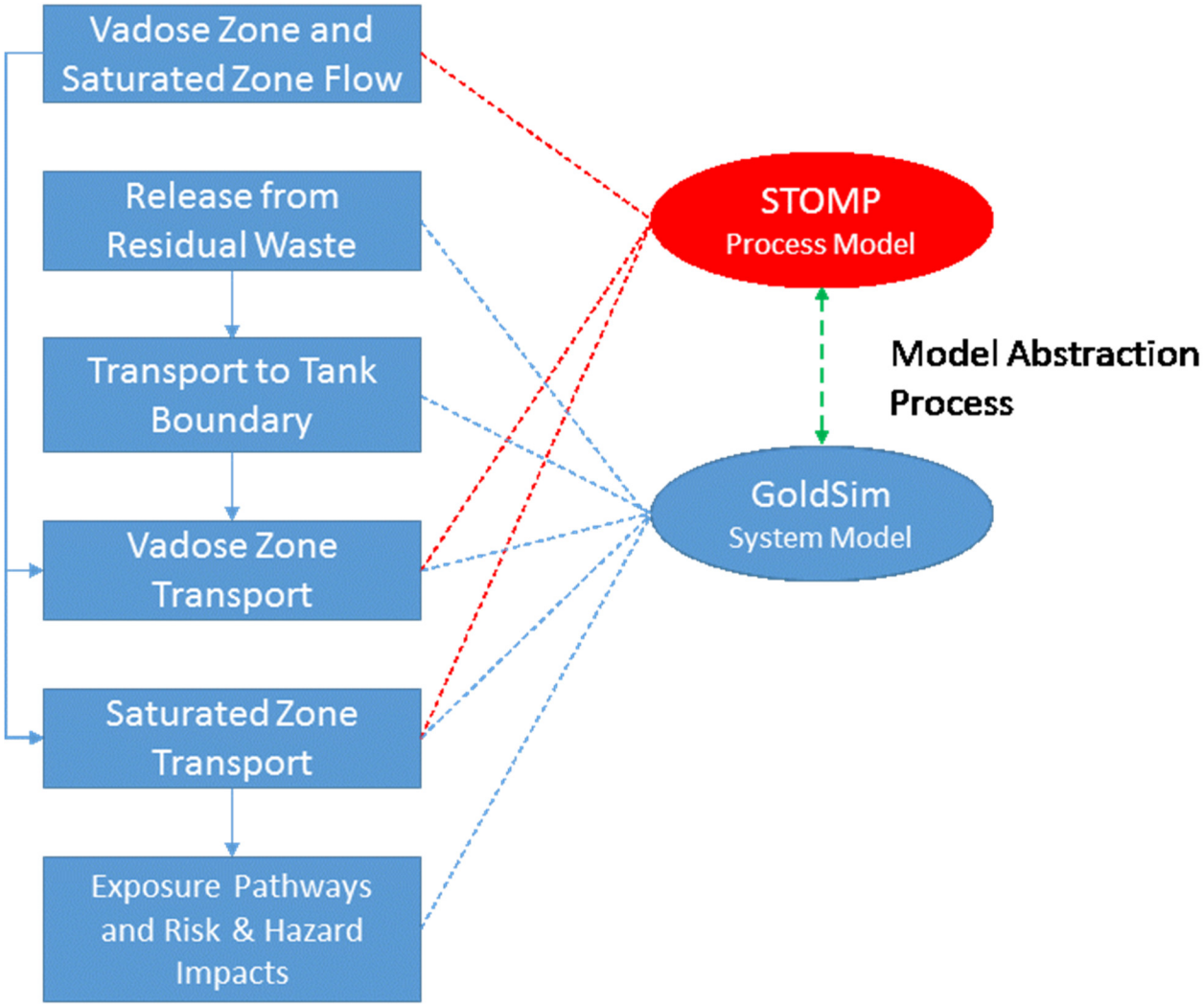
## 1.3 GENERAL FACILITY DESCRIPTION

As previously identified, WMA C (also known as the 241-C Tank Farm [C Farm]), part of the SST system, is located in the Central Plateau (see Figure 1-1), near the eastern edge of the 200 East Area. It was one of the first tank farms built and was constructed in 1944 and 1945.

The WMA C facility contains twelve 100-series tanks and four 200-series tanks (see Figure 1-5). The 100-series tanks are 75 ft in diameter, with a nominal 16-ft depth and 530,000-gal design capacity. The 200-series tanks are 20 ft in diameter with a nominal 24-ft depth and 55,000 gal design capacity. Only tanks 241-C-101 (C-101) through 241-C-106 (C-106) have concrete pits. The other 100-series tanks are equipped with centrally located salt well pump pits. The tanks sit below grade with at least 2 m (7 ft) of soil cover to provide shielding from radiation exposure to operating personnel. Tank pits are located on top of the tanks and provide access to the tanks, pumps, and associated monitoring equipment.

[3] GoldSim© simulation software is copyrighted by GoldSim Technology Group LLC of Issaquah, Washington (see http://www.goldsim.com).

**Figure 1-4. Complementary Use of Subsurface Transport Over Multiple Phases and GoldSim© in the Evaluation of Parts of the RCRA Closure Analysis.**




RCRA = Resource Conservation and Recovery Act of 1976

GoldSim© simulation software is copyrighted by GoldSim Technology Group LLC of Issaquah, Washington (see http://www.goldsim.com).
Subsurface Transport Over Multiple Phases (STOMP©) is copyrighted by Battelle Memorial Institute, 1996.

The SSTs were constructed in place with 0.95-cm (0.375-in.)-thick carbon steel (ASTM A283 Grade C) lining the bottom and 0.64-cm (0.25-in.)-thick carbon steel lining the sides of a reinforced-concrete shell. The tanks have concave bottoms (center of tanks lower than the perimeter) and a curving intersection of the sides and bottom, where the carbon steel plate is 0.8 cm (0.3125 in.) thick. The inlet and outlet lines are located near the top of the liners. There are four inlet lines on each tank, which are also known as nozzles. Pipelines from the diversion boxes to tanks C-101, 241-C-104 (C-104), 241-C-107 (C-107), 241-C-108 (C-108), 241-C-110 (C-110), and 241-C-111 (C-111) are supported by concrete viaducts. At ~3 m (9 ft 10 in.) from the tank wall, the viaduct surface steps down and the void space between the pipes and the viaduct surface is grouted. At this point, the viaduct begins fanning out from 0.8 m (2 ft 8 in.)

wide to 2.2 m (7 ft 4 in.) wide to support the spread placement of the fill lines through the tank wall. Tanks C-101, C-104, C-107, and C-110 each have one outlet line to the next tank in series. Tanks 241-C-102 (C-102), 241-C-105 (C-105), C-108, and C-111 each have one additional inlet line and one outlet line. Tanks 241-C-103 (C-103), C-106, 241-C-109 (C-109), and 241-C-112 (C-112) each have one additional inlet line from the previous tank in the series. The lines connecting each tank are also referred to as "cascade" lines since they allowed transfer of fluids between tanks using gravity flow.

To support the transfer and storage of waste within WMA C SSTs, there is a complex waste transfer system of pipelines (transfer lines), diversion boxes, vaults, valve pits, and other miscellaneous structures. These miscellaneous features of the tank farm are referred to in this document by the general term "ancillary equipment and other related components." The pipelines for WMA C are described in depth in RPP-PLAN-47559.

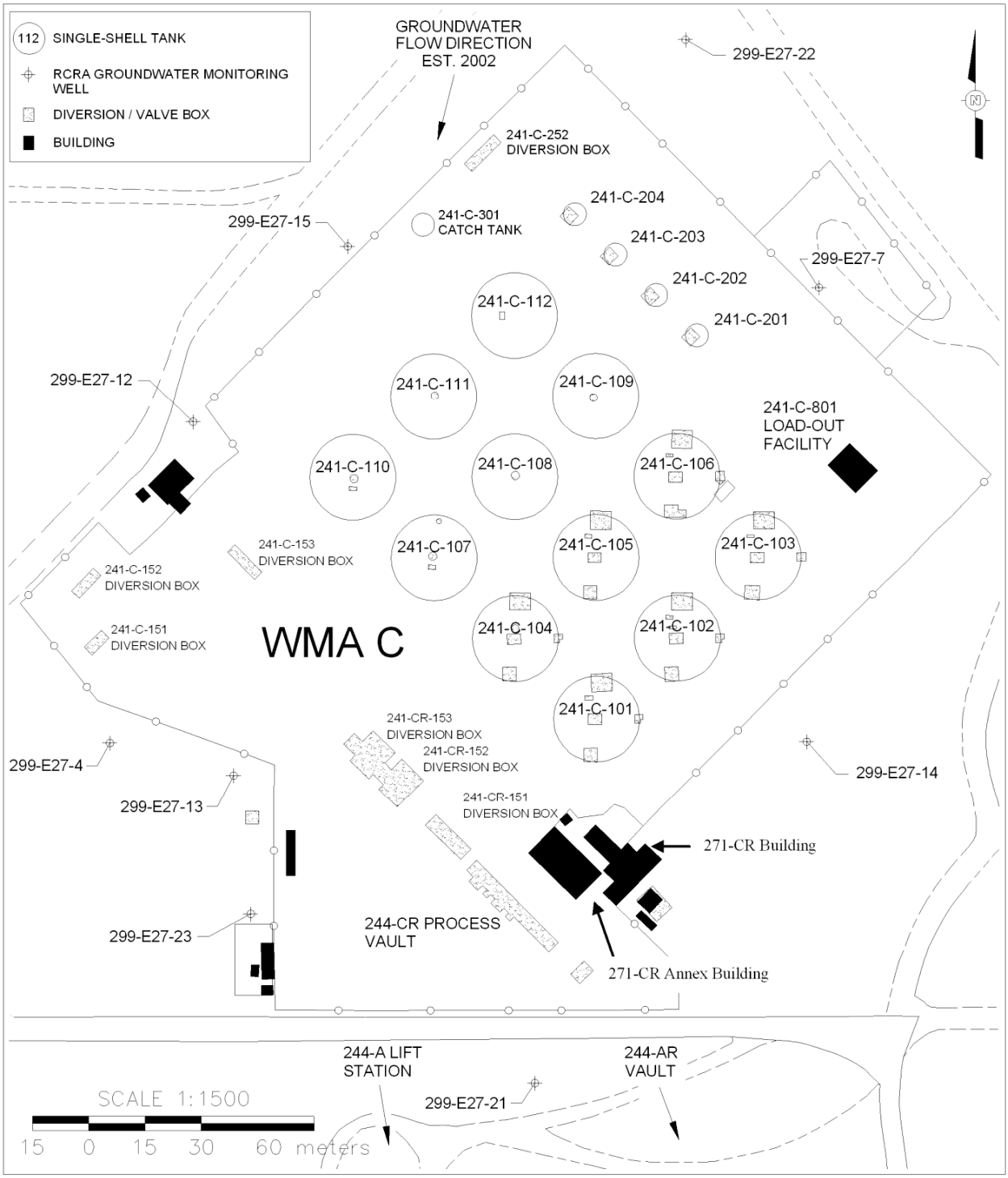
The 244-CR Process Tank Vault (244-CR vault) is located south of the tanks. The vault is a two-level, multi-cell, reinforced-concrete structure constructed below grade, which contains four underground tanks along with overhead piping and equipment. Two tanks (TK-CR-001 and TK-CR-011) have a capacity of 170,343 L (45,000 gal) each. The other two tanks (TK-CR-002 and TK-CR-003) have capacities of 55,494 L (14,700 gal) each. RPP-RPT-24257, "244-CR Vault Liquid Level Assessment and Video Inspection Completion Report" supplies a detailed description of this facility.

Fourteen unplanned releases (UPRs) have occurred within or near to WMA C (Figure 1-5 or Figure 1-6). The largest ones are associated with leaks in pipelines or diversion boxes, with releases from inlet/outlet ports of the SSTs, or with leaks from the SSTs. RPP-PLAN-39114, "Phase 2 RCRA Facility Investigation/Corrective Measures Study Work Plan for Waste Management Area C" and RPP-RPT-58339, Draft A provide more detail on these UPR sites. Note that the impacts from the UPRs are not considered under the scope of this RCA; but rather, will be addressed through the RCRA Corrective Action process.

## 1.4 A SAFETY CONCEPT AND SAFETY FUNCTIONS FOR A CLOSED WASTE MANAGEMENT AREA C

During the scoping sessions the use of FEPs was discussed. FEPs is an approach for improving the traceability and transparency of a PA. The intent of the use of FEPs is to identify conditions that may occur in the future that may affect the ability of the disposal system to perform successfully. While FEP analyses have been widely used, they have also been identified to have a number of drawbacks. In particular, as a bottom-up approach, they seek to identify all conditions of concern, without necessarily focusing on the key issues. As a result, they have in some cases led to large amounts of effort, but without a commensurate improvement in the traceability of the PA.

**Figure 1-5. Location Map of Waste Management Area C and Surrounding Area.**

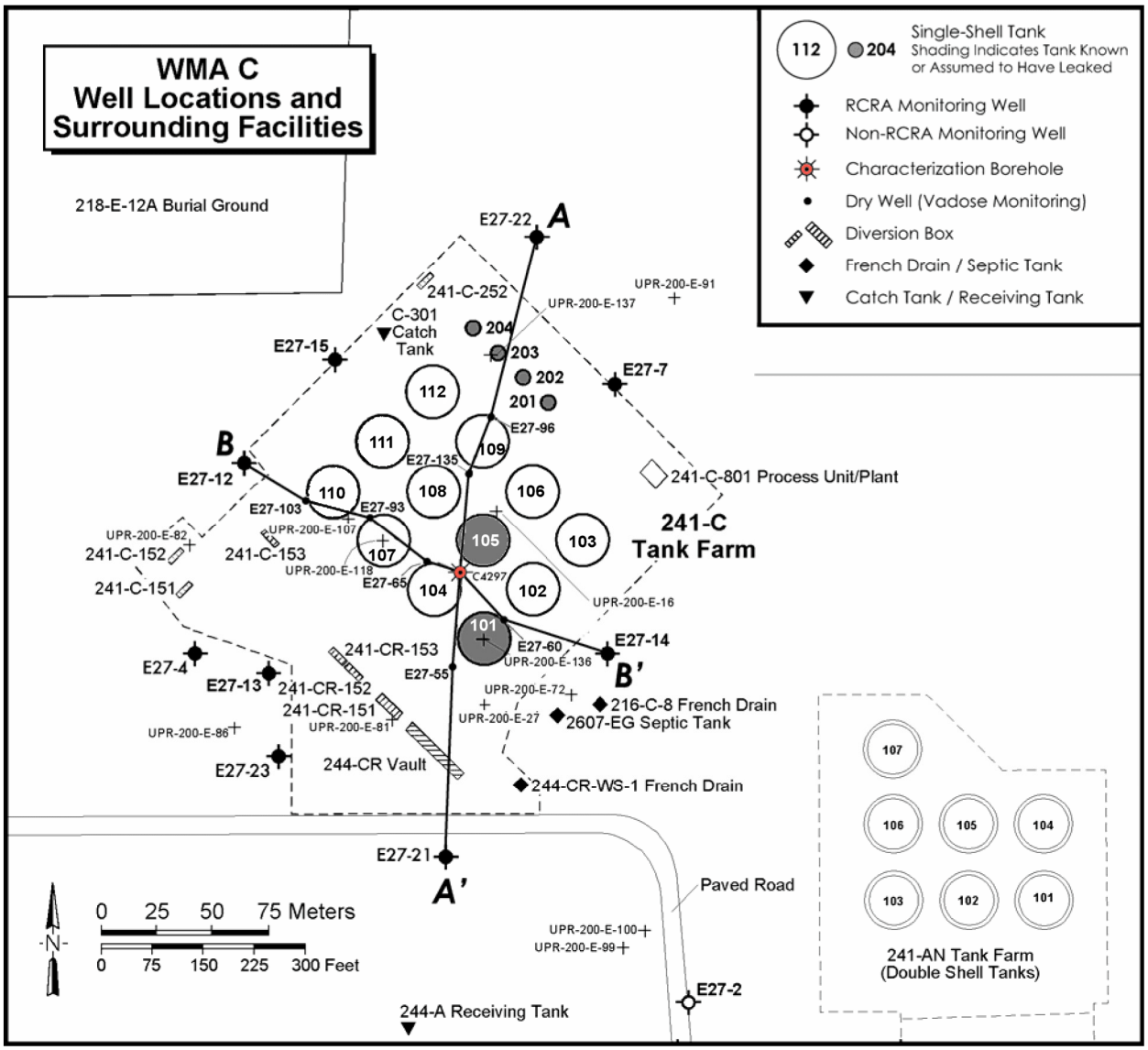



RCRA = Resource Conservation and Recovery Act of 1976 WMA = Waste Management Area

As a result of these issues with FEP-based analyses, in recent years there has been increasing attention given to safety function approaches in structuring PAs. In 2012, the Nuclear Energy

Agency published NEA No. 6923, "Methods for Safety Assessment of Geological Disposal Facilities for Radioactive Waste, Outcomes of the NEA MeSA Initiative," which provides guidance on the conduct of PAs that de-emphasized the importance of purely FEP-based approaches, and has instead recommended a blended, top-down approach that includes both FEPs and safety functions. This approach is summarized below.

**Figure 1-6. Location Map of Unplanned Release Sites of Waste Management Area C.**




RCRA = Resource Conservation and Recovery Act of 1976 WMA = Waste Management Area

A safety concept for tank closure is composed of a set of safety functions that act together to provide the long-term performance of a closed facility required in closure regulations. The safety functions represent multiple and redundant barriers, so that the loss of one or some of the safety functions continues to result in adequate performance of the overall system. A set of safety functions for WMA C are shown in Table 1-2 and are presented schematically in

Figure 1-7. The goal of the RCA is to evaluate these safety functions and to provide reasonable assurance of performance even when some of the safety functions are lost or degraded through time or disruptive events. Furthermore, confidence in the overall safety concept is enhanced if there is reasonable assurance of performance, even in the event that one or more of the safety functions are lost or are degraded in time. It is therefore reasonable to ask which FEP might affect a particular safety function in a way that might degrade its function, or to cause the safety function to act differently than expected.

**Table 1-2. List of Safety Functions for the Performance Assessment of Waste Management Area C. (2 sheets)**

| Safety Function Number | Safety Function | Safety Function Description |
|---|---|---|
| I1 | Institutional control | By rule, we assume that control of the site will be retained for 100 years. A strong potential exists that the U.S. government will retain control of the site for a much more extended period of time. |
| I2 | Societal memory | Societal memory is represented by records, deed restrictions, and other passive controls that would warn someone that additional care should be taken in the area. For a member of the public to come onsite to experience exposures to contamination from WMA C, records that the Hanford Site existed would need to be forgotten or ignored. |
| I3 | Exposure point | By rule, we assume a post-closure well is established 100 m downgradient at the point of highest exposure. It is highly unlikely that this situation will occur, and potential wells in other locations would produce much lower impacts to a member of the public. Furthermore, even if control of the site is lost, the 100 m boundary for WMA C lies under the A Complex, and does not represent a realistic exposure point. Exposures would be more likely to occur further downgradient. |
| EB1 | RCRA cover (permeability) | The final design cover has not yet been established, but is believed to be able to produce very low initial flow rates. Over some period of time this function may deteriorate. |
| EB2 | Steel shell (permeability) | The function of the carbon steel shell to limit flow through the tank is not currently explicitly accounted for in the performance assessment. It is assumed to be permeable at all times. The shell is part of the overall assessment of low flow through the tank for long periods of time. Its potential eventual failure is considered as part of the generic barrier failure cases. |
| EB3 | Steel shell (chemical) | The carbon steel shell will corrode over a period of time, leaving behind corrosion products of (primarily) iron oxides. These corrosion products are highly sorptive and tend to produce reducing conditions that are highly advantageous for limiting solubilities of key hazardous chemical and dangerous waste constituents, like chromium. This safety function is currently assumed to have no effect on system performance. |
| EB4 | Steel shell (structural) | The steel shell provides structural support preventing short-term subsidence of the closed facility. |
| EB5 | Grout in tank (permeability) | The grout acts to limit water flow through the facility, making releases dominated by diffusion from the waste. |

**Table 1-2. List of Safety Functions for the Performance Assessment of Waste Management Area C. (2 sheets)**

| Safety Function Number | Safety Function | Safety Function Description |
|---|---|---|
| EB6 | Grout in tank (chemical) | The grout acts to condition the chemistry of the waste residuals, with sorption characteristic of high pH environments. |
| EB7 | Grout in tank (chemical) | The grout provides a passive and high pH environment for steel corrosion. This safety function is not included in the assessment since the steel shell is assumed to be permeable at all times. |
| EB8 | Grout in tank (structural) | The grout provides structural support preventing subsidence of the closed facility. |
| EB9 | Tank base mat (permeability) | The tank pad, if intact, will provide a flow-limiting layer. |
| EB10 | Tank base mat (chemical) | The concrete pad is anticipated to continue to provide a high pH environment, with associated sorption, for an extended time in the future. |
| WF1 | Residual waste (chemical) | The residual waste is recalcitrant by nature, providing limitations to the amount and rate of release of contamination from it upon contact with water. |
| VZ1 | Water flow through vadose zone | The rate of water flow through the soil is slow, leading to long delay times in the vadose zone. |
| VZ2 | Sorption on vadose zone soils | Vadose zone soils sorb some of the constituents of potential concern, delaying their arrival at the water table. A number of key contaminants are not believed to sorb significantly. |
| VZ3 | Dispersion in vadose zone | Spreading of contaminants in the vadose zone, dispersing them and decreasing concentrations. |
| VZ4 | Anisotropy in vadose zone | Anisotropy affecting the dispersion in the vadose zone. |
| SZ1 | Water flow in saturated zone | Advective flow in the saturated zone leading to dilution of the contaminants. |
| SZ2 | Sorption on saturated zone soils | Saturated zone soils sorb some of the constituents of potential concern, delaying their arrival at the point of compliance. A number of key contaminants are not believed to sorb significantly. |
| SZ3 | Dispersion in saturated zone | Spreading of the plume in the saturated zone, adding dilution to the contaminant plume and lowering concentrations. |
| SZ4 | Dilution in well | Dilution caused by pumping a groundwater well to the surface where it is useable and accessible by a member of the public. This safety function is omitted from the performance assessment to make it compatible with the groundwater protection requirements. |

RCRA = Resource Conservation and Recovery Act of 1976 WMA = Waste Management Area

This approach was used to identify a set of sensitivity analyses to explore the implications of the loss of safety functions, while at the same time exploring the implications of aggregated FEPs that might affect the safety function in similar ways. Following this approach, sensitivity cases

and alternative models for the WMA C RCA were identified for those safety functions shown in Table 1-2. Examinations of what happens in the RCA model will occur when the safety function 1) behaves differently than expected, 2) is degraded compared to a base case, or 3) is lost entirely. Particular attention will be given to any FEPs identified that might affect multiple safety functions simultaneously.

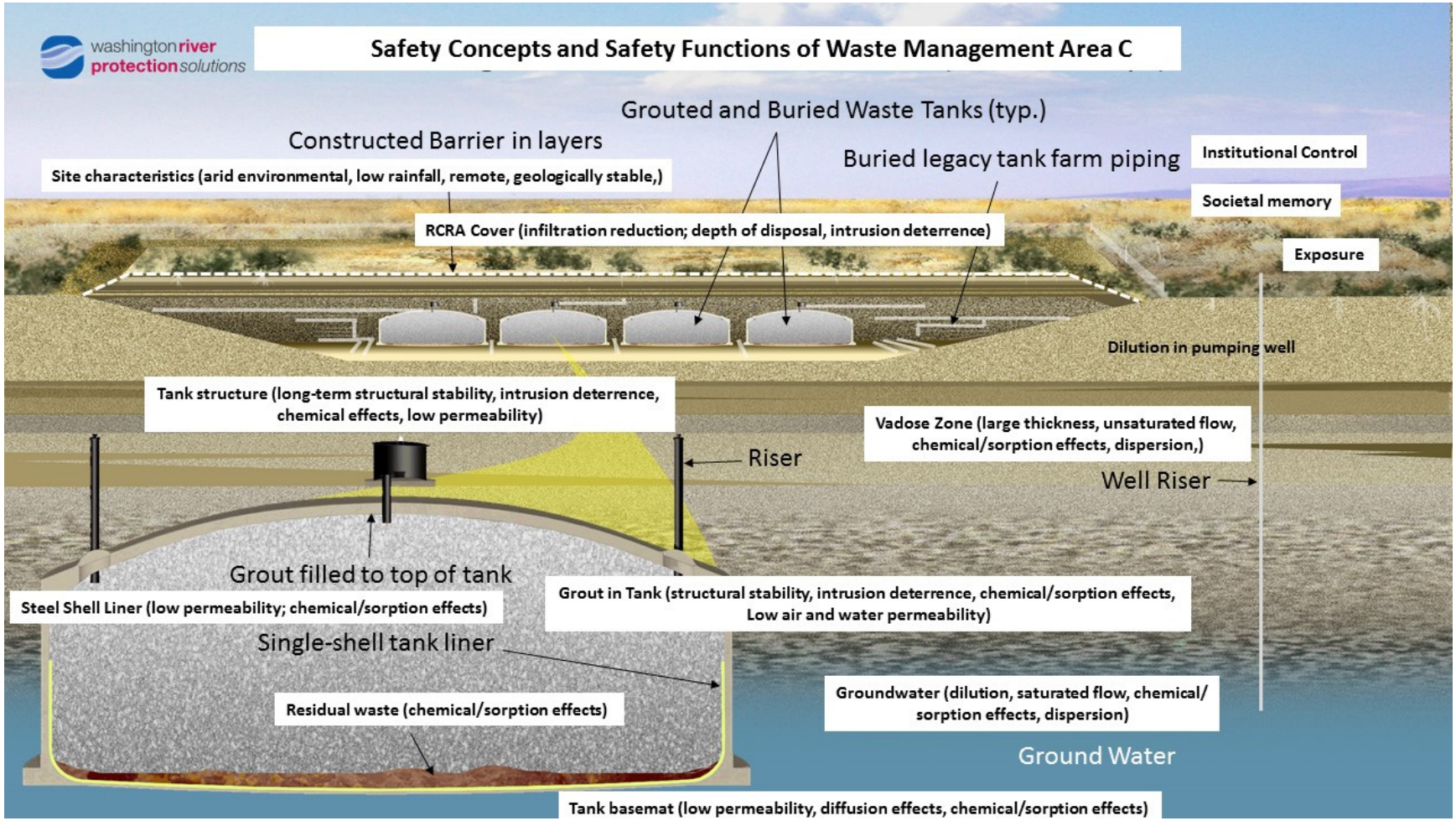
The purpose of this RCA is to evaluate the identified safety functions in order to provide DOE and Ecology the technical basis for closure decisions in the subsequent decision documents (i.e., RCRA Closure Plans and Permit Modifications). The following paragraphs provide a brief summary of the safety functions used in this this analysis.

A significant part of the overall safety concept lies in the land ownership of the Central Plateau by DOE. It is noteworthy that all of the technical calculations presented in the RCA of WMA C are predicated on the loss of the first two safety functions: loss of institutional control of the Central Plateau by DOE, followed by loss of societal memory that the Hanford Site existed. If either or both of these safety functions remain in place, the hazardous chemical impacts of releases or residual wastes from WMA C would be mitigated because the public would not have access to the site and/or would not want to use the contaminated groundwater. In the assessment context of this RCA, both of these safety functions are assumed to disappear after the institutional control period of 100 years.

To be consistent with the PA being performed under DOE O 435.1, this RCA includes an additional administrative safety function: exposure point. If the first two safety functions (institutional control and societal memory) are lost, per DOE O 435.1, this analysis makes an assumption that a groundwater well is installed 100 m (328 ft) from the disposal facility in the location of peak concentration. Additional information of potential groundwater impacts at the WMA C fenceline and other selected downgradient locations is also provided. These assumptions mean that relatively little credit is given for delay and dilution in the groundwater aquifer. Even in the event that memory of the Hanford Site is lost, people would not necessarily move to the Central Plateau and use untreated groundwater as their water source. Furthermore, since the RCA evaluates groundwater use at 100 m (328 ft) downgradient of the facility, potential impacts inferred from this analysis would reflect larger potential impacts and provide an additional margin of safety than would be realized by either those individuals that use groundwater further downgradient or those individuals that do not use groundwater at all.

The remaining parts of the safety concept involve the use of the engineering, environmental, and hydrogeological setting to provide multiple and redundant barriers to the release and migration of residual wastes from tanks and ancillary equipment. The barriers can be divided into one of three types of safety functions: structural safety, hydrological safety, and chemical safety. The safety concept for structural safety calls for backfilling the tanks with grout, leading to a highly stable underground structure. The resulting monolith of grout contained in the tank can be assumed to maintain its ability to support the soil overburden for very long periods of time. The hydrological safety functions limit the contact of water with the residual wastes, limit that rate at which contamination can be advected to the point of analysis, and provide dilution of contamination through dispersion and mixing with clean surrounding water. The chemical safety functions are intended to decrease the solubility and increase the sorption of key contaminants, and to provide a stable and passive chemical environment for the engineered barriers.

**Figure 1-7. Schematic Diagram of Safety Functions for a Closed Waste Management Area C Facility.**



## 1.5 LAND USE AND INSTITUTIONAL CONTROL ASSUMPTIONS

In September 1999, DOE issued the Final Hanford Comprehensive Land-Use Plan (HCP) EIS (DOE/EIS-0222-F, "Final Hanford Comprehensive Land-Use Plan Environmental Impact Statement"). The HCP EIS analyzed the impacts of alternatives for implementing a land-use plan for DOE's Hanford Site for at least the next 50-year planning period and lasting for as long as DOE retains legal control of some portion of the real estate. In November 1999, DOE issued its ROD establishing the HCP, which consisted of four key elements:

- A land-use map that addressed the Hanford Site as five geographic areas,
- A set of nine land-use designations that define the permissible uses for each area of the site,
- The land-use policies, and
- The implementing procedures that would govern the review and approval of future land uses.

These elements were reaffirmed in the HCP EIS Supplement Analysis (DOE/EIS-0222-SA-02, "Supplement Analysis of the Hanford Comprehensive Land-Use Plan Environmental Impact Statement") and in the amended ROD (73 FR 55824, "Amended Record of Decision for the Hanford Comprehensive Land-Use Plan Environmental Impact Statement").

The Central Plateau was designated Industrial-Exclusive by the HCP EIS to allow for continued waste management operations within the Central Plateau geographic area. The definition of Industrial-Exclusive includes treatment, storage, and disposal of all appropriate categories of wastes and related management activities. Figure 1-8 shows the Industrial-Exclusive area established by the HCP EIS within the Central Plateau.

As stated in Section 3.3.2.3.3 of the Final HCP EIS: "This [Industrial-Exclusive] designation would also allow expansion of existing facilities or development of new compatible facilities. Designating the Central Plateau as Industrial-Exclusive would be consistent with the Working Group's recommendations, current DOE management practice, other governments' recommendations, and many public stakeholder values throughout the region."

DOE/RL-2001-41, Sitewide Institutional Controls Plan for Hanford CERCLA Response Actions describes institutional controls for the current Hanford Site CERCLA response actions. The plan originally was developed to fulfill the requirement for submittal of a sitewide plan that describes how the DOE-Richland Operations Office (DOE-RL) will implement and maintain the operable unit-specific institutional controls specified in CERCLA decision documents. The plan also includes specific discussion about each of the five categories of institutional controls including warning notices, entry restrictions, fencing, land-use management, and groundwater-use management on the Hanford Site for CERCLA-based remedial actions. For all of the operational areas (i.e., including the 100, 200, and 300 Areas), this plan states: "Land use is managed according to the comprehensive land-use plan as described in DOE/EIS-0222-F and

DOE/EIS-0222-SA-01and [*sic*] in compliance with DOE orders and cleanup end states as established in CERCLA decision documents."

## 1.6 WASTE MANAGEMENT AREA C HISTORY AND PLAN FOR CLOSURE

### 1.6.1 History

This section provides a summary of the WMA C facility history with an emphasis on those features important to the RCA. Specifically, the WMA C tank farm was constructed from 1944 to 1945 and originally consisted of twelve 100-series tanks, four 200-series tanks, catch tank 241-C-301, four diversion boxes (241-C-151, 241-C-152, 241 C-153, 241-C-252) and interconnecting pipelines (Appendix D of RPP-7494, "Historical Vadose Zone Contamination from A, AX, and C Tank Farm Operations"). Construction of the tank farm is shown through a series of photographs (Figure 1-9). On February 10, 1945, the constructed facilities at WMA C were turned over to operations (HW-7-1388-DEL, "Hanford Engineer Works Monthly Report February 1945," pp. 16). However, the tanks were not utilized until March 1946 starting with the receipt of waste into the 100-series tanks and receipt of waste in the 200-series tanks in September 1947.

New facilities were constructed in WMA C in 1951 and 1952 to allow removal of the stored metal waste in tanks C-101 through C-106 as well as 241-C-201 (C-201) through 241-C-204 (C-204). New pump pits, sluice pits, and heel pits were constructed atop these 100-series SSTs for installing waste retrieval equipment through tank risers. The 244-CR vault was installed for acidification, dissolution of solids, and blending the retrieved metal waste slurries. Diversion boxes 241-CR-151, 241-CR-152, and 241-CR-153 along with concrete-encased pipelines were installed for transferring metal wastes from the SSTs to the 244-CR vault. A control room, the 271-CR building, was also constructed for operation of the 244-CR vault equipment. In 1962, building 241-C-801 was constructed to enable the recovery of $^{137}$Cs. Finally, from the 1970s through the 1990s additional pipelines and facilities were installed to support interim stabilization.

The tanks received wastes from the various chemical separations processes conducted at the Hanford Site. For a number of reasons, essentially all of the very high-activity waste streams generated during plutonium recovery operations at the Hanford Site, prior to 1980, have been reprocessed. Often, these high-activity waste streams were reprocessed multiple times by physical, chemical, and thermal means. In many cases, reprocessed high-activity waste streams were commingled with lower-activity wastes to produce the materials stored in the tanks. An extended summary of the waste processing activities that contributed to wastes in the tank farm is provided in Appendix B of DOE/ORP-2005-01, Initial Single-Shell Tank System Performance Assessment for the Hanford Site (SST PA).

Note that waste retrieval activities in WMA C have been ongoing since 2003. As of September 1, 2014, waste has been retrieved from 13 SSTs in C Farm (C-101, C-103, C-104, C-106, C-107, C-108, C-109, C-110, C-112, C-201, 241-C-202 [C-202], 241-C-203 [C-203], and C-204). Waste retrieval is completed for 11 of the 13 tanks. A practicability request to forego a

third technology has been submitted for tank C-112 (RPP-56935, "Practicability Evaluation Request to Forego a Third Retrieval Technology for Tank 241-C-112") and is under review, and tank C-106 is undergoing a HFFACO (Ecology et al. 1989) Appendix H process to determine the allowable residual waste following retrieval, and show why the threshold limit could not be met (RPP-20658, "Basis for Exception to the Hanford Federal Facility Agreement and Consent Order Waste Retrieval Criteria for Single-Shell Tank 241-C-106"). Residual tank waste constituents and/or hard heel constituents after retrieval were sampled and analyzed. Tank C-203 was not sampled, and sample results for tanks C-101, C-107 and C-112 are not yet available. As of September 30, 2014, waste has been partially retrieved and waste retrieval operations are ongoing for SSTs C-102, C-105 and C-111.

### 1.6.2 Closure

Closure of the individual SSTs and of WMA C is anticipated to occur in three major steps as identified in RPP-RPT-41918: 1) SST waste retrieval, 2) tank filling for stabilization, and 3) surface barrier placement. A general description of these steps follows.

1. For landfill closure of WMA C to occur, DOE must retrieve as much waste as technically possible (Ecology et al. 1989). Because the tank residual waste is mixed waste, it has to meet Washington State dangerous waste requirements for closure (WAC 173-303). In the HFFACO Appendix I (Ecology et al. 1989) section entitled "SST System Waste Retrieval and Closure Process," closure plans will be incorporated into the Hanford Site-Wide Permit (WA7 89000 8967).

2. The next closure action process after Ecology and DOE approval would be to fill the tanks with grout to stabilize and immobilize the residual waste to prevent further long-term degradation of the SSTs, and to discourage direct access as required for a near-surface disposal facility. At this time, the specific formulation of the grout has not yet been established, but the TC&WM EIS (Appendix E Section E1.2.5.1.1) assumed the fill material for the tanks will be similar to the cold-cap grout formulation developed by the U.S. Army Corps of Engineers (USACE) for the Hanford Grout Vault Program, and this assumption has been adopted for the purposes of this RCA.

3. The final closure activity would be placement of an engineered surface cover. This surface cover will provide a barrier to infiltration and intrusion. The specific design of the closure cover has not been finalized, but it is likely to be based on the Modified RCRA Subtitle C barrier concept (RPP-RPT-49701, "Waste Management Area C Closure – Conceptual Design Report").

The closure plan approach to fill the tanks will provide a high-quality grout throughout the tank (DOE/EIS-0391, 2012). The specific formulation of the grout has not yet been established. DOE/EIS-0391 Appendix E Section E1.2.5.1.1 (2012) assumed the fill material for the tanks will be similar to the cold-cap grout formulation developed by USACE for the Hanford Grout Vault Program. This formulation has low-hydration heat and is free-flowing, self-leveling, and

designed to generate little or no free water during curing. The USACE cold-cap grout formulation includes the following materials:

- American Petroleum Institute Class H cement (180 kg/m$^3$)
- American Society for Testing and Materials Class F fly ash (660 kg/m$^3$)
- Natural fine Aggregate (100% passing No. 8 sieve) (780 kg/m$^3$)
- Sodium Bentonite clay (23 kg/m$^3$)
- Water (330 kg/m$^3$)
- High-range, water-reducing admixture (0.17 kg/m$^3$).

## 1.7 PREVIOUS PERFORMANCE ASSESSMENTS AND OVERLAPPING ANALYSES

Over the years, numerous PAs relating to various disposal activities at the Hanford Site have been completed, including:

- WHC-EP-0645, "Performance Assessment for the Disposal of Low-Level Waste in the 200 West Area Burial Grounds"

- BHI-00169, "Environmental Restoration Disposal Facility Performance Assessment"

- WHC-SD-WM-TI-730, "Performance Assessment for the Disposal of Low-Level Waste in the 200 East Area Burial Grounds"

- WHC-SD-WM-EE-004, "Performance Assessment of Grouted Double-Shell Tank Waste Disposal at Hanford"

- PNNL-11800, "Composite Analysis for Low-Level Waste Disposal in the 200 Area Plateau of the Hanford Site"

- DOE/ORP-2000-24, Hanford Immobilized Low-Activity Waste Performance Assessment: 2001 Version.

These assessments do not directly pertain to WMA C, but represent a broad base of knowledge on other facilities at Hanford, the nature and behavior of the general geological setting, and regionally relevant issues.

A number of documents dealing with assessments for closing tank farms with specific relevance to WMA C have also been issued. Early PAs relevant to WMA C include:

- DOE/ORP-2003-11, Preliminary Performance Assessment for Waste Management Area C at the Hanford Site, Washington

- RPP-13774, "Single-Shell Tank System Closure Plan."

These older assessments were updated with newer information in relevant assessments and also summarized in the following subsections:

- DOE/ORP-2005-01, Initial Single-Shell Tank System Performance Assessment for the Hanford Site (Section 1.7.1)
- DOE/EIS-0391, "Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington" (Section 1.7.2)
- RPP-PLAN-47559, "Single-Shell Tank Waste Management Area C Pipeline Feasibility Evaluation" (Section 1.7.3).

### 1.7.1 Single-Shell Tank Performance Assessment

The SST PA (DOE/ORP-2005-01) presented an analysis of the long-term impacts of residual wastes assumed to remain after retrieval of tank wastes and closure of the SST farms. The SST PA was intended to be a comprehensive evaluation of closure of all SST WMAs at Hanford, and included WMA C in its scope, but was not exclusively focused on it. It should be noted that it was reviewed by Ecology, but not approved.

In the SST PA, a reference case set of parameters and engineering assumptions was evaluated to represent a best estimate of the closed facility performance at WMA C. The SST PA also examined a range of values for parameters to support the expected performance range of each barrier or feature in a series of sensitivity cases. To estimate the robustness of the selected set of barriers, alternative conceptualizations were analyzed using variations on the reference case design to establish the level of performance degradation that might occur. Additionally in the SST PA, residual tank waste impacts on groundwater, on air resources, and to the inadvertent intruder were shown to be limited and well below DOE O 435.1 performance objectives for the reference case used in the analysis.

### 1.7.2 Tank Closure and Waste Management Environmental Impact Statement Analysis of Waste Management Area C

The HCP EIS and subsequent supplemental analysis (DOE/EIS-0222-F; DOE/EIS-0222-SA-01, "Hanford Comprehensive Land-Use Plan Environmental Impact Statement Supplement Analysis") and RODs [64 FR 61615, "Record of Decision: Hanford Comprehensive Land-Use Plan Environmental Impact Statement (HCP EIS);" 73 FR 55824] designated a 5,064-hectare (12,513-acre) area within the Central Plateau of Hanford as Industrial-Exclusive. This area, which includes the 200 East and 200 West Areas, includes WMA C. The Industrial-Exclusive designation preserves DOE control of continuing remediation activities and use of the existing compatible infrastructure required to support activities such as radioactive and mixed waste treatment, storage, and disposal. Further, under this designation, DOE continues its Federal waste disposal mission. The Industrial-Exclusive designation also allows for the expansion of existing facilities or the development of new compatible facilities in support of ongoing missions.

**Figure 1-8. Hanford Site, Showing Land-Use Designations Including the Hanford Reach National Monument.**

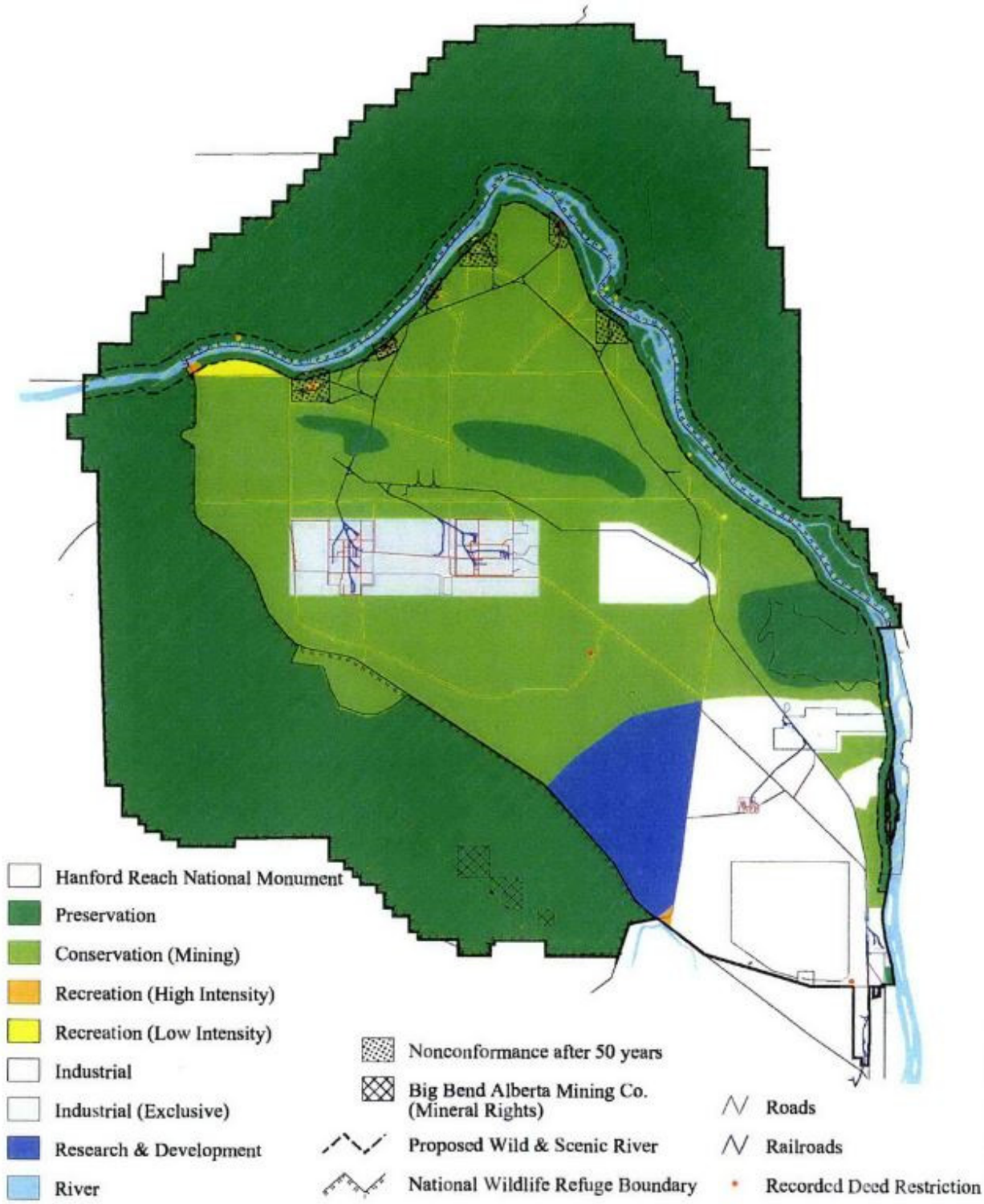
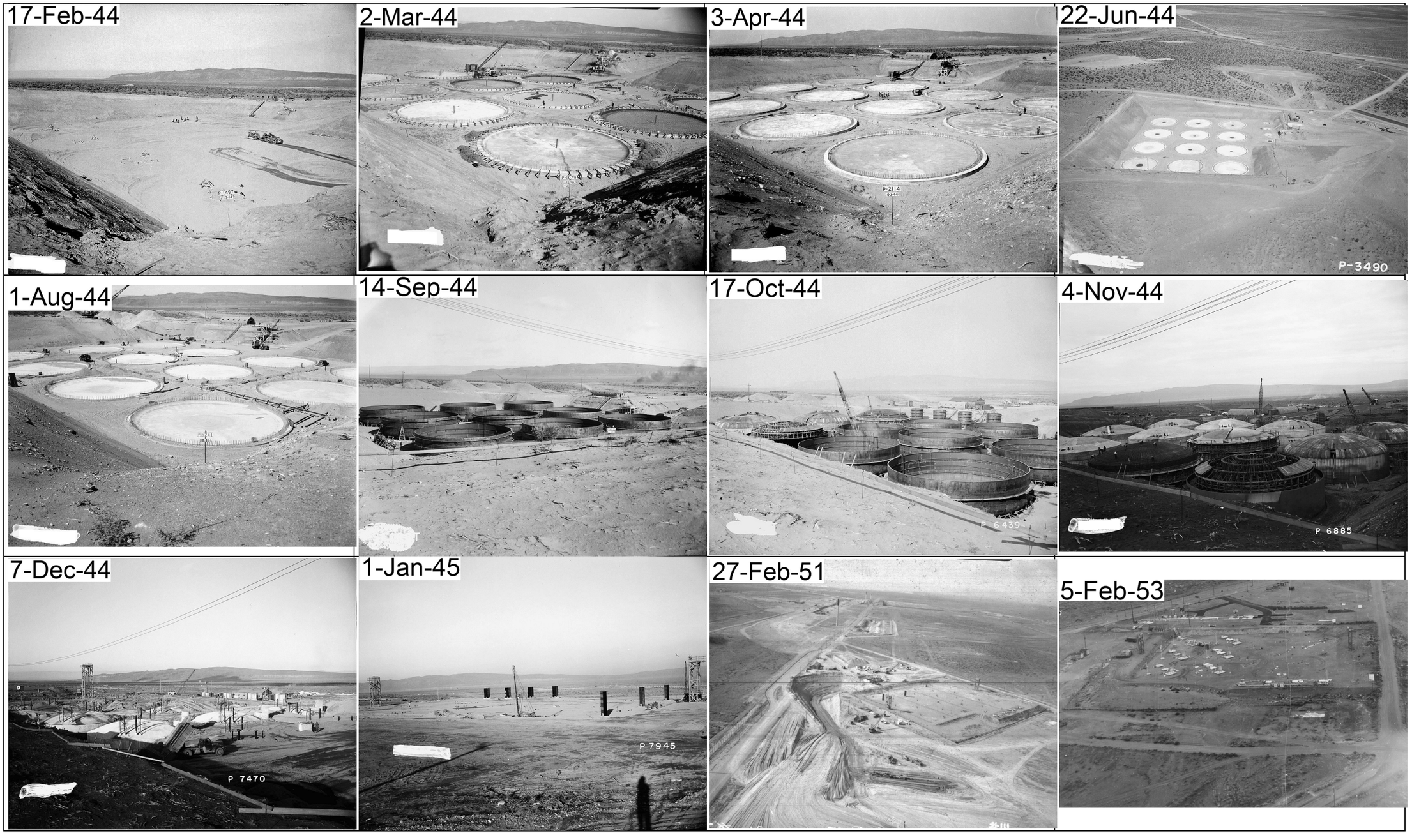


**Figure 1-9. Photographs Showing Different Stages of the Historical Construction of Tanks and Selected Ancillary Equipment in Waste Management Area C.**



The TC&WM EIS (DOE/EIS-0391) included in its scope an evaluation of residual wastes in WMA C. The EIS also included an evaluation of waste sources in the tank farm, including past tank leaks, retrieval leaks from the tanks, and UPRs from within the WMA C fenceline. In Federal Register notice 78 FR 75913, DOE issued the first in a series of RODs announcing its preferred alternative (Alternative 2B) for wastes contained in underground radioactive waste storage tanks evaluated in the Final TC&WM EIS, DOE/EIS-0391 (2012). Decisions announced in this ROD pertain to each of the three main areas analyzed in the EIS, i.e., tank closure, decommissioning of the Fast Flux Test Facility (FFTF), and waste management. This ROD amends the 1997 Tank Waste Remediation System (TWRS) ROD (62 FR 8693, "Record of Decision for the Tank Waste Remediation System, Hanford Site, Richland, WA," February 26, 1997).

As a part of the ROD issued December 13, 2013 (78 FR 75913) arising from the TC&WM EIS, the preferred closure alternative for the SST WMAs was Alternative 2B. This ROD includes retrieval of 99% of the waste currently stored in Hanford's 149 underground SSTs, landfill closure of the SST farm systems, and operation and maintenance of the tank farms. Tank Closure Alternative 2B considers vitrification treatment of waste from the Hanford 200 East and 200 West Area tank farms in accordance with the TWRS EIS ROD and supplemental analyses.

The end state of the tanks evaluated under Alternative 2B assumes that the individual WMAs of the SST waste system would be closed as landfill units under the requirements of WAC 173-303 and DOE O 435.1, as applicable, or decommissioned under DOE O 430.1B, Real Property Asset Management. The tanks and selected ancillary equipment would be filled with grout to immobilize residual waste, prevent long-term degradation of the tanks, and discourage inadvertent intruder access. Under Alternative 2B, removal and replacement of the top 4.5 m (15 ft) of soil was considered for the 241-BX and 241-SX Tank Farms, but no such actions are under consideration for WMA C. The ROD states that decisions on the extent of soil removal or treatment would be made on a tank farm or WMA basis through the RCRA closure permitting process. The closed tank system would be covered with an engineered modified RCRA Subtitle C barrier, followed by post-closure care for 100 years.

The details of the basis of the analyses of impacts from WMA C for Alternative 2B within the TC&WM EIS are provided in Appendix G. Because of the importance of the TC&WM EIS in establishing the ROD for landfill closure of WMA C and other SST WMAs, the PA effort evaluated a specific evaluation case using the current base case numerical model developed for the WMA C PA with the same residual inventories, recharge, and waste release models used for the WMA C model developed for the EIS. A comparison of results of this evaluation case with comparable results for the WMA C-specific model used in the TC&WM EIS analysis is also described and provided in Appendix G.

### 1.7.3 Waste Management Area C Pipeline Feasibility Study

Revision 1 of RPP-PLAN-47559 provided an initial scoping analysis of the post-closure consequences of residual wastes in ancillary equipment. This analysis did not consider residual wastes in tanks. For key non-radiological contaminants assumed to be left behind in waste

pipelines, human health and environmental impacts via the groundwater pathway would be well below groundwater cleanup levels.

## 1.8 SUMMARY OF KEY RCRA CLOSURE ANALYSIS ASSUMPTIONS

As previously identified, this RCA has been structured as a series of sensitivity analyses that are intended to evaluate the effect of a wide range of assumptions on site evolution and alternative concepts regarding the physical behavior of the site. The alternative analyses include sensitivity cases that evaluate conditions well outside the range of the base case analysis.

An extended list of key assumptions used in the RCA are presented in Appendix A. Specific key assumptions of this analysis are presented here that specifically relate to potential decisions regarding design features and closure of the facility.

- It has been assumed that the landfill closure of WMA C occurs in 2020, consistent with planning assumptions in the TC&WM EIS. The results of the RCA are not significantly affected by alternative assumptions about closure timing.

- The engineered cover for WMA C is not yet designed, but is assumed to be similar to the Modified RCRA Subtitle C barrier that limits infiltration through the waste primarily by evapotranspiration processes (i.e., surface barrier) based on the work done for the Hanford Prototype barrier (DOE/ORP-2008-01, RCRA Facility Investigation Report for Hanford Single-Shell Tank Waste Management Areas, Appendix C). These evapotranspiration processes are not directly modeled for this report but have been studied through field measurements, tracer studies, and numerical models to estimate net infiltration (PNNL-14744, "Recharge Data Package for the 2005 Integrated Disposal Facility Performance Assessment"; PNNL-14960, "200-BP-1 Prototype Hanford Barrier Annual Monitoring Report for Fiscal Year 2004"; "Multiple-Year Water Balance of Soil Covers in a Semiarid Setting" [Fayer and Gee 2006]). For modeling purposes, the recommended net infiltration rates from the above-referenced reports are applied to the area under the engineered cover and are varied spatially and temporally as appropriate according to the estimated or assumed time-dependent performance of a surface barrier.

- The specific formulation of the grout has not yet been established, and site-specific measurements of the chemical influence of the grout have not been performed. The chemical effect of the grout is represented by contaminant-specific distributions of distribution coefficients ($K_d$), which have been developed from international literature on sorption of radionuclides on cementitious materials. These values are generally consistent with, or more conservative than, comparable values used for the facility-specific grout at the Savannah River F and H tank farm PAs [WSRC-STI-2007-00369, "Hydraulic and Physical Properties of Tank Grouts and Base Mat Surrogate Concrete for FTF Closure" and WSRC-STI-2007-00607, "Chemical Degradation Assessment of Cementitious Materials for the HLW Tank Closure Project (U)"].

- Inventories of contaminants in retrieved tanks are based on post-retrieval sampling and measurements. Inventories for tanks that have not yet completed retrieval use the best estimates of post-retrieval conditions available at this time. These data have been estimated as of September 30, 2014. Additional sensitivity cases were identified in the 2009 through 2011 working sessions to evaluate alternative inventory assumptions.

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# 2.0 ASSESSMENT CONTEXT

As identified in Section 1, this RCA satisfies part of the IPA requirements outlined in Appendix I of the HFFACO Action Plan. The RCA is limited to the analyses of impacts from hazardous chemical and dangerous waste constituents from residual wastes in tanks and ancillary equipment, which are anticipated to be left in WMA C after closure, and is expected to satisfy those requirements under WAC 173-303-610, WAC 173-303-640(8), and WAC 173-303-665(6). The type of closure for the SSTs was identified in the TC&WM EIS ROD for landfill closure of SSTs that was published in the Federal Register on December 13, 2013 (78 FR 75913). For the landfill closure of WMA C, site closure is assumed to occur at year 2020, at which time the tanks are assumed to be filled with grout and covered with a final closure cover.

This section, Section 2 Assessment Context, includes a description of the regulatory standards for groundwater protection along with the timing and locations for points of assessment. It is comprised of the following subsections:

- Comparison of Tank Residuals with Model Toxics Control Act Soil Cleanup Levels (Section 2.1)
- Public Protection Regulatory Standards for Groundwater (Section 2.2)
- Reasonable Efforts to Minimize Releases (Section 2.3).

## 2.1 COMPARISON OF TANK RESIDUALS WITH MODEL TOXICS CONTROL ACT SOIL CLEANUP LEVELS

During the working sessions, Ecology specifically requested that the tank residual contaminant concentrations be compared against the Model Toxics Control Act (MTCA) (RCW 70.105D, "Hazardous Waste Cleanup — Model Toxics Control Act") WAC 173-340 cleanup standards in order to provide additional risk management information. In Section 4 of this document, specific comparisons are made between the concentrations of constituents taken from tank residual samples (or estimated contaminant concentrations in tank residuals from process knowledge when samples are not available) were made against the MTCA cleanup standards for soil direct contact unrestricted land use (Method B), industrial land use (Method C), and soil concentrations protective of groundwater using the fixed parameter three-phase partitioning model given in WAC 173-340-747, subsection (4) "Fixed parameter three-phase partitioning model." The comparisons in Section 4 are in the same vein as those completed for retrieval data reports (e.g., RPP-RPT-58490, "Retrieval Data Report for Single-Shell Tank 241-C-112" and RPP-PLAN-47559).

Per WAC 173-340-740, "Unrestricted Land Use Soil Cleanup Standards," and for soil cleanup levels based on human exposure via direct contact or other exposure pathways where contact with the soil is required to complete the pathway, the point of compliance shall be established in the soils throughout the site from the ground surface to 15 ft below the ground surface (Figure 2-1) [WAC 173-340-740, subsection (6) "Point of compliance," item (d)]. Under a

closure configuration, waste residuals left in the SSTs in WMA C would be located below 15 ft below ground surface (bgs), resulting in an incomplete exposure pathway.

Comparisons to soil concentrations protective of groundwater using the fixed parameter three-phase partitioning model given in WAC 173-340-747(4) are also provided in Section 4. However, it should be noted that implicit in the use of the fixed parameter three-phase partitioning model given in WAC 173-340-747 is the assumption that constituents of interest are found in soils and are immediately available to be leached by infiltrating precipitation. Under a closure configuration, constituents associated with waste residuals left in the SSTs in WMA C would be contained within a grout-filled tank, a steel tank liner, and an underlying concrete pad below the liner and would not be immediately available for leaching by infiltrating water.

Comparisons between the concentrations of dangerous waste remaining in the SSTs were not made against either WAC 173-340-900, "Tables," "Table 749-2, Priority Contaminants of Ecological Concern for Sites that Qualify for the Simplified Terrestrial Ecological Evaluation Procedure" under WAC 173-340-7492, "Simplified Terrestrial Ecological Evaluation Procedures," subsection (1) "Purpose" or WAC 173-340-900, "Table 749-3, Ecological Indicator Soil Concentrations (mg/kg) for Protection of Terrestrial Plants and Animals" under WAC 173-340-7493, "Site-Specific Terrestrial Ecological Evaluation Procedures," subsection (2) "Problem formulation step," (i) "The chemicals of ecological concern" for the following reasons.

1) The residual waste left in the SSTs is located below the point of compliance for ecological risk for both unrestricted land use and industrial/commercial with institutional controls to prevent excavation (Figure 2-1), thereby making this an incomplete pathway.

2) Both Tables 749-2 and 749-3 contain a footnote stating that the table is not intended for the purpose of evaluating sludges or waste; the full text of the footnote is given below with key statement underlined for this report.

    - Table 749-2, footnote a: "Caution on misusing these chemical concentration numbers. These values have been developed for use at sites where a site-specific terrestrial ecological evaluation is not required. They are not intended to be protective of terrestrial ecological receptors at every site. Exceedances of the values in this table do not necessarily trigger requirements for cleanup action under this chapter. <u>The table is not intended for purposes such as evaluating sludges or wastes.</u>
      This list does not imply that sampling must be conducted for each of these chemicals at every site. Sampling should be conducted for those chemicals that might be present based on available information, such as current and past uses of chemicals at the site."

    - Table 749-3, footnote a: "Caution on misusing ecological indicator concentrations. Exceedances of the values in this table do not necessarily trigger requirements for cleanup action under this chapter. Natural background concentrations may be substituted for ecological indicator concentrations

provided in this table. The table is not intended for purposes such as evaluating sludges or wastes.
This list does not imply that sampling must be conducted for each of these chemicals at every site. Sampling should be conducted for those chemicals that might be present based on available information, such as current and past uses of chemicals at the site."

## 2.2 PUBLIC PROTECTION REGULATORY STANDARDS FOR GROUNDWATER

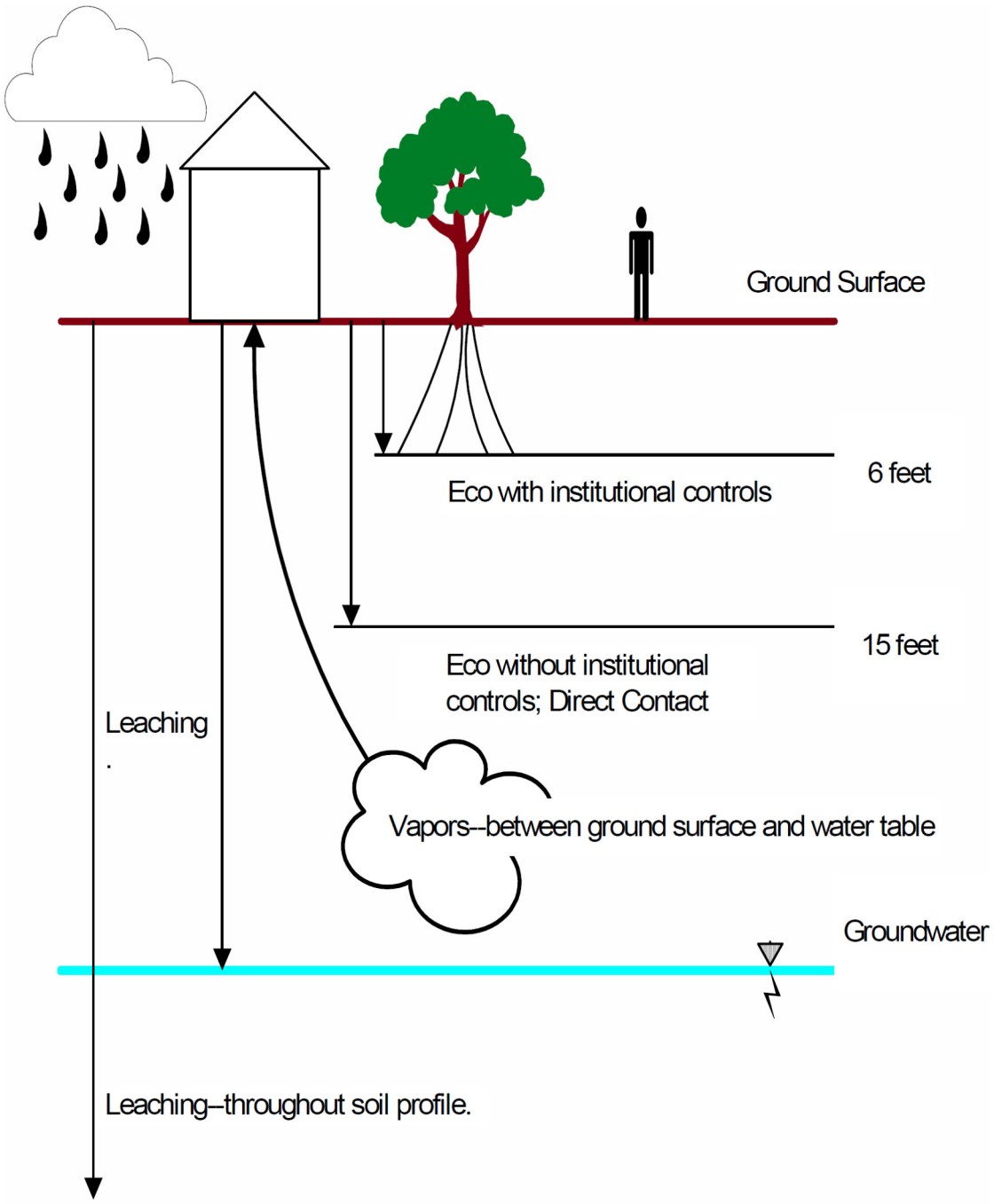
An extended discussion of the IPA regulatory requirements and other elements of the assessment context is presented in RPP-RPT-41918. The performance objectives associated with the IPA comprise a combination of requirements for DOE O 435.1, RCRA closure, and Ecology. Performance measures for the protection of groundwater will be used; a subset of applicable regulatory standards for groundwater protection is shown in Table 2-1.

### 2.2.1 Point of Assessment and Timing Assumptions

To evaluate the proposed closure actions (i.e., removal of the waste from the tank, filling the tank with grout, and the placement of the barrier) a groundwater model along with sensitivity analyses was developed. In order to evaluate the impacts to groundwater, a point of assessment in the unconfined aquifer needs to be established in which to compare model results against the performance objectives. Neither WAC 173-303 nor WAC 173-340 provided guidance as to where this point of assessment used to compare model results against performance objectives should be located.

The point of assessment for regulatory standards defined in Table 2-1 was selected to be where the highest contamination from WMA C crossed a plane perpendicular to groundwater flow direction located 100 m (328 ft) from the downgradient from the boundary of WMA C (i.e., the fenceline surrounding WMA C). The point of assessment selected is consistent with NUREG-1854, NRC Staff Guidance for Activities Related to U.S. Department of Energy Waste Determinations – Draft Final Report for Interim Use, Section 4.1.1.4 for the point of maximum exposure outside the disposal site; and it is also consistent with the requirements for points of assessment in DOE O 435.1 performance assessment of radiological impacts. Furthermore, this distance does allow plumes from different tanks within WMA C to intermingle in order to estimate total impacts from all sources within WMA C (as noted in NUREG-1854, Section 4.1.1.4). Additionally, other points of assessment are included in the sensitivity analyses (i.e., plane perpendicular to groundwater flow at the WMA C fenceline and 200 m downgradient from WMA C).

**Figure 2-1. Point of Compliance for Soils under Washington Administrative Code 173-340-740 and 173-340-745.**




**Disclaimer Notice:** This figure is intended to help the user understand WAC 173-340-740 & 745. It does not establish or modify regulatory requirements.

Source: 01-09-071, "Focus Sheet: Developing Soil Cleanup Standards Under the Model Toxics Control Act."

References:

WAC 173-340-740, "Unrestricted Land Use Soil Cleanup Standards," Washington Administrative Code, as amended.
WAC 173-340-745, "Soil Cleanup Standards for Industrial Properties," Washington Administrative Code, as amended.

**Table 2-1. Exposure Scenarios, Regulatory Standards (Target Risk, Hazard Quotients/Indices, and Groundwater Maximum Contaminant Levels), and Points of Assessment for the Waste Management Area C RCRA Closure Analysis.**

| Exposure Scenario | Regulatory Standards | | Point of Assessment | |
|---|---|---|---|---|
| | | | Operational and Active Institutional Control Periods [a] | Post-Institutional Control Period |
| Tap Water (Resident) Scenario | **Hazardous Chemicals[b]** | | Facility boundary | 100 m[c] |
| | Target Risk Level<br>Hazard Quotient | 1E-6<br>1 | | |
| | Cumulative Risk Level<br>Hazard Index | 1E-5<br>1 | | |
| | **Radionuclides** | | | |
| | Target Risk Range | 1E-6 to 1E-4 | | |
| Groundwater Protection | Federal Maximum Contaminant Level<br>2007 MTCA Groundwater Cleanup Levels | | At the source and 100 m[c] | 100 m[c] |

[a] The active institutional control period includes final closure.

[b] 2007 Model Toxics Control Act Cleanup Regulation, Washington Administrative Code 173-340, "Model Toxics Control Act – Cleanup."

[c] The point of highest projected concentration beyond a 100-meter buffer zone surrounding the disposed waste. Additionally, concentrations found in tank residuals will be compared against the standard MTCA three-phase model.

MTCA = Washington State Model Toxics Control Act RCRA = Resource Conservation and Recovery Act of 1976

The concentrations used for comparison with regulatory standards are peak concentrations in groundwater. These estimated peak groundwater concentrations are strictly applicable solely to the Ecology water resources regulatory standards. The tap water scenario applies to a point of exposure at which people may be exposed (i.e., at the wellhead of a pumping well). However, for consistency and simplicity, the calculated peak groundwater concentrations are used to evaluate the protection of water resources for the tap water scenario. Using calculated peak groundwater concentrations is a more conservative approach (i.e., yielding higher risk/hazard values), since taking into account pumping at the well for groundwater use has the potential to dilute groundwater concentrations.

### 2.2.2 Assessment Period

The assessment period being evaluated in this RCA was selected to be consistent with the time frames of analysis being examined in the DOE O 435.1 PA (i.e., the 0- to 1,000-year and the 1,000- to 10,000-year post-closure time periods). Longer time frames (10,000 years) are recommended in the analysis of low-level radioactive wastes per NRC guidance[1] (NUREG-1854,

[1] On March 26, 2015, NRC issued a proposed revision to Title 10, Code of Federal Regulations (CFR), Part 61, "Licensing Requirements for Land Disposal of Radioactive Waste" and associated guidance on treatment of time

Section 4.1.1.1) as a sensitivity and uncertainty analysis component to provide information to decision makers about potential long-term impacts. Concentration levels of some of the sorbed hazardous chemical and dangerous waste constituents begin to rise at the end of the 10,000-year analysis considered in this evaluation.

For purposes of this RCA, risk and hazard impacts will be compared with regulatory standards outlined in Table 2-1 for both the 0- to 1,000-year and 1,000- to 10,000-year post-closure time frames of analyses. Peak concentrations for longer are provided for contaminants that are rising at 10,000 years, but have not yet peaked. The closed facility is assumed to remain under institutional control for a period of 100 years after closure, at which time control and memory of the facility is assumed to be lost (NUREG-1854). This assumption about institutional controls only lasting 100 years is for the purposes of analysis only, and does not represent a DOE intent to release the facility in the future; see DOE P 454.1, Use of Institutional Controls, which specifically states "DOE will maintain the institutional controls as long as necessary to perform their intended protective purposes and seek sufficient funds."

## 2.3 REASONABLE EFFORTS TO MINIMIZE RELEASES

For WMA C, the process to minimize releases to the extent practicable is an intrinsic part of the retrieval and closure processes. The established retrieval criteria for SSTs are as defined in the HFFACO, Milestone M-045-00:

> "Closure will follow retrieval of as much tank waste as technically possible, with tank waste residues not to exceed *[10.2 $m^3$]* 360 cubic feet (cu. ft.) in each of the 100 series tanks, *[0.8 $m^3$]* 30 cu. ft. in each of the 200 series tanks, or the limit of waste retrieval technology capability, whichever is less. If the DOE believes that waste retrieval to these levels is not possible for a tank, then DOE will submit a detailed explanation to EPA and Ecology explaining why these levels cannot be achieved, and specifying the quantities of waste that the DOE proposes to leave in the tank. The request will be approved or disapproved by EPA and Ecology on a tank-by-tank basis."

When DOE completes retrieval of waste from a tank, DOE provides documentation to Ecology, known as a Retrieval Completion Certification (RCC), that DOE has completed retrieval of that tank. The RCC describes the technological approaches used to remove waste to the extent that is technically practicable. Therefore, the efforts to minimize releases from the closed facility using retrieval of waste are extensively documented and go through a regulatory review and approval process.

In addition to retrieval, releases from the facility can be minimized using design and closure methods. Alternative methods for closing the SSTs were evaluated as part of the scope of the

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frames in performance assessment (80 FR 16082, "Low-Level Radioactive Waste Disposal"; NUREG-2175, Guidance for Conducting Technical Analyses for 10 CFR Part 61 – Draft Report for Comment). At this time these regulatory changes and associated guidance are in the public comment period, and are not completed. Consequently, they are not addressed in this report.

TC&WM EIS (DOE/EIS-0391). Under the Tank Closure Alternatives, DOE evaluated each of the primary tank closure components, specifically, storage, retrieval, treatment, and disposal of tank waste and closure of the SST system. The TC&WM EIS considered a number of alternative options for retrieval, treatment, and closure of the SSTs. Specifically for residual wastes, these alternatives considered several possible approaches for SST closure, with an associated range of implications for long-term releases from the closed WMA C, as follows.

- Alternative 1: No action alternative.

- Alternative 2A: Retrieval of 99% of waste from the SSTs. The SST system would not be closed.

- Alternatives 2B, 3, and 6C: Retrieval of 99% of waste from the SSTs. Landfill closure of all SSTs under RCRA with the SSTs covered with an engineered, modified RCRA Subtitle C barrier designed to provide 500-year protection. Under these alternatives, contaminated soil would be removed down to 4.6 m (15 ft) at the 241-BX and 241-SX Tank Farms and replaced with clean soil from onsite sources. The 4.6-m (15-ft) depth would allow removal of some of the ancillary equipment prior to closure.

- Alternative 4: Retrieval of 99.9% of the waste from the SSTs. Selective clean closure of 241-BX and 241-SX Tank Farms, which means the tanks, ancillary equipment, and contaminated soil would be removed, and the remaining tank farms (including WMA C) would be closed as landfills and covered with an engineered, modified RCRA Subtitle C barrier.

- Alternative 5: Retrieval of 90% of the waste from the SSTs. The SST system would be closed as a landfill and covered with an engineered Hanford barrier, a multi-layer barrier designed to provide 1,000-year protection.

- Alternatives 6A and 6B: Retrieval of 99.9% of the waste from the SSTs. The SST system would be clean closed. Here, clean closure meant the removal or remediation of all hazardous waste such that further regulatory control under RCRA is not necessary.

Alternative 2B was selected as the preferred option in a ROD resulting from the EIS consideration of these options (78 FR 75913). By evaluating these alternatives, DOE has demonstrated reasonable efforts to minimize releases associated with the end state of WMA C.

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# 3.0 SITE AND FACILITY CHARACTERISTICS

This section provides descriptive information relevant to the WMA C site, environment, and facility to provide the basis for a conceptual model of how radionuclides and hazardous chemicals may be released following closure of the WMA. The organization of this section was taken from Performance Assessment Annotated Outline for Chapter Four given in DOE-STD-XXX, Radioactive Waste Management Disposal Authorization Statement Technical Basis Documentation Technical Standard. It is comparable to the information found in Chapter 3 "Physical Characteristics of the Study Area" in the more recent remedial investigations/feasibility studies (RI/FSs) (e.g., DOE/RL-2010-97, Remedial Investigation/ Feasibility Study for the 100-KR-1, 100-KR-2, and 100-KR-4 Operable Units, Draft A).

The assessment of radionuclide and hazardous chemical transport from WMA C and the resulting human exposure from release of those contaminants into the environment requires careful consideration of factors affecting transport processes and the potential for exposure. Topographic features and hydrogeologic characteristics strongly affect the fate and transport of contaminants potentially released from the closed site. Projected land use and population distributions affect the estimation of impacts from human exposure. Facility features control how contaminants would be released and the rate at which they are released from the facility. The waste inventory, concentration, volume, and form affect the magnitude and rate of constituent releases from the source term. Each of these topics is discussed in the following sections.

## 3.1 SITE CHARACTERISTICS

The relevant natural and demographic characteristics and data for WMA C and the surrounding area are given in this section. The purpose of this information is to provide basis for the site conceptual model and method of analysis in sufficient detail to support the PA required by HFFACO (Ecology et al. 1989) Appendix I Section 2.5. Detailed information on the topics given in this section can be found in the data packages produced for the WMA C PA scoping session meetings that took place from May 2009 through May of 2011, as well as new characterization documents that have been released since the end of the scoping sessions. References to the detailed information are provided in the summary descriptions. A listing of the scoping sessions and associated data packages are given in the introduction and Appendix A.

### 3.1.1 Geography and Demography

This section describes the geography and demography of the Hanford Site, including a description of the use of adjacent lands, the current population database, the socioeconomics of the area, past and planned DOE activities, and the results of an investigation of future uses conducted for inclusion in the "Final Hanford Comprehensive Land-Use Plan Environmental Impact Statement" and associated ROD (DOE/EIS-0222-F, 64 FR 61615). Additional detailed information on the geography and demography of the site can be found in Revision 18 of PNNL-6415, "Hanford Site National Environmental Policy Act (NEPA) Characterization."

#### 3.1.1.1 Site Location

**3.1.1.1.1 Hanford Site.** The Hanford Site encompasses ~1,517 km² (~586 mi$^2$) in Benton, Franklin, and Grant Counties, located in south-central Washington State (Figure 3-1) within the semi-arid Pasco Basin of the Columbia Plateau. Nearby towns are Richland (40 km [25 mi] to the southeast) and Yakima (80 km [50 mi] to the west), with the nearby major metropolitan areas being Spokane (201 km [125 mi] to the northeast), Seattle (241 km [150 mi] to the northwest) and Portland, Oregon (~400 km [~250 mi] downstream on the Columbia River). The Hanford Site stretches ~48 km (~30 mi) north to south and ~38 km (~24 mi) east to west, immediately north-northwest of the confluence of the Yakima and Columbia Rivers, the Cities of Kennewick, Pasco, and Richland (the Tri-Cities), and the City of West Richland.

The Columbia River flows eastward through the northern part of the Hanford Site and then turns south, forming part of the eastern Site boundary. This section of the river is known as the Hanford Reach and is a free-flowing section of the Columbia River, ~82 km (~51 mi) long. It is named after a large northward bend in the river's otherwise southbound course. It is the only section of the Columbia River in the U.S. that is neither tidal nor part of a reservoir. The following seven dams are upstream of the Hanford Site and are listed from closest to furthest from Hanford: Priest Rapids, Wanapum, Rocky Island, Rocky Reach, Wells, Chief Joseph, and Grand Coulee. Other important rivers near the Hanford Site are the Yakima River to the south and southwest and the Snake River to the east. The Cascade Mountains, which are ~160 km (100 mi) to the west, have an important effect on the climate of the area.

The Yakima River runs near the southern boundary of the Hanford Site, joining the Columbia River at the City of Richland. Rattlesnake Mountain, Yakima Ridge, and Umtanum Ridge form the southwestern and western boundaries of the Site, and Saddle Mountain forms its northern boundary. The plateau of the central portion of the Hanford Site is punctuated by two small east-west ridges, Gable Butte and Gable Mountain. Lands adjoining the Hanford Site to the west, north, and east are principally range and agricultural areas.

**3.1.1.1.2 Waste Management Area C.** Waste Management Area C is one of 12 SST farms that were built from 1943 to 1962 and designed to store and transfer mixed waste generated as a part of Hanford Site operations. A complete description of WMA C is given in Section 3.2 Facility Design and Operational Features. It is located within the Hanford Site in the east central portion of the 200 East Area (Figures 3-1 and 3-2). The WMA C boundary is represented by the fenceline surrounding the C Farm (Figure 3-3), which encloses an area of ~3.4 hectares (~8.5 acres). In Figure 3-3, the pipelines emanating out of the diversion boxes have been color coded to the diversion box, thereby allow the reader to follow the pipelines and associated connections. Waste Management Area C is located 11.3 km (7 mi) west of the Columbia River, with the groundwater gradient toward the Columbia River.

#### 3.1.1.2 Site Description

**3.1.1.2.1 Hanford Site Description.** The Hanford Site is a relatively undeveloped area of shrub-steppe (a drought-resistant, shrub and grassland ecosystem) that contains a rich diversity of plant and animal species. This area has been protected from disturbance, except for fire, over

the past 60 years. This protection has allowed plant species and communities that have been displaced by agriculture and development in other parts of the Columbia Basin to thrive at the Hanford Site.

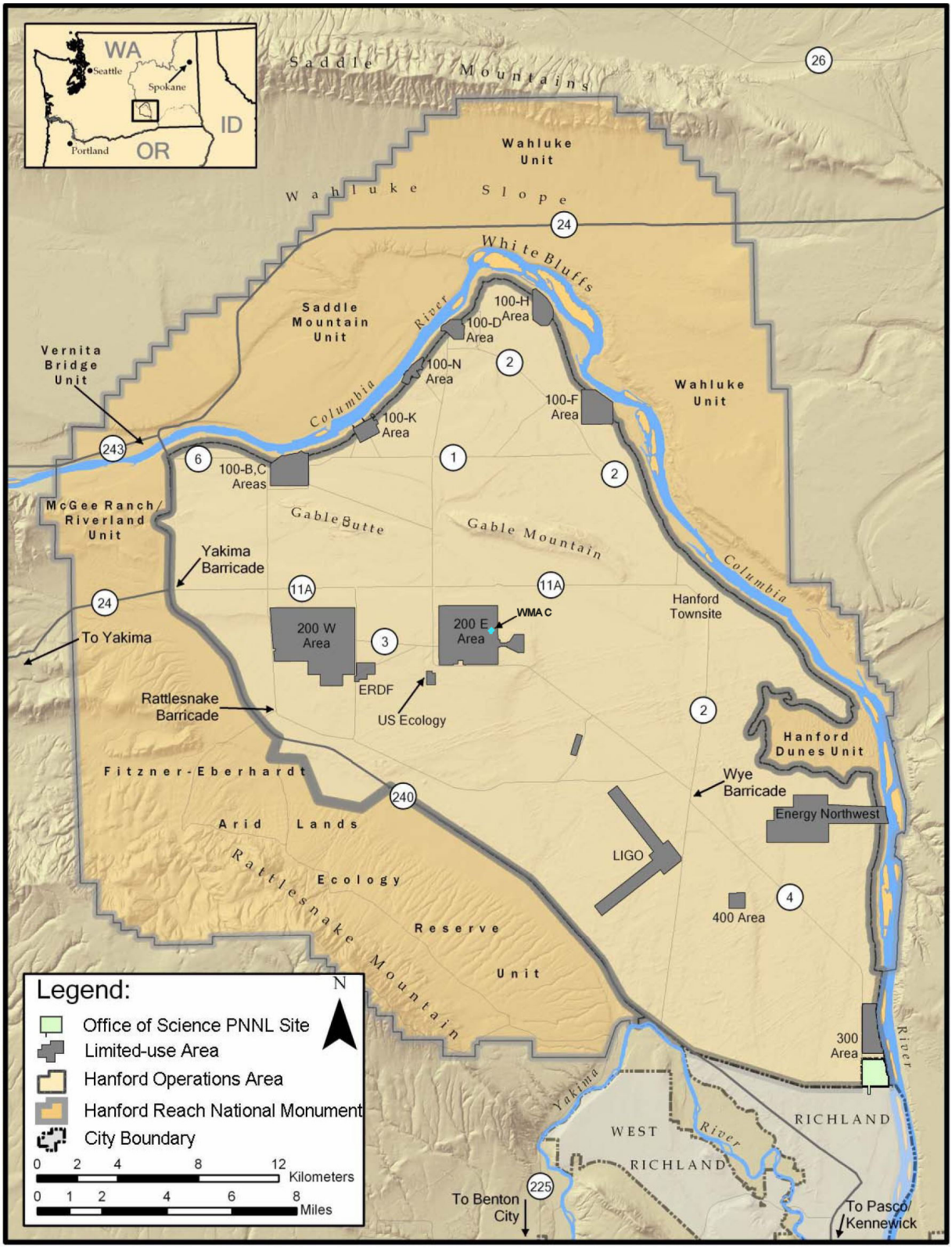
In the past, the Hanford Site was a U.S. Government defense materials production site that included nuclear reactor operation, uranium and plutonium processing, the storage and processing of spent nuclear fuel (SNF), and the management of radioactive and hazardous chemical wastes. The current mission at Hanford includes managing waste products, cleaning up the Site, researching new ideas and technologies for waste disposal and cleanup, and reducing the size of the Site [PNNL-20548, "Hanford Site Environmental Report for Calendar Year 2010 (Including Some Early 2011 Information)," page v.]. Present Hanford programs are diversified and include the management of radioactive waste, cleanup of waste sites and soil and groundwater contaminated by past waste releases, stabilization and storage of SNF, research into renewable energy and waste disposal technologies, cleanup of contamination, and stabilization and storage of plutonium.

Hanford is owned and used primarily by DOE, but portions of it are owned, leased, or administered by other Government agencies. Public access to the Site is limited to travel on the Route 4 and Route 10 access roads as far as the Wye Barricade, State Routes 24 and 240, and the Columbia River. By restriction of access, the public is shielded from portions of the Site formerly used for the production of nuclear materials and currently used for waste storage and disposal. Only ~6% of the land area has been disturbed and is actively used, leaving mostly vacant land with widely scattered facilities (Revision 17 of PNNL-6415, page 4.144). Figure 3-4 shows the generalized land use at Hanford as developed in the "Final Hanford Comprehensive Land-Use Plan Environmental Impact Statement" (DOE/EIS-0222-F, 64 FR 61615) and modified by the designation of the Hanford Reach National Monument (65 FR 37253, "Establishment of the Hanford Reach National Monument").

In June 2000, a Presidential proclamation (65 FR 37253) established the 78,914-hectare (195,000-acre) Hanford Reach National Monument to protect the nation's only un-impounded stretch of the Columbia River above Bonneville Dam and the largest remnant of the shrub-steppe ecosystem that once blanketed the Columbia River Basin. In 2003, DOE and the U.S. Fish and Wildlife Service began management of the monument. The U.S. Fish and Wildlife Service administered three major management units of the monument totaling ~668 km² (~258 mi$^2$). These included (1) the Fitzner/Eberhardt Arid Lands Ecology Reserve Unit, a 310-km² (120-mi$^2$) tract of land in the southwestern portion of the Hanford Site; (2) the Saddle Mountain Unit, a 129-km² (50-mi$^2$) tract of land located north-northwest of the Columbia River and generally south and east of State Highway 24; and (3) the Wahluke Unit, an 225-km² (87-mi$^2$) tract of land located north and east of both the Columbia River and the Saddle Mountain Unit.

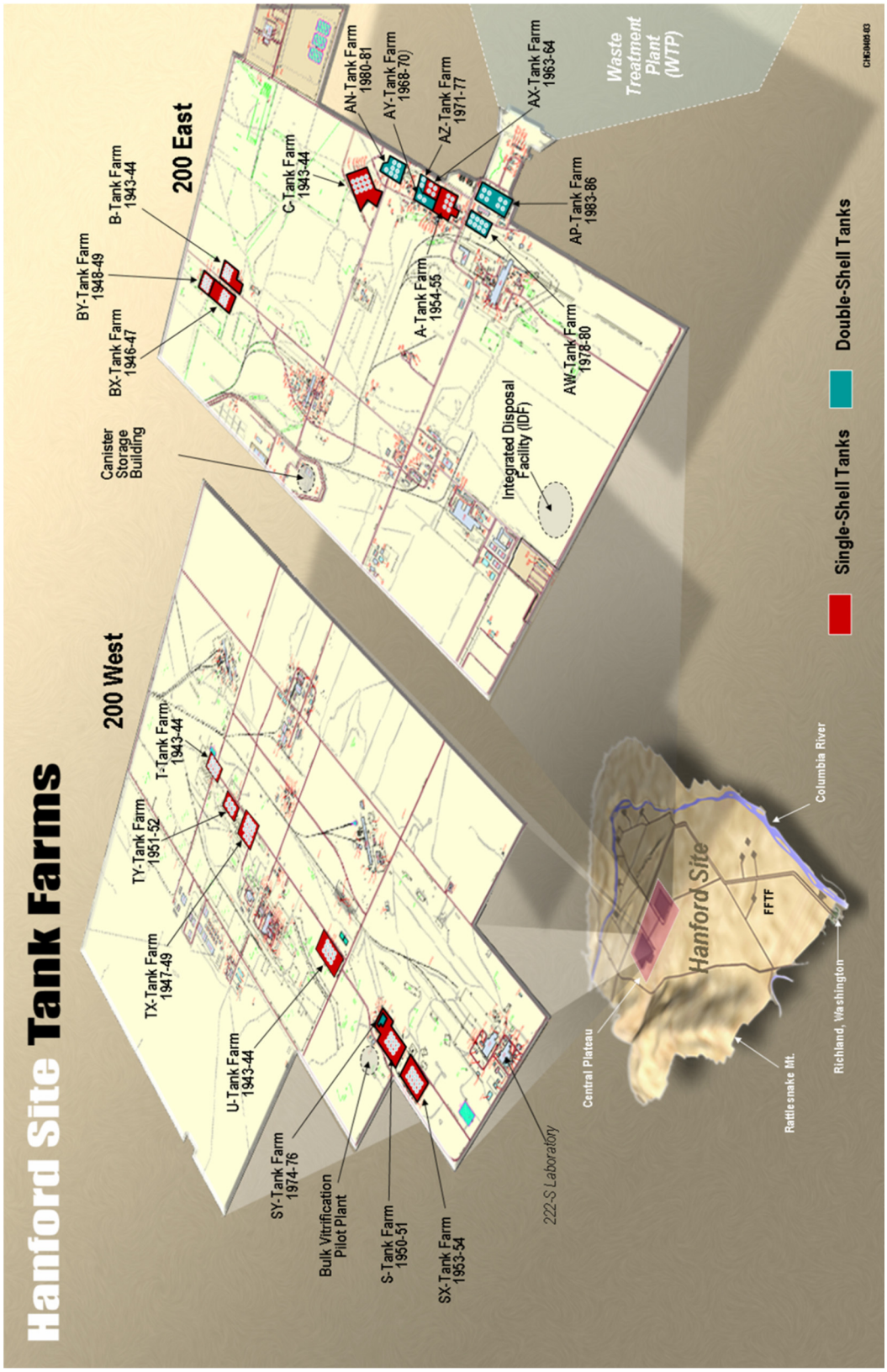
**3.1.1.2.2 Waste Management Area C.** This section provides a summary description of WMA C (Section 3.2 provides a complete detailed description of the WMA). Waste Management Area C is one of 12 tank farms that make up the SST system. The Hanford Site SST system consists of 149 underground SSTs and processing equipment, and was designed and constructed between 1940 and 1964 to transport and store radioactive and hazardous chemical wastes generated from irradiated nuclear fuel processing. One of the first tank farms built, WMA C was constructed in 1944 and 1945.

**Figure 3-1. U.S. Department of Energy's Hanford Site and Surrounding Area.**



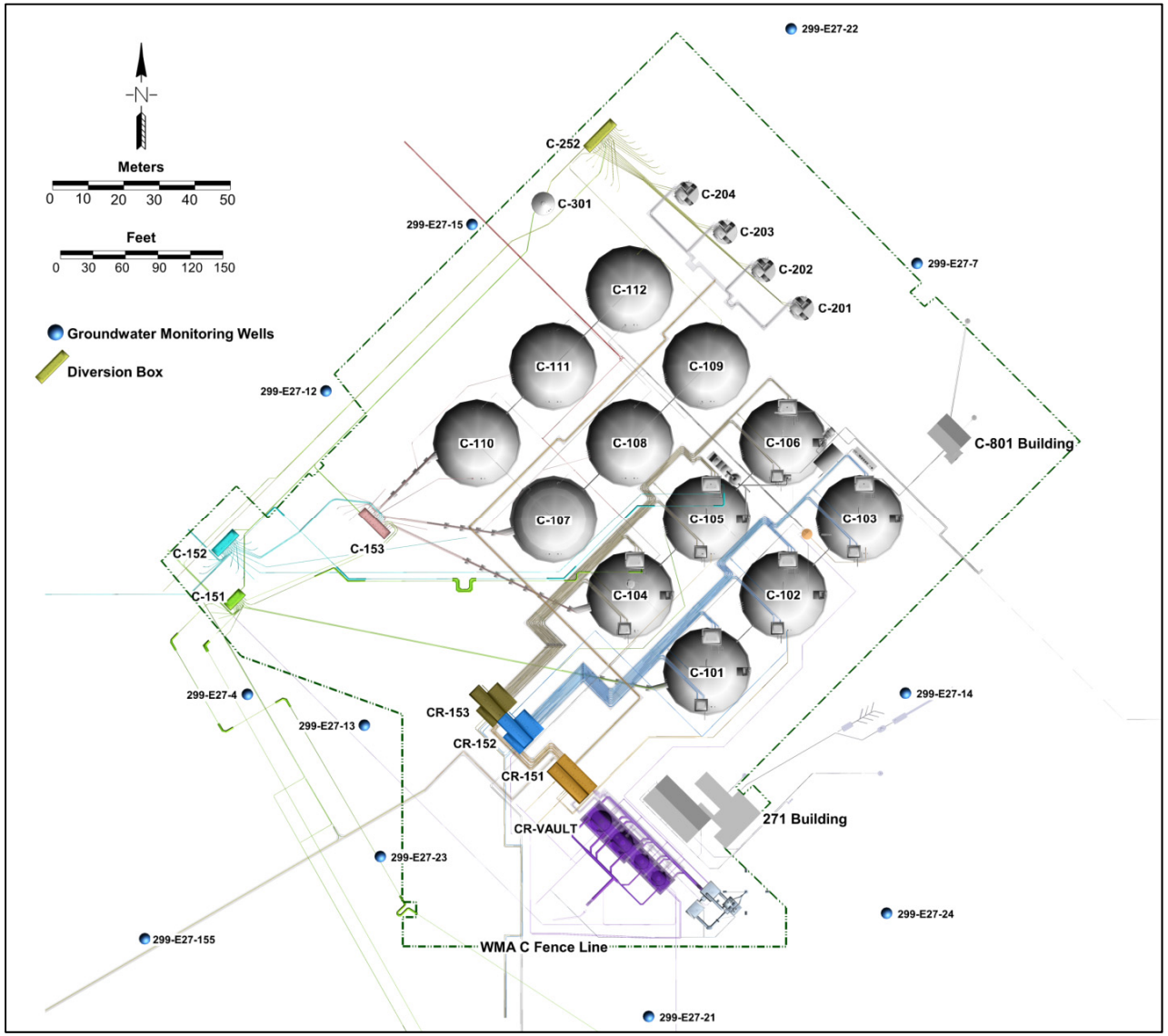

ERDF = Environmental Restoration Disposal Facility
LIGO = Laser Interferometer Gravitational Wave Observatory
PNNL = Pacific Northwest National Laboratory
WMA = Waste Management Area

**Figure 3-2. Facilities in the 200 East and 200 West Areas.**



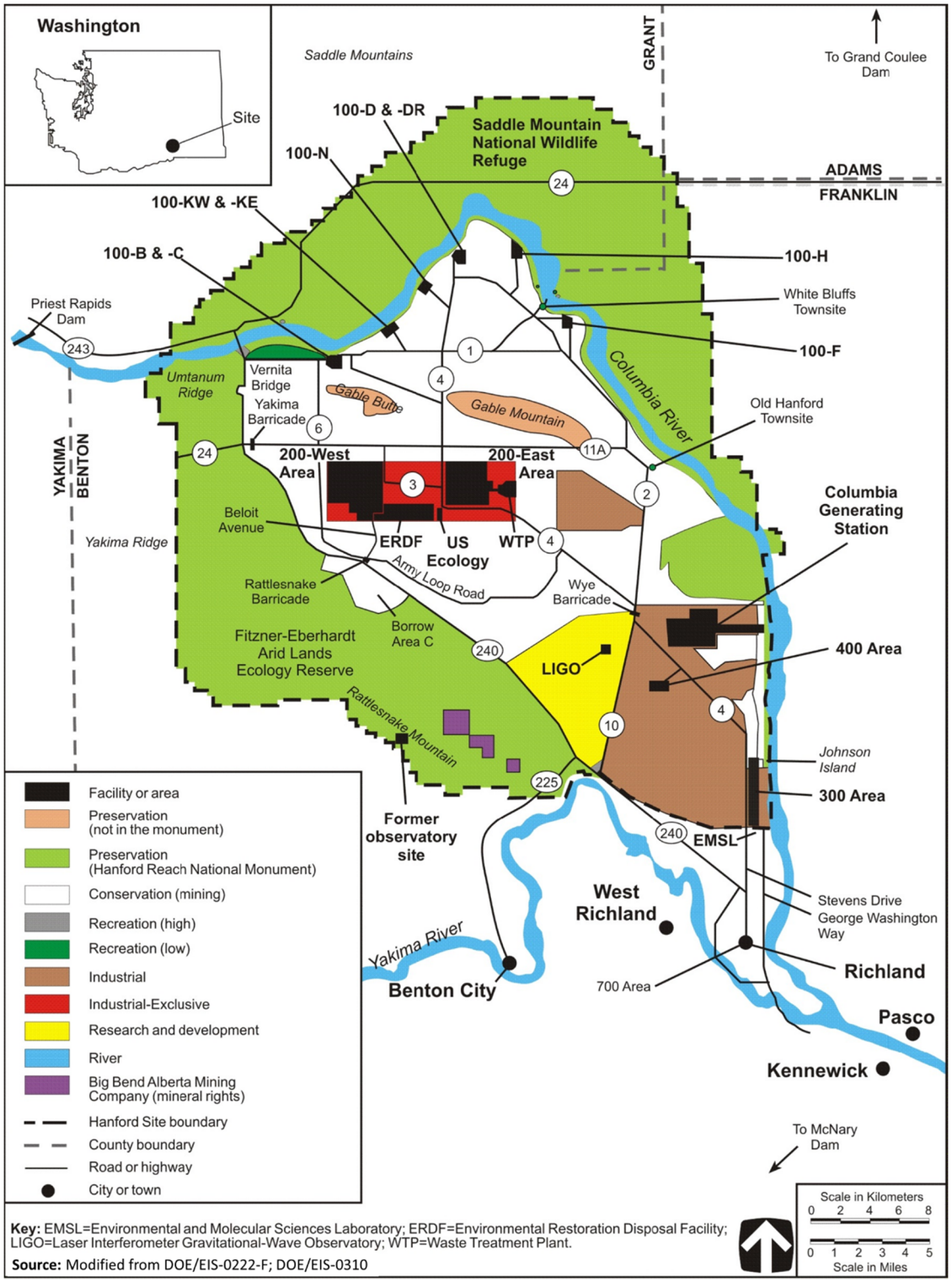

FFTF = Fast Flux Test Facility

**Figure 3-3. Waste Management Area C Tanks and Associated Infrastructure.**




WMA = Waste Management Area

**Figure 3-4. Generalized Land Use of the Hanford Site and Adjacent Areas.**




References:

DOE/EIS-0222-F, "Final Hanford Comprehensive Land-Use Plan Environmental Impact Statement."

DOE/EIS-0310, "Final Programmatic Environmental Impact Statement for Accomplishing Expanded Civilian Nuclear Energy Research and Development and Isotope Production Missions in the United States, Including the Role of the Fast Flux Test Facility."

WMA C contains twelve 100-series tanks and four 200-series tanks (see Figure 3-4). The 100-series tanks are 75 ft in diameter, with a nominal 16-ft depth and 530,000-gal design capacity. The 200-series tanks are 20 ft in diameter with a nominal 24-ft depth and 55,000-gal design capacity. Other specific details of these tanks are provided in Sections 1.3 and 3.2. The transfer and storage of waste within WMA C SSTs was supported by a complex waste transfer system of pipelines (transfer lines), diversion boxes, vaults, valve pits, and other miscellaneous structures.

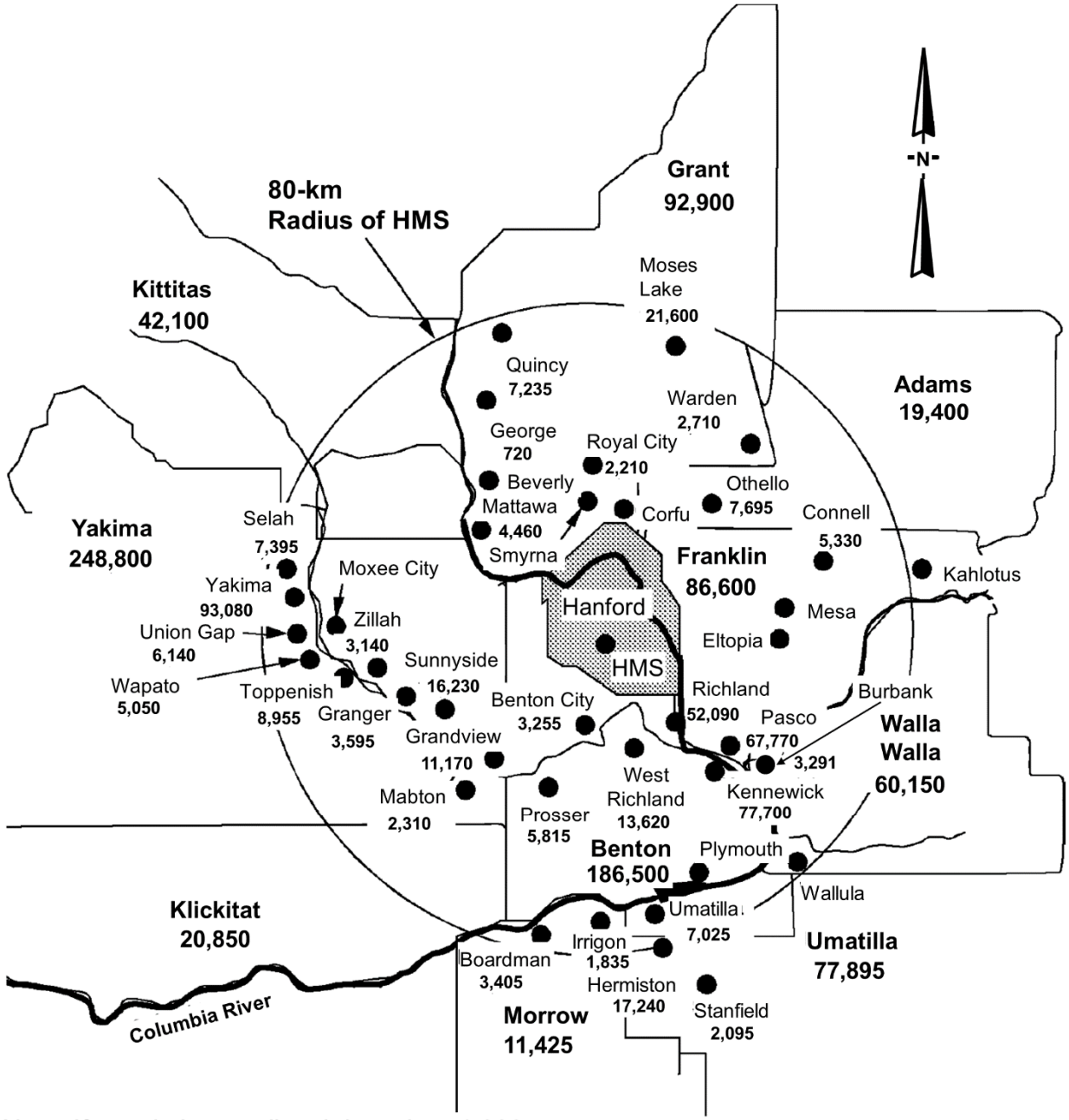
Additionally, 14 UPRs have occurred within or near to WMA C. The largest ones are associated with releases from pipelines or diversion boxes, with releases from inlet/outlet ports of the SSTs, or with leaks from the SSTs. RPP-PLAN-39114 and RPP-RPT-58339 provide more detail on these UPR sites. As identified in Section 1, the impacts from the UPRs are not considered under the scope of this RCA; but rather, will be addressed through the RCRA Corrective Action process.

**3.1.1.3 Population Distribution.** Demographic data are used within a performance assessment to help set the exposure scenarios for assessing dose/risk and to select dosimetry parameters. The population data for Washington are for April 1, 2014 from Office of Financial Management (OFM) April 1 Official Population Estimates (State of Washington Office of Financial Management, Queried 05/17/2015, [April 1 official population estimates], http://www.ofm.wa.gov/pop/april1/default.asp). The population data for Oregon are from the Population Research Center at Portland State University, which provides the official post-census estimate of population numbers for Oregon, and are used to disburse State revenues to Oregon counties and cities. The estimates were published April 15, 2014 for the July 1, 2013 populations (Portland State University College of Urban & Public Affairs: Population Research Center, Queried 05/17/2015, [Population Estimates and Reports], http://www.pdx.edu/prc/population-reports-estimates).

The major population centers within an 80-km (50-mi) radius of the Hanford Site are shown in Figure 3-5, along with their estimated 2013 to 2014 populations. The 80-km (50-mi) radius is centered on the Hanford Meteorological Station (HMS), located ~1.7 km (~1.0 mi) east of WMA T in the 200 West Area, and 6.6 km (4.1 mi) west of WMA C. Portions of Benton, Franklin, Adams, Grant, Kittitas, Yakima, Klickitat, and Walla Walla Counties in Washington, and Morrow and Umatilla Counties in Oregon, lie within the 80-km (50-mi) radius. Most of the people reside in the counties of Benton and Franklin, which are two of the fastest-growing counties in Washington with rates of growth during the 2000s of 23% and 58%, respectively. From 2010 to April 1, 2014, Benton and Franklin counties continue to be the fastest-growing counties in the State with rates of growth of 6.5% and 10.8%, respectively.

The largest population center within the 80-km (50-mi) radius of the Site is the Tri-Cities (i.e., Richland, Kennewick, and Pasco), located ~40 km (25 mi) to the southeast of HMS for Richland, and 56 km (35 mi) to the southeast of HMS for Kennewick and Pasco. Other major population centers include Moses Lake, 64 km (40 mi) to the north-northeast of HMS; Yakima, 69 km (40 mi) to the west of HMS; and Umatilla, 75 km (47 mi) to the south-southeast of HMS. The Washington cities of Ellensburg and Walla Walla lie just beyond the 80-km (50-mi) radius.

**Figure 3-5. Population Centers with Estimated Population within 80-km (50-mi) of the Hanford Meteorological Station.**




Note: If population not listed, less than 1,000
Data: Washington State April 2014, Oregon July 2013
HMS = Hanford Meteorological Station

In 2010, ~586,500 people resided within 80 km (50 mi) of the HMS (PNNL-20631, "Hanford Site Regional Population-2010 Census"). This total represents an increase in population of 29% from 1990 to 2000 and 21% from 2000 to 2010 (PNNL-20631). Because WMA C's location is near the center of the Hanford Site, the resident population within 16 km (10 mi) is estimated to

be only 15, and 13,000 within 32 km (20 mi) (PNNL-20631). About 186,000 people, located mostly to the southwest and the southeast, live between 32 and 48 km (20 and 30 mi) from WMA C (PNNL-20631). The population numbers have grown since 2010.

**3.1.1.4 Uses of Adjacent Lands.** This section describes the socioeconomics of the region, historical use of the land, and the expected future use of the land.

**3.1.1.4.1 Socioeconomics.** The principal driving forces of the Tri-Cities' economy since the early 1970s are: 1) DOE and its contractors operating the Hanford Site; 2) Energy Northwest (formerly the Washington Public Supply System) which operates a nuclear power plant just north of Richland; and 3) the agricultural community, including a substantial food-processing component. Although DOE activities, agriculture and food processing are the dominant industries, there has been a substantial rise in the number of visitors to the Tri-Cities over the last several years resulting in tourism playing an increasing role in helping to diversify and stabilize the area's economy. Overall tourism expenditures for 2011 were $393 million, up from $299 million in 2005. The socioeconomics of the area surrounding the Hanford Site are more fully described in Section 4.7 of PNNL-6415.

The land use classification around the Hanford Site varies from urban to rural. Most of the land south of the Hanford Site is urban, including the Tri-Cities, while much of the land to the north and east is irrigated crop land. Most of the irrigation water comes from the Bureau of Reclamation Columbia Basin Project, which uses the water behind Grand Coulee Dam as the primary water source. The water is transported via canals to the areas north and east of the Columbia River. The land to the west of the Hanford Site is used for irrigated agriculture near the Yakima River and dry-land farming at the higher elevations. The Columbia River is used by the cities of Richland, Pasco, and Kennewick for drinking water. It is also used for recreation and hydroelectric power production for the western United States.

Additionally, the Hanford Reach contains islands, riffles, gravel bars, oxbow ponds, and backwater sloughs that support some of the most productive salmon spawning areas in the Northwest, including the largest remaining stock of wild fall chinook salmon in the Columbia Basin. The loss of other spawning grounds on the Columbia and its tributaries has increased the importance of the Hanford Reach's fisheries.

**3.1.1.4.2 Early Historical Use of the Land.** In prehistoric and early historic times, American Indians of various tribal affiliations heavily populated the Hanford Reach, and some of their descendants still live in the region. Present-day tribal members retain traditional secular and religious ties to the region, and many have knowledge of the ceremonies and lifestyles of their culture. The Washani, or Seven Drums religion, which has ancient roots, is still practiced by many American Indians. Native plant and animal foods, some of which can be found at Hanford, are used in ceremonies performed by tribal members (DOE/EIS-0310, "Final Programmatic Environmental Impact Statement for Accomplishing Expanded Civilian Nuclear Energy Research and Development and Isotope Production Missions in the United States, Including the Role of the Fast Flux Test Facility," pages 3-125).

Significant non-Indian settlement of the region began relatively late. In 1888, small irrigation companies and farmer cooperatives began to develop irrigation systems in the Columbia Basin. The agricultural economy of the region saw upswings and downswings, from agricultural price increases during World Wars I and II, drought during the 1920s, and the Great Depression during the 1930s. While, principally, non-Indian farmers lived on the adjacent private lands, members of the Wanapum Band continued to reside on portions of the future Hanford Site that remained in Federal ownership. In 1942, ~19,000 people lived in Benton and Franklin counties. Pasco was the largest population center, with ~3,900 people (WHC-MR-0293, "Legend and Legacy: Fifty Years of Defense Production at the Hanford Site"). The City of Richland had a population of ~200 people (Drummers and Dreamers [Relander 1956]).

In the early 1940s, almost all of the land that would at some time be considered part of the Hanford Site was being used for crops or grazing. More than 88% (~152,971 ha [378,000 ac]) was sagebrush range land interspersed with volcanic outcroppings, where some 18,000 to 20,000 sheep grazed during winter and spring. Some 11% (almost 19,830 ha [49,000 ac]) was farmland, much of it irrigable but not all under cultivation. Less than 1% (less than 809 ha [2,000 ac]) consisted of town plots, right of ways, school sites, cemeteries, and similarly used land, most of it in or near the three small communities of Richland, Hanford, and White Bluffs (United States Army in World War II, Special Studies -- Manhattan: The Army and the Atomic Bomb [Jones 1985]).

**3.1.1.4.3 Past and Present U.S. Department of Energy Activities at the Hanford Site.** In 1943, the Hanford Engineer Works was established as one of the three original Manhattan Project sites and USACE began construction of the Hanford Site to produce plutonium for national defense. It was the first nuclear production facility in the world. The region was selected because of its remoteness and because it had abundant electrical power from Grand Coulee Dam (located ~230 mi [~370 km] upstream from the old Hanford town site), a functional railroad, clean water from the Columbia River, and available sand and gravel for construction. The USACE divided the site into a number of operational areas which are briefly summarized below (for more information on the description of each operational area, please see PNNL-6415, Revision 18 or DOE/EIS-0391).

- **100 Areas:** These areas of the Site are situated along the shore of the Columbia River in the northern portion of the Site and contain nine retired nuclear reactors. The irradiated fuel produced in the 100 Areas reactors was transported by rail to the 200 Areas.

- **200 Areas:** Fuel reprocessing, plutonium and uranium separation, plutonium finishing, and waste management including treatment, storage, and disposal activities, have been conducted in the 200 Areas. Waste from the research and development activities and fuel fabrication activities in the 300 Area, reactor operation programs conducted in the 100 Areas, and FFTF in the 400 Area is sent to the 200 Areas for storage and disposal. Waste management activities are scheduled to continue until the mid-21st century. Waste management facilities are located in the 200 Areas, which are surrounded by

security fencing. The following major facilities, many of which are inactive, are located in the 200 Areas (Figure 3-2):

- Burial trenches, burial grounds, low-level waste burial grounds
- 18 underground storage tank farm areas including the 241-A, 241-AN, 241-AP, 241-AW, 241-AX, 241-AY, 241-AZ, 241-B, 241-BX, 241-BY, 241-C, 241-S, 241-SX, 241-SY, 241-T, 241-TX, 241-TY, and 241-U Tank Farms
- Very large fuel processing and recovery facilities including the B, T, U, and Z Plants, and the Reduction-Oxidation (REDOX) and Plutonium Uranium Extraction (PUREX) facilities
- Tank wastewater evaporator facilities (242-A, 242-S, and 242-T Evaporators)
- Office and warehouse buildings.

Between and just south of the 200 East and West Areas is the ERDF (Figures 3-1 and 3-4). This facility is a trench system and will hold most of the contaminated soil and materials from facility decontamination and decommissioning and Hanford Site remediation. Washington State leases a 3.9-$km^2$ (1.5-$mi^2$) parcel located between the 200 West and 200 East Areas, which, in turn, subleases a portion of this land to U.S. Ecology, Inc., a private company, for the disposal of commercially-generated low-level radioactive waste.

- **300 Area:** This area of the Site is located just north of Richland and was the location of nuclear fuel fabrication and research and development activities.

- **400 Area:** This area of the Site is located northwest of the 300 Area. It is the location of FFTF, a 400-megawatt thermal, liquid-metal (sodium) cooled nuclear research and test reactor owned by DOE. The facility, which operated for ~10 years, has been shut down since 1993 and is currently being deactivated.

- **600 Area:** This area of the Site includes the Hanford Reach National Monument and all the land not included in the 100, 200, 300, and 400 Areas. The Hanford Reach National Monument, established in 2000 (65 FR 37253), totals 792.6 $km^2$ (306 $mi^2$) and includes Fitzner-Eberhardt Arid Lands Ecology Reserve Unit, Saddle Mountain Wildlife Refuge Unit, McGee Ranch/Riverlands Unit, and land 0.40 km (0.25 mi) inland from the mean high-water mark on the south and west shores of the 82 km (51 mi)-long Hanford Reach of the Columbia River. It also includes the Federally-owned islands in the Hanford Reach and the sand dune area northwest of the Energy Northwest site. This designation establishes the protection and management of the land encompassing the monument. A separate memorandum allows for the incorporation of additional Hanford Site lands into the monument as the land is remediated.

- **Former 700 Area:** This area of the Site was the original location for administrative activities for the Hanford Site and was located where the Federal Building is located today (DOE/RL-97-02, National Register of Historic Places Multiple Property Documentation Form - Historic, Archaeological and Traditional Cultural Properties of the Hanford Site, Washington). It is no longer part of the Hanford Site.

- **Former 1100 Area:** This area of the Site was the location of general stores and transportation maintenance facilities for the Hanford Site. The 1100 Area was located between the 300 Area and the city of Richland, encompassing an area of ~311 hectares (768 acres). In September 1996, the 1100 Area was declared remediated and EPA issued a delisting of this area of the Site from the National Priorities List (DOE/RL-96-16, Screening Assessment and Requirements for a Comprehensive Assessment: Columbia River Comprehensive Impact Assessment). Most of the 1100 Area has been incorporated into the city of Richland and is no longer a part of the Hanford Site (DOE/RL-88-30, Hanford Site Waste Management Units Report).

For more than 40 years, the primary mission at Hanford was associated with the production of nuclear materials for national defense. Land management and development practices at the Hanford Site were driven by resource needs for nuclear production, chemical processing, waste management, and research and development activities. The DOE developed infrastructure and facility complexes to accomplish this work, but large tracts of land used as protective buffer zones for safety and security purposes remained undisturbed. These buffer zones preserved a biological and cultural resource setting unique in the Columbia Basin region.

In the late 1980s, the primary DOE mission changed from defense materials production to environmental restoration. In 1989, DOE entered into the HFFACO (Tri-Party Agreement) with EPA and Ecology (Ecology et al. 1989).

The Hanford Site encompasses more than 2,963 waste management units and contaminated groundwater plumes that have been grouped into 75 operable units (OUs). Each OU has complementary characteristics such as geography, waste content, type of facility, and relationship to contaminant plumes. The grouping into designated OUs allows for economies of scale to reduce the cost and number of characterization investigations and remedial actions required to complete environmental cleanup (WHC-EP-0216, “Preliminary Operable Units Designation Project”).

**3.1.1.4.4 Future Hanford Land Use.** In 1992, DOE, EPA, and Ecology gathered a group of stakeholders (Hanford Future Site Uses Working Group [HFSUWG]) to study potential future uses for the Hanford Site land. This HFSUWG issued a summary (“The Future for Hanford: Uses and Cleanup, Summary of the Final Report of the Hanford Future Site Uses Working Group” [HFSUWG 1992a]) and a detailed report (“The Future for Hanford: Uses and Cleanup, The Final Report of the Hanford Future Site Uses Working Group” [HFSUWG 1992b]) of its findings. The “Final Hanford Comprehensive Land-Use Plan Environmental Impact Statement” (DOE/EIS-0222-F) is heavily based on the work of the HFSUWG. However, DOE land use planning extends for only 50 years instead of the 100 years forecast by the HFSUWG.

HFSUWG (1992a) contains the following statement about near-term use of the 200 Areas, called the Central Plateau in the report:

> "The presence of many different types of radionuclides and hazardous constituents in various volumes, forms and combinations throughout the site poses a key challenge to the Hanford cleanup. To facilitate cleanup of the rest of the site, wastes from throughout the Hanford site should be concentrated in the Central Plateau. … Waste storage, treatment, and disposal activities in the Central Plateau should be concentrated within this area as well, whenever feasible, to minimize the amount of land devoted to, or contaminated by, waste management activities. This principle of minimizing land used for waste management should specifically be considered in imminent near-term decisions about utilizing additional uncontaminated Central Plateau lands for permanent disposal of [sic] grout."

The report continues on the subject of future use options (HFSUWG 1992a):

> "In general, the Working Group desires that the overall cleanup criteria for the Central Plateau should enable general usage of the land and groundwater for other than waste management activities in the horizon of 100 years from the decommissioning of waste management facilities and closure of waste disposal areas."

Based on conversations of the HFSUWG, they could not agree on a definition of "general use." For the "foreseeable future," the HFSUWG developed options involving waste treatment, storage, and disposal of DOE low-level radioactive waste. The differences among the options are whether offsite waste (radioactive and/or hazardous) would be allowed to be disposed of on the Hanford Site. Finally, the report states (HFSUWG 1992a):

> "The working group identified a single cleanup scenario for the Central Plateau. This scenario assumes that future uses of the surface, subsurface, and groundwater in and immediately surrounding the 200 West and 200 East Areas would be exclusive. … Surrounding the exclusive area would be a temporary surface and subsurface exclusive buffer zone composed of at least the rest of the Central Plateau…As the risks from waste management activities decrease, it is expected that the buffer zone would shrink commensurately."

For nearer-term land use planning, the ROD (64 FR 61615) for the "Final Hanford Comprehensive Land-Use Plan Environmental Impact Statement" (DOE/EIS-0222-F) identifies near-term land uses for the Hanford Site. The ROD prescribes the use in the 200 Areas as exclusively industrial (primarily waste management) with much of the surrounding land having the use of preservation or conservation. The Hanford Reach National Monument was established along the Columbia River corridor as well as in lands at the northern and western edges of the Site (65 FR 37253). For further discussion of Hanford land uses, the reader is referred to DOE/EIS-0222-F and DOE/RL-2009-10, Hanford Site Cleanup Completion Framework.

### 3.1.2 Meteorology and Climatology

The climate of the Pasco Basin, where the Hanford Site is located, can be classified as either mid-latitude semiarid or mid-latitude desert, depending on which climatological classification system is being used. Large diurnal temperature variations are common, resulting from intense solar heating and night-time cooling. Summers are warm and dry with abundant sunshine. Daytime high temperatures in June, July, and August can exceed 40°C (104°F). Winters are cool with occasional precipitation that makes up ~44% of the yearly total. During the winter, outbreaks of cold air associated with modified arctic air masses can reach the area and cause temperatures to drop below -18°C (0.4°F). Overcast skies and fog occur during the fall and winter months.

The region's climate is greatly influenced by the Pacific Ocean and the Cascade Mountain Range to the west, and other mountain ranges to the north and east. The Pacific Ocean moderates temperatures throughout the Pacific Northwest, and the Cascade Range generates a rain shadow that limits rain and snowfall in the eastern half of Washington State. The Cascade Range also serves as a source of cold air drainage, which has a considerable effect on the wind regime on the Hanford Site. Mountain ranges to the north and east of the region shield the area from the severe winter storms and frigid air masses that move southward across Canada.

**3.1.2.1 Current Data.** Climatological data for the Hanford Site are compiled at the HMS, which is located on the Central Plateau, just outside the northeast corner of the 200 West Area and ~4 km (3 mi) west of the 200 East Area. To characterize meteorological differences accurately across the Hanford Site, the HMS operates a network that currently contains 30 monitoring stations (Figure 3-6). Data are collected and processed at each station, and information is transmitted to the HMS every 15 minutes. This monitoring network has been in full operation since the early 1980s. Data from the HMS capture the general climatic conditions for the region and describe the specific climate of the Central Plateau. Meteorological measurements have been made at the HMS since late 1944. Before the HMS was established, local meteorological observations were made at the old Hanford town site (1912 through late 1943) and in Richland (1943 to 1944) (PNNL-6415). Meteorological data collected at the HMS are considered to be representative of conditions at WMA C.

**3.1.2.2 Temperature and Humidity.** Daily and monthly averages and extremes of temperature, dew point temperature, and relative humidity for 1945 through 2004 are reported in PNNL-15160, "Hanford Site Climatological Summary 2004 with Historical Data." From 1945 through 2010, the record maximum temperature was 45°C (113.0°F) recorded in August 1961, July 2002, and July 2006. The record minimum temperature was -30.6°C (-23.1°F) in February 1950. Normal monthly average temperatures ranged from a low of -0.2°C (31.7°F) in December to a high of 24.6°C (76.3°F) in July. During winter, the highest monthly average temperature at the HMS was 6.9°C (44.4°F) in February 1991, and the record lowest was -11.1°C (12.1°F) in January 1950. During summer, the record maximum monthly average temperature was 27.9°C (82.2°F) in July 1985, and the record minimum was 17.2°C (63.0°F) in June 1953. Table 3-1 provides the average monthly temperatures for the last 13 years along with average annual temperature. The bottom two rows provide the average annual temperature from 1947 to 2013, and the normal temperature which is a 30-year average from 1980 to 2010. The

normal annual relative humidity at the HMS is 54%. Humidity is highest during winter, averaging ~76%, and lowest during summer, averaging ~36%.

**3.1.2.3 Precipitation.** Average annual precipitation at the HMS is 17 cm (6.8 in.). During 1995, the wettest year on record, 31.3 cm (12.3 in.) of precipitation was measured; during 1976, the driest year, only 7.6 cm (3 in.) was measured. The wettest season on record was the winter of 1996-1997 with 14.1 cm (5.4 in.) of precipitation; the driest season was the summer of 1973, when only 0.1 cm (0.03 in.) of precipitation was measured. Most precipitation occurs during the late autumn and winter, with more than half of the annual amount occurring from November through February. Days with greater than 1.3 cm (0.50 in.) precipitation occur on average less than one time each year. Table 3-2 provides the monthly and average annual precipitation at HMS since 2000. The bottom two lines provide the average yearly precipitation since 1947 and normal precipitation, which is a 30-year average from 1980 to 2010.

Average snowfall ranges from 0.25 cm (0.1 in.) during October to a maximum of 13.2 cm (5.2 in.) during December and decreases to 1.3 cm (0.5 in.) during March. The record monthly snowfall of 59.4 cm (23.4 in.) occurred during January 1950. The seasonal record snowfall of 142.5 cm (56.1 in.) occurred during the winter of 1992-1993. Snowfall accounts for ~38% of all precipitation from December through February.

**3.1.2.4 Wind.** On the Hanford Site, the prevailing wind direction is from the northwest all year long. The secondary wind direction is from the southwest. Summaries of wind directions indicate that winds from the northwestern quadrant occur most often during winter and summer. During spring and fall, the frequency of southwesterly winds increases, with a corresponding decrease in the northwesterly flow. Monthly average wind speeds are lowest during winter months, averaging ~3 m/s (6 to 7 mi/hr), and highest during summer, averaging ~4 m/s (8 to 9 mi/hr). Wind speeds well above average are usually associated with southwesterly winds. However, summertime drainage winds are generally northwesterly and frequently exceed 13 m/s (30 mi/hr). These winds are most prevalent over the northern portion of the Hanford Site. Figure 3-6 shows the 2010 wind roses (i.e., diagrams showing direction and frequencies of wind) measured at a height of 9 m (30 ft) for the 30 meteorological monitoring stations located at and around the Hanford Site. Figure 3-7 provides wind roses for the same stations from 1982 to 2006 (PNNL-6415).

The monthly and annual prevailing wind directions, average speeds, and peak gusts are summarized in Tables 5.1 through 5.4 of PNNL-15160. The annual average wind speed for meteorological records kept from year 1945 to 2004 is calculated to be ~3.4 m/s (7.6 mi/hr) at 15.2 m (50 ft) above the ground. During 2010, the average wind speed was 3.6 m/s (8.1 mi/hr), which was 0.2 m/s (0.5 mi/hr) above normal (PNNL-20548).

**3.1.2.5 Severe Weather.** Concerns about severe weather usually center on hurricanes, tornadoes, and thunderstorms. Fortunately, the occurrence of hurricanes and tornadoes is infrequent and their scale is generally small in the northwestern portion of the United States. According to the records of the HMS and the National Severe Storms Forecast Center database, only 24 separate tornados have occurred between 1916 and 1994 within 160 km (100 mi) of the Hanford Site. Only one of these tornadoes was observed within the boundaries of the Hanford

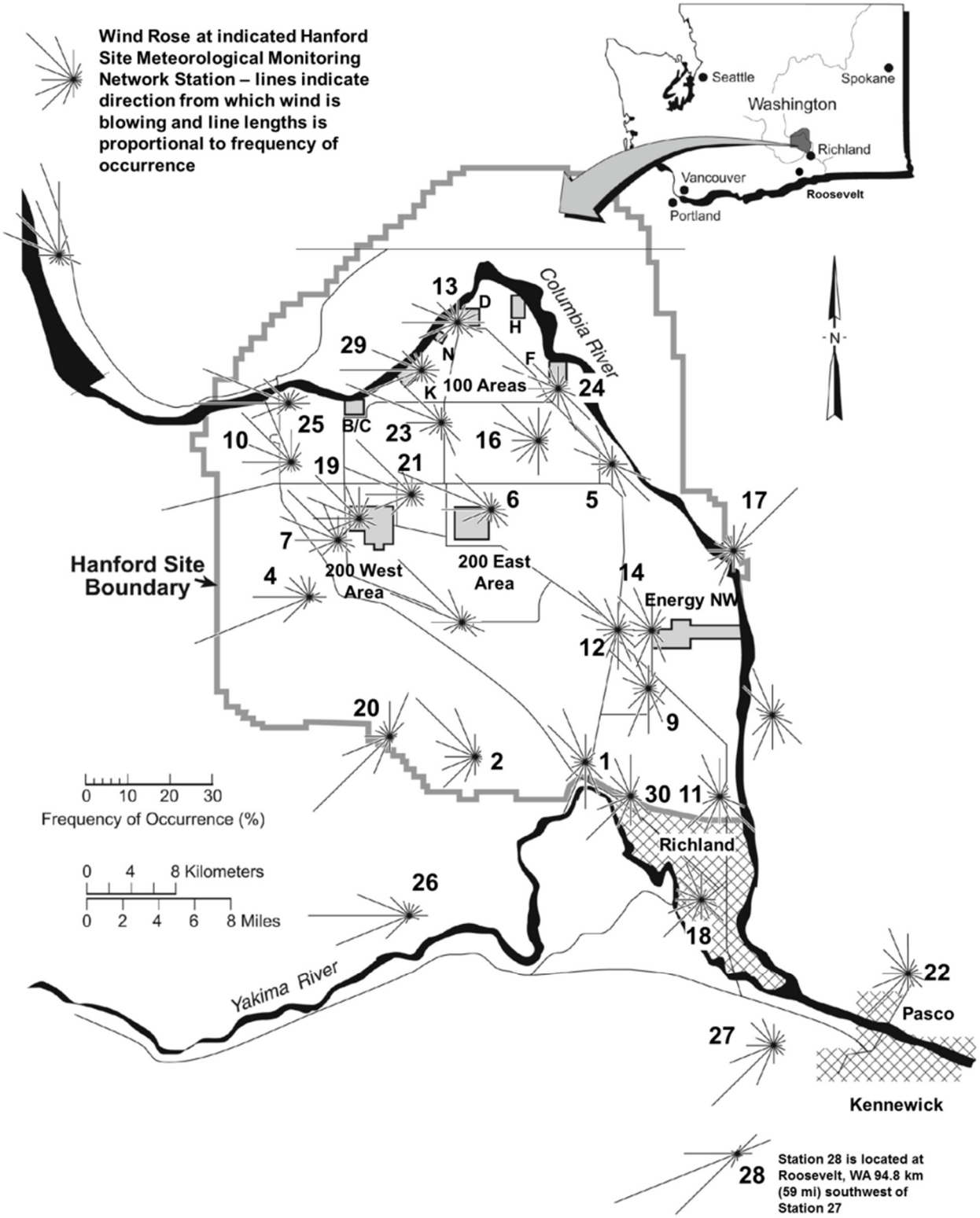
Site itself (at the extreme western edge), and no damage resulted. The estimated probability of a tornado striking a point at the Hanford Site is $9.6 \times 10^{-6}$/yr. Hurricanes do not reach the interior of the Pacific Northwest.

Severe winds are associated with thunderstorms or the passage of strong cold fronts. The average occurrence of thunderstorms in the vicinity of the HMS is 10 per year. They are most frequent during the summer; however, they have occurred in every month. High speed winds at the Site are more commonly associated with strong cold frontal passages. In rare cases, intense low pressure systems can generate winds of near-hurricane force. The greatest peak wind gust was 130 km/hr (81 mi/hr), recorded at 15 m (49 ft) above ground level at the HMS. Extrapolations based on 35 years of observation indicate a return period of ~200 years for a peak gust in excess of 145 km/hr (90 mi/hr) at 15 m (49 ft) above ground level.

**3.1.2.6 Climate Change.** In Global Climate Change Impacts in the United States: A State of Knowledge Report from the U.S. Global Change Research Program, Karl et al. (2009) projects that in the Pacific Northwest, regionally averaged temperatures are expected to increase 1.7 to 5.6 °C (3 to 10°F) during this century. They also noted that temperatures rose 0.83°C (1.5°F) over the past century and some areas saw increases up to 2.2°C (4.0°F). Karl et al. (2009) also suggests that winter precipitation will increase and summer precipitation will decrease. Most of the concern is with snowpack because it dominates water storage for irrigation and hydro system functioning. Scenarios of future climate for the Pacific Northwest, Climate Impacts Group (Mote et al. 2008) stated that the best estimate of future temperature change in the Pacific Northwest is 0.28°C (0.5°F) per decade until about 2050. Mote et al. (2008) estimated precipitation changes would range from -10% to +20% by the year 2080. They also noted that warming will be greater in summer than in the other seasons.

For an analysis of recharge in the 200 East Area, PNNL-13033, "Recharge Data Package for the Immobilized Low-Activity Waste 2001 Performance Assessment" represented future climate conditions by scaling the current temperature and precipitation data to match paleoclimate observations derived from pollen data. "Vegetation and climate change in northwest America during the past 125 kyr" (Whitlock and Bartlein 1997) described a 125,000-year paleoclimate record constructed from the pollen record in cores taken from Carp Lake, near Goldendale, Washington. Carp Lake is located ~175 km (~109 mi) southwest of the Hanford Site, at an elevation of 714 m (2,343 ft). Similar pollen records at the Hanford Site were eliminated during the glacial flooding 13,000 years ago. Thus, Carp Lake provides a proxy for paleoclimate information relevant to the Hanford Site. BHI-00144, "Long-term Climate Change Effects Task for the Hanford Site Permanent Isolation Barrier Development Program: Final Report" described the Carp Lake pollen interpretation relative to precipitation and temperature. For the entire Holocene (i.e., the last 10,000 years), the data suggest that annual temperatures and precipitation ranged from 0 to 2.8°C (0 to 5°F) warmer and 0 to 50% drier compared to modern climate. During the glacial period prior to the Holocene, annual temperatures ranged from 0.2°C (0.36°F) warmer to 2.5°C (4.5°F) cooler and precipitation ranged from 75 to 128% of modern levels. In summary, for the last 100,000 years, annual precipitation ranged from 50 to 128% of modern levels and annual temperatures ranged from -2.5 to 2.8°C (-4.5 to 5°F) of modern levels. These ranges appear to bracket the latest estimates for precipitation and temperature changes in the Pacific Northwest. Figures 3-8 and 3-9 illustrate the pollen-derived precipitation and temperature records, respectively.

**Figure 3-6. Hanford Meteorological Monitoring Network Wind Roses in 2010 at the 9.1 m (30 ft) Level.**




Adapted from PNNL-20548, "Hanford Site Environmental Report for Calendar Year 2010 (Including Some Early 2011 Information)."

**Table 3-1. Monthly and Average Annual Temperatures at Hanford Meteorological Station since 2000 (°C).**

| YEAR | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | ANNUAL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **2000** | 0.5 | 3.7 | 7.1 | 13.0 | 16.2 | 21.1 | 24.2 | 23.3 | 17.6 | 11.2 | 1.1 | -1.2 | 11.4 |
| **2001** | 0.8 | 2.1 | 8.2 | 10.8 | 17.6 | 19.2 | 24.4 | 25.4 | 20.6 | 11.9 | 6.0 | 1.6 | 12.4 |
| **2002** | 3.1 | 3.6 | 5.8 | 11.8 | 15.6 | 22.0 | 26.4 | 24.2 | 19.1 | 10.2 | 5.0 | 2.9 | 12.4 |
| **2003** | 3.3 | 4.4 | 9.4 | 11.2 | 16.2 | 22.5 | 26.8 | 24.7 | 20.7 | 14.1 | 3.2 | 0.5 | 13.1 |
| **2004** | -1.6 | 2.8 | 9.8 | 12.7 | 16.4 | 21.3 | 26.4 | 25.5 | 18.3 | 12.5 | 4.3 | 2.2 | 12.6 |
| **2005** | -1.1 | 3.2 | 9.4 | 12.0 | 17.9 | 20.3 | 25.3 | 24.8 | 18.4 | 12.4 | 3.5 | -2.6 | 11.9 |
| **2006** | 3.6 | 2.3 | 7.2 | 11.2 | 17.0 | 21.3 | 26.7 | 23.8 | 19.3 | 11.3 | 4.4 | -1.7 | 12.2 |
| **2007** | -1.8 | 3.2 | 8.6 | 11.3 | 17.3 | 20.3 | 27.2 | 23.3 | 18.7 | 10.8 | 4.0 | 0.4 | 11.9 |
| **2008** | -2.7 | 4.8 | 6.3 | 9.3 | 17.6 | 20.1 | 25.1 | 23.7 | 18.9 | 11.3 | 5.7 | -3.9 | 11.3 |
| **2009** | -0.7 | 1.7 | 5.5 | 10.9 | 16.8 | 21.9 | 26.5 | 24.6 | 20.2 | 10.1 | 5.0 | -4.1 | 11.6 |
| **2010** | 3.3 | 5.6 | 8.3 | 11.8 | 14.4 | 19.4 | 24.8 | 23.7 | 18.8 | 12.3 | 2.6 | 0.9 | 12.2 |
| **2011** | 0.9 | 1.7 | 6.7 | 9.1 | 14.0 | 19.4 | 23.0 | 24.7 | 20.8 | 12.3 | 3.6 | -0.7 | 11.3 |
| **2012** | 0.2 | 3.2 | 7.6 | 12.7 | 16.2 | 18.9 | 25.6 | 25.4 | 19.7 | 11.6 | 5.6 | 2.4 | 12.4 |
| **2013** | -1.2 | 3.9 | 7.9 | 12.0 | 17.3 | 21.0 | 27.1 | 25.4 | 20.7 | 11.4 | 3.6 | -2.8 | 12.2 |
| **AVERAGE** | -0.4 | 3.2 | 7.4 | 11.6 | 16.6 | 20.7 | 24.9 | 24.0 | 19.1 | 11.7 | 4.5 | 0.1 | 11.9 |
| **NORMAL** | 0.8 | 3.4 | 8.1 | 11.9 | 16.7 | 20.9 | 25.1 | 24.3 | 19.1 | 11.7 | 4.7 | -0.5 | 12.2 |

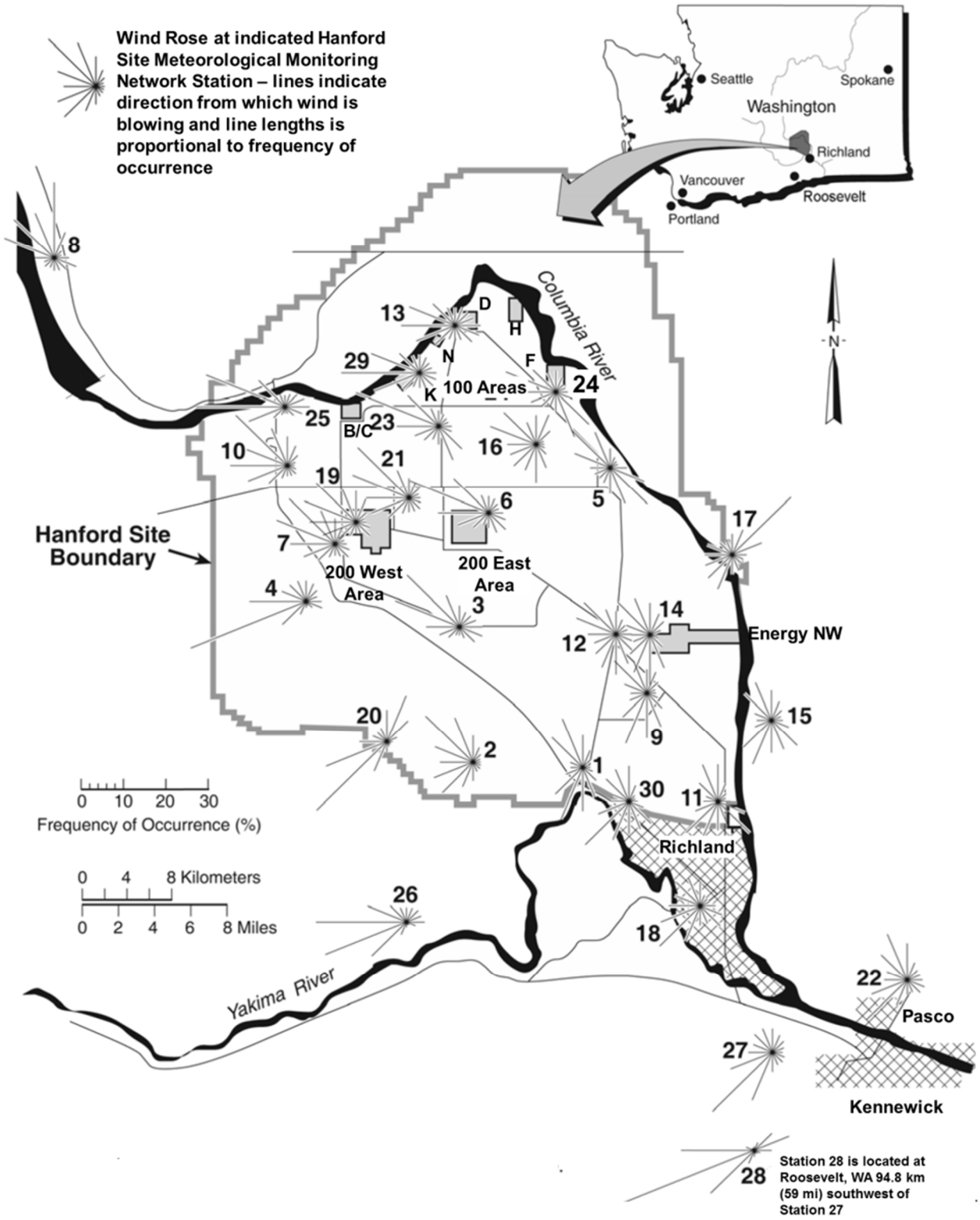
[1] Normal is a 30-year average from 1980 to 2010.

**Table 3-2. Monthly and Average Annual Precipitation at Hanford Meteorological Station since 2000 (cm).**

| YEAR | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | ANNUAL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **2000** | 2.77 | 2.84 | 2.39 | 1.45 | 1.96 | 0.64 | 1.17 | Trace | 1.42 | 1.45 | 2.74 | 1.70 | 20.52 |
| **2001** | 0.74 | 1.07 | 1.70 | 2.11 | 0.20 | 3.23 | 0.13 | 0.20 | 0.33 | 0.94 | 4.24 | 2.03 | 16.92 |
| **2002** | 1.07 | 1.70 | 0.48 | 0.74 | 0.41 | 1.65 | 0.41 | 0.03 | Trace | 0.30 | 0.97 | 5.99 | 13.74 |
| **2003** | 4.75 | 2.08 | 0.66 | 5.66 | 0.20 | Trace | 0.00 | 1.17 | 0.61 | 0.18 | 0.38 | 4.98 | 20.68 |
| **2004** | 5.38 | 2.34 | 0.91 | 0.53 | 2.26 | 2.08 | 0.08 | 2.41 | 0.36 | 2.18 | 0.74 | 0.94 | 20.22 |
| **2005** | 2.36 | 0.10 | 0.79 | 0.66 | 2.01 | 0.15 | 0.23 | 0.15 | 1.68 | 0.74 | 2.26 | 5.11 | 16.23 |
| **2006** | 3.00 | 1.04 | 0.61 | 3.30 | 1.45 | 3.38 | Trace | Trace | 0.53 | 1.93 | 1.80 | 4.45 | 21.49 |
| **2007** | 0.36 | 1.93 | 1.88 | 0.66 | 0.76 | 1.14 | 0.18 | 0.81 | 1.45 | 0.53 | 2.87 | 1.35 | 13.92 |
| **2008** | 3.25 | 1.40 | 0.51 | 0.20 | 1.42 | 0.99 | Trace | 1.22 | 0.10 | 0.56 | 1.88 | 2.41 | 13.94 |
| **2009** | 2.92 | 1.63 | 2.03 | 0.99 | 0.46 | 0.41 | Trace | 0.10 | 0.15 | 1.98 | 1.42 | 1.80 | 13.89 |
| **2010** | 3.15 | 1.42 | 0.51 | 1.50 | 3.38 | 2.92 | 1.17 | 0.33 | 2.41 | 1.57 | 2.90 | 4.62 | 25.88 |
| **2011** | 1.35 | 0.08 | 2.21 | 0.64 | 3.10 | 0.99 | 0.30 | Trace | 0.13 | 1.96 | 0.30 | 0.25 | 11.30 |
| **2012** | 2.77 | 1.70 | 1.63 | 1.55 | 0.56 | 3.84 | 0.38 | Trace | 0.08 | 1.05 | 0.80 | 1.41 | 8.18 |
| **2013** | 0.41 | 0.23 | 0.99 | 0.76 | 4.06 | 3.45 | 0.03 | 0.61 | 1.07 | 0.97 | 0.91 | 0.18 | 13.67 |
| **AVERAGE** | 2.36 | 1.57 | 1.27 | 1.19 | 1.37 | 1.42 | 0.51 | 0.58 | 0.76 | 1.37 | 2.18 | 2.62 | 17.22 |
| **NORMAL[1]** | 2.39 | 1.78 | 1.45 | 1.40 | 1.30 | 1.30 | 0.58 | 0.46 | 0.79 | 1.24 | 2.41 | 3.05 | 18.14 |

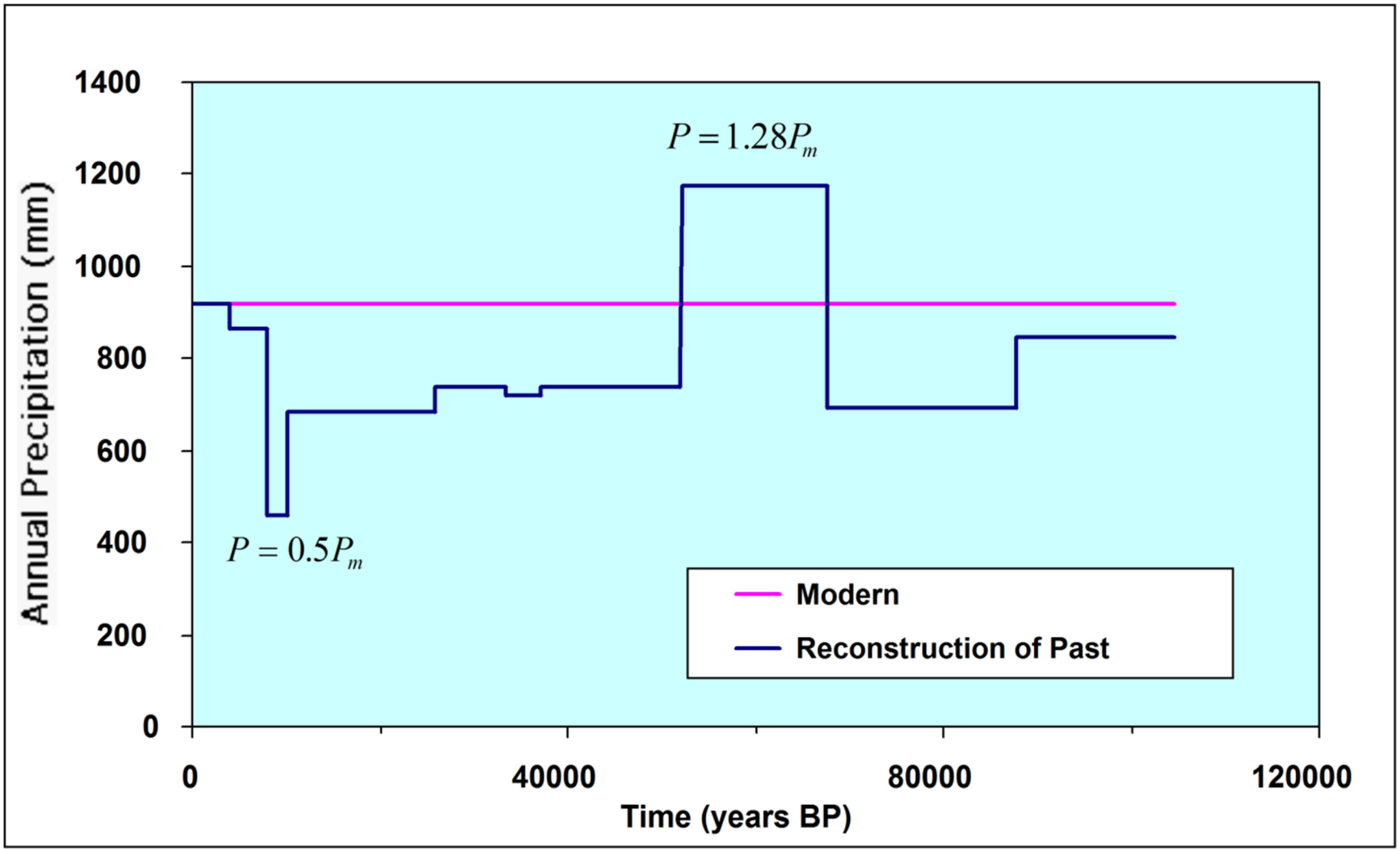
[1] Normal is a 30 year average from 1980 to 2010.

**Figure 3-7. Hanford Meteorological Monitoring Network Wind Roses from 1982 to 2006 at the 9.1 m (30 ft) Level.**



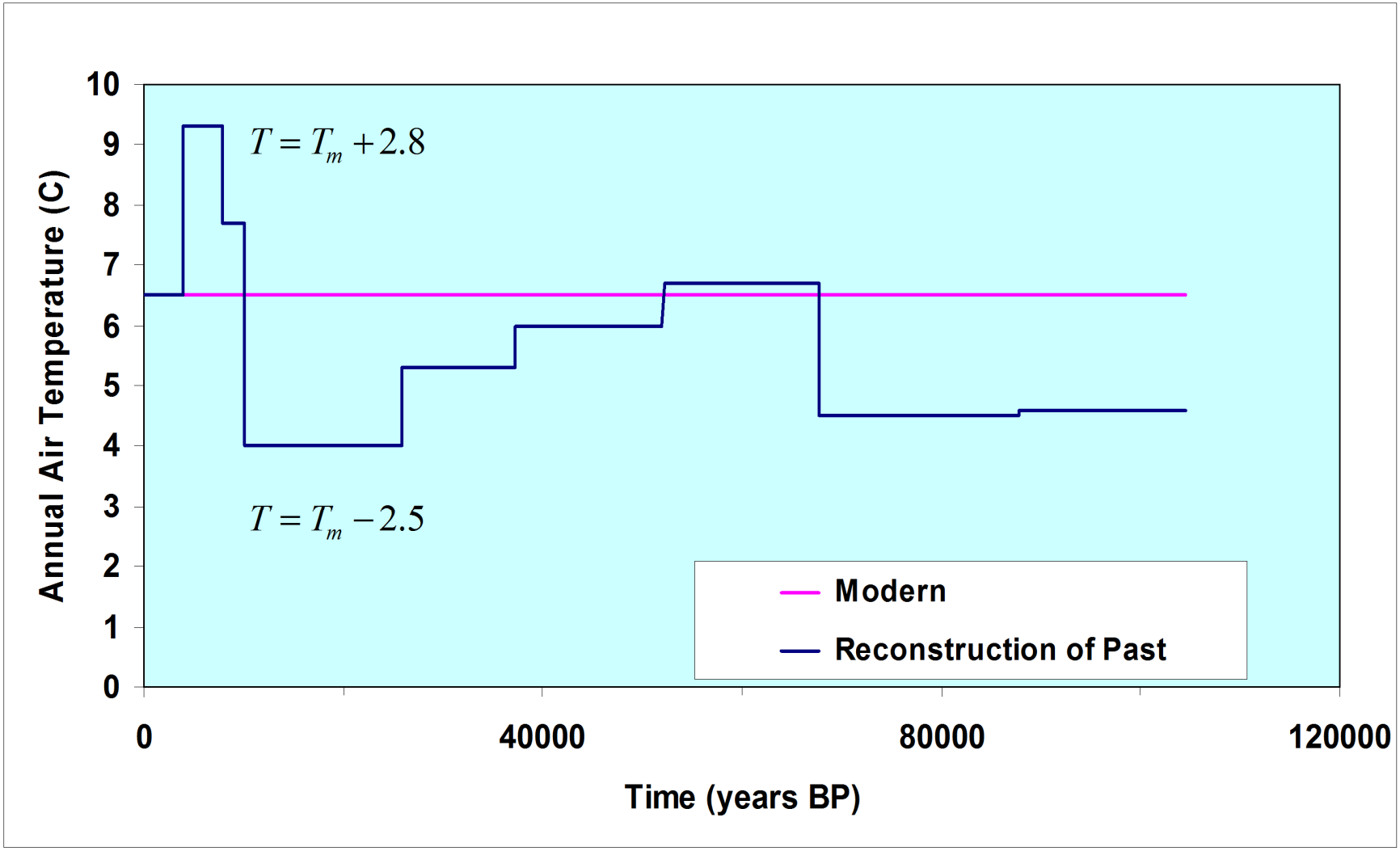

Adapted from PNNL-6415, "Hanford Site National Environmental Policy Act (NEPA) Characterization."

**Figure 3-8. Precipitation Reconstruction for Past 100,000 Years Based on Pollen Data.**




BP = before present

**Figure 3-9. Temperature Reconstruction for Past 100,000 Years Based on Pollen Data.**




BP = before present

### 3.1.3 Ecology

This section summarizes the ecology of the Hanford Site (PNNL-6415, Section 4.5; DOE/EIS-0391, Section 3.7), highlighting the 200 Areas where WMA C is located. The information in this section emphasizes plant and animal activities that may affect exposure pathways. The primary impact would be through roots penetrating and animals burrowing through surface barriers into a disposal facility. Secondarily, the types of plants and animals and their density can affect net recharge to groundwater, which is greatly influenced by surface vegetation and burrowing. PNNL-6415 details both the terrestrial and aquatic ecology of the Hanford Site and presents extensive listings of plant and animal species, but this section considers only terrestrial ecological effects because WMA C is not located near significant aquatic ecological systems.

The Hanford Site consists of primarily undeveloped land. Chemical processing facilities, nuclear reactors that have been shut down, and supporting facilities occupy only ~6% of the site. Most of the Hanford Site has not experienced tillage or agricultural grazing since the early 1940s.

The Hanford Site is characterized as a shrub-steppe ecosystem that is adapted to the mid-latitude semiarid climate of the region. These ecosystems are typically dominated by a shrub overstory with a grass understory. In the early 1800s, dominant plants in the area were big sagebrush (*Artemisia tridentata*) and an understory consisting of perennial Sandberg's bluegrass (*Poa sandbergii*) and bluebunch wheatgrass (*Pseudoregneria spicata*). Other species included threetip sagebrush, bitterbrush, gray rabbitbrush, spiny hopsage, needle and thread grass, Indian rice grass, and prairie June grass.

With the advent of settlement, livestock grazing and agricultural production contributed to colonization by non-native vegetation species that currently dominate portions of the landscape. Although agriculture and livestock production were the primary subsistence activities at the turn of the century, these activities ceased when the Hanford Site was designated in 1943. No farming has occurred on the Hanford Site since the government took control of the site.

The dominant non-native species, cheat grass, is an aggressive colonizer and has become well established across the Site. Over the past decade, several knapweed species also have become persistent invasive species in areas not dominated by shrubs. Range fires that historically burned through the area during the dry summers eliminated fire-intolerant species (e.g., big sagebrush) and allowed more opportunistic and fire-resistant species to establish. Of the 590 species of vascular plants recorded for the Hanford Site, ~20% are non-native. Wildfires are frequent on the Hanford Site. Several of the more recent fires are shown on Figure 3-10 and are described on page 3-7 of DOE/EIS-0391. Vegetation loss due to fires and firefighting activities exposed the soil to erosion by subsequent wind and rain, and can enhance recharge by removing vegetation from evapotranspiration barriers placed over the site.

Figure 3-11 illustrates vegetation and land cover in and around the 200 East Area following the 24 Command (June/July 2000) and Wautoma Fires (August 2007). Most of the 200 Areas were not directly impacted by either fire (see Figure 3-10). Undisturbed portions of the 200 Areas are characterized by the following communities: big sagebrush/bunchgrass-cheat grass, cheat grass-

bluegrass, crested wheatgrass-bunchgrass-cheat grass, and gray rabbit brush/cheat grass-bluegrass. The former two communities are prominent in the 200 East Area, while the latter two are more common in the 200 West Area. Most of the waste disposal and storage sites are covered by non-native vegetation or are kept in a vegetation-free condition by the controlled application of approved herbicides because plants could potentially accumulate waste constituents. Where vegetation is present, it aids in stabilizing surface soil, controlling soil moisture, or displacing more-invasive, deep-rooted species like Russian thistle (PNNL-6415, page 4.98). Due to the disturbed nature of most of the 200 Areas, wildlife use is limited; however, surveys have recorded the badger, coyote, Great Basin pocket mouse, mule deer, long-billed curlew, killdeer, horned lark, Say's phoebe, American robin, American kestrel, western meadowlark, and common raven [PNNL-14133, "Blanket Biological Review for General Maintenance Activities Within Active Burial Grounds, 200 E and 200 W Areas, ECR #2002-200-034," page 3; PNNL-14233, "Biological Review of the Hanford Solid Waste EIS – Borrow Area C (600 Area), Stockpile and Conveyance Road Area (600 Area), Environmental Restoration Disposal Facility (ERDF) (600 Area), Central Waste Complex (CWC) Expansion (200 West), 218-W-5 Expansion Area (200 West), New Waste Processing Facility (200 West), Undeveloped Portion of 218-W-4C (200 West), Western Half & Northeastern Corner of 218-W-6 (200 West), Disposal Facility Near Plutonium-Uranium Extraction (PUREX) Facility (200 East), ECR #2002-600-012b," pages 9, 10; PNNL-16620, "Ecological Data in Support of the Tank Closure and Waste Management Environmental Impact Statement Part 2: Results of Spring 2007 Field Surveys"].

All WMAs in the tank farm system are actively managed to prevent vegetation, insects, and wildlife from using the WMA as habitat, including WMA C. Herbicides and pesticides are used on a regular basis and fences are placed around the perimeter to keep larger animals out. Without a source of food within the WMA, smaller animals are less likely to enter. Figure 3-12 provides the size of the habitat areas within 152 m (500 ft) of WMA C.

### 3.1.4 Geology, Seismology, and Volcanology

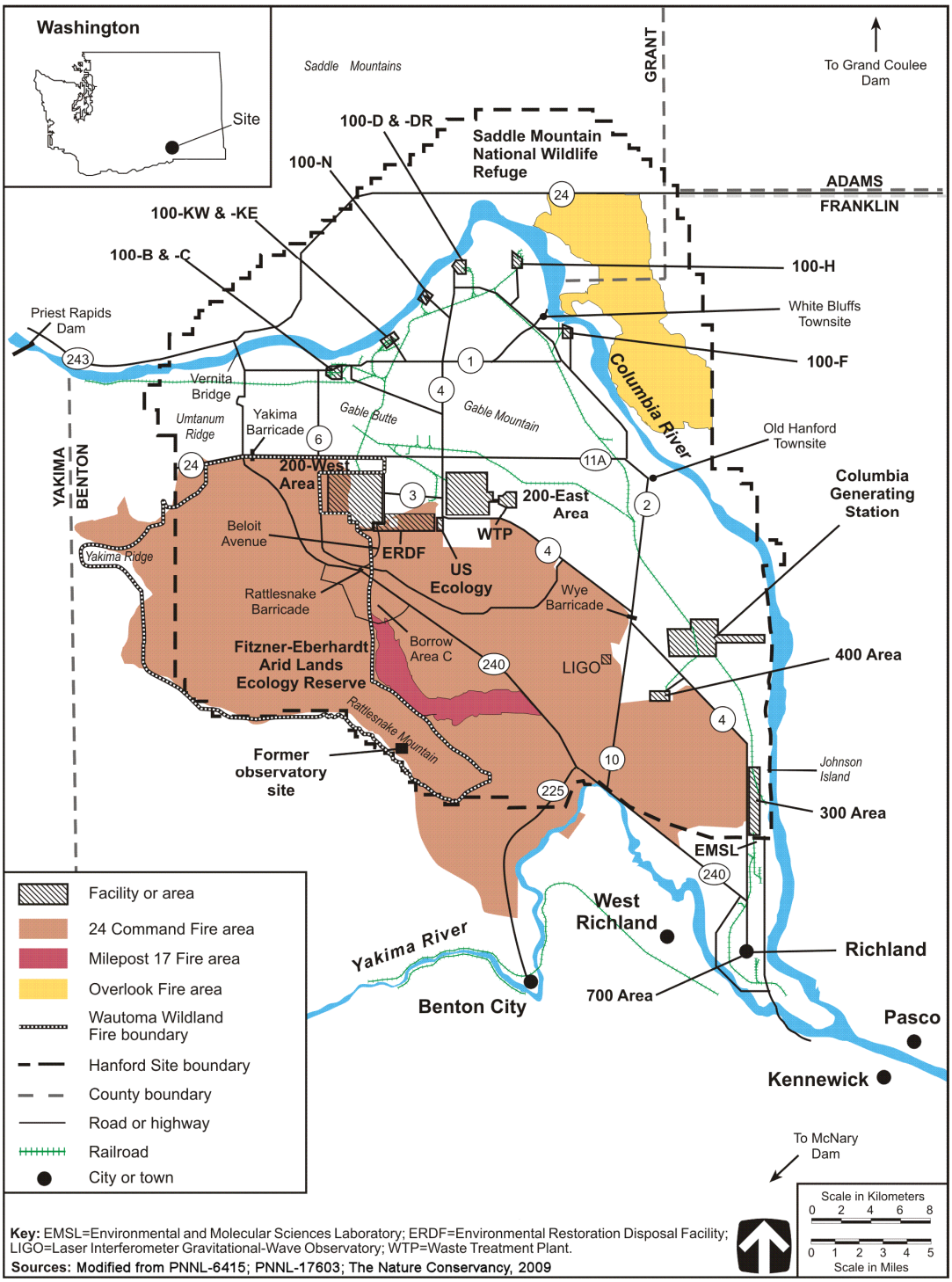
Since the Hanford Site started operating in the early 1940s, a large volume of information on the geology, seismology, and volcanology of the Site has been collected and evaluated. Over the last several years, the following two data packages have been prepared to describe the geology, hydrology, and geochemistry of the SST system and WMA C:

1) RPP-RPT-46088, "Flow and Transport in the Natural System at Waste Management Area C"

2) PNNL-15955, "Geology Data Package for the Single-Shell Tank Waste Management Areas at the Hanford Site."

Most of the data included in the geologic data package were collected by (or used by) several projects between about 1980 and the present. Those projects include the Basalt Waste Isolation Project, the Skagit Hanford Nuclear Project, the Washington Public Power Supply System safety analysis, several PAs, and numerous regulatory-driven geologic and hydrologic characterizations, assessments, and monitoring projects.

**Figure 3-10. Extent of Area Burned During Recent Fires at the Hanford Site.**




Source: DOE/EIS-0391, "Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington."

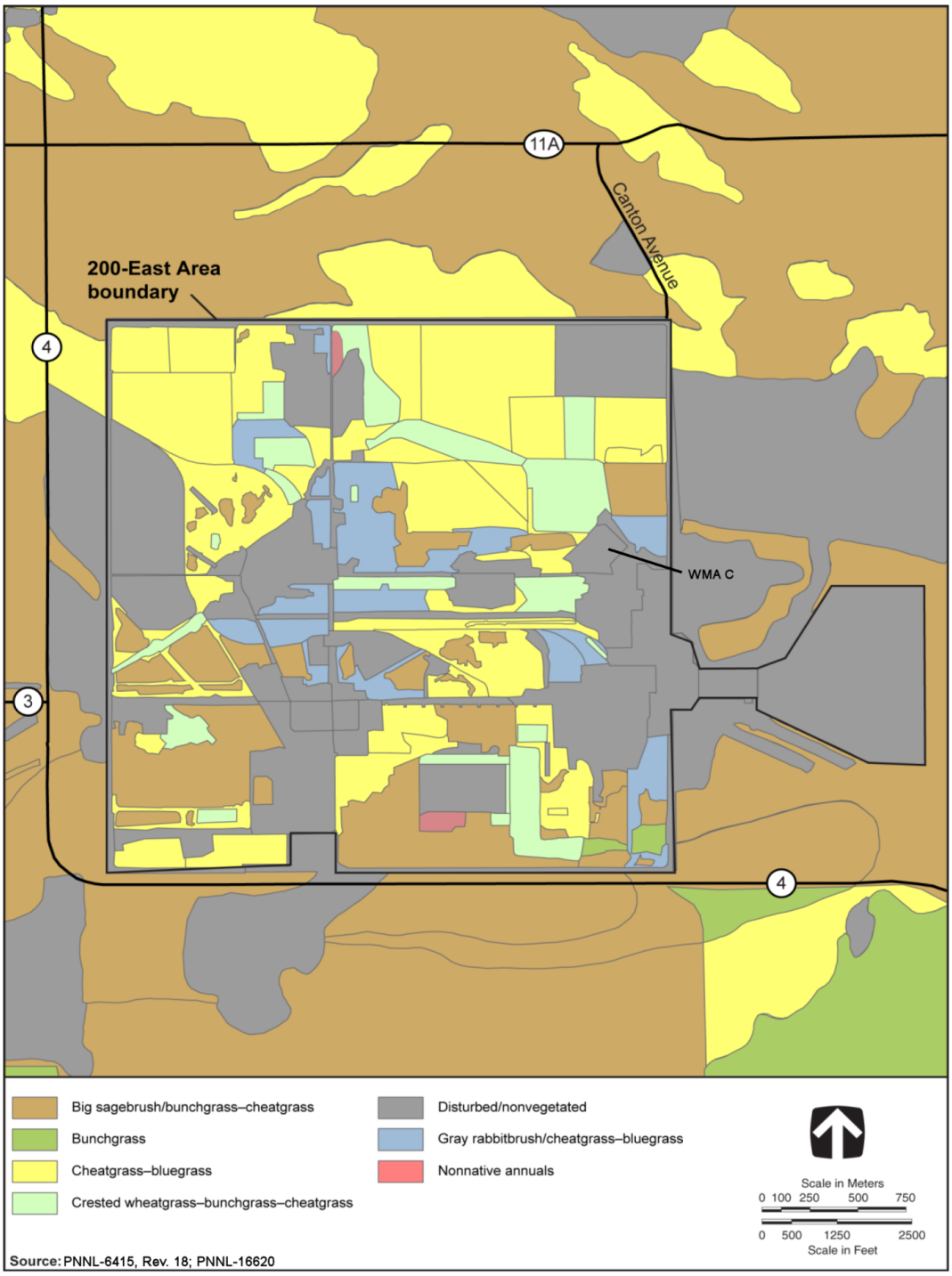
References:

PNNL-6415, "Hanford Site National Environmental Policy Act (NEPA) Characterization."

PNNL-17603, "Hanford Site Environmental Report for Calendar Year 2007."

The Nature Conservancy, Queried 08/05/2009, [About the Fires @ ALE Project], http://depts.washington.edu/firesale/project/ale_project.shtml.

**Figure 3-11. Vegetation Communities in and near 200 East Area.**




WMA = Waste Management Area

Modified from DOE/EIS-0391, "Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington."

References:

PNNL-6415, "Hanford Site National Environmental Policy Act (NEPA) Characterization" Rev. 18.

PNNL-16620, "Ecological Data in Support of the Tank Closure and Waste Management Environmental Impact Statement Part 2: Results of Spring 2007 Field Surveys."

The technical aspects of all of these projects, and thus the data, interpretations of the data, and conclusions, have been overseen by one or more regulatory agencies and stakeholder groups including the NRC, the National Academy of Science, the Defense Nuclear Facilities Safety Board (DNFSB), the EPA, the U.S. Geological Survey, the Washington State Departments of Ecology and Health, the Oregon Department of Energy, and the Yakama, Nez Perce, and Wanapum Indian Nations and the Confederated Tribes of the Umatilla Reservation. The high level of oversight has helped ensure a rigorous understanding of bounding geologic, seismic, and volcanic risks.

This section provides a summary of the data in the two data packages, highlighting those aspects that are important to developing the conceptual model describing transport of contaminants away from the waste facility to a receptor. This section will focus on the regional and Hanford Site geologic framework. The geology of WMA C is discussed in Section 3.1.9 Waste Management Area C Site Characterization.

**3.1.4.1 Regional Geologic Framework.** The Hanford Site (Figure 3-13) lies within the Columbia Plateau, a broad plain situated between the Cascade Range to the west and the Rocky Mountains to the east, and is underlain by the Miocene Columbia River Basalt Group (CRBG) (Figure 3-14). The northern Oregon and Washington portion of the Columbia Plateau is often called the Columbia Basin because it forms a lowland surrounded on all sides by mountains. The low-relief plains of the Central Plains physiographic region and anticlinal ridges of the Yakima Folds region dominate the physiographic setting of the Hanford Site. In the central and western parts of the Columbia Basin and Pasco Basin where the Hanford Site is located, the basalt is underlain predominantly by Tertiary continental sedimentary rocks and overlain by late Tertiary and Quaternary fluvial and glacio-fluvial deposits. All these were folded and faulted during the Cenozoic Era to form the current landscape of the region.

The Columbia Basin is a structurally and topographically low area surrounded by mountains ranging in age from the late Mesozoic to recent (Figure 3-14). The Columbia Basin is composed of two fundamental sub-provinces, the Palouse Slope and the Yakima Fold Belt (Figure 3-14). The Palouse Slope is a stable, undeformed area overlying the old continental craton that dips westward toward the Hanford Site. The Yakima Fold Belt is a series of anticlinal ridges and synclinal valleys in the western and central parts of the Columbia Basin. The edge of the old continental craton lies at the junction of these two structural sub-provinces and is currently marked by the Ice Harbor dike swarm of the CRBG east of the Hanford Site. The Blue Mountains sub-province of the Columbia River flood-basalt province is a northeast trending anticlinorium that extends 250 km from the Oregon Cascades to Idaho and forms the southern border of the Columbia Basin and the southern part of the Columbia Plateau.

**3.1.4.1.1 Lava Flows.** Lava flows erupted over a period of time from 17 to 6 million years ago. Under the Hanford Site, basaltic lava deposits (CRBG) are over 4 km (13,000 ft) thick ("Volcanism and Tectonism in the Columbia River Flood-Basalt Province," page 386, plate 1 [Reidel and Hooper 1989]), spreading over portions of Idaho, Oregon, and Washington. The Columbia Basin encloses the CRBG. A depression in the lower part of the Columbia Basin is referred to as the Pasco Basin (Figure 3-14). The Pasco Basin is bounded by the Saddle Mountains to the north, Naneum Ridge to the west, Rattlesnake Hills to the south, and the

Palouse Slope to the east, generally the area north of where the Snake River flows into the Columbia River. Geographically, the ridges surrounding the Hanford Site and vicinity define the Pasco Basin, which contains Ringold Formation sediment from the ancestral Columbia River and sediment deposited by the Ice Age floods.

**3.1.4.1.2 Crustal Folding.** During and after the eruption of the lava flows, the Earth's tectonic forces buckled and folded the basalt in the western Columbia Basin into generally east-west trending, long, narrow ridges (anticlines), and intervening valleys (synclines). Collectively, this is identified as the Yakima Fold Belt.

**3.1.4.1.3 Ancestral Columbia River Deposits.** The ancestral Columbia River repeatedly changed its course over the past 15 million years, depositing gravel, sand, silt, and clay (RHO-BWI-ST-14, "Subsurface Geology of the Cold Creek Syncline," "Chapter 2 – Suprabasalt Sediments of the Cold Creek Syncline Area"; "Paleodrainage of the Columbia River System on the Columbia Plateau of Washington State – A Summary" [Fecht et al. 1987]; DOE/RW-0164, Consultation Draft Site Characterization Plan Reference Repository Location, Hanford Site, Washington; "Late Cenozoic Structure and Stratigraphy of South-Central Washington" [Reidel et al. 1994]; Open File Report 96-8, "The Miocene to Pliocene Ringold Formation and Associated Deposits of the Ancestral Columbia River System, South-Central Washington and North-Central Oregon"). Uplifting basalt ridges diverted the course of the Columbia River from a southerly direction (toward Goldendale) to an easterly direction (toward Wallula Gap) and left behind the Ringold Formation (Fecht et al. 1987). Later regional uplift associated with the Cascade Mountains caused the river to cut through its own earlier deposits (the Ringold Formation) exposing the White Bluffs. Within the Hanford Reach, the Columbia River continues to erode the White Bluffs. Groundwater seepage from irrigation along the bluffs makes them unstable. Consequently, the White Bluffs are land sliding and sloughing into the Columbia River along much of the shoreline (Fecht et al. 1987).

**3.1.4.1.4 Ice Age Floods.** During the Pleistocene, cataclysmic floods inundated the Pasco Basin several times when ice dams failed in northern Washington ("Quaternary Geology of the Columbia Plateau" [Baker et al. 1991]). The Ice Age floods began as early as 2.5 million years ago ("Long History of Pre-Wisconsin, Ice Age Cataclysmic Floods: Evidence from Southeastern Washington State" [Bjornstad et al. 2001]) with the most recent occurring 18,000 to 13,000 years ago. Current interpretations suggest as many as 40 flooding events occurred as ice dams holding back glacial Lake Missoula repeatedly formed and broke. In addition to larger major flood episodes, there were probably numerous smaller individual flood events. Deciphering the history of cataclysmic flooding in the Pasco Basin is complicated, not only because of floods from multiple sources but also because the paths of Missoula floodwaters migrated and changed course with the advance and retreat of the Cordilleran Ice Sheet.

Along with sedimentological evidence for cataclysmic flooding in the Pasco Basin, high-water marks and faint strandlines occur along the basin margins. Temporary lakes were created when flood waters were hydraulically dammed, resulting in the formation of the short-lived Lake Lewis behind Wallula Gap. High water mark elevations for Lake Lewis (Figure 3-15), inferred from ice-rafted erratics on ridges, range from 370 to 385 m (1,214 to 1,261 ft) above sea level.

The sediment deposited by the cataclysmic flood waters has been informally called the Hanford formation because the best exposures and most complete deposits are found there. The coarse-grained flood facies (gravel-dominated facies of DOE/RL-2002-39, Standardized Stratigraphic Nomenclature for Post-Ringold-Formation Sediments Within the Central Pasco Basin) is generally confined to relatively narrow tracts within or near flood channel ways. The plane-laminated sand facies (sand-dominated facies of DOE/RL-2002-39), on the other hand, occurs as a broad sheet over most of the central basin.

**3.1.4.2 Hanford Site Geologic Framework.** The previous section provided the regional geologic framework. This section provides a summary of the geologic structure and stratigraphy unique to the Hanford Site. Please see the geologic data packages for more complete descriptions.

**3.1.4.2.1 Geologic Structure.** The Cold Creek syncline (Figure 3-16) lies between the Umtanum Ridge-Gable Mountain uplift and the Yakima Ridge uplift and is an asymmetric and relatively flat-bottomed structure. The Cold Creek syncline began developing during the eruption of the CRBG and has continued to subside since that time. The 200 Areas lie on the northern flank, and the bedrock dips gently (approximately 5°) to the south. The deepest parts of the Cold Creek syncline, the Wye Barricade depression and the Cold Creek depression, are ~12 km (7.5 mi) southeast of the 200 Areas and southwest of the 200 West Area, respectively (Figure 3-16).

The Wahluke syncline north of Gable Mountain is the principal structural unit that contains the 100 Areas. The Wahluke syncline is an asymmetric and relatively flat-bottomed structure similar to the Cold Creek syncline. The northern limb dips gently (approximately 5°) to the south. The steepest limb is adjacent to the Umtanum Ridge-Gable Mountain structure.

The 200 East Area is located on the eastern part of the Cold Creek bar, which is along the northern flank of the Cold Creek syncline (Figure 3-16). Another deep structural low, the Wye Barricade depression, developed along the Cold Creek syncline southeast of the 200 East Area. The May Junction fault is a normal fault that marks the western boundary of the depression.

The 200 East Area sits at the southern end of a series of secondary doubly plunging anticlines and synclines that are associated with the Umtanum Ridge-Gable Mountain anticlinal structure. Waste Management Areas A, AX, B-BX-BY, and C in the 200 East Area lie near the southern flank of the closest secondary anticline. A fault was recently detected during drilling of seismic test boreholes at the Waste Treatment Plant. The fault caused some displacement in the Pomona Basalt that lies beneath the Elephant Mountain Member but is not thought to have caused any displacement in younger basalts or overlying sediments (PNNL-16407, “Geology of the Waste Treatment Plant Seismic Boreholes”).

**3.1.4.2.2 Stratigraphy.** The generalized stratigraphy of the Pasco Basin and Hanford Site is shown in Figure 3-17. The principal rocks exposed at the surface of the surrounding ridges are the CRBG and intercalated sedimentary rocks of the Ellensburg Formation. In the low-lying basins and valleys, these are overlain by younger sedimentary rocks of the Ringold Formation, Cold Creek unit (CCU), and the Pleistocene cataclysmic flood deposits of the Hanford

formation. Figure 3-18 provides an approximate west to east cross section through the Hanford Site.

**Columbia River Basalt Group and Ellensburg Formation:** The Elephant Mountain Member is the uppermost basalt flow beneath the 200 Areas and much of the Hanford Site. Where folds and faults have formed basalt ridges, other flows from the Saddle Mountains, Wanapum, and Grande Ronde Formations are exposed.

The Ellensburg Formation is intercalated with and overlies the CRBG in the Pasco Basin and includes epiclastic and volcaniclastic sedimentary rocks ("Stratigraphic and Lithologic Variations in the Columbia River Basalt" [Waters 1961]; USGS Bulletin 1457-G, "Revisions in stratigraphic nomenclature of the Columbia River Basalt Group"). The upper Ellensburg Formation consists of sand and gravel marking mainstream deposits and sand, silt, and clay overbank deposits that are sandwiched between basalt flows. Along with the more permeable basalt flow bottoms and flow tops, these sediments form the uppermost confined basalt aquifer system beneath the Hanford Site. The upper, younger Ellensburg Formation interbedded with the Saddle Mountains Basalt (as noted on Figure 3-17 as part of the CRBG) reflects changes in river courses, with sediments from the Columbia River becoming dominant as developing anticlinal ridges pushed the Columbia River east and basalt flows pushed the Clearwater-Salmon system to the south . Relatively few boreholes in the 200 Areas penetrate the Ellensburg Formation. Those boreholes that do penetrate the Ellensburg Formation generally find tuffaceous siltstones and sandstones, with conglomerates marking ancient main river channels. The Ellensburg stratigraphy of the Hanford Site has been discussed in more detail in Fecht et al. (1987).

The uppermost basalt flow beneath the Central Plateau is the Elephant Mountain Member (RHO-BWI-ST-14, "Chapter 3 – Wanapum and Saddle Mountains Basalts of the Cold Creek Syncline Area"). The top of basalt surface dips to the southwest beneath the 200 West Area and to the south-southwest beneath the 200 East Area. Low-amplitude secondary folds such as the one to the northeast of the 200 East Area may occur throughout the area and have probably not been fully identified. Between the 200 East Area and Gable Gap to the north, the Elephant Mountain has been eroded to expose underlying basalt flows. There is also a suspected window eroded through the Elephant Mountain near the northeast corner of the 200 East Area.

**Post-Columbia River Basalt Sediments:** The Hanford Site and tank farms are situated on a sequence of Ringold Formation, CCU, and Hanford formation sediments overlying the CRBG (Figure 3-19). The upper Miocene to middle Pliocene record of the Columbia River system in the Columbia Basin is represented by the upper Ellensburg and Ringold Formations. Except for local deposits (e.g., the CCU), there is a hiatus (erosion or lack of sedimentation) in the stratigraphic record between the end of the Ringold Formation deposition (3.4 Ma) and the beginning of Pleistocene (1.6 Ma) time (DOE/RW-0164, DOE/RL-2002-39).

**Ringold Formation:** The Ringold Formation at the Hanford Site is up to 185 m (607 ft) thick in the deepest part of the Cold Creek syncline south of the 200 West Area and 170 m (55 ft) thick in the western Wahluke syncline near the 100 B Area. The Ringold Formation pinches out against the Gable Mountain, Yakima Ridge, Saddle Mountains, and Rattlesnake Mountain anticlines. It

is largely absent in the northern and northeastern parts of the 200 East Area. It consists of semi-indurated clay, silt, pedogenically altered sediment, fine- to coarse-grained sand, and granule to cobble gravel. Ringold Formation strata typically are below the water table on the Hanford Site, and the textural variations influence groundwater flow.

In the Pasco Basin, the lower half of the Ringold Formation, the member of Wooded Island, is the main unconfined aquifer under the Hanford Site and contains five separate stratigraphic intervals dominated by the fluvial gravel facies. These gravels, designated units A, B, C, D, and E, are separated by intervals containing deposits typical of the overbank and lacustrine facies (WHC-SD-EN-EE-004, "Revised Stratigraphy for the Ringold Formation, Hanford Site, South-Central Washington"). In the 200 Areas, only fluvial gravel units A and E occur. Between these two gravel units in many places is the lowermost of the fine-grained.

The upper part of the Ringold Formation, informally called the member of Taylor Flat (BHI-00184, "Miocene- to Pliocene-Aged Suprabasalt Sediments of the Hanford Site, South-Central Washington") consists of the sequence of fluvial sands, overbank deposits, and lacustrine sediments overlying unit E. This corresponds to the upper unit as originally defined by "Ringold Formation of Pleistocene Age in Type Locality, the White Bluffs, Washington" (Newcomb 1958) along the White Bluffs in the eastern Pasco Basin. The fluvial sand facies is the principal facies of the upper part under the tank farms at the Hanford Site.

**Cold Creek Unit:** The CCU (DOE-RL-2002-39) includes all material underlying the Hanford formation, overlying the Ringold Formation in the vicinity of the 200 West Area, and may extend over most of the central Pasco Basin. The CCU distinguishes itself from the Hanford and Ringold formations because it was formed when the Ringold Formation was eroding and relatively little was being deposited at the Hanford Site. This subunit is found locally in the Cold Creek syncline in the subsurface.

The CCU is laterally discontinuous and overlies the tilted and truncated Ringold Formation in an unconformable relationship in the western Cold Creek syncline in the vicinity of the 200 West Area (DOE/RL-2002-39). To the east, the pre-Missoula gravels replace the calcrete and silt-dominated subunits of the CCU. The CCU appears to be correlative to other side stream alluvial, eolian, and pedogenic deposits found near the base of the ridges bounding the Pasco Basin on the north, west, and south. These sedimentary deposits are inferred to have a late Pliocene to early Pleistocene age on the basis of stratigraphic position and magnetic polarity of interfingering loess units (DOE/RW-0164).

Distribution of the CCU depends in part on erosion and weathering of the underlying Ringold Formation and post-depositional erosion by the Ice Age floods ("Buried carbonate paleosols developed in Pliocene-Pleistocene deposits of the Pasco Basin, south-central Washington, U.S.A." [Slate 1996]). The thickness of the Cold Creek deposit ranges from 0 to 20 m (0 to 66 ft). Locally the CCU contains very hard rock that formed as precipitation evaporated and left behind minerals forming what geologists call caliche or hardpan. This layer can influence contaminant migration by slowing its rate of downward movement and potentially diverting contaminants laterally (Slate 1996). However, CCU as described above is largely absent from the 200 East Area.

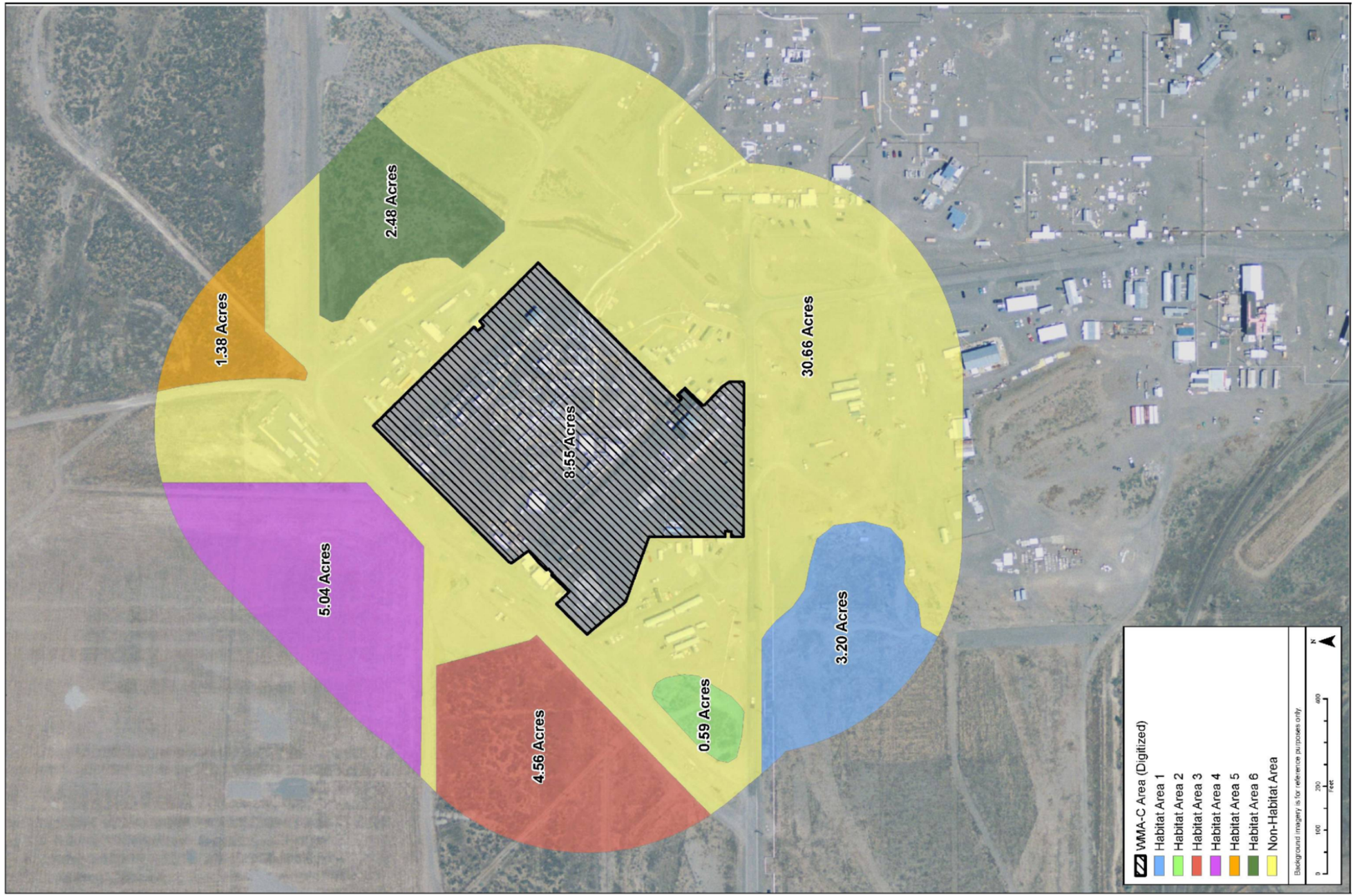



**Figure 3-12. Habitat Areas within a 500 Foot Perimeter of Waste Management Area C.**

WMA = Waste Management Area

**Figure 3-13. Geologic Elements of the Pasco Basin Portion of the Columbia Basin, Washington.**

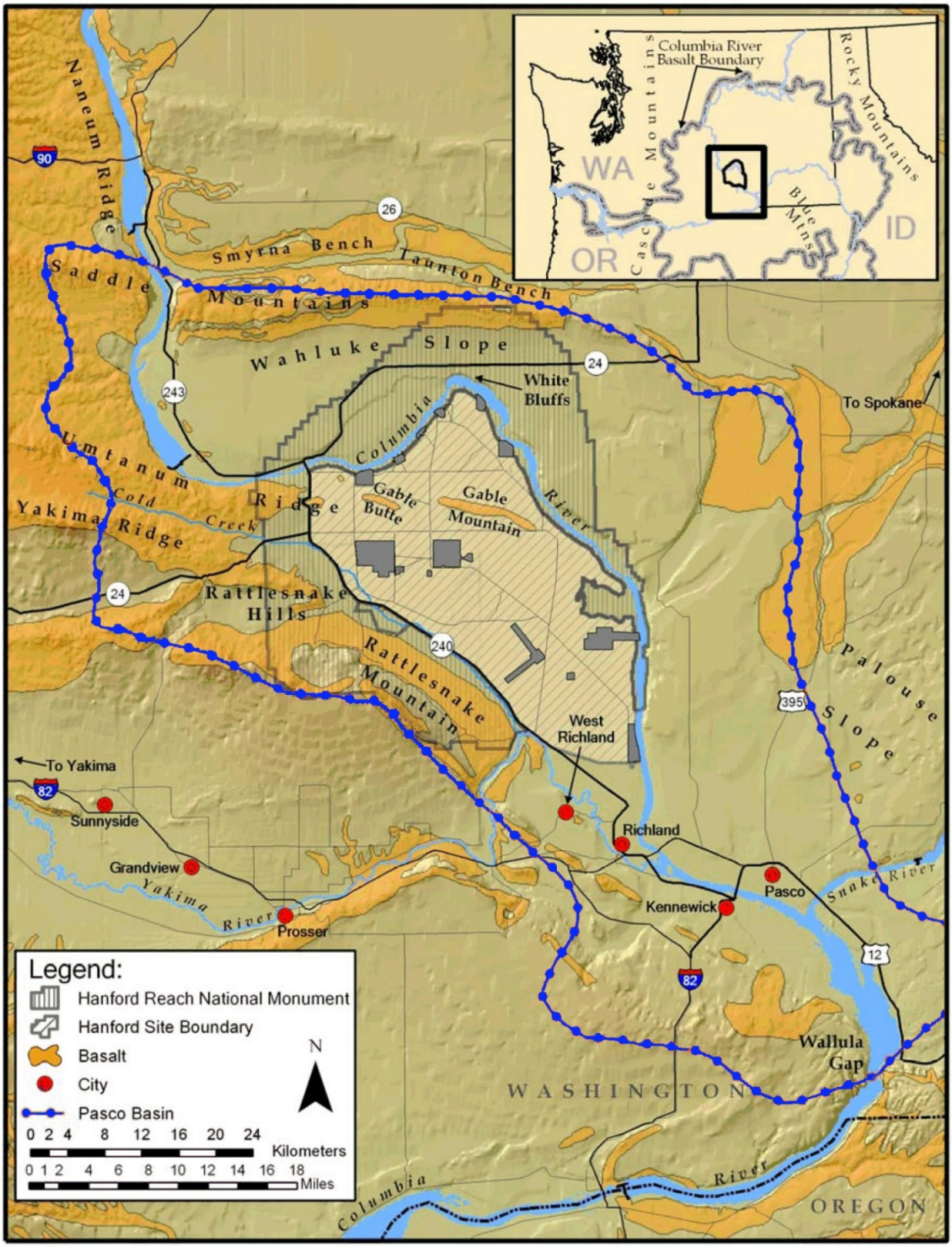
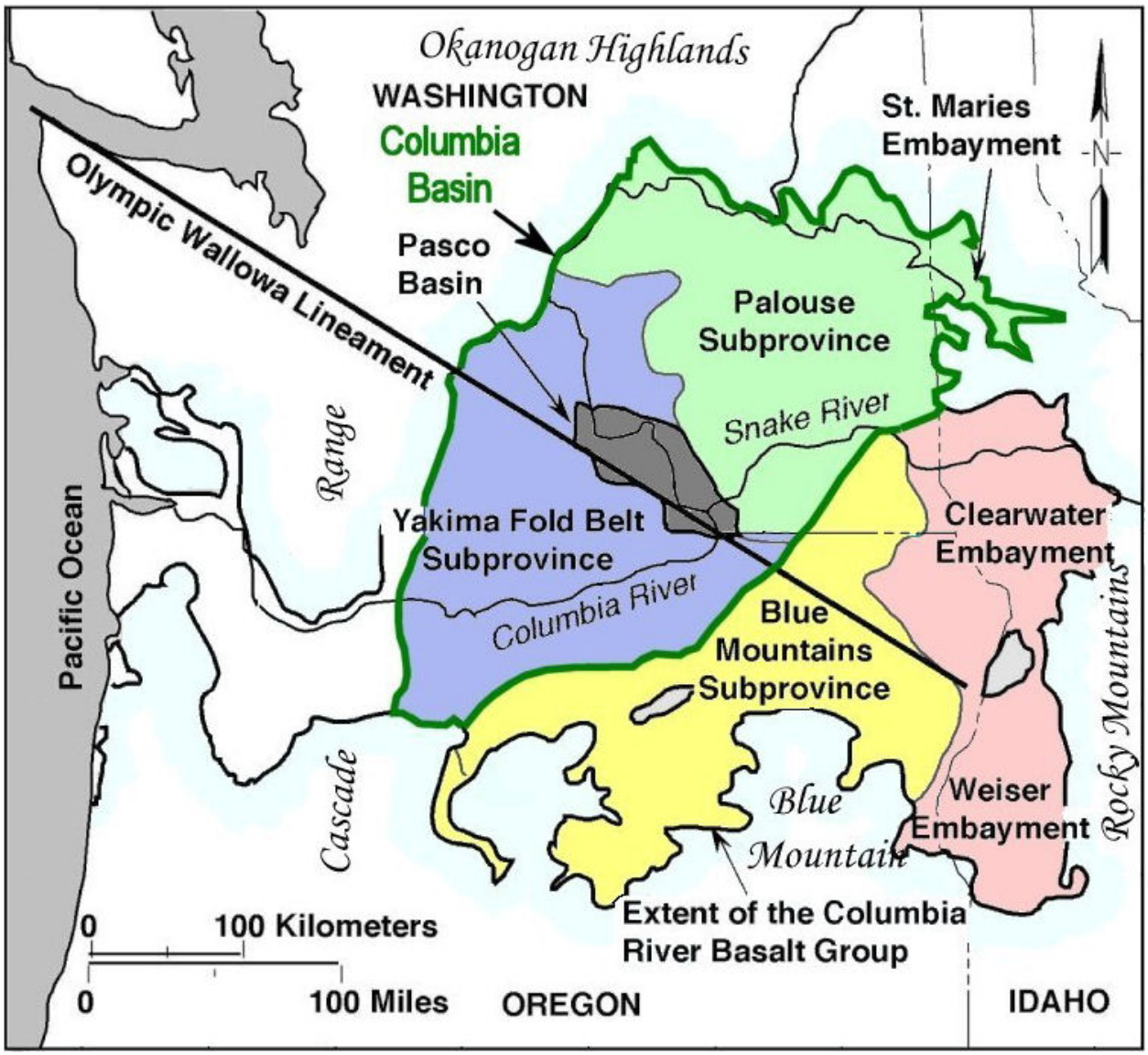


**Figure 3-14. Geologic Setting of the Columbia Basin and Pasco Basin.**




**Hanford formation**: The Hanford formation is the informal name given to all glacio-fluvial deposits from cataclysmic Ice Age floods found in the Pasco Basin (RHO-BWI-ST-4, "Geologic Studies of the Columbia Plateau: A Status Report"). Sources for floodwaters included glacial Lake Missoula, and ice-margin lakes that formed around the margins of the Columbia Plateau and Lake Bonneville (Baker et al. 1991). On average, interglacial conditions lasting ~50,000 years have been separated by major glacial advances, also averaging ~50,000 years. To date, Ice Age flood deposits from only four of the major glacial events that occurred between 1 million and 13,000 years ago are identified within the Pasco Basin (Baker et al. 1991; Open File Report 94-8, "Geologic Map of the Richland 1:100,000 Quadrangle, Washington"). Evidence to support the other major glacial cycles in the Pasco Basin either are masked or have been destroyed by subsequent Ice Age floods.

**Figure 3-15. Flood in the South of the Hanford Site, Washington, between 18,000 to 13,000 Years Ago.**

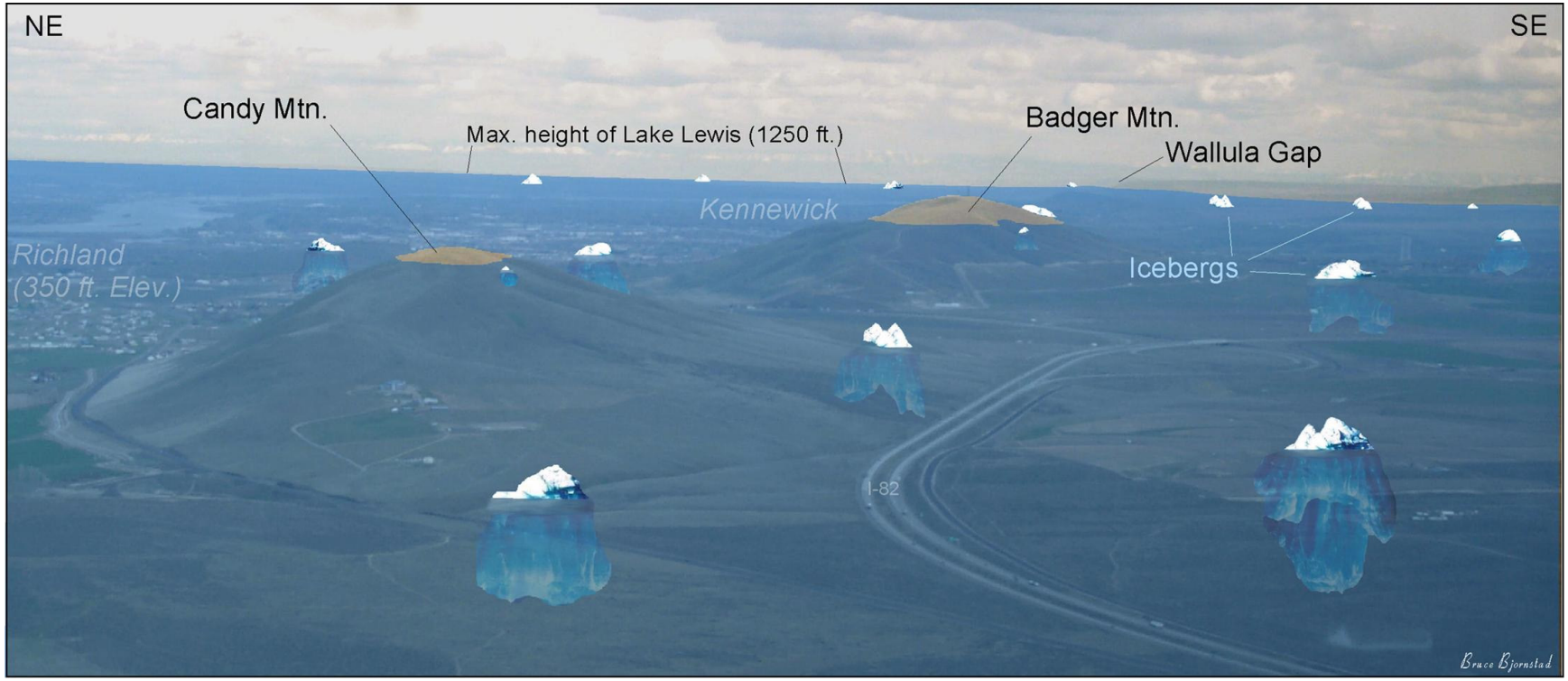


**Figure 3-16. Geologic and Geomorphic Map of the 200 Areas and Vicinity.**

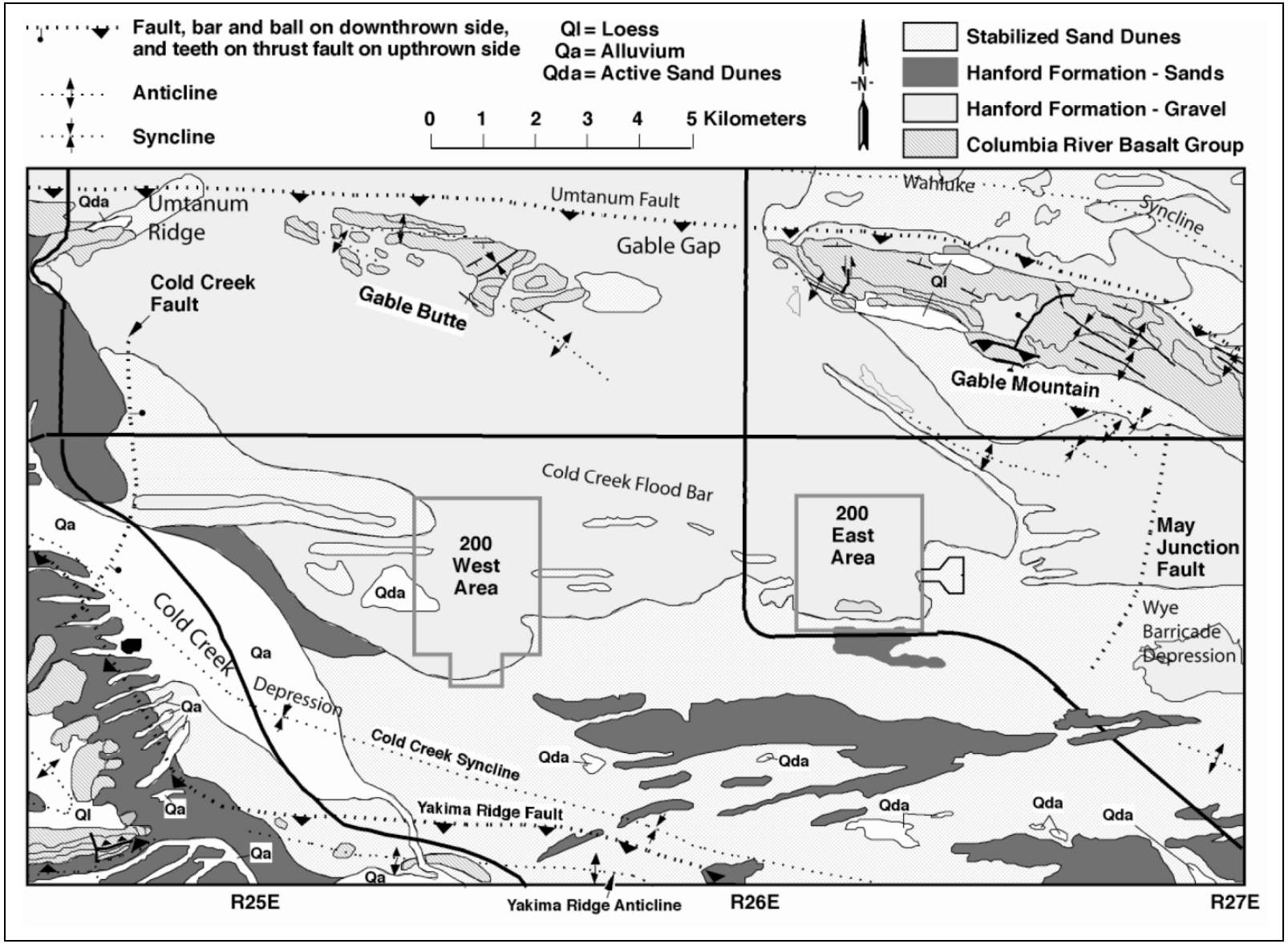


**Figure 3-17. Generalized Stratigraphy of the Hanford Site Including the Central Plateau.**

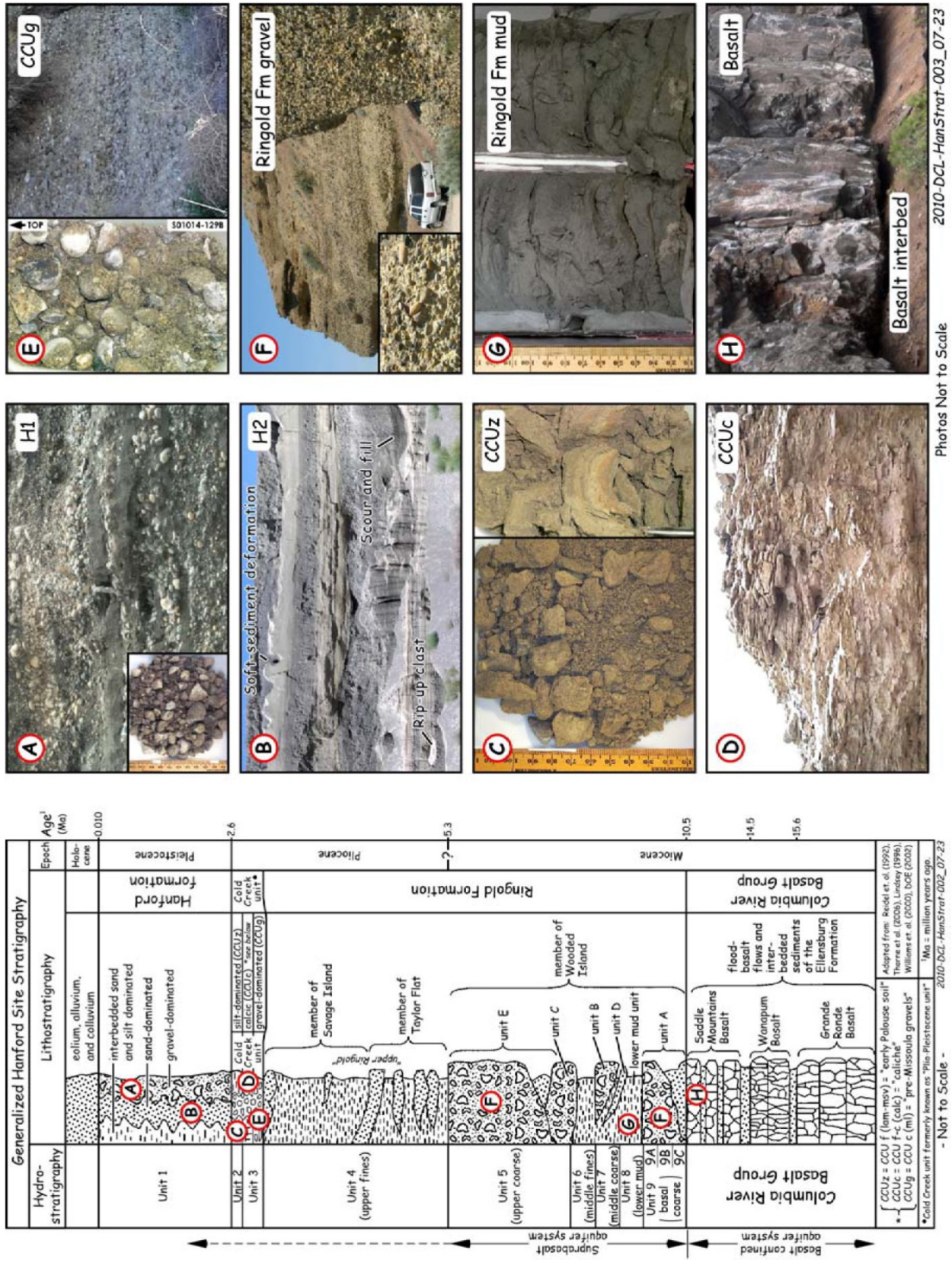


**Figure 3-18. Cross-Section Running through the Central Plateau of the Hanford Site.**

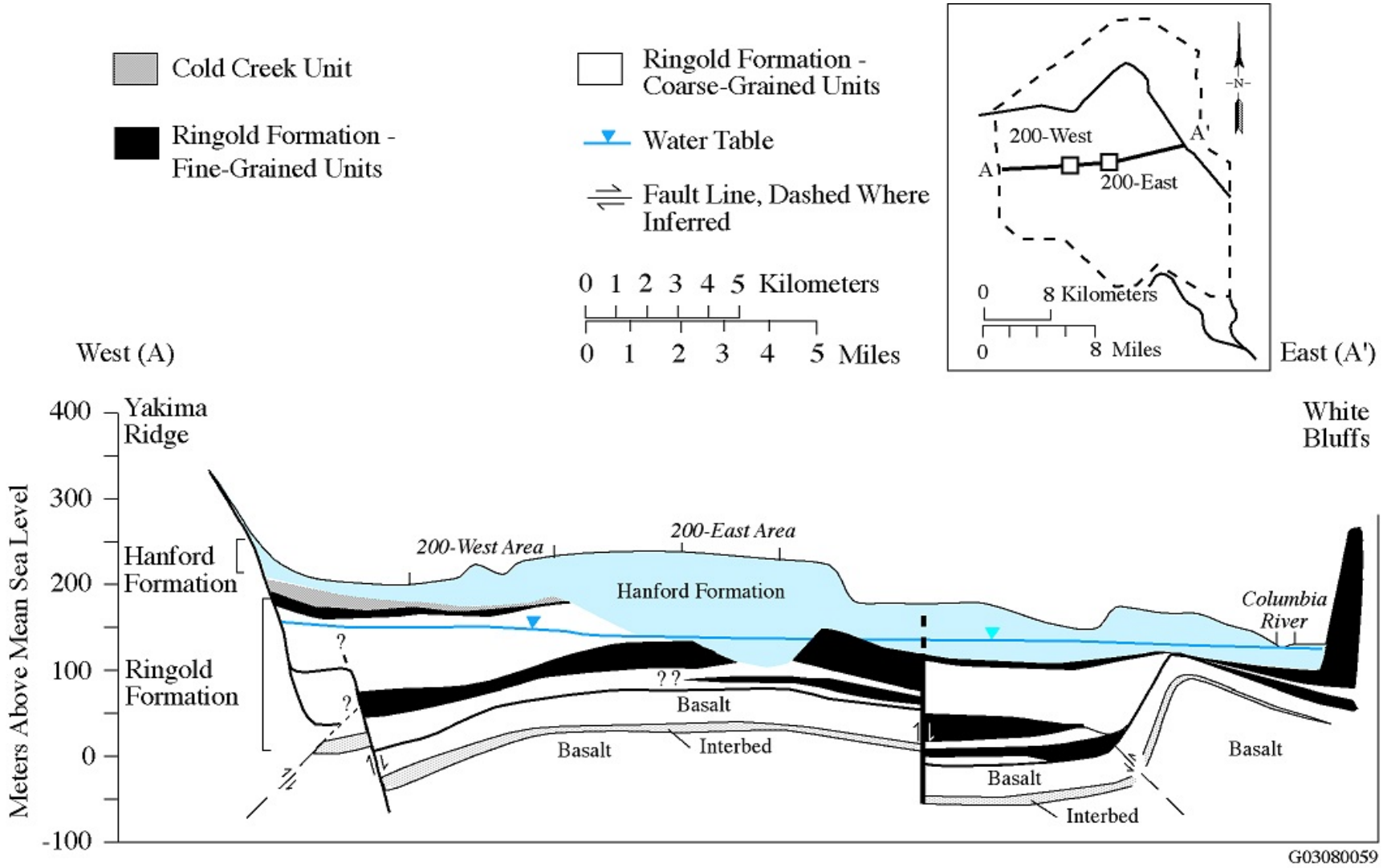
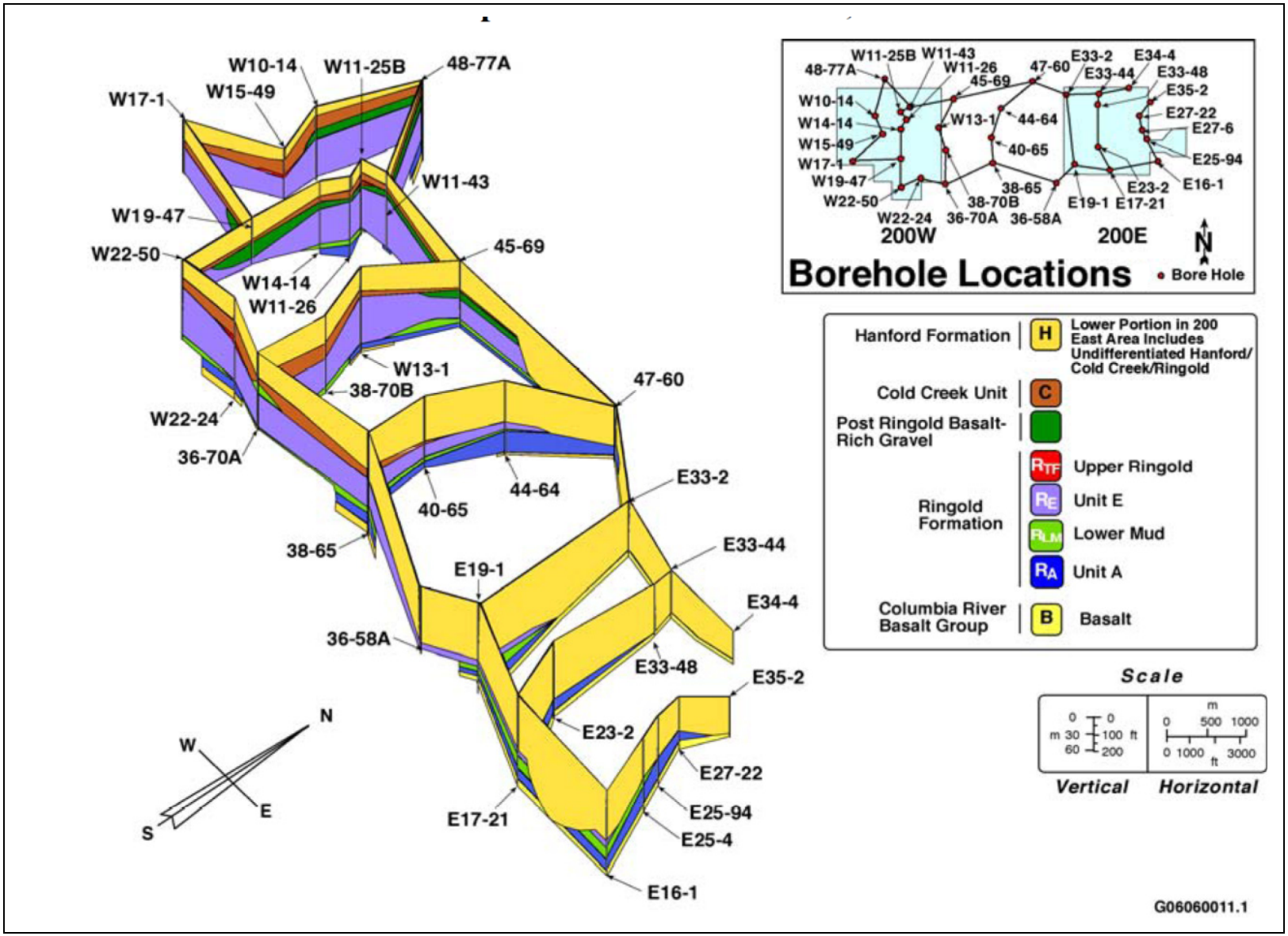


**Figure 3-19. Fence Diagram of Sediment Overlying the Columbia River Basalt Group in the Central Plateau, Hanford Site.**



When the Ice Age floodwaters entered the Pasco Basin, they quickly became impounded behind Wallula Gap, which was too restrictive for the volume of water involved. Floodwaters formed temporary lakes with shorelines up to 381 m (1,250 ft) in elevation. The lakes lasted not more than a few days ("Magnitudes and implications of peak discharges from glacial Lake Missoula" [O'Connor and Baker 1992]). The deposits that were left after the floodwater receded, known as the Hanford formation, blanket low-lying areas over most of the Hanford Site. These Ice Age floods created Cold Creek bar (Figure 3-20), a giant, streamlined deposit of gravel, sand, and silt that extends for 19.3 km (12 mi) downstream of Umtanum Ridge. Gravel-dominated deposits, laid down under the strongest flood currents, are generally restricted to the north side of the bar. At the south end of the bar, where flood currents were gentler, interbedded sand and silt deposits were laid down. In between these two areas deposits of predominantly sand accumulated, which includes the area beneath C Farm.

The Hanford formation consists of mostly unconsolidated sediments that cover grain sizes from pebble to boulder gravel, fine- to coarse-grained sand, silty sand, and silt. The formation is further subdivided into gravel-, sand-, and silt-dominated facies, which transition into one another laterally with distance from the main, high-energy, flood channels. Beneath much of the Hanford Site the Hanford formation has been locally subdivided into several informal subunits. WHC-SD-EN-TI-290, "Geologic Setting of the Low-Level Burial Grounds" subdivides the Hanford formation in the 200 East and West Areas into 3 basic units: H1, H2, and H3. H1 is described as consisting of a gravel facies-dominated interval in the upper part of the formation throughout much of the 200 East and West Areas. Unit H2 is described as a predominantly sand facies-dominated unit, which increases in predominance within the formation from north to south across the same area. The H3 unit is generally described as a mixed sand and gravel facies unit found comprising the lower part of the formation in much of the 200 East Area, and possibly locally in the 200 West Area.

Furthermore, PNNL-19702, "Hydrogeologic Model for the Gable Gap Area, Hanford Site" identified five paleochannels (A through E) running through the Central Plateau that are filled with coarse-grained, highly permeable flood deposits of the Hanford formation. These paleochannels may have initially formed during Ringold time, and if so, were further deepened during cataclysmic flooding which removed all Ringold-age deposits from the channel. Paleochannel D, which has a remnant of Ringold Formation along its east side, might be an example of a Ringold-age channel that was cut deeper during Ice Age flooding. Paleochannel D runs from the northwest corner through to the southeast corner of 200 East Area.

**Holocene Surficial Deposits:** Holocene surficial deposits consist of silt, sand, and gravel that form a thin layer across much of the Hanford Site. These sediments were deposited by a combination of eolian and alluvial processes.

**Tank Farm Backfill:** The shallowest sediments found within the confines of the tank farm are described primarily as basaltic pebble-cobble gravel with a sand and silt matrix. This material is commonly brown in color and contains construction debris, including nails, wood, and cement. These strata are interpreted to be tank farm backfill, which is consistent with previous interpretations of area geology (ARH-LD-132, "Geology of the 241-C Tank Farm"). Moisture logs collected in many of the tank farm leak detection borings show increased moisture ~12 to

13 m (40 to 42 ft) bgs. This is interpreted to be moisture accumulating above the compacted base of the original tank farm excavation. No soil has developed over the backfill and the vegetation within the WMA is controlled through herbicides.

**3.1.4.2.3 Clastic Dikes.** Clastic dikes are found in the Hanford formation and locally in other sedimentary units (RHO-BWI-C-64, "Clastic Dikes Of The Pasco Basin, Southeastern Washington, Final Report"; BHI-00230, "Geologic Field Inspection of the Sedimentary Sequence at the Environmental Restoration Disposal Facility"; BHI-01103, "Clastic Injection Dikes of the Pasco Basin and Vicinity – Geologic Atlas Series"). Clastic dikes (Figure 3-21) are vertical to sub-horizontal fissures filled by multiple layers of unconsolidated sand, silt, clay, and minor gravel aligned parallel to sub-parallel to dike walls. Clastic dikes range in vertical extent from 0.3 m to 55 m (1 ft to 180 ft). In cross-section, clastic dikes range from 1 millimeter to 1.8 m (0.04 in. to 6 ft) in thickness, and in plan view clastic dikes extend up to 100 m (328 ft) along strike. Clastic dikes form a branching pattern that in plan view forms polygons many feet across. Where the dikes intersect the ground surface, a feature known as patterned ground is observed. Patterned ground features are most abundant when Hanford formation sand-dominated and silt-dominated facies are at or near ground surface. BHI-01103 summarizes the location at Hanford where clastic dikes have been identified. Clastic dikes are inferred to be present beneath the SST farms, and at least locally, they cross-cut the Plio-Pleistocene boundary (WHC-EP-0698, "Groundwater Impact Assessment Report for the 216-U-14 Ditch"). BHI-01103 did not identify any clastic dikes in the vicinity of WMA C.

**3.1.4.2.4 200 Areas Topography.** Figure 3-22 shows the 200 Areas and the WMAs in a perspective view (note that the vertical to horizontal exaggeration in this figure is 5:1). The 200 Areas Central Plateau contains a topographic high in between the 200 East and 200 West Areas with gently dipping sides, except in the northwest corner of the 200 West Area. The WMAs were always located downhill from the waste-generating facilities to allow gravity flow in the pipelines from the facilities to the tanks. The relative flatness of the WMAs means that the final topography will be determined by the surface cover and grading of the surrounding soil.

**3.1.4.2.5 Surface Soils.** The Holocene deposits and exposed Hanford formation sediments have experienced soil development and evolved into identifiable soil types. BNWL-243, "Soil Survey Hanford Project in Benton County Washington" describes 15 different surface soil types on the Hanford Site, varying from sand to silty and sandy loam. Various classifications, including land use, are also given in BNWL-243. These soil types control the flux of water reaching the water table (i.e., recharge) (PNNL-13033). The soils found in the Central Plateau in and around the 200 Areas are Quincy Sand (formally known as Rupert Sand), Burbank Loamy Sand, and Ephrata Sandy Loam. BNWL-243 described these types of soil as follows.

- **Quincy Sand (formally known as Rupert Sand).** This mapping unit represents one of the most extensive soils on the Hanford Site. The surface is a brown to grayish-brown coarse sand, which grades to a dark grayish-brown sand at ~1 m (~36 in.). Rupert soils developed under grass, sagebrush, and hopsage in coarse sandy alluvial deposits, which were mantled by wind-blown sand. Relief characteristically consists of hummocky terraces and dune-like ridges. This soil may be correlated as Quincy Sand, which was not

separated here. Active sand dunes are present. Some dune areas are separated; however, many small dunes, blow-outs, and associated small areas of Ephrata and Burbank soils are included.

- **Burbank Loamy Sand.** This is a dark-colored (surface is very dark grayish-brown; subsoil is dark grayish-brown), coarse-textured soil which is underlain by gravel. The surface soil is usually 0.41 m (~16 in.) thick but can be 0.76 m (30 in.) thick. The gravel content of the subsoil may range from 20 to 80% by volume.

- **Ephrata Sandy Loam.** The surface of this soil is dark colored with subsoil that is dark grayish-brown and medium-textured. It is underlain by gravelly material that may extend for many feet.

- **Esquatzel Silt Loam.** This soil is not found within the 200 Areas Central Plateau, but rather to the south of the 200 West Area. It is mentioned here because it is a possible source for borrow material needed for the Modified RCRA Subtitle C Barrier (D&D-25575, "Silt Borrow Source Field Investigation Report"). It is deep dark-brown soil formed in recent alluvium and is derived from loess and lake sediment. The subsoil grades to dark grayish-brown in many areas, but color and texture of the subsoil are variable because of the stratified nature of the alluvial deposits.

Since the end of the Pleistocene, the main geologic process at the Hanford Site has been wind. After the last Missoula flood drained from the Pasco Basin, winds moved the loose, unconsolidated material until vegetation was able to stabilize it. Stabilized sand dunes cover much of the Pasco Basin, but there are areas, such as along the Hanford Reach National Monument, where active sand dunes remain.

**3.1.4.3 Seismology.** The historic record of earthquakes in the Pacific Northwest dates from about 1840. The early part of this record is based on newspaper reports of human perception of shaking and structural damage as classified using the Modified Mercalli Intensity (MMI) scale; the early record is probably incomplete because the region was sparsely populated. The historical record appears to be complete since 1905 for MMI V and since 1890 for MMI VI ("Earthquake Recurrence Rate Estimates for Eastern Washington and the Hanford Site," CONF-8910192--18 [Rohay 1989]). Seismograph networks did not start providing earthquake locations and magnitudes of earthquakes in the Pacific Northwest until about 1960. A comprehensive network of seismic stations that provides accurate locating information for most earthquakes of magnitude greater than 2.5 was installed in eastern Washington during 1969. Currently, measured seismic activity for the Hanford Site is reported quarterly and annually (e.g., PNNL-20302, "First Quarter Hanford Seismic Report for Fiscal Year 2011"). Figure 3-23 provides summaries of known events at and around the Hanford Site between 1890 and 2005 (PNNL-6415).

Three horizontal layers of stratigraphy related to seismicity exist at the Hanford Site and vicinity including the CRBG, the pre-basalt sediments, and the crystalline basement. About 75% of Hanford Site earthquake events originate in the CRBG layer. The pre-basalt sedimentary layer has been the origin of 8% of the events, and the crystalline basement has been the origin of 17% of these events (Revision 5-C of RPP-13033, "Tank Farms Documented Safety Analysis").

**Figure 3-20. Isopach Map of the Ice Age Flood Deposits (Hanford Formation).**

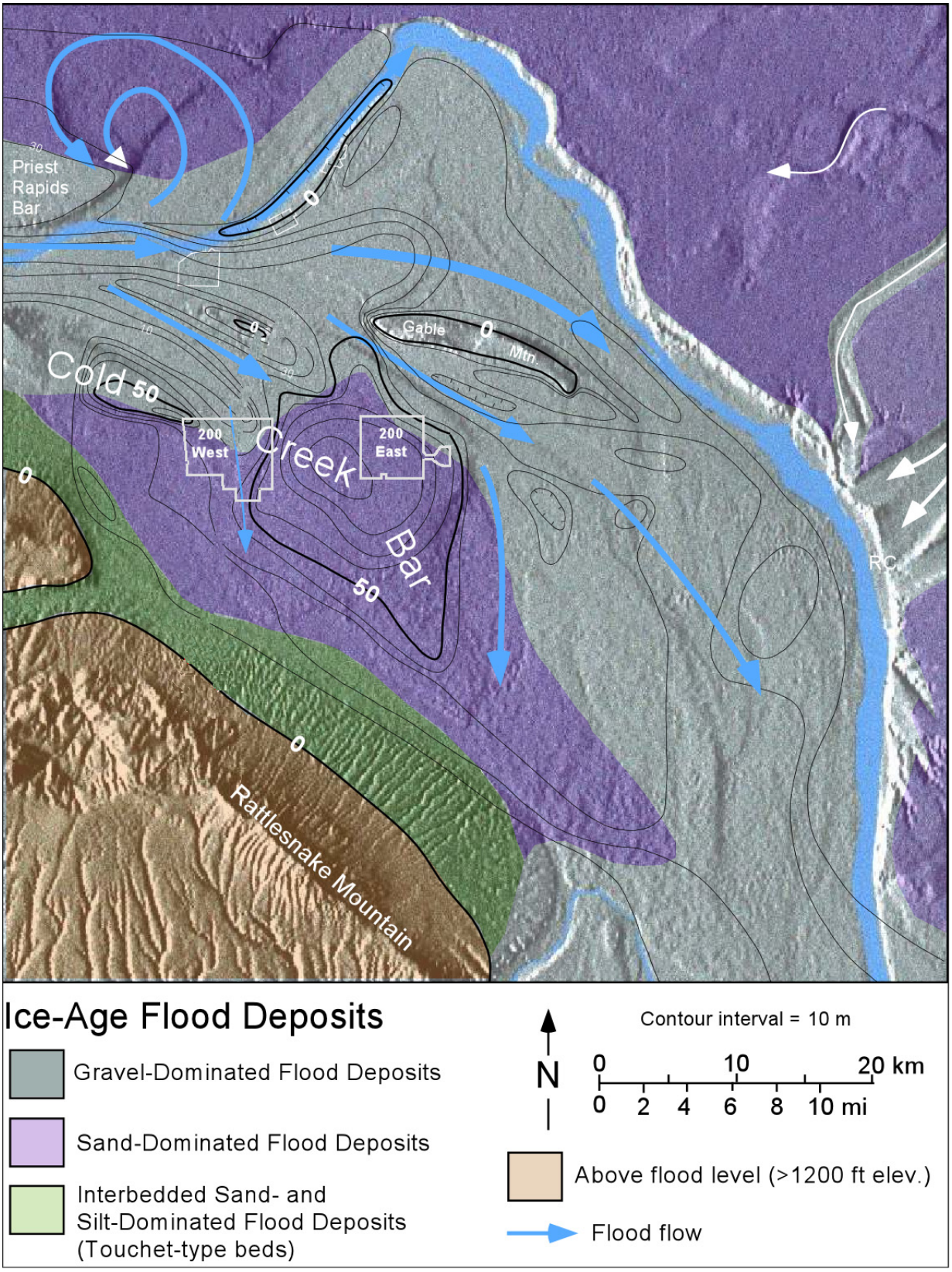
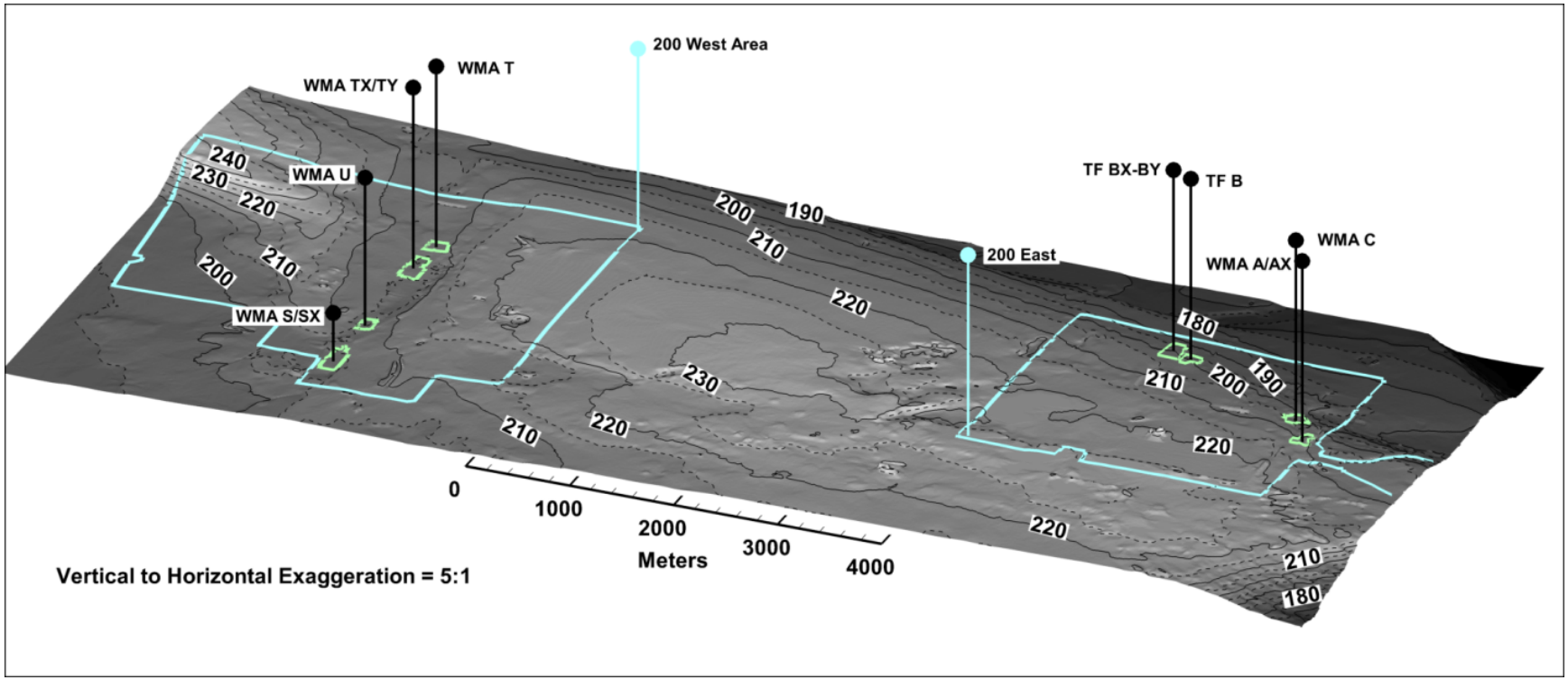


**Figure 3-21. Typical Type II Clastic Injection Dike Exposed in a Wall of the Environmental Restoration Disposal Facility Excavation Exposed during Construction. The facility is located on the 200 Area Pleistocene Glacio-fluvial Flood Bar in the central Hanford Site.**

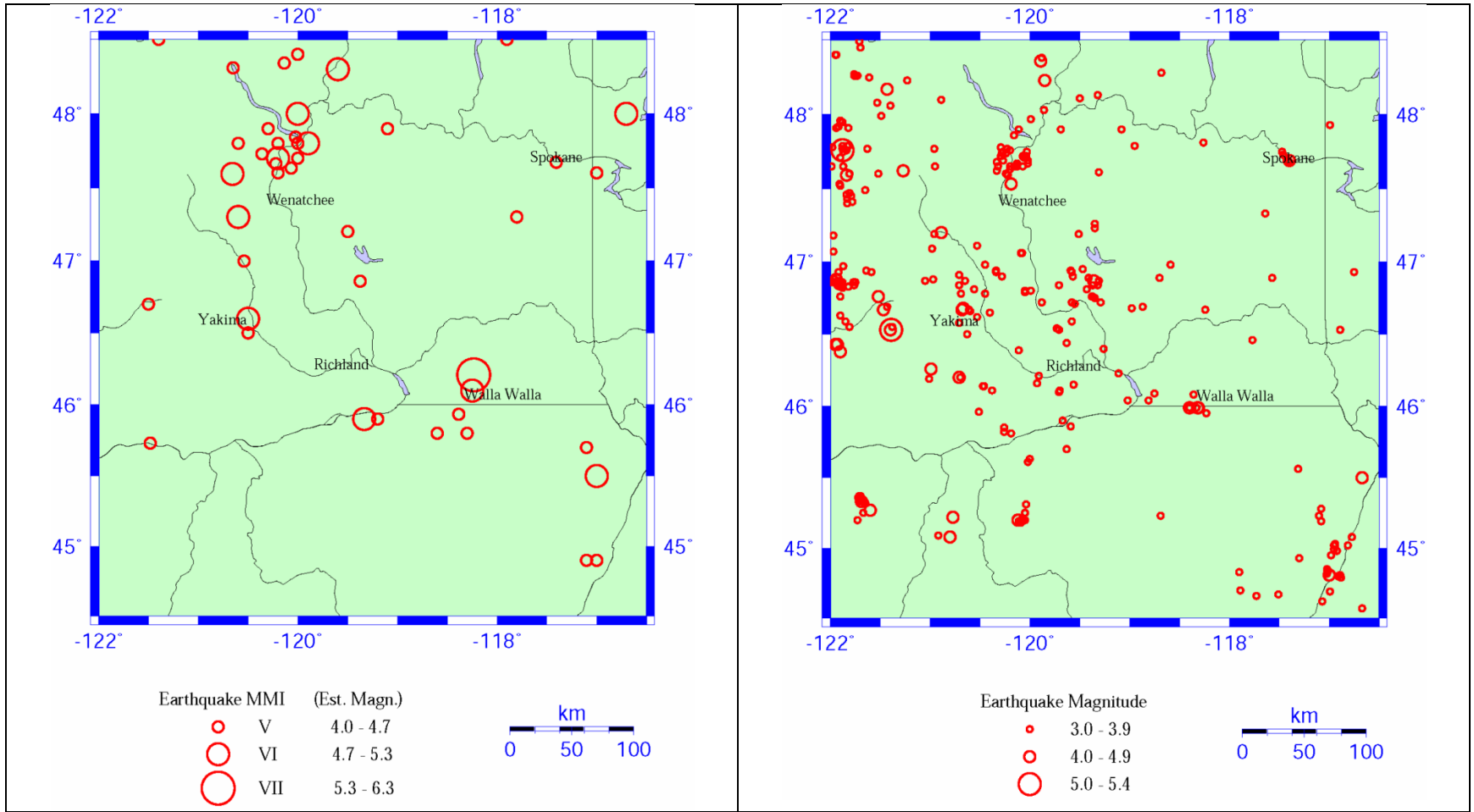
Source: BHI-01103, *Clastic Injection Dikes of the Pasco Basin and Vicinity – Geologic Atlas Series*.

**Figure 3-22. Topography of the 200 Areas Central Plateau in Meters above Mean Sea Level.**




WMA = Waste Management Area

**Figure 3-23. Historical Earthquake Activity of the Columbia Basin, Washington, and Surrounding Areas.**




***Left:*** *Historical Earthquake Activity of the Columbia Basin, Washington, and Surrounding Areas. All earthquakes between 1890 and 1970 with a Modified Mercalli Intensity (MMI) V or larger and/or a magnitude 4 or larger are shown ("Earthquake Recurrence Rate Estimates for Eastern Washington and the Hanford Site," CONF-8910192--18 [Rohay 1989]).*

***Right:*** *Earthquake Activity of the Columbia Basin, Washington, and Surrounding Areas as Measured by Seismographs. All earthquakes between 1970 and 2005 with Richter magnitudes of 3 or larger are shown (Northern California Earthquake Data Center, Queried 09/2005, [Advanced National Seismic System (ANSS) Catalog Search], http://www.quake.geo.berkeley.edu/anss/catalog-search.html).*

Source: PNNL-6415, "Hanford Site National Environmental Policy Act (NEPA) Characterization."

The most frequent seismic occurrences at the Hanford Site are earthquake swarms (Figure 3-24) that consist of multiple small energy events that fall within a small energy range and are constrained temporally (weeks to months) and spatially (5 to 10 km [3 to 6 mi] in length). Swarms tend to reoccur in particular locations, ~90% of individual earthquakes are at Richter scale magnitudes of 2 or less, and 70% to 80% of them occur at depths less than 4 km (2.5 mi) bgs.

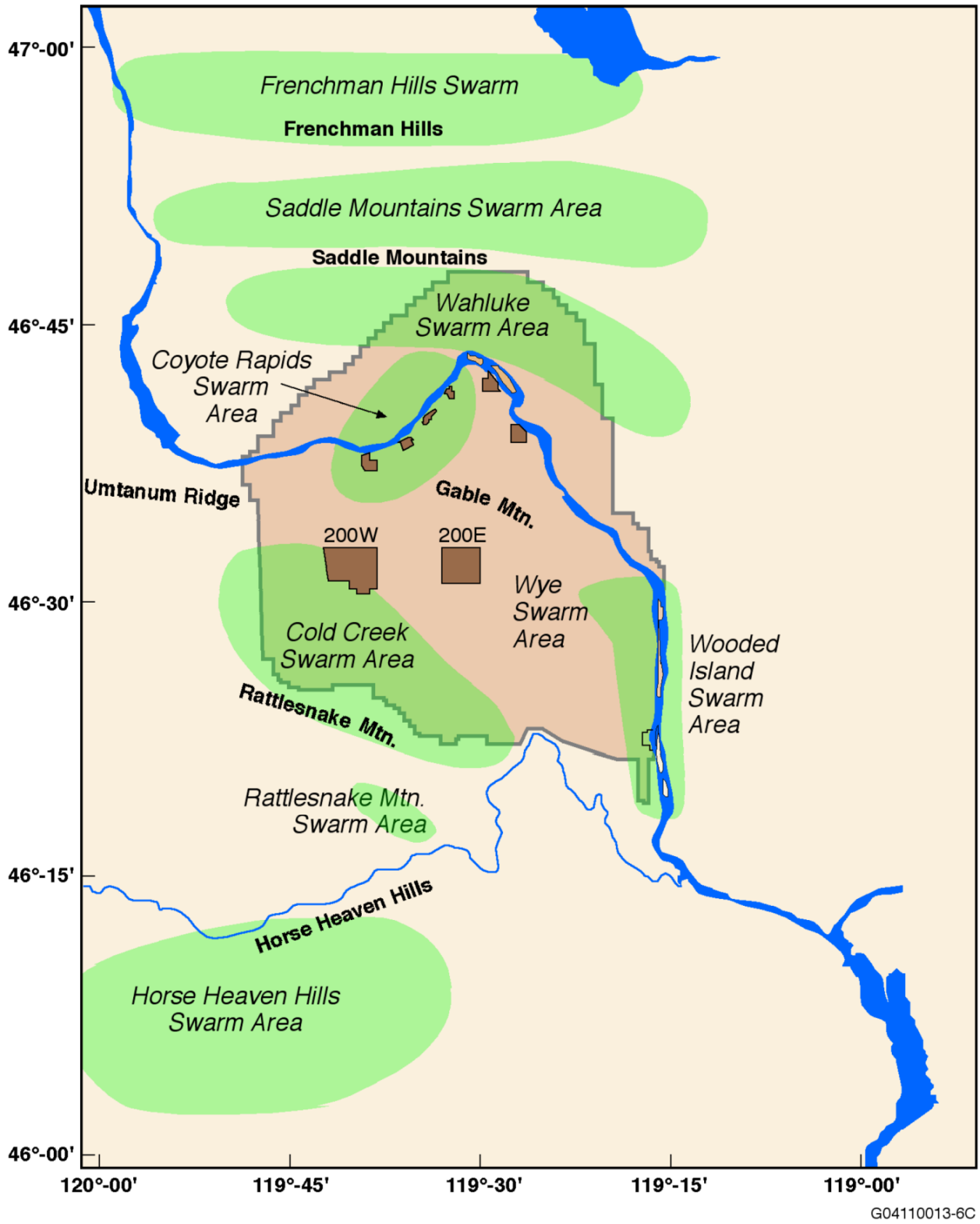
Larger isolated earthquakes also occur nearby (DOE/RW-0164). The largest single event earthquake recorded near the Hanford Site occurred in Milton-Freewater, Oregon, located ~80 km (50 mi) away in 1936 at a Richter magnitude of 5.75 and a maximum MMI of VII. The two next largest nearby earthquakes occurred north of the Hanford Site in 1917 and 1973 near Othello, Washington, ~49 km (30 mi) north of the 200 Areas with magnitudes above 4 on the Richter scale and MMI of V. The 1973 earthquake occurred ~1 km (0.6 mi) bgs. Since 1973, 80 small earthquakes (2.5 to 4.3 magnitudes) have been recorded within a radius of 90 km (56 mi) of the Hanford Site Central Plateau, the closest being a magnitude 3.3 event with the epicenter 8 km (5 mi) north of the 200 Areas. Earthquake depths vary for isolated events and have been estimated as deep as 30 km (~19 mi).

Greater magnitude earthquakes have been recorded at greater distances from the Hanford Site at the edges of the Columbia Plateau, along the coastal subduction zones to the west and in the Rocky Mountains to the east. The Columbia Plateau, which is made up of thick and extensive sequences of flood basalt layers in the Columbia River Group, extends well beyond the Hanford Site covering parts of eastern Washington, eastern Oregon, and Idaho. Notable events in these areas are the 2001 “Nisqually earthquake” in the Puget Sound (6.8 magnitude), an approximate magnitude 6.8 to 7.4 earthquake in north-central Washington in 1872 near Lake Chelan, the 1959 Hebgen Lake earthquake (7.5 magnitude) in western Montana, and the 1983 Borah Peak earthquake in eastern Idaho (7.3 magnitude).

The gross pattern of seismic activity around the Hanford Site is consistent with our understanding of regional tectonic characteristics of the Northwest. That is, the flood basalts form a large and relatively competent block of rock that is surrounded by numerous complex zones of active faults where large-scale stresses, imposed primarily by the ongoing subduction of the Pacific and Juan de Fuca Plates underneath the North American Plate, are mostly relieved. Consequently, relatively minimal stress relief occurs in the Columbia Plateau and earthquake energy is correspondingly small. This means that potential ground motion that accompanies these earthquakes is also relatively small.

Relative movement is commonly quantified as some fraction of gravitational acceleration (g) and has been usually correlated with earthquake magnitude. For the range of earthquake magnitudes suggested by data summarized above for the Hanford Site (<3 to 6), peak accelerations between <0.0017 and 0.18 g are proposed. The associated range of motion is generally imperceptible compared to clearly felt movement that can result in minimal building damage. A probabilistic seismic hazard analysis (WHC-SD-W236A-TI-002, “Probabilistic Seismic Hazard Analysis, DOE Hanford Site, Washington”) estimated that a 0.1 g horizontal acceleration would occur every 500 years and a 0.2 g acceleration would occur every 2,500 years.

**Figure 3-24. Earthquake Swarm Areas in the Vicinity of the Hanford Site.**



**3.1.4.4 Volcanology.** Two types of volcanic hazards have affected the Hanford Site in the past 20 million years. The hazards were (1) continental flood basalt volcanism that produced the CRBG and (2) volcanism associated with the Cascade Range. Several volcanoes in the Cascade Range are currently considered to be active, but activity associated with flood basalt volcanism has ceased.

The flood basalt volcanism that produced the CRBG occurred between 17 and 6 million years ago. Most of the lava was extruded during the first 2 to 2.5 million years of the 11-million-year volcanic episode. Volcanic activity has not recurred during the last 6 million years, suggesting that the tectonic processes that created the episode have ceased. The recurrence of CRBG volcanism is not considered to be a credible volcanic hazard (DOE/RW-0164).

Volcanism in the Cascade Range was active throughout the Pleistocene Epoch and has remained active through the Holocene Epoch. The eruption history of the current Holocene Epoch best characterizes the most likely types of activity in the next 100 years. Many of the volcanoes have been active in the last 10,000 years, including Mount Mazama (Crater Lake) and Mount Hood in Oregon; and Mount Saint Helens, Mount Adams, and Mount Rainier in Washington. The Hanford Site is 150 km (~93 mi) from Mount Adams, 175 km (109 mi) from Mount Rainier, and 200 km (124 mi) from Mount Saint Helens, the three closest active volcanoes. At these distances, the deposition of tephra (ash) is the only potential hazard. Mount Saint Helens has been considerably more active throughout the Holocene Epoch than Mount Rainier or Mount Adams, which is the least active of the three. WHC-SD-GN-ER-30038, "Volcano Ashfall Loads for the Hanford Site" concludes that the Hanford Site is sufficiently distant from the Cascade Range volcanoes that hazards from lava flows, pyroclastic flows and surges, landslides, lahars, and ballistic projectiles are below a probability of concern.

**3.1.4.5 Subsurface Subsidence and Liquefaction.** Field and laboratory studies that have been completed at many of the tank farm sites are summarized in WHC-SD-GN-ER-30009, "Bibliography and Summary of Geotechnical Studies at the Hanford Site." These studies reveal that there are no areas of potential surface or subsurface subsidence, uplift, or collapse at the Hanford Site, with the minor exceptions of the Cold Creek and Wye Barricade depressions, neither of which are close to WMA C. With the exception of the loose superficial wind-deposited silt and sand in some locations, the in-place soils are competent and form good foundations.

Liquefaction is the sudden decrease of shearing resistance of a cohesionless soil, caused by the collapse of the structure by shock or strain, and is associated with a sudden but temporary increase of the pore fluid pressure. Saturated or near-saturated soil (sediments) are required for liquefaction to occur. The average volumetric moisture content at WMA C is less than 10% (see Section 3.1.9.2.2). Therefore, liquefaction of soils beneath the tank farms would not a credible hazard because the water table is greater than 65 m (213 ft) bgs.

### 3.1.5 Hydrology

This section presents the summary of the hydrology/hydrogeology (water and soil characteristics) of the Hanford Site, focusing on surface water, recharge, characteristics of the

unsaturated zone or vadose zone and the saturated zone or groundwater. Due to waste disposal operations at the Hanford Site, the hydrology of the Site has been studied and monitored in detail. Therefore, the information presented in this section will primarily be a summation of previous work highlighting those characteristics that affect the WMA C PA. For additional detail, see the following references.

- PNNL-20548, "Hanford Site Environmental Report for Calendar Year 2010 (Including Some Early 2011 Information)" provides the overview of the characterization and monitoring activities conducted at the Hanford Site during the calendar year.

- DOE/RL-2013-22, Hanford Site Groundwater Monitoring Report for 2012. This document describes the groundwater monitoring activities during the fiscal year.

- Revision 18 of PNNL-6415, "Hanford Site National Environmental Policy Act (NEPA) Characterization" provides a standardized description of the Hanford Site environment.

- DOE/ORP-2008-01, RCRA Facility Investigation Report for the Hanford Single-Shell Tank Waste Management Areas. This document describes the Phase 1 vadose zone characterization efforts at the SST farms.

These overview documents will contain references to site-specific documents that describe the hydrology for a particular waste site (e.g., WMA C). A summary of the hydrology for WMA C is given in Section 3.1.9 Waste Management Area C Site Characterization

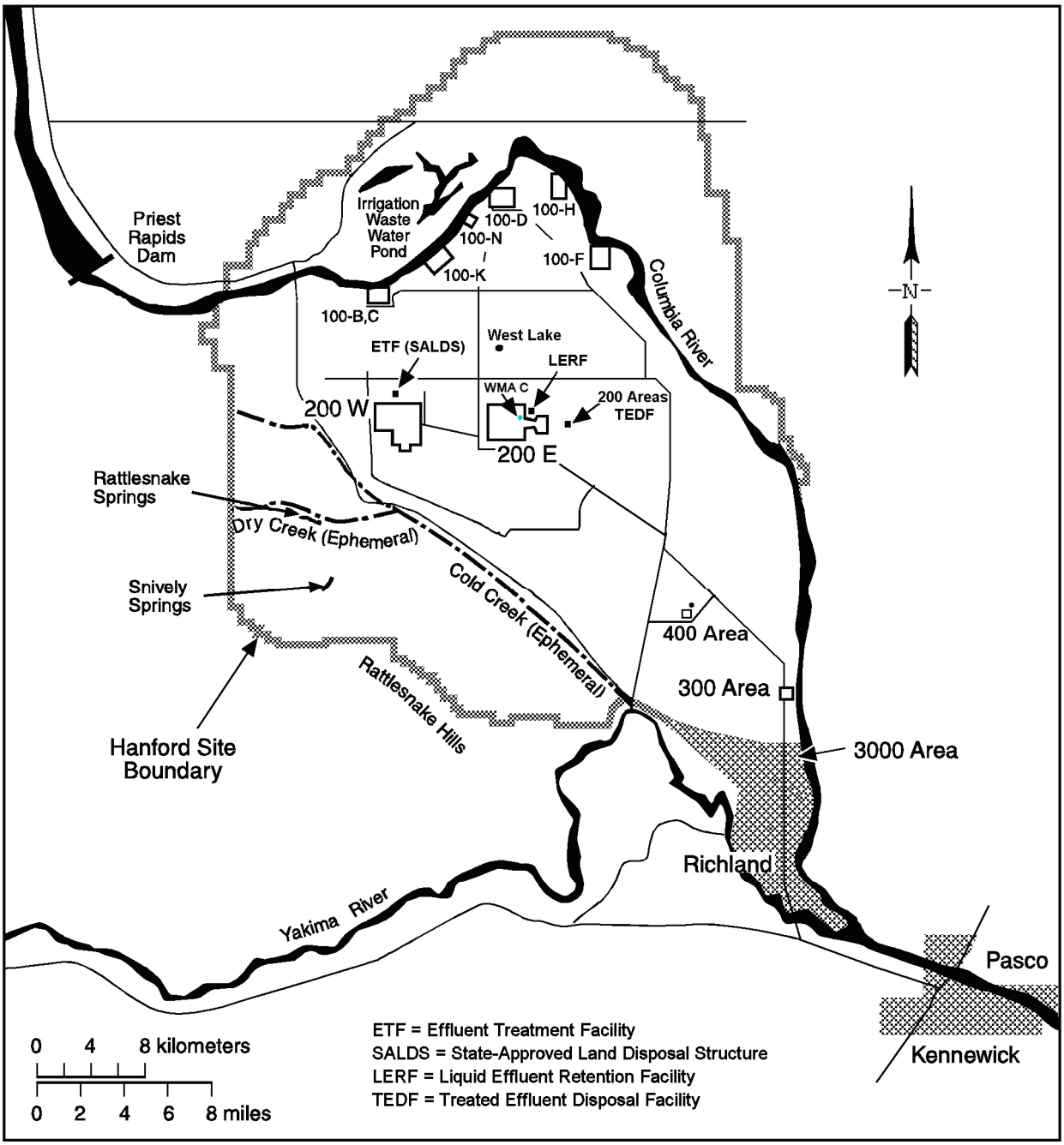
**3.1.5.1 Surface Water.** Surface water at the Hanford Site includes the Columbia River, Columbia Riverbank seepage, springs, and ponds. Intermittent surface streams, such as Cold Creek, may also contain water after large precipitation or snowmelt events. In addition, the Yakima River flows along a short section of the southern boundary of the Hanford Site (Figure 3-25), and there is surface water associated with irrigation east and north of the Site.

**3.1.5.1.1 Columbia River.** The Columbia River is the second largest river in the contiguous United States in terms of total flow and is the dominant surface-water body on the Hanford Site. The original selection of the Hanford Site for plutonium production and processing was based, in part, on the occurrence of abundant water provided by the Columbia River. The existence of the Hanford Site has precluded development of this section of the river. Waste left at WMA C following closure could impact the Columbia River through the groundwater pathway. Waste Management Area C is located ~11.2 km (7 mi) from the Columbia River.

The Columbia River originates in the mountains of eastern British Columbia, Canada, and drains an area of ~680,000 $km^2$ (262,480 $mi^2$) enroute to the Pacific Ocean. Columbia River flow at the U.S. Geological Survey gauging station, located just west of the Hanford Site boundary (located downstream of Priest Rapids Dam), has been measured during a 90-year period from 1917 to 2007. Daily average flows during this period ranged from 570 to 19,500 $m^3/s$ (20,000 to 690,000 $ft^3/s$). The lowest and highest flows occurred before the construction of upstream dams. During the 10-year period from 1997 through 2006, the average flow rate was also ~3,300 $m^3/s$

(116,500 $ft^3/s$). The river elevation is ~121 m (396 ft) near the 100 B and C areas and ~105 m (343 ft) at the 300 Area.

**Figure 3-25. Surface Water Features including Rivers, Ponds, Major Springs, and Ephemeral Streams on the Hanford Site, Washington.**

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The Columbia River flows through the northern part and along the eastern border of the Hanford Site with these areas of the Hanford Site draining into the Columbia River. Except for the

Columbia River estuary, the only unimpounded stretch of the river in the United States is the Hanford Reach, which extends from Priest Rapids Dam (located upstream of the Site) downstream ~82 km (51 mi) to the northern upstream extent of Lake Wallula (formed by McNary Dam), which begins above Richland. The Hanford Reach of the Columbia River was recently incorporated into the land area established as the Hanford Reach National Monument.

Flows in the Hanford Reach are directly affected by releases from Priest Rapids Dam; however, Priest Rapids operates as a run-of-the-river dam rather than a storage dam. Flows are controlled to generate power and promote salmon egg and embryo survival. Several drains and intakes are also present along the Hanford Reach, including irrigation outfalls from the Columbia Basin Irrigation Project, intakes at the Columbia Generating Station operated by Energy Northwest, and Hanford Site intakes for onsite water use.

The State of Washington has promulgated water quality standards for the Columbia River, WAC 173-201A, "Water Quality Standards for Surface Waters of the State of Washington." The Hanford Reach of the Columbia River has been designated as Class A (Excellent). This designation requires that the water be usable for substantially all needs, including drinking water, recreation, and wildlife. The DOE has conducted routine water-quality monitoring of the Columbia River since 1958.

**3.1.5.1.2 Yakima River.** The Yakima River, which follows a small length of the southwest boundary of the Hanford Site, has much lower flows than the Columbia River. The average flow, based on nearly 72 years of daily flow records (U.S. Geological Survey, Queried 09/2015, [USGS Water Data for the Nation], http://waterdata.usgs.gov/nwis/nwis), is ~104 $m^3/s$ (3,530 $ft^3/s$), with an average monthly maximum of 470 $m^3/s$ (17,550 $ft^3/s$), and minimum of 4.6 $m^3/s$ (165 $ft^3/s$). The Yakima River System drains surface runoff from approximately one-third of the Hanford Site. Contaminant plumes in groundwater that originate from the Hanford Site do not reach the Yakima River and, because the elevation of the river surface is higher than the adjacent water table (based on well water-level measurements), groundwater is expected to flow from the Yakima River into the aquifer underlying the Site rather than from the aquifer into the river (PNL-10195, "Three-Dimensional Conceptual Model for the Hanford Site Unconfined Aquifer System: FY 1994 Status Report").

**3.1.5.1.3 Springs and Streams.** Springs are found on the slopes of Rattlesnake Hills (Figure 3-25) along the western edge of the Site (DOE/RW-0164). An alkaline spring is located at the east end of Umtanum Ridge ("Biodiversity Inventory and Analysis of the Hanford Site, 1997 Annual Report" [The Nature Conservancy 1998]). Rattlesnake and Snively Springs form small surface streams (Figure 3-25). Water is discharged from Rattlesnake Springs and flows in Dry Creek for ~3 km (1.6 mi) before disappearing into the ground. Cold Creek and its tributary, Dry Creek, are ephemeral streams within the Yakima River drainage system in the southwestern portion of the Site. These streams drain areas to the west of the Site and cross the southwestern part of the Site toward the Yakima River. When surface flow occurs, it infiltrates rapidly and disappears into the surface sediments in the western part of the Site. The quality of water in these springs and streams varies depending on the source; they are upgradient of Hanford waste and plumes of contaminated groundwater found on the Hanford Site.

**3.1.5.1.4 Flooding.** Columbia River flow is regulated by three upstream dams in Canada and by seven upstream dams in the United States. The Hanford Reach, ~80 km (50 mi) long, extends from Priest Rapids Dam to just north of the 300 Area. Flow through the Hanford Reach fluctuates significantly and is controlled at Priest Rapids Dam. The three dams with the largest reservoirs upstream from the Hanford Site are the Mica and Hugh Keenleyside dams in Canada and the Grand Coulee Dam in the United States. The controlled flow of the Columbia River caused by these dams results in a lower flood hazard for high-probability floods (e.g., 100-yr floods); however, dam-failure scenarios are significant potential contributors that result in high flood flows.

The probable maximum flood for the Columbia River downstream of Priest Rapids Dam has been calculated to be 40,000 $m^3/s$ (1.4 million $ft^3/s$) (Figure 3-26) and is greater than the 500 year flood. This flood would inundate parts of the 100 Area adjacent to the Columbia River, but the central portion of the Hanford Site would remain unaffected [DOE/RW-0070, Nuclear Waste Policy Act (Section 112), Environmental Assessment, Reference Repository Location, Hanford Site, Washington]. The USACE has derived the Standard Project Flood with both regulated and unregulated peak discharges given for the Columbia River downstream of Priest Rapids Dam ("Water Control Manual for McNary Lock and Dam, Columbia River, Oregon and Washington" [USACE 1989]). The regulated Standard Project Flood for this part of the river is given as 15,200 $m^3/s$ (54,000 $ft^3/s$) and the 100 year regulated flood as 12,400 $m^3/s$ (440,000 $ft^3/s$). Impacts to the Hanford Site are negligible and would be less than the probable maximum flood.

The USACE evaluated a number of scenarios on the effects of failures of Grand Coulee Dam, assuming flow conditions on the order of 11,325 $m^3/s$ (400,000 $ft^3/s$). The discharge resulting from a 50% breach at the outfall of Grand Coulee Dam was determined to be 595,000 $m^3/s$ (21 million $ft^3/s$). In addition to the areas inundated by the probable maximum flood, the remainder of the 100 Area, the 300 Area, and nearly all of Richland would be flooded (DOE/RW-0070) as shown in Figure 3-26. No determinations were made for breaches greater than 50% of Grand Coulee Dam, for failures of dams upstream, or for associated failures downstream of Grand Coulee. Based on a 1951 USACE study (USACE 1951, "Artificial Flood Possibilities on the Columbia River"), the 50% breach scenario was believed to represent the largest realistically conceivable flow resulting from either a natural or human-induced breach (DOE/RW-0070). It was also assumed that a scenario such as the 50% breach would occur only as the result of direct explosive detonation, and not because of a natural event such as an earthquake, and that even a 50% breach under these conditions would indicate an emergency situation in which there might be other overriding major concerns.

A flood scenario of a 50% breach of Grand Coulee Dam results in a flood level of ~143.3 m (470 ft) above mean sea level at Columbia River mile 365; this low point is the closest flood route to the 200 Areas Plateau. River mile 365 is ~45.7 m (150 ft) below the ground surface of the lowest elevation tank farm. The 50% breach of the Grand Coulee Dam would not impact the 200 East and 200 West areas or the land within the 600 Area (i.e., between the 200 East and 200 West areas) occupied by tank farm facilities. Therefore, this scenario bounds all other Columbia River flood scenarios. UCRL-21069, "Probabilistic Flood Hazard Assessment for the

N Reactor, Hanford, Washington" provides a detailed hazard assessment of other flood scenarios.

The Yakima River is ~19.3 km (12 mi) south of and greater than 61 m (200 ft) in elevation below the 200 East and 200 West areas. The Yakima River is not a flood hazard for the tank farm facilities. During 1980, a flood risk analysis of Cold Creek was conducted as part of the characterization of a basaltic geologic repository for high-level radioactive waste. In lieu of 100- and 500-year floodplain studies, a probable maximum flood evaluation was performed based on a large rainfall or combined rainfall/snowmelt event in the Cold Creek and Dry Creek watershed (RHO-BWI-C-120/PNL-4219, "Flood Risk Analysis of Cold Creek near the Hanford Site") (Figure 3-27). The probable maximum flood discharge rate for the lower Cold Creek Valley was 2,265 $m^3/s$ (80,000 $ft^3/s$) compared to 564 $m^3/s$ (19,900 $ft^3/s$) for the 100 year flood. Modeling indicated that State Route 240, along the Hanford Site's southwestern and western areas, would not be usable. Based on the information presented in this section, flooding of WMA C would not be a credible scenario.

**3.1.5.1.5 Columbia Riverbank Springs**. During the early 1980s, researchers identified 115 springs along the Benton County shoreline of the Hanford Reach (PNL-5289, "Investigation of Ground-Water Seepage from the Hanford Shoreline of the Columbia River"). Seepage occurs both below the river surface and on the exposed riverbank, particularly at low river stage. Riverbank springs flow intermittently, apparently influenced primarily by changes in river level. In many areas, water flows from the river into the aquifer at high river stage and then returns to the river at low river stage. This "bank storage" phenomenon has been modeled numerically for the 100 H Area (PNNL-13674, "Zone of Interaction Between Hanford Site Groundwater and Adjacent Columbia River: Progress Report for the Groundwater/River Interface Task Science and Technology Groundwater/Vadose Zone Integration Project"). In areas of contaminated groundwater, riverbank springs are also generally contaminated. The concentrations in seeping water along the riverbank may be lower than groundwater; however, the mixing between river water and the contaminated aquifer contributed to the fluctuating bank storage phenomenon.

Contamination historically has been detected in near-shore samples downstream from riverbank springs (PNNL-20548). Riverbank springs are monitored for radionuclides at each of the 100 Areas, the Hanford town site, and the 300 Area. Detected radionuclides include $^{90}Sr$, $^{99}Tc$, $^{129}I$, $^{234}U$, $^{235}U$, and $^{238}U$, and tritium, as well as arsenic, chromium, chloride, fluoride, nitrate, and sulfate. Metals and anions (chloride, fluoride, nitrate, and sulfate) were detected in spring water from samples collected in 2005. Concentrations of volatile organic compounds were near or below their detection limits in all samples. Trichloroethylene (TCE) was detected (1.4 µg/L [0.19 oz/gal]) in one sample from the 300 Area and was the only analyte detected at all shoreline spring sampling locations. Trichloroethylene has been consistently detected at low concentrations in the 300 Area shoreline spring water (PNNL-20548).

**3.1.5.1.6 Non-Riverine Surface Water.** The occurrence of non-riverine surface water on the Hanford Site is shown in Figure 3-25. These surface water bodies include West Lake and the 200 Areas Treated Effluent Disposal Facility (TEDF) disposal ponds (see next section). West Lake is located north of the 200 East Area and 5 km (3 mi) north-northwest of WMA C, and is a natural feature recharged from groundwater (ARH-CD-775, "Geohydrologic Study of

the West Lake Basin"; PNL-7662, "An Evaluation of the Chemical, Radiological, and Ecological Conditions of West Lake on the Hanford Site"). West Lake is the only natural pond at the Hanford Site. West Lake has not received direct effluent discharges from Site facilities; rather, its existence is caused by the intersection of the elevated water table with the land surface in the topographically low area. Water levels of West Lake fluctuate with water table elevation, which is influenced by wastewater discharges in the 200 Areas. The water level and size of the lake has been decreasing over the past several years because of reduced wastewater discharge.

Several naturally-occurring vernal ponds, which are not depicted on Figure 3-25, are located near Gable Mountain and Gable Butte (The Nature Conservancy 1998). The formation of these ponds in any particular year depends on the amount and temporal distribution of precipitation and snowmelt events. The vernal ponds range in size from ~6.1 m by 6.1 m to 45.73 m by 30.5 m (20 ft by 20 ft to 150 ft by 100 ft), and were found in three clusters. Approximately ten were documented at the eastern end of Umtanum Ridge, seven were observed in the central part of Gable Butte, and three were found at the eastern end of Gable Mountain.

**3.1.5.1.7 Disposal Ponds.** The TEDF in the 200 Areas consists of two disposal ponds. These ponds are each 0.02 $km^2$ (0.008 $mi^2$) in size and receive industrial wastewater permitted in accordance with WAC 173-216, "State Waste Discharge Permit Program." The wastewater percolates into the ground from the disposal ponds. Current disposal ponds (i.e., 200 Area TEDF) have an artificial influence on net contributions to the water table. Since these ponds are located between the WMAs and the Columbia River, they could impact the groundwater flow path. However, the disposal activities within the 200 Areas are not expected to exist after current operations end, so their long-term influence is not considered in this WMA C PA.

Historical Site activities discharged contaminated effluent to liquid waste sites, which caused the groundwater table to rise on the Central Plateau (DOE/RL-2001-54, Central Plateau Ecological Evaluation) creating artificial ponds and wetlands. In 1995, these management practices ceased, eliminating all man-made wetlands, with the exception of a small wetland identified in the 200 East Area during the 2001 Ecological Compliance Assessment Program survey.

**3.1.5.2 Recharge.** Two types of recharge, natural and anthropogenic, occur at the Hanford Site. Natural recharge occurs as the result of the process of water from rain, snow, and other sources moving downward through the soil and reaching the top of the groundwater aquifer. Anthropogenic recharge occurs as a result of water and/or liquids applied to the surface and/or subsurface by human activities. Examples of anthropogenic recharge would include intentional releases of waters and/or wastes into ponds, ditches, and/or cribs; the uncontrolled release of water from testing of fire hydrants; the use of water to wash down, excavate, and/or decontaminate equipment or facilities; the collection of water in low-lying areas with improper drainage control (i.e., ponding of snow melt or precipitation in tank farm areas); water recharge down man-made preferential pathways (i.e., unsealed wells or boreholes); or the unintentional or unplanned loss of waters and/or waste fluids or liquids from tanks and/or water and waste transfer pipelines.

**3.1.5.2.1 Runoff.** Total estimated precipitation over the Pasco Basin is ~$9 \times 10^8$ $m^3$ (~$3.2 \times 10^{10}$ $ft^3$) annually (DOE/RW-0164). This was calculated by multiplying the average

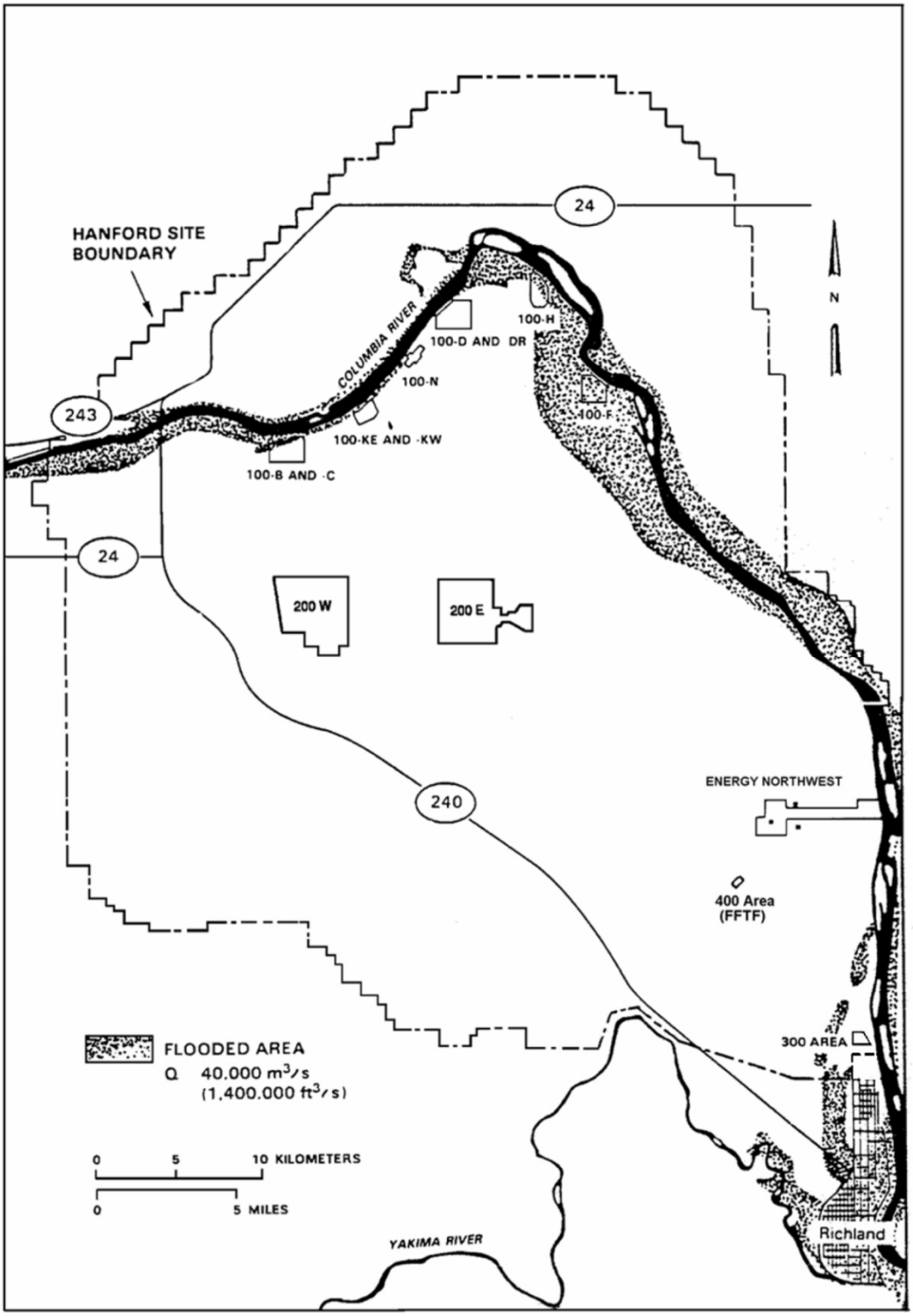
annual precipitation averaged over the Pasco Basin by the 4,900 $km^2$ (1,900 $mi^2$) basin area. Precipitation varies both spatially and temporally with higher amounts generally falling at higher elevations. As noted in Section 3.1.2.3, annual precipitation measured at the HMS has varied from 6.8 to 31.3 cm (7.6 to 12.3 in.) since 1947. Most precipitation occurs during the late autumn and winter, with more than half of the annual amount occurring from November through February. Mean annual runoff from the Pasco Basin is estimated at $<3.1 \times 10^7$ $m^3$/yr ($<1.1 \times 10^9$ $ft^3$/yr), or ~3% of the total precipitation (DOE/RW-0164). Most of the remaining precipitation is lost through evapotranspiration. However, some precipitation that infiltrates the soil is not lost to evaporation or transpiration and eventually recharges the groundwater flow system.

**3.1.5.2.2 Natural Recharge.** The recharge rate at a specific location is determined by the soil, plant, and weather conditions that control the water balance at that location. The water balance describes the storage and movement of water in and out of the soil, which is the upper part of the unsaturated zone that experiences soil-forming processes and encompasses the evaporation and plant root zone. Water arrives at the soil surface in the form of precipitation, either as rain or snow. Plant water uptake and evaporation, both of which are influenced by weather conditions, remove water stored in the soil and return it to the atmosphere. Deep drainage is the movement of stored water downward below the root zone. Once water is below the root zone, gravity continues to draw the water downward until it eventually recharges the water table.

"Variations in Recharge at the Hanford Site" (Gee et al. 1992) and "Estimating Recharge Rates for a Groundwater Model Using a GIS" (Fayer et al. 1996) estimate that recharge rates from precipitation across the Hanford Site range from near zero to over 100 mm/year (3.94 in./yr). Recharge is variable both spatially and temporally. It is greatest in areas where coarse-textured soils bare of deep-rooted vegetation exist and in years with rapid snowmelt events and precipitation during cool months. The magnitude of recharge at a particular location is influenced by five main factors: climate, soils, vegetation, topography, and springs and streams. Events such as the fire that burned vegetation from a large portion of the Hanford Site during the summer of 2000 also affect recharge rates. Fayer et al. (1996) used several types of field data and computer modeling to estimate the areal distribution of mean recharge rates for the soil and vegetation conditions at the Hanford Site, including any disturbance by Hanford Site operations.

Figure 3-28 shows how the recharge rate is affected by both the presence and type of plants. Shrubs with deep root systems tend to produce lower recharge rates because the deep roots can access a greater volume of soil and thus more stored water. In contrast, grasses with shallow root systems tend to produce higher recharge rates because the roots can access only a smaller volume of soil (and, thus, less stored water). In addition to rooting depth differences, shrubs tend to be active for a much greater portion of the year than grasses. Having a longer period of activity gives the shrubs a greater likelihood of finding and extracting soil water. Without any plants, water is removed only via evaporation from the soil surface. Annual changes in weather and plant activity ensure that recharge is never absolutely constant. However, the impacts from annual plant and weather changes on recharge are muted when recharge is measured below the root zone and averaged over decades. The result is a recharge rate that appears to be fairly constant.

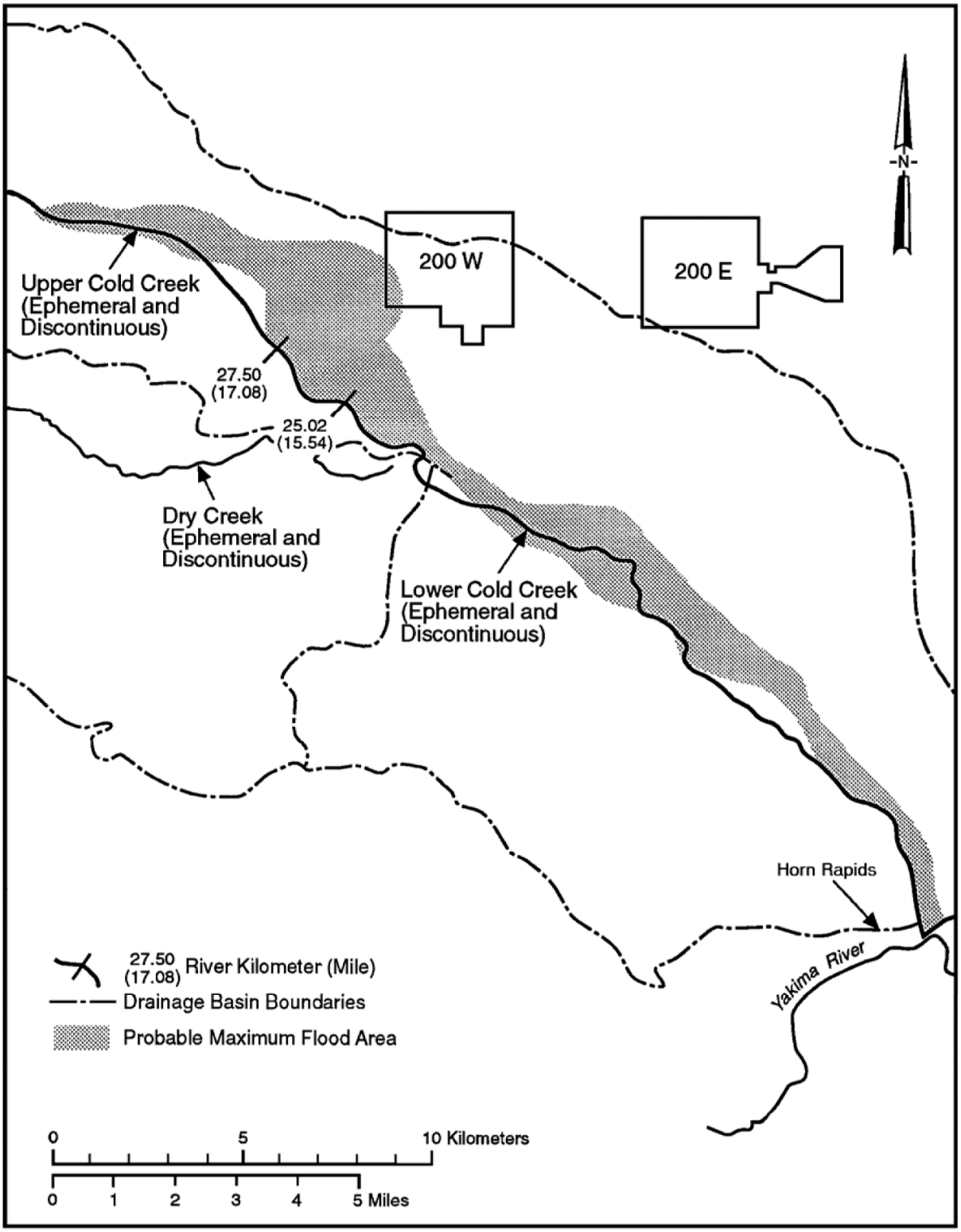
**Figure 3-26. Flood Area for the Probable Maximum Flood on the Hanford Site, Washington, as Determined by the Upper Limit of Precipitation and Maximum Runoff.**




Reference: DOE/RW-0070, Nuclear Waste Policy Act (Section 112), Environmental Assessment, Reference Repository Location, Hanford Site, Washington.

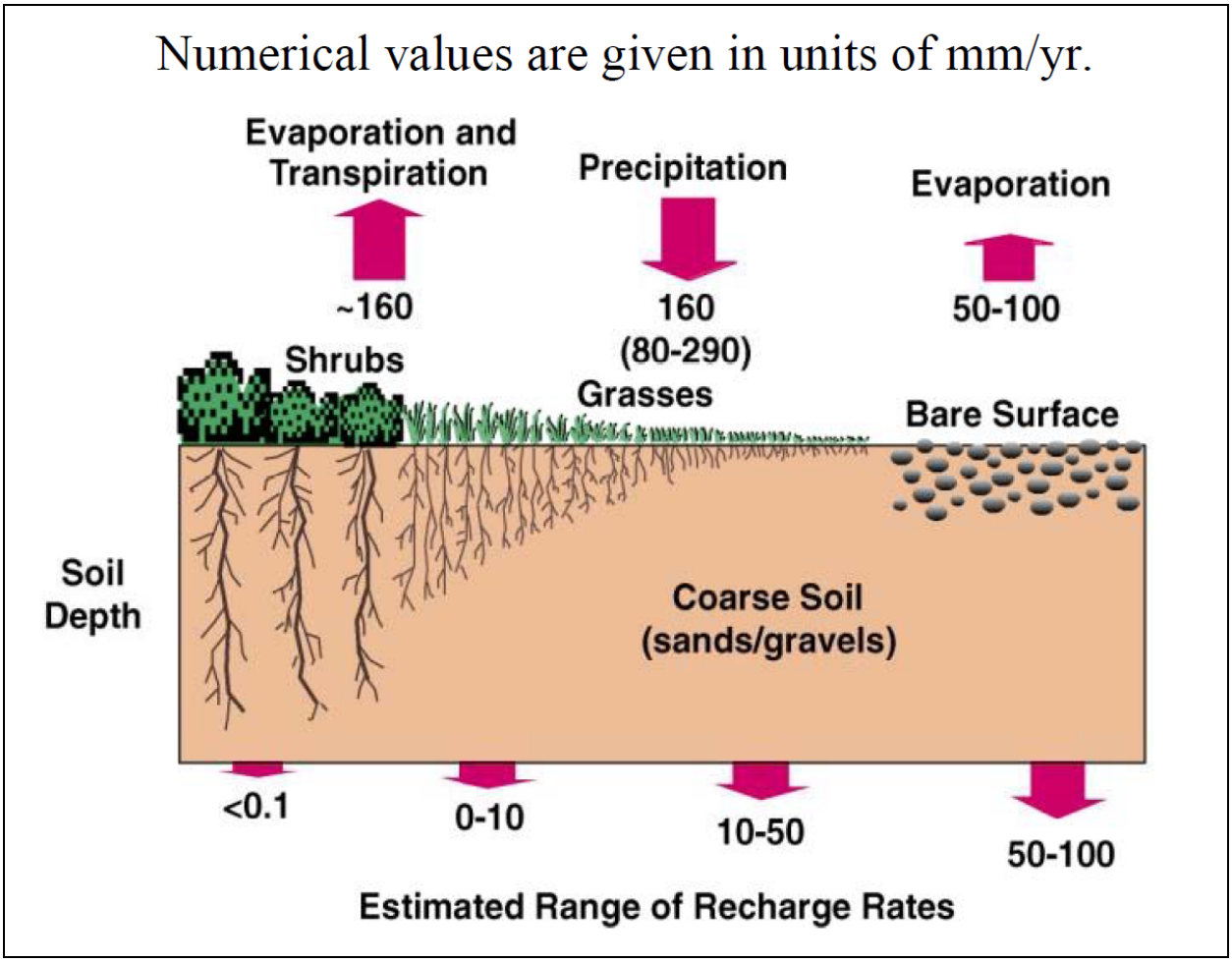
FFTF = Fast Flux Test Facility

**Figure 3-27. Extent of Probable Maximum Flood in Cold Creek Area, Hanford Site, Washington, delineated using the U.S. Army Corps of Engineers' HEC-2 Water Surface Profiles Model.**




Reference: RHO-BWI-C-120/PNL-4219, "Flood Risk Analysis of Cold Creek near the Hanford Site."

**Figure 3-28. Recharge Dependence on Surface Conditions.**

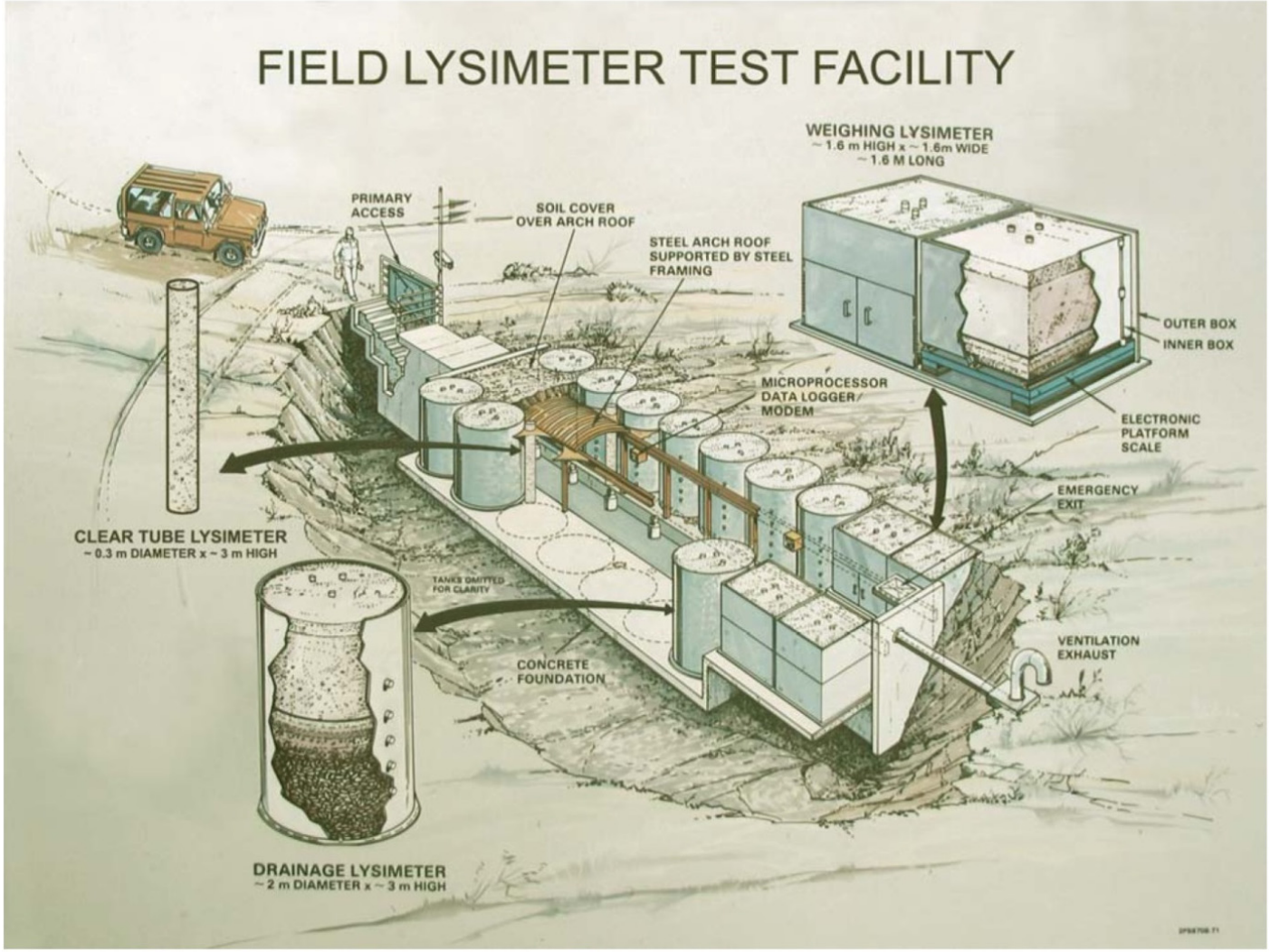



Measurements of recharge on the Hanford Site for over 20 years for a variety of precipitation rates, soil, and vegetation conditions, including conditions representative of evapotranspiration barrier have been made at the Field Lysimeter Test Facility (FLTF) (PNNL-16688, "Recharge Data Package for Hanford Single-Shell Tank Waste Management Areas"). The site is located close to the 200 West Area eastern fence and within a few hundred of the HMS. Figure 3-29 is a cut-away drawing of a key lysimeter facility in operation at the Hanford Site. The FLTF contains 18 large lysimeters (surface areas of 2.3 and 3.1 $m^2$ [24.8 and 33.4 $ft^2$]; depth from 1.5 to 3.0 m [4.9 to 9.8 ft]) and 6 smaller lysimeters (surface area is 0.07 $m^2$ [0.75 $ft^2$]; depth 3.0 m [9.8 ft]).

Treatments include variations of material types and thicknesses, the presence of vegetation, and the use of irrigation to mimic the increased precipitation of a possible future climate. Data from this facility include drainage, water content, matric potential, temperature, and vegetation observations. Challenges for the measurement technique include impacts on recharge (the act of measuring can affect the measurement), difficulty of replicating natural soil conditions in a container, cost of establishing measurement facilities, and length of time needed to gather enough data to get a reasonable estimate of the recharge rate.

**Figure 3-29. Recharge Dependence on Surface Conditions.**

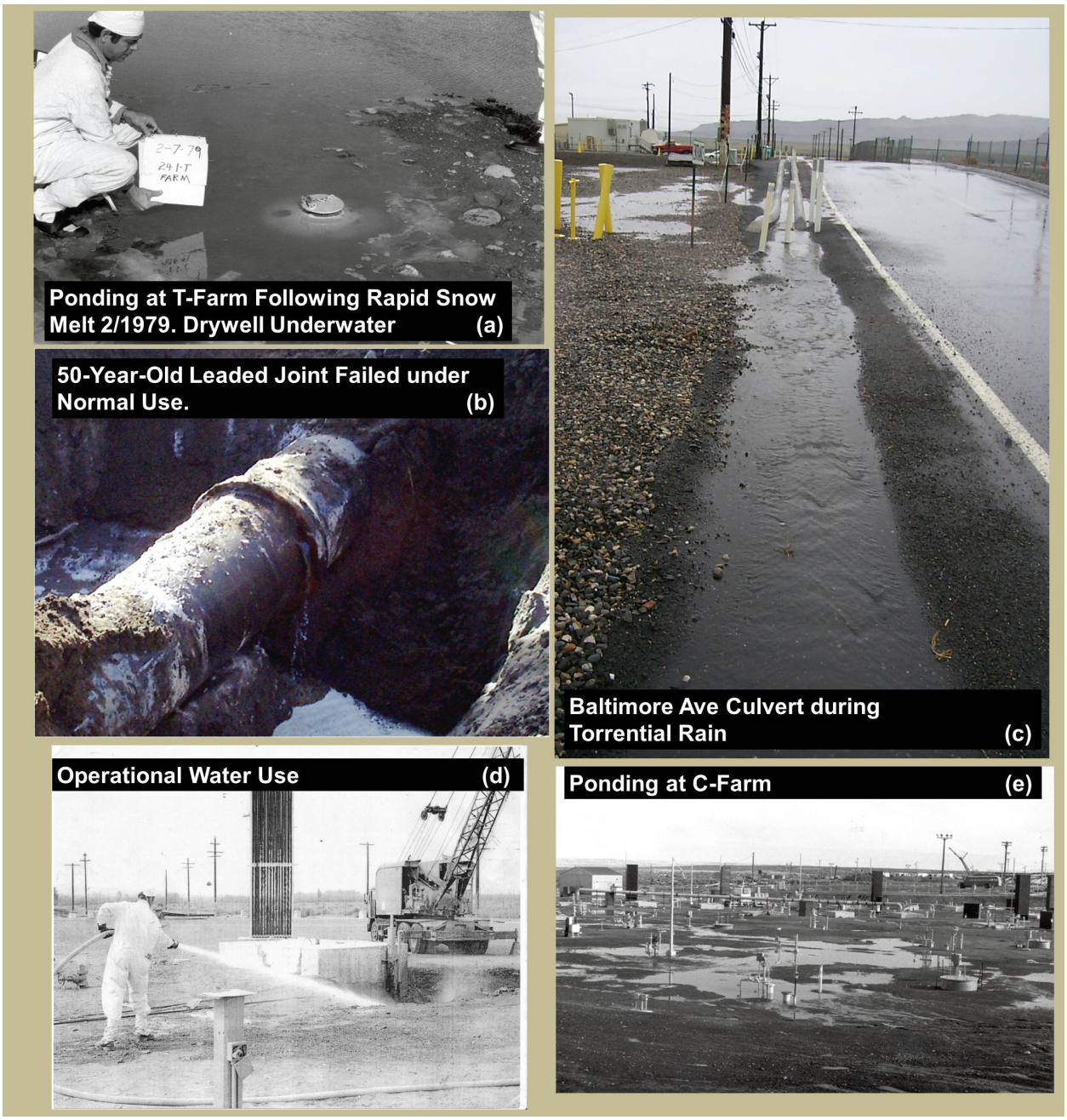
Data collection at the FLTF began in November 1987. Three separate lysimeter designs are included in the facility.




FLTF = Field Lysimeter Test Facility

**3.1.5.2.3 Anthropogenic Recharge.** Over and above natural recharge, human activities within the tank farms can provide additional recharge. This occurs because of manmade sources (e.g., leaking waterlines, waste lines, or tanks, testing of fire hydrants, excavation with water), preferential pathways (unsealed abandoned wells or poorly capped boreholes), and improper drainage control (ponding of precipitation at tank farms). Figure 3-30 provides examples of a number of these conditions.

**Figure 3-30. Examples of Anthropogenic Recharge in the 200 Area. (Photographs a – c are from DOE/ORP-2008-01 Appendix K, Photographs d and e are Archive Photos).**




Reference: DOE/ORP-2008-01, RCRA Facility Investigation Report for Hanford Single-Shell Tank Waste Management Areas.

The amount of anthropogenic recharge due to pipeline leaks and improper drainage is extremely difficult to quantify. For example, if a waterline developed a small leak on the order of a quart per minute, that would lead to an additional volume of ~49,000 L (~130,000) gal released per year. That is equivalent to increasing the natural recharge over the ~3.24-hectare (8-acre) WMA C by 15%. Additionally, the records do not indicate when and how much water was applied during operations [Figure 3-30(d)] or how often ponding occurred on WMA C [Figure 3-30(e)]. Scoping calculations examining the potential effects of anthropogenic recharge on the release and transport of contaminants in past tank waste leaks and losses from WMA C facilities are evaluated and described in RPP-RPT-59197, "Analysis of Past Tank Waste Leaks and Losses in the Vicinity of Waste Management Area C at the Hanford Site, Southeast Washington."

However, for future conditions, anthropogenic recharge is not expected to be a factor in release from the WMAs because in the late 1990s and early 2000s two major efforts took place to eliminate anthropogenic recharge within Hanford's SST System. The first effort was interim stabilization of the SSTs by removing pumpable liquids from the SSTs to mitigate potential future leaks from them. Furthermore, these tanks will be filled with grout prior to the placement of a recharge barrier. The second effort was to apply interim measures to reduce/stop additional recharge in the tank farms. Surface water controls have been constructed to reduce surface water run-on from major meteorological events and from breaks in waterlines. Also, waterlines that were determined unnecessary have been isolated, cut, and capped. Waterlines that were found to be necessary for continued operations have been leak tested and any lines found to be leaking were replaced (DOE/ORP-2008-01). Once retrieval operations cease, the remaining waterlines are expected to be taken out of service.

Vadose Zone. The vadose zone is that part of the geologic media which extends from the earth's surface to the water table. At the Hanford Site, the thickness of the vadose zone ranges from 0 m (0 ft) near the Columbia River to greater than 100 m (328 ft) under parts of the Central Plateau (PNNL-13080, "Hanford Site Groundwater Monitoring: Setting, Sources, and Methods"). Unconsolidated glacio-fluvial sands and gravels of the Hanford formation make up most of the vadose zone (Figure 3-17). In some areas, such as most of the 200 West Area and in some of the 100 Areas, the fluvial-lacustrine sediments of the Ringold Formation make up the lower part of the vadose zone. The CCU also makes up part of the vadose zone. The integrated knowledge obtained from previous and ongoing studies provides a good conceptual understanding of the geologic, hydraulic, and geochemical environment and its controls on the distribution and movement of contaminants within the vadose zone (PNNL-14702, "Vadose Zone Hydrogeology Data Package for Hanford Assessments"). Figure 3-19 provides a fence diagram of sediment overlying the Columbia River Basalt Group in the Central Plateau. In the 200 East Area around WMA C, the undifferentiated low Hanford gravels (H3), CCU, Ringold formation would replace the CCU and upper Ringold and Ringold E shown in this figure.

The primary features relevant to the vadose zone flow and transport include the hydrogeologic materials (and their physical, hydraulic, and geochemical properties), subsurface conditions (e.g., fluid statics and thermal conditions), and fluid properties. Other features relevant to the vadose zone conceptual model, such as climate and weather statistics, terrestrial ecology, and projected land use were given in the previous sections.

**3.1.5.2.4 Hydrostratigraphy.** The vadose zone stratigraphy influences the movement of liquid through the soil column. The vadose zone beneath the 200 East Area can be subdivided into six principal hydrostratigraphic units, including three units within the Hanford formation, a fluvial gravel facies of the CCU (equivalent to the Pre-Missoula Gravels of "Appendix 2R - Stratigraphic Investigation of the Skagit/Hanford Nuclear Project," in Skagit/Hanford Nuclear Project, Preliminary Safety Analysis Report [Webster and Crosby 1982] and WHC-SD-ER-TI-003, "Geology and Hydrology of the Hanford Site: A Standardized Text for Use in Westinghouse Hanford Company Documents and Reports"), and two units belonging to the Ringold Formation (WHC-SD-EN-TI-012, "Geologic Setting of the 200 East Area: An Update"; WHC-SD-EN-TI-019, "Hydrogeologic Model for the 200 East Groundwater Aggregate Area"; PNNL-12261, "Revised Hydrogeology for the Suprabasalt Aquifer System, 200-East Area and Vicinity, Hanford Site, Washington"; DOE/RL-2002-39).

The Hanford formation units include (1) an upper gravel-dominated facies, (2) a sand-dominated facies, and (3) a lower gravel-dominated facies. Over most of the 200 East Area, the Hanford sand-dominated facies lies between the upper and lower gravel-dominated facies (WHC-SD-EN-TI-012; WHC-SD-EN-TI-019; DOE/RL-2002-39). Based on borehole samples, the upper and lower gravel-dominated facies appear to have similar physical and chemical properties. The Ringold Formation in the 200 East Area is, for the most part, eroded away in the northern half of the 200 East Area. Here, the Hanford formation lies directly on top of basalt bedrock. With the dropping water table, basalt crops out above the water table and, thus, is unsaturated beneath the northeastern portion of the 200 East Area. Underneath WMA C, the top of the unconfined aquifer lies within a unit composed of undifferentiated gravels from the lower Hanford formation gravels (H3), the CCU, and the Ringold formation.

The vadose zone stratigraphy influences the potential for spreading of liquid within the soil column. Where conditions are favorable, lateral spreading of liquid effluent and/or local perched water zones may develop. Lateral spreading can occur along any strata with contrasting hydraulic conductivity. Where low-permeability layers within the Hanford formation have been documented, they are thin (0.5 m [1.6 ft] or less) and laterally discontinuous. Low-permeability layers within the sand-dominated facies of the Hanford formation are generally thicker and more continuous than those in the gravel-dominated facies. Some paleosols and facies changes (i.e., the contact between fine-grained and coarser-grained facies) may be fairly continuous over the range of 100 m (328 ft) or so, with some lateral spreading of crib effluent noted on that same scale. Lateral spreading can delay the arrival of contaminants at the water table but may cause mixing of the subsurface plume at one site with that of an adjacent site. Spreading may also require increasing the area of surface barriers to cover wider plumes.

Clastic dikes have also been observed in the Hanford formation beneath the 200 East Area. Their most important feature is their potential to either enhance or inhibit vertical and lateral movement of contaminants in the subsurface, depending on textural relationships (BHI-01103). For example, the vertically-oriented clay skins within clastic dikes may locally form an impediment to lateral flow. This could then cause ponding (perching) of the water and eventual breakthrough to underlying strata.

Sublinear channel-cut scour and fill features occur within the Hanford formation and may act as preferential pathways in the horizontal direction. Other types of heterogeneity are associated with stratigraphic pinch-out or offlapping/onlapping of facies.

**3.1.5.2.5 Hydraulic and Transport Properties.** Accurate predictions of flow and transport in the vadose zone require a detailed characterization of the hydrologic properties and their variability, as well as estimates of transport parameters such as dispersivity. In particular, data that are essential for quantifying the water storage and flow properties of unsaturated soil include the soil moisture characteristics (i.e., soil moisture content versus pressure head, and unsaturated hydraulic conductivity versus pressure head relations) for sediment in various geologic units.

Data on particle-size distribution, moisture retention, and saturated hydraulic conductivity ($K_s$) have been cataloged for over 284 samples from throughout the Hanford Site, including 12 locations in the 200 East and West Areas (WHC-EP-0883, "Variability and Scaling of Hydraulic Properties for 200 Area Soils, Hanford Site"; "Evaluation of van Genuchten-Mualem Relationships to Estimate Unsaturated Hydraulic Conductivity at Low Water Contents" [Khaleel et al. 1995]; "Correcting Laboratory-Measured Moisture Retention Data for Gravels" [Khaleel and Relyea 1997]; PNNL-13672, "A Catalog of Vadose Zone Hydraulic Properties for the Hanford Site"; WMP-17524, "Vadose Zone Hydraulic Property Letter Reports"; and "On the Hydraulic Properties of Coarse-Textured Sediments at Intermediate Water Contents" [Khaleel and Heller 2003]). Laboratory analyses of the hydraulic properties of samples collected at Hanford have been performed at a number of different laboratories using techniques similar to those described by Methods of Soil Analysis, Part 1—Physical and Mineralogical Methods (Klute 1986).

Macrodispersivity estimates for non-reactive species have been estimated using the "Three-dimensional stochastic analysis of macrodispersion in aquifers" (Gelhar and Axness 1983) equation where the longitudinal macrodispersivity depends on the mean pressure head. HNF-4769, "Far-Field Hydrology Data Package for Immobilized Low-Activity Tank Waste Performance Assessment" estimated a longitudinal macrodispersivity of ~1 m (~3 ft) for the sand-dominated facies of the Hanford formation in the 200 East Area. The transverse dispersivities have been estimated as one tenth of the longitudinal values ("A Critical Review of Data on Field-Scale Dispersion in Aquifers" [Gelhar et al. 1992]). Based on a survey of literature, Stochastic Subsurface Hydrology (Gelhar 1993) examined the longitudinal vadose zone dispersivities as a function of the scale of the experiment, and found an increase of dispersivity with an increase in scale.

**3.1.5.2.6 Vadose Zone Contamination.** The Hanford Site has more than 800 past-practice liquid-disposal facilities. Mixed radioactive liquid waste was discharged to the vadose zone through reverse (injection) wells, French drains, cribs, ponds, trenches, and ditches. From 1944 through the late 1980s, 1.5 to 1.7 billion $m^3$ (396 to 449 billion gal) of effluent were disposed to the soils (PNNL-SA-32152, "A Short History of Plutonium Production and Nuclear Waste Generation, Storage, and Release at the Hanford Site"). Most effluent was released in the 200 Areas. The largest groundwater contaminant plumes emanating from the 200 Areas are those of tritium and nitrate. The major source for both was discharges from chemical processing of irradiated nuclear fuel rods.

Also present are $^{99}Tc$ and $^{129}I$ that, like tritium and nitrate, are mobile in both the vadose zone and groundwater. The major sources of $^{99}Tc$ and $^{129}I$ were discharges to liquid disposal facilities. Vadose zone sources for these contaminants remain beneath many past-practice disposal facilities. However, other than physical sampling and laboratory analysis, few direct ways exist to monitor tritium, nitrate, $^{99}Tc$, and $^{129}I$ in the vadose zone.

Approximately 280 UPRs in the 200 Areas also contributed contaminants to the vadose zone (DOE/RL-96-81, Waste Site Grouping for 200 Areas Soil Investigations). Many of these were associated with tank farm operations, and have contributed significant contamination to the vadose zone. Over the past 15 years, a significant effort has been implemented to better understand and quantify vadose zone contamination in and around the WMAs. These investigations have focused on developing a better understanding of major releases and of the potential impacts on groundwater quality. These efforts have integrated information from a number of different DOE and Hanford Site projects and have focused on evaluating the past release events that contribute the bulk of subsurface contamination.

The information sources used for the SST WMA-level vadose zone investigations included baseline spectral gamma logging of the ~750 shallow monitoring boreholes (referred to as drywells) within each of the seven WMAs, as well as assessments of the historical gross gamma logging data from each WMA. "Gross gamma logging" refers to logs in which gamma activity is measured without regard to energy level. The gross gamma log simply reports the total gamma activity as a function of depth. Drywell gross gamma logging data were used as part of the tank farm leak detection program until 1994. "Spectral gamma logging" refers to logs in which energy spectra are collected in the borehole. In a spectral gamma log, individual gamma photons are counted as a function of energy level. This allows radionuclides to be identified and quantified on the basis of gamma activity at specific energy levels. From 1995 to 2000, spectral gamma logging was performed in the existing drywell network to develop a baseline understanding of subsurface contamination conditions in each of the SST WMAs. Results of the baseline spectral gamma logging project are summarized in a series of 12 reports (one for each SST farm). In 2000, DOE/RL-99-36, Phase 1 RCRA Facility Investigation/Corrective Measures Study Work Plan for Single-Shell Tank Waste Management Areas was issued to collect vadose zone characterization data in the single-shell WMAs, and characterization data related to this work plan was collected from 2000 to 2008.

Vadose zone characterization efforts have included drilling, sampling, and soil analysis in multiple SST WMAs, coupled with review of historical process records and gamma logging data. The information collected during this time is provided in DOE/ORP-2008-01. Since the issuance of this report, a Phase 2 vadose characterization program was initiated at WMA C to collect additional vadose zone data (RPP-PLAN-39114). The results of the vadose zone sampling at WMA C are documented in RPP-RPT-58339.

In 2007, a process was started (RPP-32681, "Process to Assess Tank Farm Leaks in Support of Retrieval and Closure Planning") to re-assess SST leak volumes based on a synthesis of available information, including vadose zone borehole drilling and sampling data from DOE/ORP-2008-01, gamma-ray logging data, and historical information. In Table 3-3 of HNF-EP-0182, "Waste Tank Summary Report for Month Ending August 31, 2005," Rev. 209,

67 tanks were classified as "confirmed or suspected" of having leaked contaminated liquid to the vadose zone. These classifications were assigned based largely on data and priorities from the period of tank farm operations. As a result of the re-assessment process, the most recent "Waste Tank Summary Report for Month Ending May 31, 2014" (HNF-EP-0182, Rev. 317, Table 3-2) has 64 tanks classified "confirmed or suspected" of having leaked. The re-assessment has added one new tank to the list (C-105) and removed five tanks (241-A-103, C-110, C-111, 241-SX-104, 241-SX-110) from the list. Vadose zone inventory estimates based on the revised leak volumes are being developed. Presently, inventory estimates are available for WMA C (RPP-RPT-42294, "Hanford Waste Management Area C Soil Contamination Inventory Estimates," Rev. 2), 241-A and 241-AX Tank Farms (RPP-RPT-37956, "Hanford 241-A and 241-AX Tank Farms Leak Inventory Assessments Report"), 241-B Tank Farm (RPP-RPT-49089, "Hanford B-Farm Leak Inventory Assessments Report"), 241-BX Tank Farm (RPP-RPT-47562, "Hanford BX-Farm Leak Assessments Report"), 241-BY Tank Farm (BY Farm) (RPP-RPT-43704, "Hanford BY-Farm Leak Assessments Report"), WMA U (RPP-RPT-50097, "Hanford 241-U Farm Leak Inventory Assessment Report"), 241-TX Tank Farm (RPP-RPT-50870, "Hanford 241-TX Farm Leak Inventory Assessment Report"), and WMA T (RPP-RPT-55084, "Hanford 241-T Farm Leak Inventory Assessment Report"). Uncertainties in leak volume estimates are addressed as part of the inventory estimates.

**3.1.5.3 Groundwater.** This section describes the relevant characteristics of the groundwater hydrology, which has been studied and monitored in detail because of the waste disposal operations at the site. The hydrology characteristics of the Hanford Site are important to the definition of potential pathways for the WMA C contaminants to the public and the estimation of the magnitudes of the environmental impacts. Evaluating this pathway requires information about the types of aquifers present, depths to the water table, and regional flow paths toward surface water discharge points. Surface water flow represents a pathway for carrying contaminants to the public. Because the uppermost unconfined aquifer is considered the primary pathway for possible contaminant transport from the WMA C, it is especially important in this PA.

The discussion focuses on the geohydrology of the 200 Areas but also includes information on the Hanford Site in general, highlighting those aspects that were important to the modeling of the post-closure system performance. This information was summarized largely from material presented in PNNL-6415, DOE/RL-2014-32, Hanford Site Groundwater Monitoring Report for 2013 and PNNL-20548, as follows.

- "Hanford Site Environmental Report for Calendar Year 2010 (Including Some Early 2011 Information)" (PNNL-20548) provides the overview of the characterization and monitoring activities conducted at the Hanford Site during the calendar year.

- Hanford Site Groundwater Monitoring Report for 2014 (DOE/RL-2014-32) describes the groundwater monitoring activities during the fiscal year.

- "Hanford Site National Environmental Policy Act (NEPA) Characterization" (PNNL-6415) provides a standardized description of the Hanford Site environment.

Groundwater beneath the Hanford Site is found in both an upper unconfined aquifer system and deeper basalt-confined aquifers. The unconfined aquifer system is also referred to as the suprabasalt aquifer system because it is within the sediments that overlie the basalt bedrock. Portions of the suprabasalt aquifer system are locally confined. However, because the entire suprabasalt aquifer system is interconnected on a site-wide scale, it is referred to in this report as the Hanford unconfined aquifer system.

**3.1.5.3.1 Basalt-Confined Aquifer System.** The upper basalt-confined aquifer groundwater system occurs within basalt fractures and joints, interflow contacts, and sedimentary interbeds within the upper Saddle Mountains Basalt. The thickest and most widespread sedimentary unit in this system is the Rattlesnake Ridge interbed, which is present beneath much of the Hanford Site. Groundwater also occurs within the Levey interbed, which is present only in the southern portion of the Site. A small interflow zone occurs within the Elephant Mountain Member of the upper Saddle Mountains Basalt and may be significant to the lateral transmission of water. The upper basalt-confined aquifer system is confined by the dense, low-permeability interior portions of the overlying basalt flows and in some places by silt and clay units of the lower Ringold Formation that overlie the basalt. Approximately 50 wells screened in the upper basalt-confined aquifer have been sampled or had water levels measured in recent years.

The horizontal hydraulic conductivities of most of these basalt-confined aquifers fall in the range of $10^{-10}$ to $10^{-4}$ m/s ($3 \times 10^{-10}$ to $3 \times 10^{-4}$ ft/s). Saturated but relatively impermeable dense interior sections of the basalt flows have horizontal hydraulic conductivities ranging from $10^{-15}$ to $10^{-9}$ m/s ($3 \times 10^{-15}$ to $3 \times 10^{-9}$ ft/s), about five orders of magnitude lower than some of the confined aquifers that lie between these basalt flows (DOE/RW-0164). Hydraulic-head information indicates that groundwater in the basalt-confined aquifers generally flows toward the Columbia River and, in some places, toward areas of enhanced vertical inter-aquifer flow within the unconfined aquifer system (PNNL-16346, “Hanford Site Groundwater Monitoring for Fiscal Year 2006”; DOE/RW-0164; SD-BWI-TI-335, “Fresh-Water Potentiometric Map and Inferred Flow Direction of Ground Water Within the Mabton Interbed, Hanford Site, Washington State -- January 1987”).

The DOE monitors groundwater quality in the upper basalt-confined aquifer system because of the potential for downward migration of contaminants from the overlying unconfined aquifer in areas where confining units are absent or fractured. The upper basalt-confined aquifer system is not affected by contamination as much as the unconfined aquifer. Contamination found in the upper basalt-confined aquifer system is most likely to occur in areas where the confining units have been eroded away or were never deposited, and where past disposal of large amounts of wastewater resulted in downward hydraulic gradients.

Researchers have identified areas of intercommunication between the contaminated unconfined aquifer and the upper basalt-confined aquifer by geochemical signatures and the presence of nitrate and tritium in groundwater in some basalt-confined wells near 200 East Area (PNL-10817, “Hydrochemistry and Hydrogeologic Conditions within the Hanford Site Upper Basalt Confined Aquifer System”). However, groundwater monitoring data do not indicate that contamination has migrated into the upper basalt-confined aquifer. Because of poor seals in wells constructed prior to implementation of WAC 173-160, “Minimum Standards for

Construction and Maintenance of Wells," intercommunication between aquifers has permitted groundwater flow from the unconfined aquifer to the underlying confined aquifer in the past, increasing the potential to spread contamination. Section 2.14.2 of DOE/RL-2008-01 further discusses communication between the upper basalt-confined aquifer system and the overlying aquifers. The small amount of contamination detected in the upper basalt-confined aquifer is attributed to areas where confining units of basalt have been partially removed by erosion or are absent, or where wells provided a pathway for migration. The basalt-confined aquifer system would not provide a pathway for contaminants from WMA C to the accessible environment.

**3.1.5.3.2 Unconfined Aquifer System.** The base of the uppermost aquifer system is defined as the top of the uppermost basalt flow, with the top of the system being the water table. This aquifer system is bounded laterally by anticlinal basalt ridges and is ~152 m (500 ft) thick near the center of the Pasco Basin. Within the Hanford Site, this uppermost aquifer system lies at depths ranging from less than 0.3 m (1 ft) below the ground surface near West Lake and the Columbia and Yakima Rivers, to more than 107 m (350 ft) in the central portion of the Cold Creek syncline. Groundwater in the unconfined aquifer at the Hanford Site generally flows from recharge areas in the elevated region near the western boundary of the Hanford Site toward the Columbia River on the eastern and northern boundaries. The Columbia River is the primary discharge area for the unconfined aquifer. The Yakima River borders the Hanford Site on the southwest and is generally regarded as a source of recharge.

The unconfined aquifer system underlying the Hanford Site exists within sediments deposited on top of the Columbia River Basalts. It is composed primarily of the Ringold Formation and overlying Hanford formation. Figure 3-31 is a hydrogeologic map of the units present at the water table surface in June 1998, which represents the top of the unconfined aquifer just prior to the start of active remediation. In the 200 West Area, the water table occurs almost entirely in the Ringold Unit E gravels, while in the 200 East Area, it occurs primarily in the Hanford formation and in the Ringold Unit A gravels (Figure 3-18). Along the southern edge of the 200 East Area, the water table is in the Ringold Unit E gravels. The upper Ringold facies were eroded in most of the 200 East Area by the ancestral Columbia River and, in some places, by the Missoula floods that subsequently deposited Hanford gravels and sands on what was left of the Ringold Formation (DOE/RL-2002-39). Because the Hanford formation and possibly the CCU sand and gravel deposits are much more permeable than the Ringold gravels, the water table is relatively flat in the 200 East Area, but groundwater flow velocities are higher.

The hydrology of the 200 Areas has been strongly influenced by the discharge of large quantities of wastewater to the ground. Between 1944 and the mid-1990s, an estimated $1.68 \times 10^{12}$ L ($4.44 \times 10^{11}$ gal) of liquid was discharged to disposal ponds, trenches, and cribs. Wastewater discharge has decreased since 1984 and currently only contributes a volume of recharge in the same range as the estimated natural recharge from precipitation. The largest volumes of discharge around the 200 East Area were to the 216-B Pond system, the 216-A-25 (Gable Mountain) pond system, and several of the PUREX cribs in the southeast corner of 200 East Area. Figure 3-32 shows the liquid discharge history for the two ponds. The Gable Mountain Pond is estimated to have received ~293 billion L (77 billion gal) of effluent, while the 216-B Pond to have received ~256 billion L (68 billion gal) of effluent. In the 200 West Area, the largest volumes of discharge were to the 216-T Pond system and the 216-U-10 Pond

(Figure 3-33). The 216-T Pond system is estimated to have received ~424 billion L (112 billion gal) of effluent (WHC-EP-0815, "Groundwater Impact Assessment Report for the 216-T-4-2 Ditch"), while the 216-U Pond to have received ~158 billion L (41.7 billion gal) of effluent (WHC-EP-0707, "216-U-10 Pond and 216-Z-19 Ditch Characterization Studies").

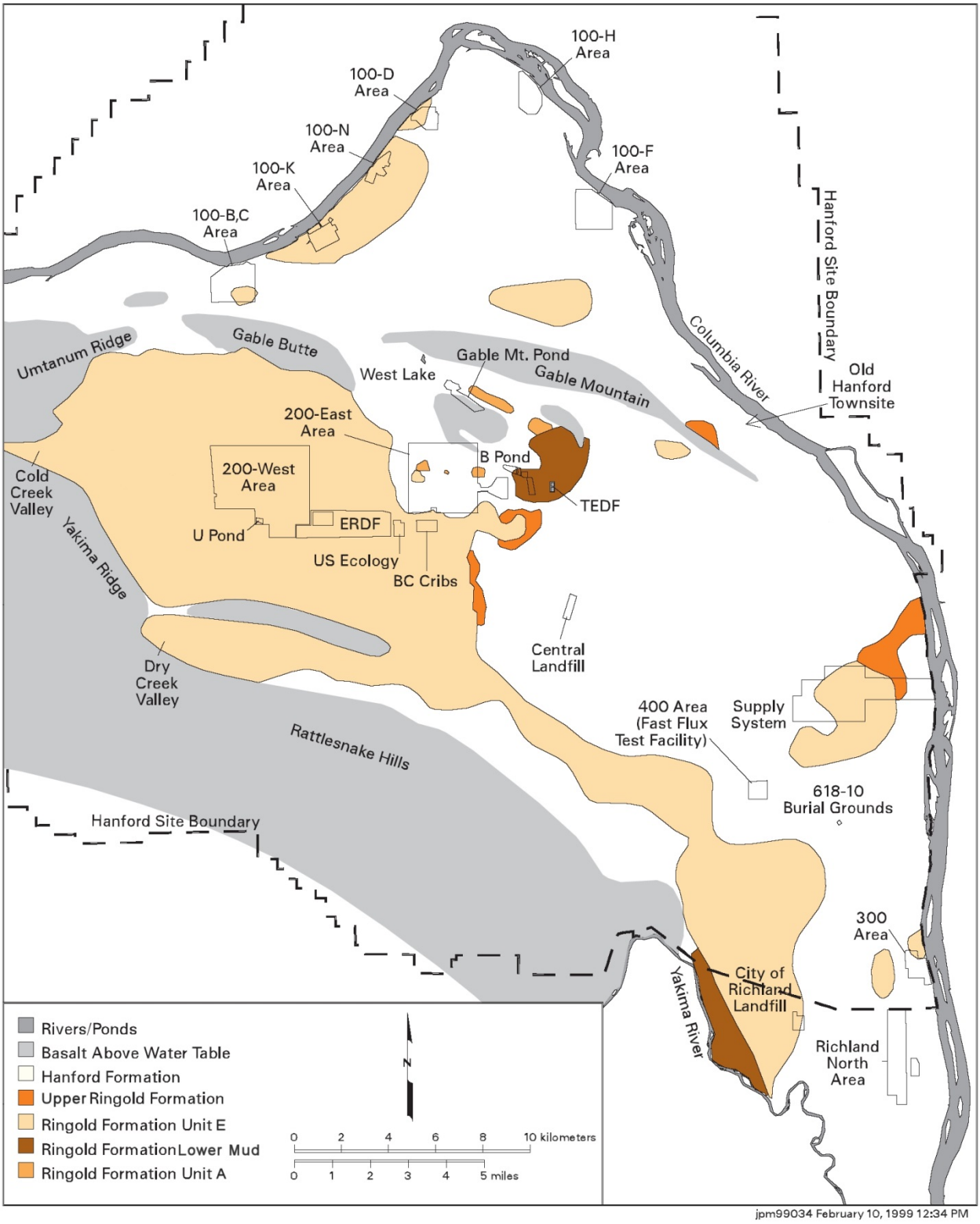
Figure 3-34 shows a series of water table elevation maps for the time periods representing pre-operational conditions, operational conditions, and present day conditions for the Hanford Site. The first water table map (Figure 3-34a) is a hind cast map of water table elevations (ERDA-1538, "Final Environmental Impact Statement, Waste Management Operations, Hanford Reservation, Richland, Washington") prior to the start of significant Hanford Site wastewater discharges. This water map includes the effects of limited irrigation near the former towns of White Bluff and Hanford, but not the effects of extensive irrigation now common in Cold and Dry Creeks. The 1944 water table contours indicate that groundwater flow is easterly toward the Columbia River with a relatively uniform hydraulic gradient (~1.5 m/km [5 ft/mi]). Regional groundwater flow was generally toward the east-northeast, while flow north of Gable Mountain was more to the north.

The pre-Manhattan Project water table in the 200 West Area and 200 East Area was ~123 m (404 ft) and 120 m (394 ft) above sea level, respectively (BNWL-B-360, "Selected Water Table Contour Maps and Well Hydrographs for the Hanford Reservation, 1944-1973"). In the 200 West Area, the water table elevation increased rapidly from 1949 to 1956, but appeared to stabilize between the late 1960s and the late 1980s. Water levels began to decline in the late 1980s when wastewater discharges in the 200 West Area were reduced. In the 200 East Area, the water table elevation increased rapidly from 1954 to 1963. The water table declined somewhat in the late 1960s and early 1970s, but then increased again in the early 1980s before beginning a final decline throughout the 1990s when wastewater discharges in the 200 East Area were reduced.

During operations, water levels in the uppermost and unconfined aquifer rose as much as 26 m (85 ft) and 9 m (30 ft) beneath the 200 West Area and 200 East Area, respectively, because of artificial recharge caused by liquid waste disposed from the mid-1940s to 1995. Figure 3-34b shows water table mounding present in the 200 Areas for June 1987. The volume of water that was discharged to the ground at the 200 West Area was actually less than that discharged at the 200 East Area. However, the lower hydraulic conductivity of the aquifer near the 200 West Area inhibited groundwater movement in this area, resulting in a higher groundwater mound.

Presently, groundwater in the unconfined aquifer generally flows from upland areas in the west toward the regional discharge area north and east along the Columbia River (Figure 3-34c). Steep hydraulic gradients occur in the western, eastern, and northern regions of the Site. Shallow gradients occur southeast of 100-FR and in a broad arc extending from west of 100-BC toward the southeast between Gable Butte and Gable Mountain (Gable Gap), through the 200 East Area and into the central portion of the Site. The reduction of wastewater discharges has caused water levels to drop significantly; however, a residual groundwater mound beneath the 200 West Area is still present today as shown by the curved water table contours near this area. Additionally, small groundwater mounds exist near the 200 Area TEDF and State-Approved Land Disposal Site wastewater disposal sites.

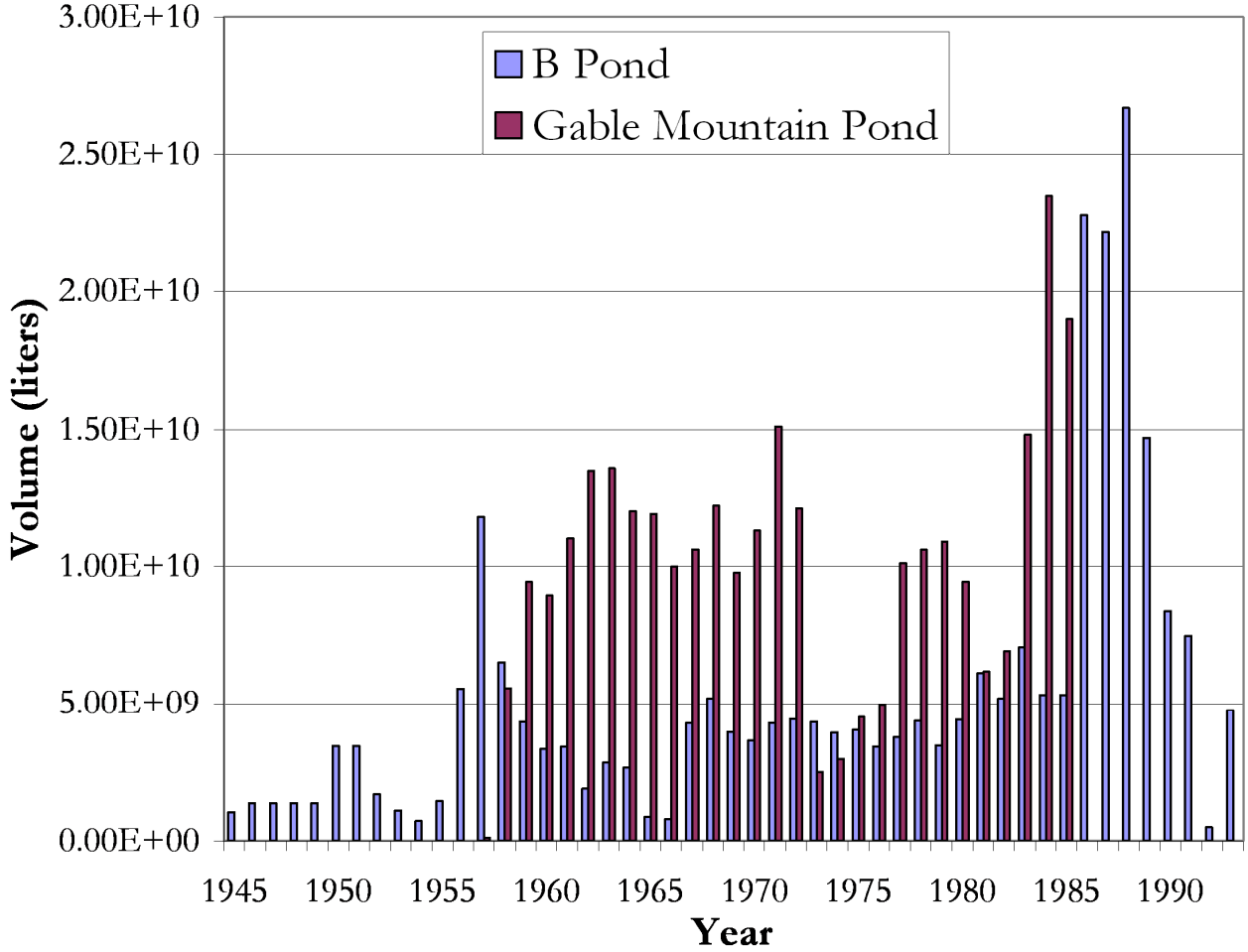
**Figure 3-31. Hydrogeologic Units Present at the Water Table in June 1998.**




Source: WCH-520, "Performance Assessment for the Environmental Restoration Disposal Facility, Hanford Site, Washington."

ERDF = Environmental Restoration Disposal Facility TEDF = Treated Effluent Disposal Facility

**Figure 3-32. Discharge History for the 216-B Pond System and Gable Mountain Pond.**




Comparing the approximate rate of water table decline in the 200 East Area with that in the 200 West Area shows that the rate of decline is three to four times faster in the 200 West Area. This is probably due, in part, to the greater increase in water level due to U Pond than to B Pond. Also, the water table gradient is extremely flat in the 200 East Area, whereas the gradient is steeper beneath the 200 West Area. This indicates that a small increment of water table decline must be spread out over a much larger area in the 200 East Area than in the 200 West Area.

The groundwater mounds drastically changed the flow direction causing radial flow from the discharge areas, and, in some areas, resulted in a complete reversal of flow direction. Until about 1980, the edge of the mounds migrated outward from the sources. Groundwater levels have declined over most of the Hanford Site since 1984 because of decreased wastewater discharges (DOE/RL-2014-32), and since 1996, when all non-permitted discharges to the ground ceased, groundwater flow has begun to return to pre-Hanford Site conditions.

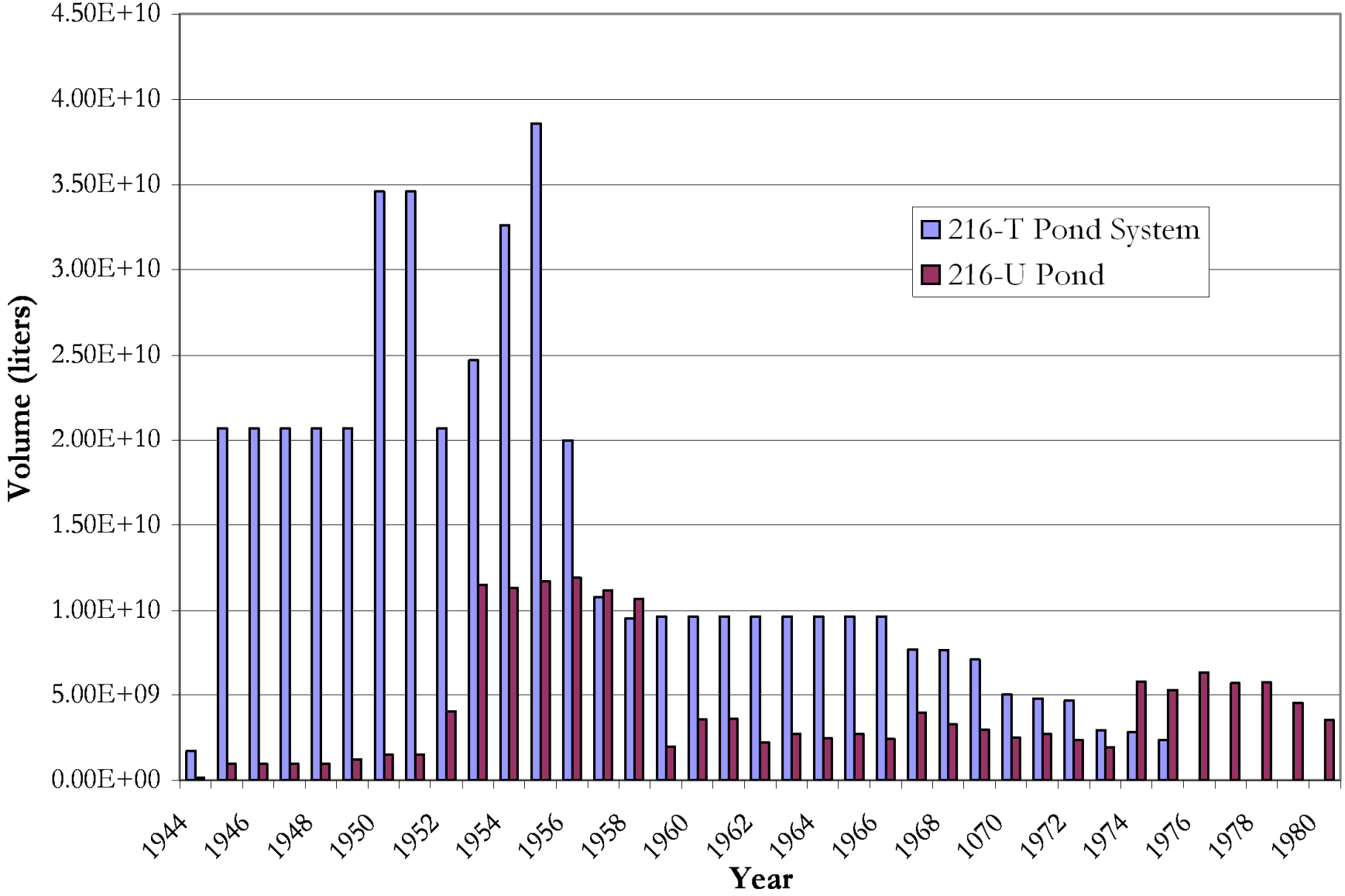
The dominant source of water in the unconfined aquifer beneath the 200 East Area and vicinity is inflow from the west. Formerly, the direction of groundwater flow diverged beneath the 200 East Area, with some water flowing toward the north through Gable Gap and some flowing southeast. The flow direction changed during 2011; since then flow has been toward the south

and southeast across much of the 200 East Area. This change in flow directions is important because contaminant plumes located in the northwest corner of the 200 East Area located near and under the B Complex (WMA B-BX-BY and nearby Cribs) could flow under WMA C.

A limited amount of hydraulic property data is available from testing of wells. Hydraulic test results from wells on the Hanford Site have been compiled for the Hanford Groundwater Monitoring Project and for environmental restoration efforts (BNWL-1709, "Collection and Analysis of Pump Test Data for Transmissivity Values"; PNL-8337, "Summary and Evaluation of Available Hydraulic Property Data for the Hanford Site Unconfined Aquifer System"; PNL-10835, "Comparison of Constant-Rate Pumping Test and Slug Interference Test Results at the Hanford Site B Pond Multilevel Test Facility"; PNNL-13342, "Analysis of the Hydrologic Response Associated with Shutdown and Restart of the 200-ZP-1 Pump-and-Treat System"; PNNL-13378, "Results of Detailed Hydrologic Characterization Tests – Fiscal Year 1999"; PNNL-13514, "Results of Detailed Hydrologic Characterization Tests – Fiscal Year 2000"; PNNL-14058, "Prototype Database and User's Guide of Saturated Zone Hydraulic Properties for the Hanford Site"; PNNL-14113, "Results of Detailed Hydrologic Characterization Tests – Fiscal Year 2001"; WHC-SD-EN-TI-014, "Hydrogeologic Model for the 200 West Groundwater Aggregate Area"; and WHC-SD-EN-TI-019). Most hydraulic tests were conducted within the upper 15 m (49 ft) of the aquifer, and many were open to more than one geologic unit. In some cases, changes in water table elevation may have significantly changed the unconfined aquifer transmissivity at a well since the time of the hydraulic test. Few hydraulic tests within the Hanford Site unconfined aquifer system have yielded accurate estimates of aquifer-specific yield.

Horizontal hydraulic conductivities of sand and gravel facies within the Ringold Formation generally range from ~1 to 100 m/day (3 to 328 ft/day), compared to 10 to 7,000 m/day (33 to 23,000 ft/day) for the Hanford formation and the coarse-grained multi-lithic facies of the CCU (pre-Missoula gravels) (DOE/RW-0164; PNNL-13641, "Uncertainty Analysis Framework – Hanford Site-Wide Groundwater Flow and Transport Model"; PNNL-14058; PNNL-14656, "Borehole Data Package for Four CY 2003 RCRA Wells 299-E27-4, 299-E27-21, 299-E27-22, and 299-E27-23 at Single-Shell Tank, Waste Management Area C, Hanford Site, Washington"; PNNL-14804, "Results of Detailed Hydrologic Characterization Tests – Fiscal Year 2003"; WHC-SD-EN-TI-019). Because the Ringold Formation sediments are more consolidated and partially cemented, they are ~10 to 100 times less permeable than the sediments of the overlying Hanford formation. Before wastewater disposal operations at the Hanford Site, the uppermost aquifer was mainly within the Ringold Formation, and the water table extended into the Hanford formation at only a few locations ("Geology and Ground-Water Characteristics of the Hanford Reservation of the U.S. Atomic Energy Commission, Washington" [Newcomb et al. 1972]). However, wastewater discharges raised the water table elevation across the site. The general increase in groundwater elevation caused the unconfined aquifer to extend upward into the Hanford formation over a larger area, particularly near the 200 East Area. This resulted in an increase in groundwater velocity because of both the greater volume of groundwater and the higher permeability of the newly-saturated Hanford formation sediments.

**Figure 3-33. Discharge History for the 216-T Pond and 216-U Pond.**



**3.1.5.3.3 Existing Groundwater Contamination.** When the Hanford Site was operating, spent fuel reprocessing, isotope recovery operations, and associated waste management activities occurred within the 200 East and 200 West Areas located in the central portion of the Site. Waste disposal within the 200 Areas began with startup of plutonium-separation operations in late 1944 (WHC-MR-0521, "The Plutonium Production Story at the Hanford Site: Processes and Facilities History"). Three separations processes were used. The earliest was the bismuth-phosphate process, which was used between 1944 and 1956 at T Plant in the 200 West Area (200-ZP groundwater interest area), and between 1945 and 1952 at B Plant in the 200 East Area (200-BP). The REDOX process was used between 1952 and 1967 at the REDOX Plant in the 200 West Area (200-UP). Finally, the PUREX process was used from 1956 to 1972, and again from 1983 to 1989 at the PUREX Plant in the 200 East Area (200-PO).

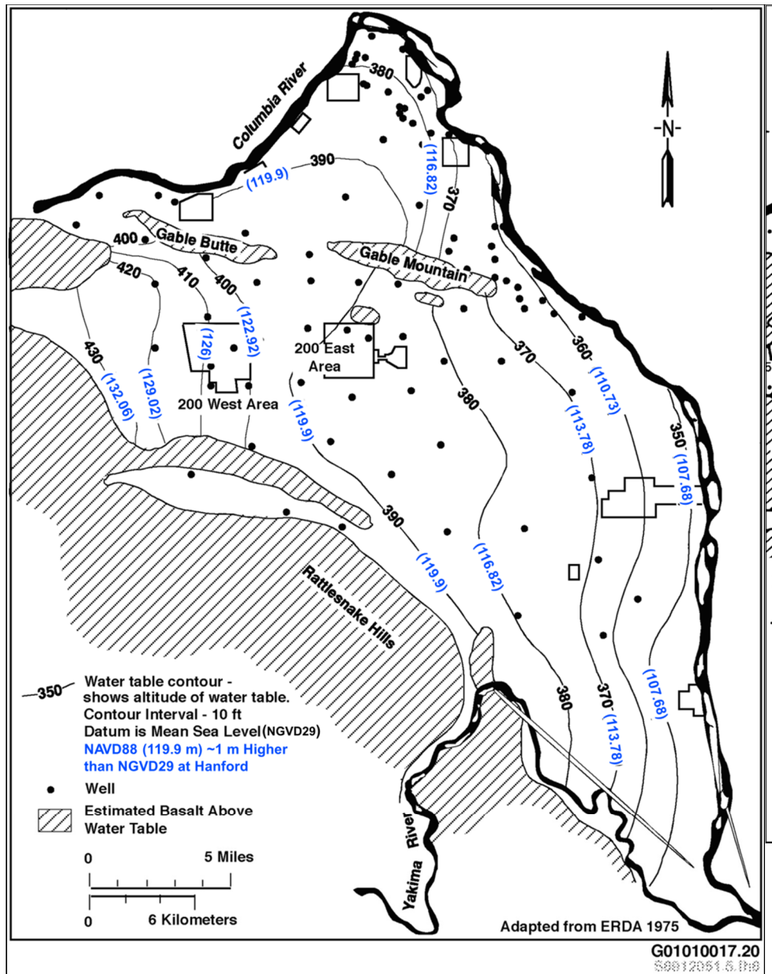
Beginning in 1949, the product from the separations plants was further processed at the Plutonium Finishing Plant (PFP) (200-ZP), which operated until 1989. Other chemical processes performed in the 200 Areas included uranium recovery, using the tributyl phosphate (TBP) process at U Plant (200-UP) between 1952 and 1957, and radionuclide recovery by various methods at B Plant (200-BP) between 1963 and 1983 [PNL-SA-23121 S, "Hanford Technical Exchange Program: Process Chemistry at Hanford (Genesis of Hanford Wastes)"]. Each chemical processing facility generated multiple waste streams and used multiple waste sites for waste management and disposal.

Additionally, the 200 Areas contain seven SST WMAs: A-AX, B-BX-BY, and C within the 200 East Area and S-SX, T, TX-TY, and U within the 200 West Area. Unplanned releases (e.g., tank liner leaks or releases from cascade lines or spare ports) have contaminated the vadose zone and some of this contamination has migrated downward to the groundwater (e.g., PNNL-11810, "Results of Phase I Groundwater Quality Assessment for Single-Shell Tank Waste Management Areas S-SX at the Hanford Site"). Migration through the vadose zone may have been facilitated in the past by additions of water from various sources, most notably nearby wastewater ditches and cribs, water supply pipeline leaks, and rainfall/snowmelt runoff events. Nitrate, chromium and $^{99}$Tc from many of the tank farms, as well as uranium specifically from WMA B-BX-BY, form substantial groundwater plumes. These plumes generally are expanding in areal extent and exhibit increasing constituent concentrations indicating that contaminants continue to enter the groundwater from the vadose zone.

The intentional disposal of waste streams to ponds, ditches, and cribs, combined with the UPRs from the WMAs has resulted in a complex mixture of soil and groundwater contamination that complicates the process of interpreting specific contaminant sources for specific plumes.

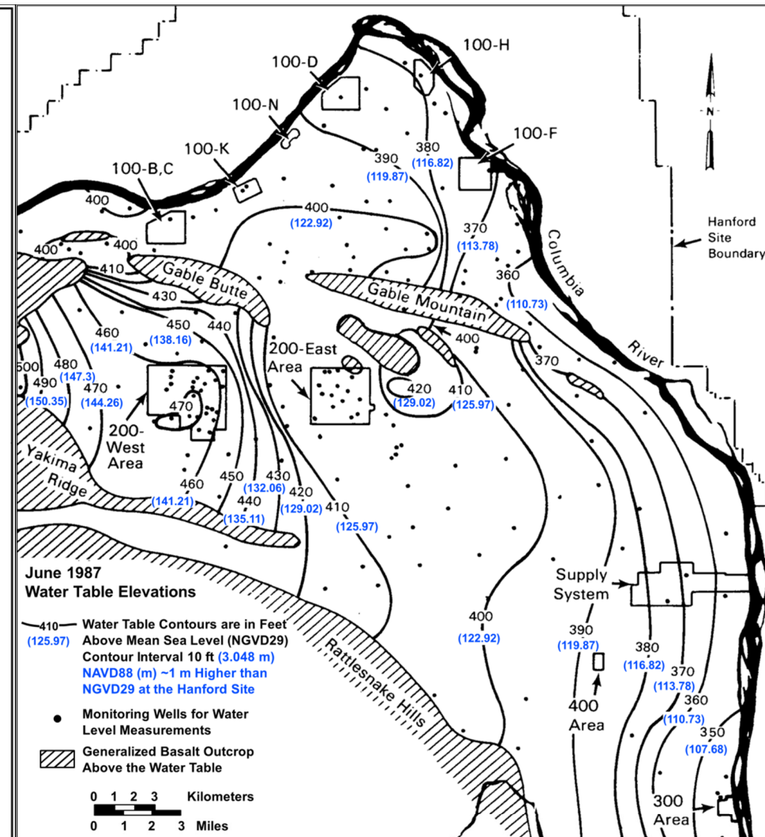
Groundwater monitoring is/has been performed on a regular basis to evaluate levels of contamination, movement of groundwater plumes, and changes to the unconfined/confined aquifers. Each year an annual groundwater monitoring report is issued with the most recent being DOE/RL-2014-32. This annual report provides monitoring results for the AEA, as required by DOE Orders; for RCRA treatment, storage, and disposal units; and for CERCLA groundwater OUs.

**Figure 3-34a. Hind Cast Water Table Map of the Hanford Site, January 1944.**



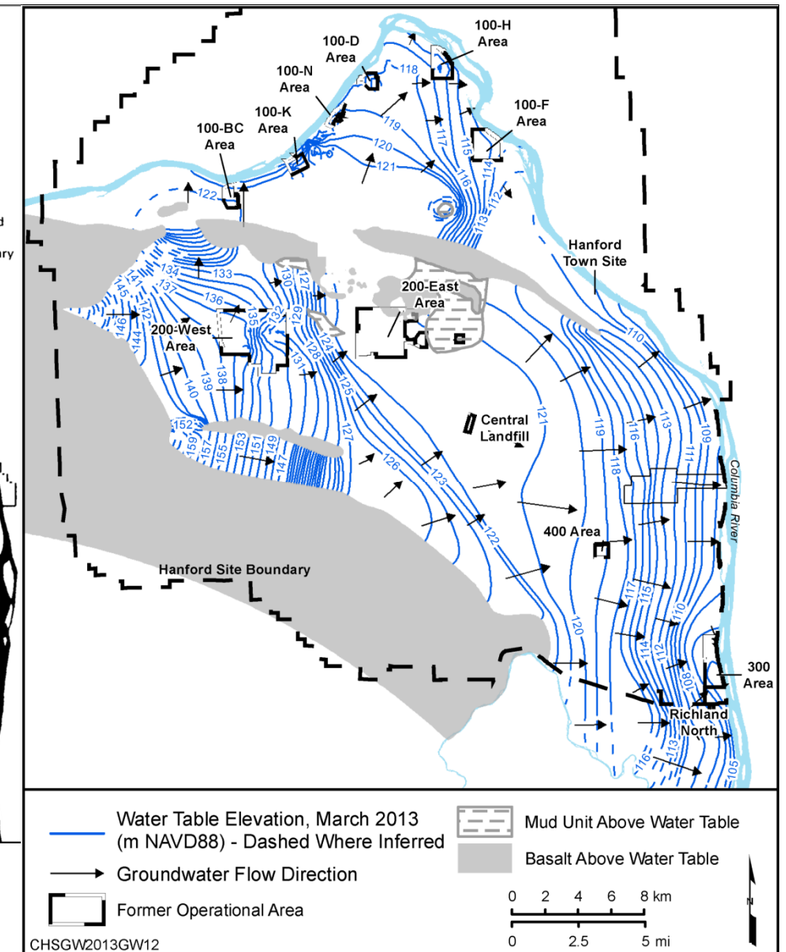

ERDA 1975 refers to ERDA-1538, "Final Environmental Impact Statement, Waste Management Operations, Hanford Reservation, Richland, Washington."

**Figure 3-34b. Water Table Elevations for June 1987.**




Reference: PNL-6464, "Environmental Monitoring at Hanford for 1987."

**Figure 3-34c. Water Table Elevations for 2013.**




Source: DOE/RL-2014-32, Hanford Site Groundwater Monitoring Report for 2013.

The annual report divides the Central Plateau into four geographical groundwater interest areas (200-BP-5, 200-PO-1, 200-UP-1, and 200-ZP-1). These groundwater interest areas encompass groundwater contamination from the 200 East and 200 West Areas and regions into which this contamination has migrated beyond the Central Plateau (Figure 3-35). WMA C falls within the 200-BP-5 groundwater interest area, which also contains WMA B-BX-BY.

Groundwater contaminant plumes of tritium, nitrate, and $^{129}$I formed when the waste discharged to ponds and cribs reached the aquifer. These contaminants form regional plumes originating on the Central Plateau (Figure 3-35). The tritium and nitrate plumes have decreased in area over the years as a result of dispersion and radioactive decay (tritium only); the area of $^{129}$I has remained stable. A large carbon tetrachloride plume originated in the 200 West Area. Other groundwater contaminants in the Central Plateau include $^{99}$Tc, uranium, $^{90}$Sr, trichloroethene, cyanide, and other dangerous waste constituents.

The unconfined aquifer within the 200 East Area boundary is the primary aquifer impacted by past waste disposal operations and is associated with the suprabasalt sediment of the Ringold Formation, CCU, and Hanford formation (Figure 3-17). The greatest concentration/activity of nitrate, $^{99}$Tc, and uranium is in the 200-BP-5 groundwater interest area within the northwest portion of the 200 East Area, also referred to as the B Complex (e.g., 241-B-BX-BY single-shell underground storage tank [UST] area "Waste Management Area B-BX-BY" and adjacent liquid waste sites). These plumes extend both to the northwest and southeast within an ancestral Columbia River paleochannel that incised semi-consolidated gravels and cohesive fluvial-lacustrine Ringold deposits. With the groundwater flow in the vicinity of the B Complex changing flow direction from northwest through Gable Gap to the southeast toward the Columbia River and through the paleochannel, contaminant plumes in the vicinity of the B Complex could intersect contaminant plumes originating at WMA C in the near future.

Below is a summary description for existing groundwater contamination in the 200-BP-5 groundwater interest area taken from DOE/RL-2014-32 (the reader is referred to that document for more information) for the following contaminants:

- Tritium
- $^{129}$I
- Nitrate
- $^{99}$Tc
- Uranium
- Cyanide.

**Tritium**

The major sources of tritium within the 200-BP-5 groundwater interest area were the 216-B-50 and 216-B-57 cribs located north and northwest of BY Farm, 216-BX-102 UPR from SST 241-BX-102 (BX-102), 216-B-3 pond just east of the 200 East Area and the 216-B-12 Crib ~750 m (2,460 ft) south-southwest of the WMA B-BX-BY. However, at 216-B-12 crib, the source could also be from the 200-PO-1 sources (DOE/RL-2014-32). The size of the tritium plume in the upper part of the unconfined aquifer within 200-BP-5 has decreased since 2003.

The decline is attributed with radioactive decay, dispersion, and possibly diminishing levels of drainage from the vadose zone at certain locations. The maximum tritium levels near the 216-B-50 and 216-B-57 cribs are ~22,000 pCi/L; at the BX-102 site, the maximum tritium levels are on the order of 25,000; at the 216-B-12 crib, the levels range from 94,000 pCi/L to 150,000 pCi/L and finally at the 216-B-3 pond the maximum levels observed are ~42,000 pCi/L. While tritium is found in the unconfined aquifer underneath WMA C at levels below the drinking water standard (DWS) (20,000 pCi/L), WMA C is not considered a source for the tritium.

**Iodine-129**

There are three sources of $^{129}$I in southeast 200 East Area (216-A-10 Crib vicinity, 216-A-29 Ditch, and B Pond) were contributors to the widespread distribution of $^{129}$I within the 200 East Area and Gable Gap. Other potential sources of $^{129}$I to groundwater include the BY Cribs, 241-BX-102 UPR, and the 216-B-8 Crib. Overall $^{129}$I activity in 2013 within 200-BP-5 groundwater interest area ranged from ~7 pCi/L near WMA C (299-E27-22 [Figure 3-4]) to less than 1 pCi/L at wells in the northern part of Gable Gap. The northwest plume extent reflects the primary flow path in the late 1980s when discharges to Gable Mountain Pond were terminated. Although WMA C is not considered a source for $^{129}$I, all 12 groundwater monitoring wells at WMA C had $^{129}$I levels exceeding DWS (1 pCi/L). The levels at WMA C ranged from 2.5 to 7.5 pCi/L. Iodine-129 levels detected near WMA C have been relatively consistent over the past two decades.

**Nitrate**

The most extensive plume in 2013 within 200-BP-5 groundwater interest area is the nitrate (Figure 3-35). Nitrate sources have been identified as: BY Cribs (located just to the north of BY Farm), 216-B-7A&B Cribs, 216-B-8 Crib, SST 241-BX-102 UPR, releases with 241-B Tank Farm (B Farm) (part of WMA B-BX-BY), 216-B-12 Crib, 216-B-5 Injection Well, 216-B-2-2 Ditch, WMA C, Gable Mountain Pond, and Gable Gap. The highest nitrate levels observed in 2013 were at B Farm with a level of close to 1,700 mg/L (0.23 oz/gal), followed by the BY Cribs at ~1,400 mg/L (0.19 oz/gal). Contaminant levels drop off to ~300 to 800 mg/L (0.04 oz/gal to 0.11 oz/gal) at 241-BX-102 UPR and 216-B-7A&B Cribs. Waste Management Area C is the source of nitrate found at monitoring wells around WMA C. A total of three wells had nitrate levels above the DWS (45 mg/L [0.006 oz/gal]). The highest level observed was 110 mg/L (0.015 oz/gal) at well 299-E27-14 (Figure 3-4) on the east side of the tank farm. The contaminant level has been fairly constant at well 299-E27-14 for the past several years. The other two wells at WMA C with levels above the DWS are 299-E27-21 (~46 mg/L [0.006 oz/gal]) and 299-E-27-24 (70 mg/L [0.009 oz/gal]).

**Technetium-99**

Technetium-99 sources have been identified at BY Cribs, 216-B-7A&B Cribs, 216-B-8 Crib, 241-BX-102 UPR, releases with B Farm (WMA B-BX-BY), WMA C and Gable Gap. Three general plume areas are present within 200-BP-5 groundwater interest area (Figure 3-35); one area north of 200 East, one near WMA B-BX-BY, and one near WMA C. The largest of the

three plumes is near WMA B-BX-BY and sources include the BY Cribs, 216-B-7A&B Cribs, 216-B-8 Crib, 241-BX-102 UPR, and releases associated with the B Farm. The greatest $^{99}$Tc activity in 200-BP-5 groundwater interest area in 2013 occurred at well 299-E33-18, with a maximum activity of 36,000 pCi/L. The ratio of $^{99}$Tc to nitrate in groundwater is potentially useful for evaluating source contributions. The $^{99}$Tc-to-nitrate ratio associated with this area indicates a potentially different source than the other high activity wells in this area, due to the greater $^{99}$Tc activity and lower nitrate concentration. This is consistent with the type of waste released; metal waste from tank 241-BX-102.

Technetium-99 in 200-BP-5 groundwater interest area is primarily from liquid waste associated with the BY Cribs, which received a mean inventory of 128.6 Ci of $^{99}$Tc (Appendix C of RPP-26744, "Hanford Soil Inventory Model, Rev. 1"). Prior to the 2011 groundwater flow reversal, $^{99}$Tc activity beneath the BY Cribs exceeded 30,000 pCi/L in all three wells located within the BY Cribs footprint. The increased activity was the result of minimal groundwater flow between 2006 and 2011 and continuous $^{99}$Tc infiltration into the aquifer at an average activity of ~3.8 µCi/L based on RPP-26744. Since 2011 this concentrated $^{99}$Tc plume has migrated and expanded to the southeast as a result of the groundwater flow reversal in this area.

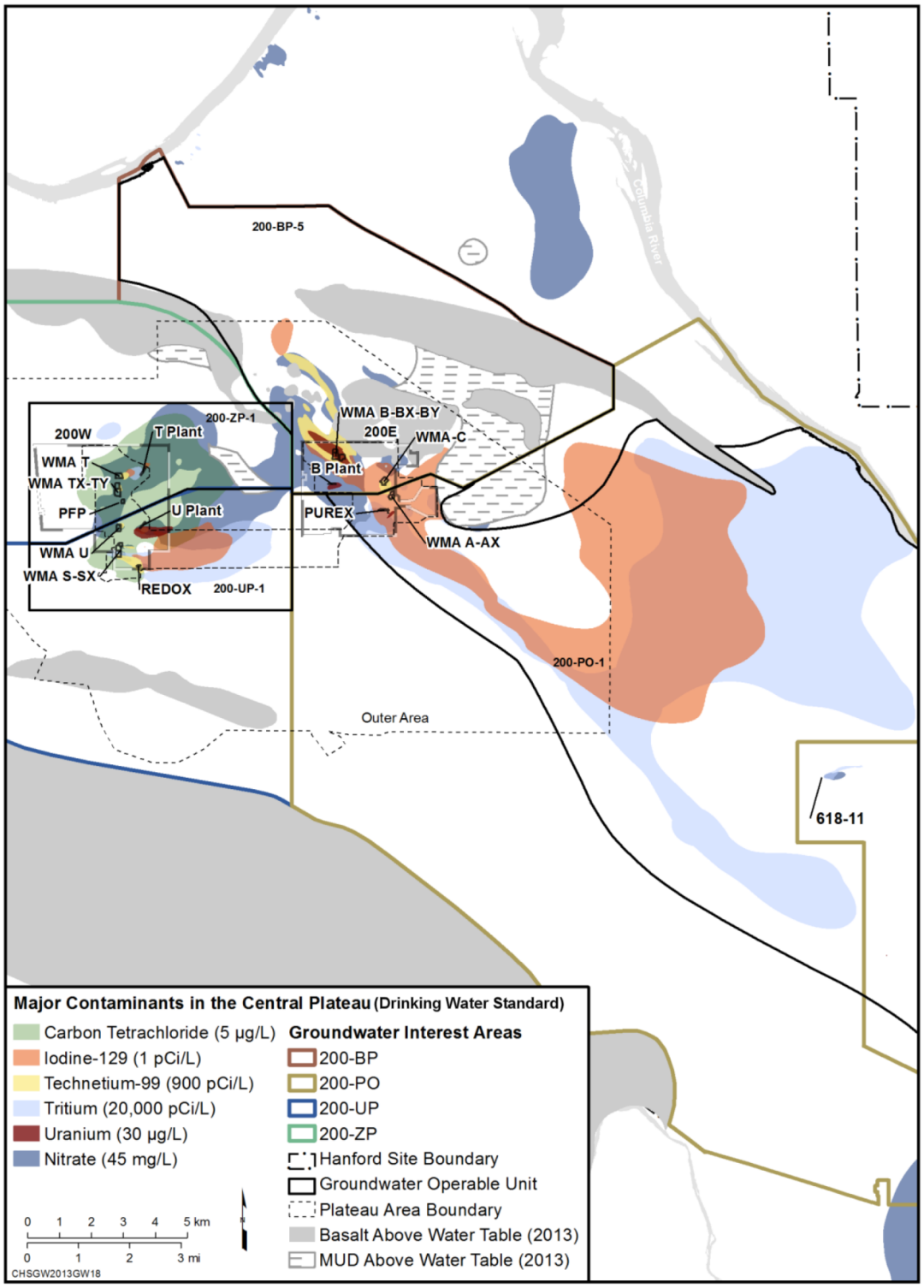
**Uranium**

Uranium found in 200-BP-5 groundwater interest area primarily originated from large disposal inventories to the 216-B-12 Crib and the 241-BX-102 UPR. The uranium inventory disposed to these sites exceeded 10,000 kg, which is at least an order of magnitude greater than other waste sites within 200-BP-5 groundwater interest area. Rough order of magnitude calculations indicated that 1,050 kg (2,310 lbs) of water-extractable uranium may reside in the Cold Creek silt-dominated unit ~3 m (10 ft) above the aquifer. The estimate was based on sample results from three boreholes in an east-west orientation within the perched water zone. The highest concentration of uranium observed in the unconfined aquifer in 2013 was 3,330 µg/L ($4.4 \times 10^{-4}$ oz/gal) (DWS is 30 µg/L [$4.4 \times 10^{-6}$ oz/gal]) at well 299-E33-18 (~80 m [262 ft] due east of 241-BX Tank Farm). At WMA C, uranium has leaked from the SSTs and/or pipelines. RPP-35484, "Field Investigation Report for Waste Management Areas C and A-AX" reported $^{236}$U in vadose zone samples as an indication of irradiated fuel fission product being released to the soil. However, it is not clear as to the source of uranium in the groundwater. It may be from WMA C or may be the result of slightly contaminated groundwater flowing into the area around WMA C. There are no clear trends over the last 6 years in the groundwater data for uranium and the concentrations found in groundwater wells bounding WMA C are 3 to 10 times less than the DWS (i.e., ~2 to 11 µg/L [$2.7 \times 10^{-7}$ to $1.5 \times 10^{-6}$ oz/gal]).

**Cyanide**

Cyanide found in 200-BP-5 groundwater interest area originated from disposal of TBP wastes scavenged for $^{137}$Cs. After scavenging was completed, the tank supernate, including the remaining dissolved ferrocyanide compounds, was discharged to the BY Cribs at the B Complex. In the late 1990s, cyanide concentrations began to increase in the groundwater beneath the BY Cribs along with nitrate and $^{99}$Tc. In addition, low concentrations of cyanide detected in the vicinity of WMA C are attributed to historical releases of ferrocyanide-containing waste at that facility.

**Figure 3-35. Groundwater Contamination for 2013 which Originated within the Central Plateau along with Central Plateau Groundwater Interest Areas.**




Source: DOE/RL-2014-32, Hanford Site Groundwater Monitoring Report for 2013.

PFP = Plutonium Finishing Plant
PUREX = Plutonium Uranium Extraction (facility)
REDOX = Reduction-Oxidation (facility)
WMA = Waste Management Area

As of 2013, cyanide is the only dangerous waste constituent determined as impacting groundwater from C Farm. More specifically, cyanide only exceeded the detection limit in three wells in 2013 (299-E27-14, 299-E27-23, and 299-E27-24 [Figure 3-4]). The concentrations were significantly less than the 200 µg/L ($2.7 \times 10^{-5}$ oz/gal) DWS. By the end of 2013 the cyanide concentrations in two of the wells were below the detection limit. The highest concentration, 13.9 µg/L ($1.9 \times 10^{-6}$ oz/gal), in December 2013 was in well 299-E27-24, which is screened across the bottom of the aquifer. During 2013 the cyanide concentration in this well ranged between 8.64 and 13.9 µg/L ($1.2 \times 10^{-6}$ oz/gal and $1.9 \times 10^{-6}$ oz/gal).

**3.1.5.3.4 Groundwater Travel Times.** Travel time of water through the unconfined aquifer from the 200 East Area to the Columbia River has been estimated to be in the range of 10 to 30 years (Open File Report 87-222, "Subsurface Transport of Radionuclides in Shallow Deposits of the Hanford Nuclear Reservation, Washington – Review of Selected Previous Work and Suggestions for Further Study"; PNL-6328, "Estimation of Ground-Water Travel Time at the Hanford Site: Description, Past Work, and Future Needs"). This is because of large volumes of recharge from wastewater that were disposed in the 200 Areas between 1944 and the mid-1990s, and the relatively high permeability of Hanford formation sediments, which are below the water table between the 200 East Area and the Columbia River. Analysis of the tritium plume in DOE/RL-2009-85, Remedial Investigation Report for the 200-PO-1 Groundwater Operable Unit estimated a travel time of 33 years. DOE/RL-2009-85 further states that this estimate is likely to be conservative (i.e., overstates the groundwater contamination migration rates compared to current conditions) because of the past groundwater mounding in the Central Plateau.

### 3.1.6 Geochemical Properties

The Hanford formation sediment in the 200 Areas consists of glacio-fluvial materials deposited by cataclysmic Ice Age floods. The mineralogy of this sediment is highly variable, depending on grain size. Gravel-dominated sediment tends to have a high abundance of lithic fragments (mostly basaltic, with some plutonic, metamorphic, and detrital caliche fragments) (DOE/RL-2002-39). Finer-grained facies have proportionally less lithic fragments and more quartz, feldspar, and mica grains. Microprobe analysis of the sand and finer-grained fraction indicates dominance by quartz (18 to 67.1% by weight), plagioclase (5.1 to 41.5%) and microcline (1.8 to 30.1%) (RHO-ST-23, "Geology Of The Separation Areas, Hanford Site, South-Central Washington"; PNL-8889, "Solid-Waste Leach Characteristics and Contaminant-Sediment Interactions, Volume 1: Batch Leach and Adsorption Tests and Sediment Characterization"; PNNL-14202, "Mineralogical and Bulk-Rock Geochemical Signatures of Ringold and Hanford Formation Sediments"). Other common minerals include amphiboles up to 36.6%, pyroxenes up to 27.5%, mica (biotite/illite) up to 13.1%, and calcite up to 6.5% by weight. Smectite clays represent a few weight percent of the bulk sand fraction (3.3 to 5% [PNL-8889]) and generally dominate the clay fraction (RHO-ST-23). PNNL-14586, "Geologic Data Package for 2005 Integrated Disposal Facility Waste Performance Assessment" reported chlorite concentrations generally <3% by weight except for one sample that had 8% by weight of chlorite.

Hanford formation sediment is typified as having low organic carbon content, generally <0.1% by weight (PNL-8889), and low-to-moderate cation exchange capacity (2.6 to

7.8 milli-equivalents per 100 g [3.53 oz] [PNL-8889]). The sediment has a slightly basic pH when wetted (PNL-8889 found the pH of saturation extract ranging from 7.66 to 8.17). Small amounts of detrital calcium carbonate (calcite) are common and can act as a weak buffer.

Empirical bulk distribution coefficient ($K_d$) data for Hanford formation and Ringold Formation sediments are fairly abundant for dilute waste solutions and groundwater (PNNL-13895, "Hanford Contaminant Distribution Coefficient Database and Users Guide"). Fewer $K_d$ data are available for the CCU sediments, or for high ionic strength waste solutions with slightly acidic to slightly basic pH values. A relatively small amount of $K_d$ data exists for the combined high ionic-strength/highly-basic tank liquors for many common radionuclides. These distribution coefficient ($K_d$) data have been well tabulated [PNNL-13895; PNNL-11800; PNL-7297, "Hanford Waste-Form Release and Sediment Interaction – A Status Report with Rationale and Recommendations for Additional Studies"; PNNL-13037, "Geochemical Data Package for the Hanford Immobilized Low-Activity Tank Waste Performance Assessment (ILAW PA)," Rev. 1; PNNL-11485, "Radionuclide Adsorption Distribution Coefficients Measured in Hanford Sediments for the Low Level Waste Performance Assessment Project"; PNNL-11965, "Effects of Aging Quartz Sand and Hanford Site Sediment with Sodium Hydroxide on Radionuclide Sorption Coefficients and Sediment Physical and Hydrological Properties: Final Report for Subtask 2a"; and PNNL-13037, "Geochemical Data Package for the 2005 Hanford Integrated Disposal Facility Performance Assessment," Rev. 2]. In most instances, adsorption appears to be the controlling geochemical process, but neutralization of acid waste by the alkaline sediment and neutralization of basic tank waste can cause precipitation of some contaminant species within the sediment pores. Outside the zone of pH neutralization, adsorption is considered to be the dominant contaminant retardation process in the vadose zone.

### 3.1.7 Natural Resources

The following section discusses the natural geologic and water resources on the Hanford Site. The Central Plateau of the Hanford Site has no important natural resources.

**3.1.7.1 Geologic Resources.** Geologic resources at the Hanford Site are very limited. Hanford Site mineral resources include sand, gravel, silt, clay, and aggregate. Historically, these resources were extracted at several quarries or pits at the Hanford Site and used for road construction and maintenance, and waste burial activities. No major mining operations exist in the Hanford Site area. Oil and gas exploration have occurred; however, no economically viable accumulations were found.

**3.1.7.2 Water Resources.** The Columbia River is used as a source of both drinking water and industrial water for several Site facilities (PNNL-20548). The water systems of Richland, Pasco, and Kennewick withdrew a large portion of the 48.8 billion L (12.9 billion gal) used during 2006 from the Columbia River. Each city operates its own supply and treatment system, located downgradient and downriver of the Site. The Richland water supply system derives ~82% of its water directly from the Columbia River, while the remainder is split between a well field in north Richland (that is recharged from the river) and groundwater wells.

The City of Richland's total water usage during 2006 was 20.1 billion L (5.3 billion gal). The Kennewick system uses two wells and the Columbia River for its water supplies. These wells

serve as the sole source of water between November and March and can provide ~40% of the total maximum supply of 94.6 billion L/day (25 million gal/day). Total 2006 usage in Kennewick was 13.4 billion L (3.5 billion gal). A significant number of Kennewick's residents (~22,000 residential customers) draw irrigation water from the Kennewick Irrigation District, which has the Yakima River as its source. The City of Pasco system also draws from the Columbia River for its water needs. During 2006, Pasco consumed 15.3 billion L (4.1 billion gal). Energy Northwest operates the Columbia Generating Station northeast of the 400 Area. Energy Northwest uses Columbia River water for both potable and process/cooling water applications.

### 3.1.8 Natural Background Radiation

The Hanford Site has an extensive monitoring program. Studies have been directed at determining background levels of possible contaminants in the soil (DOE/RL-92-94, Hanford Site Background: Part 1, Soil Background for Nonradioactive Analytes; DOE/RL-95-55, Hanford Site Background: Evaluation of Existing Soil Radionuclide Data) and in the groundwater (WHC-EP-0595, "Westinghouse Hanford Company Operational Groundwater Status Report, 1990-1992"). Also, reports are issued annually covering general environmental conditions (PNNL-6415) and groundwater monitoring (DOE/RL-2014-32).

Low concentrations of some longer-lived radionuclides such as isotopes of cesium, plutonium, potassium, strontium, and uranium are detectable that are associated with particulate matter that accumulated in riverbed sediments (PNNL-20548). The levels were similar to those measured in previous years. No discernible increase in concentration could be attributed to current Hanford Site operations. DOE/RL-91-45, Hanford Site Risk Assessment Methodology, summarizes all the measurements taken to determine radionuclide background levels at the Hanford Site (see Appendix B, Section B.2.8).

Recent annual Hanford Site environmental reports (e.g., PNNL-20548) estimate that the total annual dose from Hanford Site operations in 2010 to a hypothetical maximally-exposed individual at an offsite location was ~0.18 mrem. The air-pathway annual dose was 0.053 mrem (excluding radon) and 0.067 mrem (including radon). These radiation exposures are small compared to other natural and human-produced sources that are estimated to contribute ~365 mrem annual dose to individuals living near the Hanford Site (NCRP Report No. 93, "Ionizing Radiation Exposure of the Population of the United States").

### 3.1.9 Waste Management Area C Site Characterization

The previous sections provided summary information on the Hanford Site characteristics. This section provides a brief summary of the characterization of the vadose zone and unconfined aquifer in and around WMA C, including contamination in both the vadose zone and unconfined aquifer. Since the late 1990s there has been an extensive effort to characterize the vadose zone and unconfined aquifer around WMA C. These efforts are described in numerous documents including, but not limited to, DOE/ORP-2008-01 Appendix L; DOE/RL-2014-32; GJO-98-39-TAR/GJO-HAN-18, "Hanford Tank Farms Vadose Zone: C Tank Farm Report"; GJO-98-39-TARA/GJO-HAN-18, "Hanford Tank Farms Vadose Zone: Addendum to the

C Tank Farm Report"; RPP-PLAN-39114; RPP-RPT-56356, "Development of Alternative Digital Geologic Models of Waste Management Area C"; and RPP-RPT-58339. For more detailed information, please refer to the characterization documents.

The principal driver for site characterization at WMA C is a number of confirmed or suspected waste loss events which occurred in WMA C (labeled as UPRs in Figure 3-36) during its operational history. These included suspected tank leaks and known waste losses from waste transfer piping systems. The current understanding of contaminant occurrences and environmental conditions at WMA C is described in RPP-ENV-33418, "Hanford C-Farm Leak Inventory Assessments Report" and DOE/ORP-2008-01. The primary contamination zones currently identified in WMA C include a localized high $^{137}Cs$ activity zone near the bottom of the southwest part of tank C-105 and three UPRs near waste transfer pipelines and diversion boxes in the southwest part of WMA C. Sampling at groundwater wells (299-E27-21 and 299-E27-23) along the southern boundary of WMA C (Figure 3-3) had results for $^{99}Tc$ at concentrations greater than 25 times the DWS of 900 pCi/L.

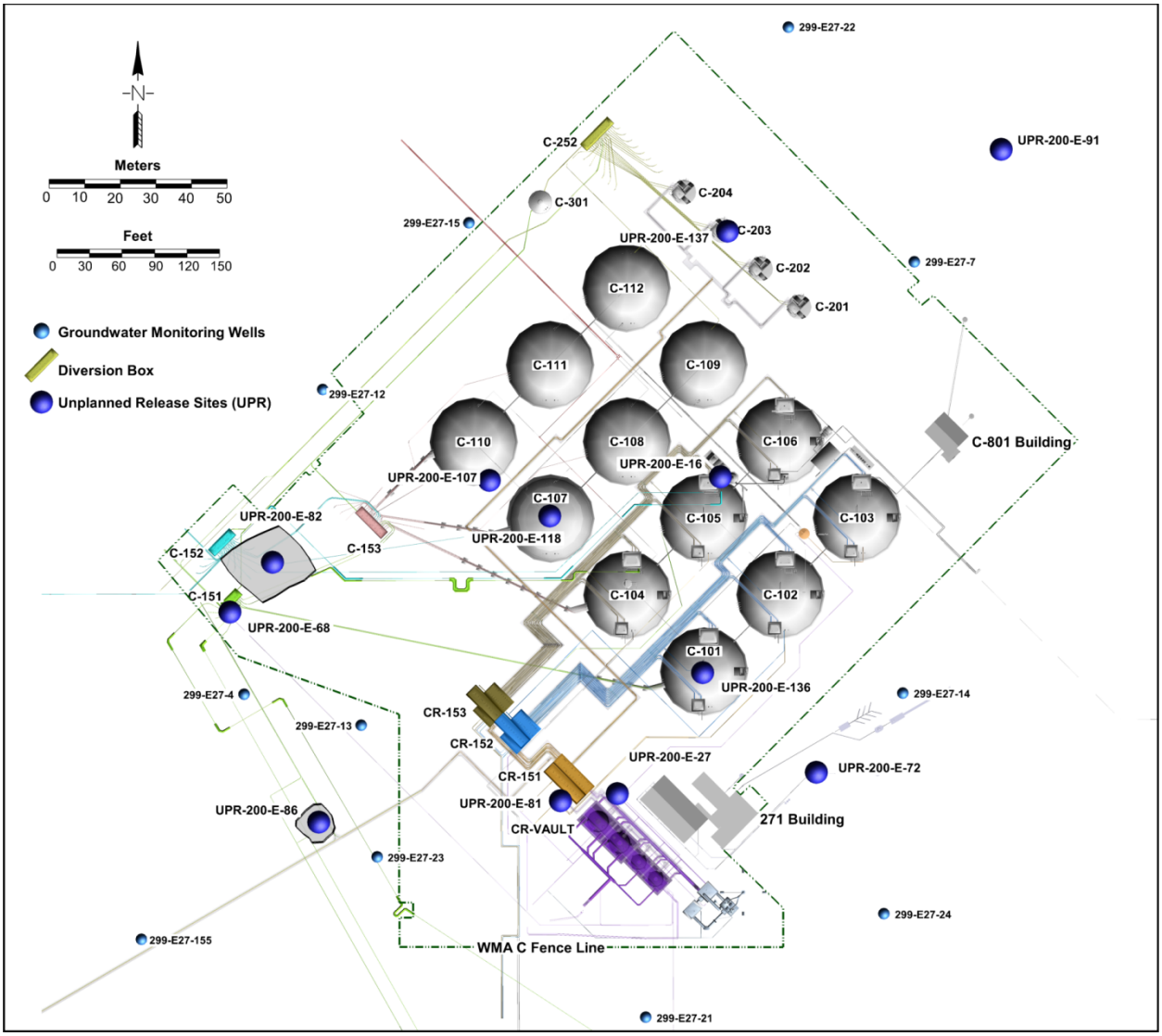
**3.1.9.1 Geology.** The geology of WMA C is summarized from the information provided in DOE/ORP-2008-01, RPP-RPT-46088, and RPP-RPT-56356. A generalized fence diagram through WMAs A-AX and C is shown in Figure 3-37.

Six stratigraphic units lie within WMAs A-AX and C. From oldest to youngest, the primary geologic units are:

- Columbia River Basalt Group
- Undifferentiated Hanford lower gravelly sequence (H3 unit)/Cold Creek/Ringold formations
- Hanford formation – sand sequence (H2 unit)
- Hanford formation – upper gravelly sequence (H1 unit)
- Backfill
- Recent deposits.

The general characteristics of these units are described in more detail in Section 3.1.4, RPP-RPT-46088 and RPP-RPT-56356. At WMA C, it is not possible to separate out the Ringold Formation, CCU and the lower gravely sequence of the Hanford formation (H3). In the vicinity of WMA C, this unit is referred to as undifferentiated H3, CCU and Ringold Formation ($H_3/CC_u/RF$). The SSTs at WMA C were emplaced in an excavation of the Hanford formation sediments of the upper, gravel-dominated (H1) unit. This excavation may also locally intercept the upper portions of the sand-dominated Hanford (H2) unit. Once the tanks were built, the excavation was backfilled with reworked sediments of the upper, gravel-dominated (H1) unit. The water table or the unconfined aquifer's surface lies ~60 m (~200 ft) below the bottom of the tank farms excavations within the undifferentiated $H_3/CC_u/RF$.

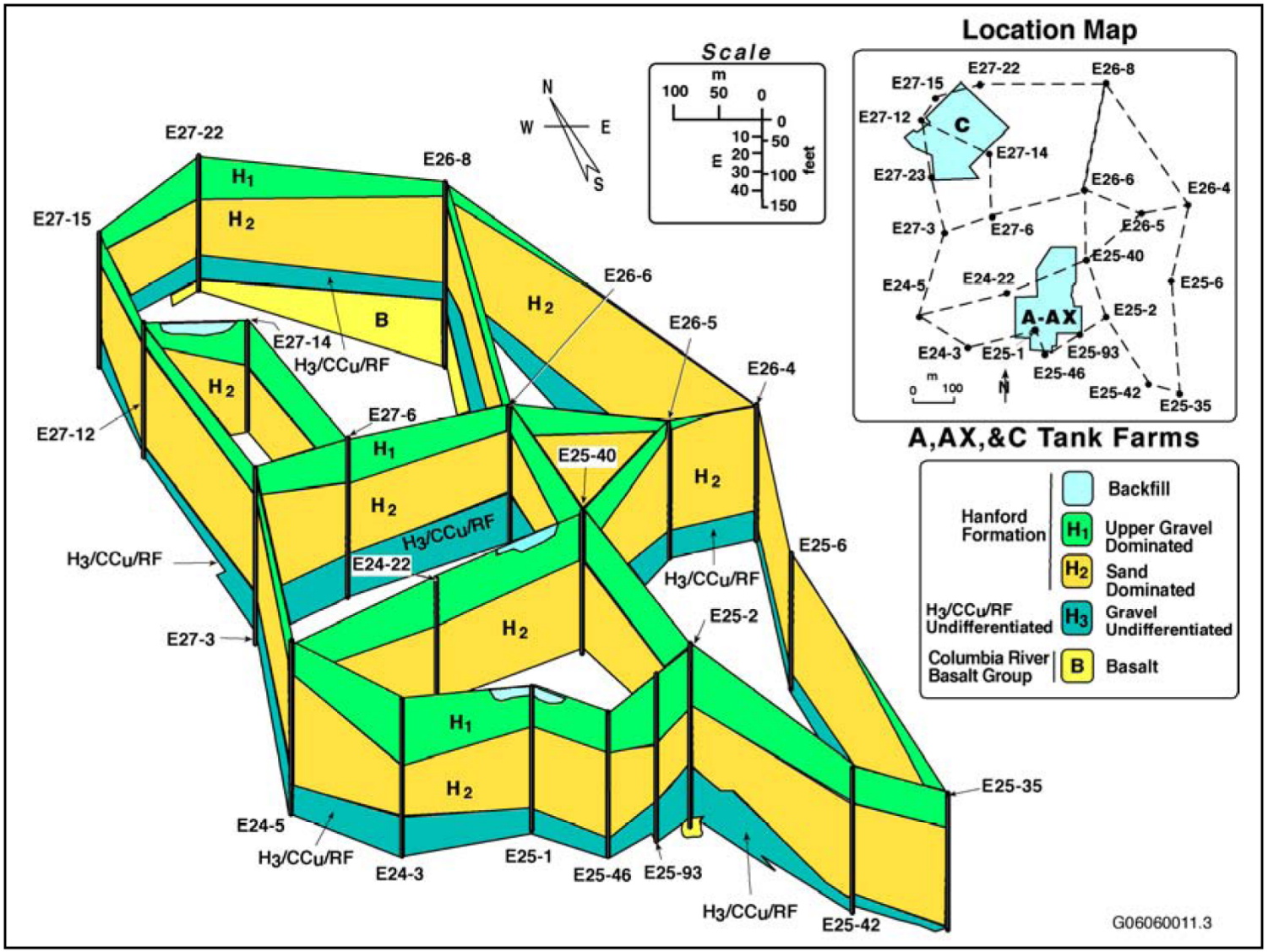
**Figure 3-36. Waste Management Area C Tanks, Infrastructure, and Associated Unplanned Releases.**




WMA = Waste Management Area

The geologic strata underlying WMA C was characterized in conjunction with soil sampling and borehole logging for radionuclides and hazardous waste constituents as part of the Phase 1 and 2 RCRA Facility Investigations at WMA C. The borehole and geologic logging was used to identify the elevations of tops of the geologic units in the vicinity of WMA C. Specifically potassium, uranium, thorium (K-U-T) data from geophysical logs were used to map the tops of the different geologic units at WMA C (RPP-RPT-56356). Two alternative geologic models were developed based on this data.

**Figure 3-37. Fence Diagram Showing Cross-Sections through Waste Management Areas A-AX and C.**




Source: RPP-RPT-46088, "Flow and Transport in the Natural System at Waste Management Area C."

Additional conceptual models are being developed with detailed heterogeneous representations of the geologic framework at WMA C. One is a facies-based model based primarily on a geostatistical analysis of the K-U-T data collected in selected direct push boreholes within WMA C; the other is based on geostatistical evaluations of volumetric moisture content measured in multiple direct push boreholes and drywells within WMA C.

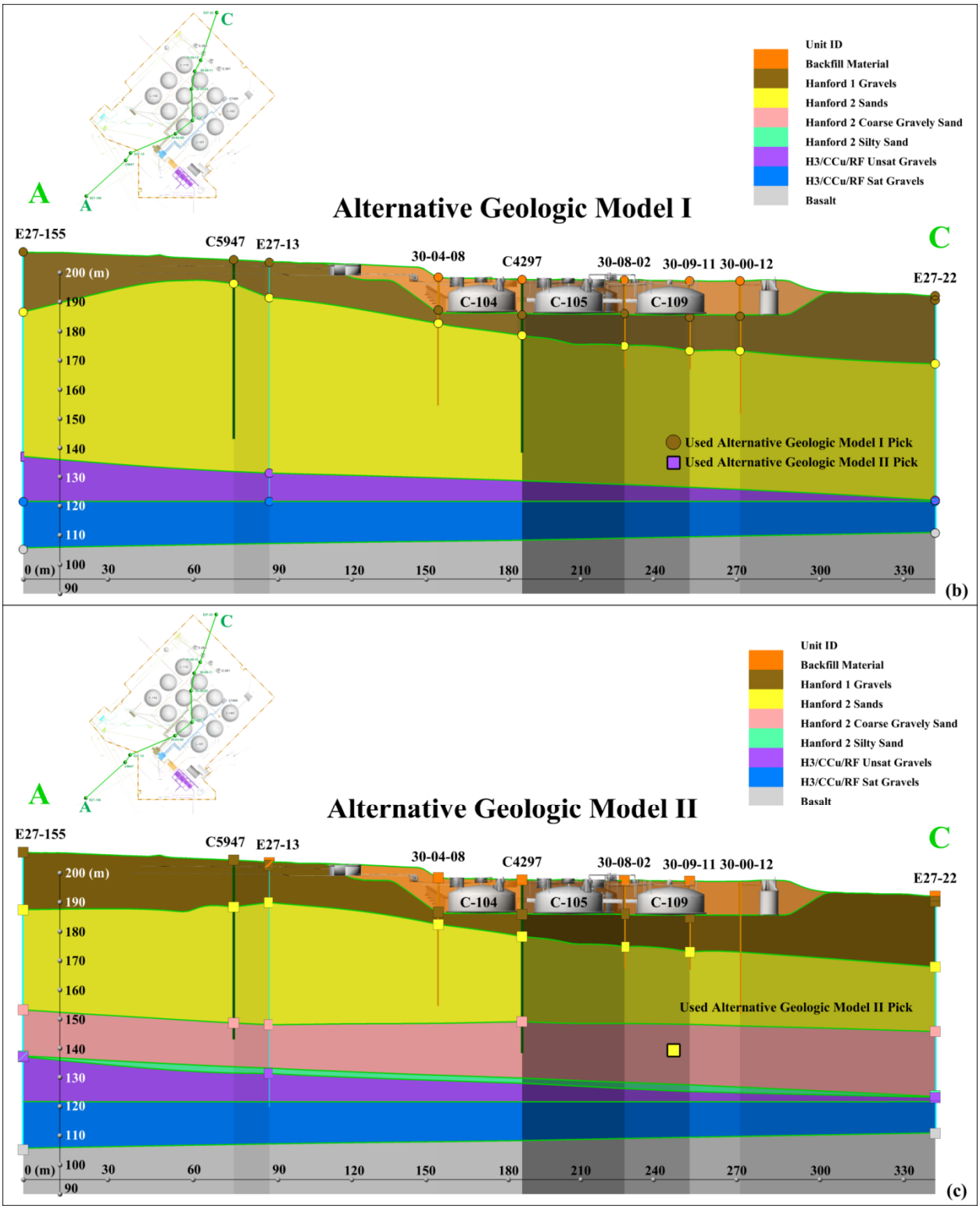
The major difference between the two existing developed alternative models is whether or not a sandy gravel facies is to include a silt layer identified at the bottom of the H2 subunit in the vicinity of WMA C. The K-U-T data (i.e., a lower gross gamma and potassium count) indicates that there is a coarsening of the sand at the bottom of the H2 turning more into a sandy gravel. Underlying this sandy gravel facies is a silt unit with a strong potassium peak and occasional strong natural uranium peak. The difficulty in making this determination is that there are few direct pushes or drywells that are at a sufficient depth to obtain both good geophysical logs and geologic logs (with drill cuttings). The drill cuttings from some of the nearby groundwater wells indicated that there was definite fining of the sands along with some silt found at the vertical location as indicated by the K-U-T data in the geophysical logs, but a competent silt layer was not observed. Alternative Geologic Model I does not include the sandy gravel and underlying silt unit with the H2 unit, while Alternative Geologic Model II does include them. The existence of these layers could cause increased lateral movement in the vadose zone. A series of fence diagrams showing the differences between the two models within WMA C is given in RPP-RPT-56356. The fence diagram for both these models running southwest to northeast through the center of WMA C is given in Figure 3-38.

**3.1.9.2 Hydrology.** Following is an overview of the hydrology of the vadose zone and uppermost, unconfined aquifer beneath WMA C. More detailed information supporting this section can be found in DOE/ORP-2008-01, RPP-RPT-46088, and RPP-RPT-58339.

**3.1.9.2.1 Vadose Zone – Monitoring and Characterization Activities.** Waste Management Area C has 70 drywell monitoring boreholes (see Figure 3-39) available for leak detection monitoring and to provide access for limited vadose zone characterization (e.g., geophysical logging). These drywells were drilled from 1944 to 1982. In 1997, C Farm drywells were logged using a high-resolution spectral gamma logging system. This effort was part of the baseline characterization for WMA C. Results are documented in GJO-98-39-TAR/ GJO-HAN-18 and its associated addendum GJO-98-39-TARA/GJO-HAN-18. The depth ranges for most of these drywells is between 30.5 and 45.7 m bgs (100 and 150 ft bgs). The deepest drywell in WMA C is 47.2 m bgs (155 ft bgs) (30-00-03), and the maximum logged depth is 43.6 m bgs (143 ft bgs) (30-04-08).

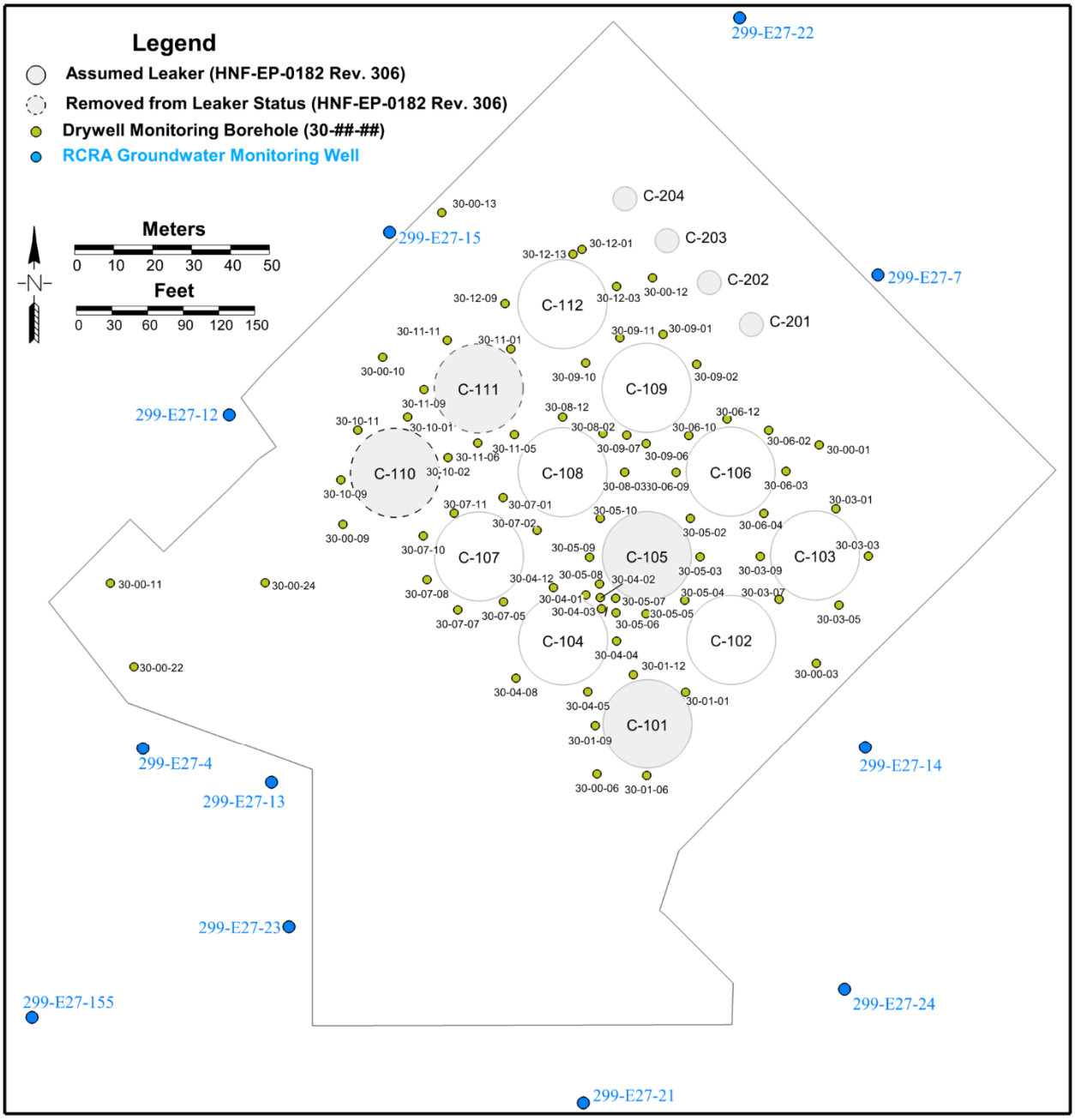
The major gamma-emitting contaminants associated with WMA C are $^{137}$Cs and $^{60}$Co with lesser amounts of $^{154}$Eu. These contaminants are located mostly in and around areas of confirmed or suspected tank and pipeline leaks. Although most of the drywells are deeper than the surrounding contamination, some zones of contamination extend deeper than nearby drywells. Consequently, the maximum depth of vadose zone contamination is not known in some areas of WMA C.

**Figure 3-38. Fence Diagram of Alternative Geologic Models to be Used in Waste Management Area C.**




H3/CCu/RF = undifferentiated H3, Cold Creek Unit and Ringold Formation

**Figure 3-39. Vadose Zone and Groundwater Monitoring Network for Waste Management Area C.**




Reference: HNF-EP-0182, "Waste Tank Summary Report for Month Ending September 30, 2013," Rev. 306.

RCRA = Resource Conservation and Recovery Act of 1976

Since 2004, extensive vadose characterization activities have been conducted at WMA C in support of the RCRA corrective action. The characterization was divided into two phases. The first phase concentrated on characterizing an area of high $^{137}Cs$ concentrations observed in drywells at the depth of the base of tank C-105 below the cascade line running between tanks C-104 and C-105 and the pipeline leak known as UPR-200-E-82 close to the

241-C-152 diversion box. The characterization borehole drilled next to tank C-105 was the deepest characterization within WMA C at 59.9 m (196.5 ft) bgs at the time. Results from soil sampling show the greatest concentration of $^{99}$Tc (8.4 piCi/g) and nitrate (20 µg/g [$2.7 \times 10^{-6}$ oz/gal]) at 41.1 to 47.2 m bgs (~135 to 155 ft bgs). Slant direct pushes underneath UPR-200-E-82 found $^{99}$Tc (28.6 pCi/g) and nitrate (19.7 µg/g [$2.6 \times 10^{-6}$ oz/gal]) centered below the pipeline leak at 23.5 m bgs (77 ft bgs). Complete results of the first phase of characterization are documented in DOE/ORP-2008-01 Appendix L.

The second phase started in 2008 and characterization data was collected per the work plan (RPP-PLAN-39114). For Phase 2, site characterization data was collected at the 23 sites identified in Figure 3-40a. Each characterization site was given a letter map designation. The site characterization activities for Phase 2 included the following:

a. Soil collection and analysis through direct push boreholes technology

b. Geophysical logging at drywell boreholes and groundwater monitoring wells

c. Surface Geophysical Exploration

d. Tissue sampling for ecological risk assessment

e. Possible sampling of vadose zone during the installation of any new groundwater wells within ~30 m (~100 ft) of WMA C.

RPP-PLAN-39114 provides a complete description of what was to be collected at each of these sites. During the preparation of the work plan for the Phase 2 characterization, a transitional characterization (Phase 1.5) effort was undertaken and vadose zone characterization took place at two past UPR sites (UPR-200-E-81 and UPR-200-E-86) (Figure 3-40b). This transitional characterization effort was called “near-term characterization” and focused on the deployment of hydraulically-driven direct push technology to push boreholes (i.e., Phase 1.5) for geophysical logging, placement of deep electrodes, and collection of soil samples. The results of both the transitional characterization and the Phase 2 characterization efforts are given in RPP-RPT-58339.

**3.1.9.2.2 Vadose Zone – Moisture Content.** Moisture content data from both neutron logging and laboratory analyses were collected during both Phase 1 and 2 characterization efforts of the RCRA Facility Investigation. A statistical summary of this moisture content data is provided here. The reader is referred to Appendix B for additional detailed information about this moisture content data and its use in the PA model development process.

The neutron logging data came from two drywells and 63 direct push boreholes. Laboratory measured moisture content (weight % converted to volumetric moisture content) came from one groundwater well (299-E27-22) and one characterization borehole (C4297).

The spacing for the neutron logging of moisture content varied from 0.05 m to 0.15 m (~0.15 ft to 0.5 ft). The spacing on the laboratory samples was greater. A total 32,912 measurements were made and moisture content ranged 0.11 to 30.64 volumetric percent, with a mean of 5.69,

and a median of 5.09. Furthermore, the formations were identified in each well/borehole/direct push and a statistical analysis of volumetric moisture content data was run for each formation (Table 3-3). The locations for the moisture content measurements are shown in Figure 3-41.

**3.1.9.2.3 Vadose Zone – Contamination.** Figure 3-42 provides a visualization of the vadose zone contamination beneath WMA C as represented by $^{137}$Cs data and the $^{99}$Tc at borehole C4297. This figure is a three-dimensional (3-D) perspective of WMA C providing locations of tanks and associated drywells. Tanks considered to be leakers are based on information in HNF-EP-0182, "Waste Tank Summary Report for Month Ending February 28, 2015," Rev. 326. For $^{137}$Cs each drywell is represented with a single vertical line. Shaded rings around the drywells indicate the level of vadose zone contamination based on spectral gamma logging results. Only the more significant soil contamination zones (i.e., $^{137}$Cs contamination levels greater than 10 pCi/g) are shown.

Spectral gamma logging data provided in Figure 3-42 indicate the presence of contamination in the region between tanks C-104 and C-105. The most concentrated contamination occurs at drywell 30-05-07 on the southwest side of tank C-105 (Figure 3-42), where two high $^{137}$Cs concentration zones occur at and below the tank bottom (DOE/ORP-2008-01). Also shown on Figure 3-42 are sample locations showing where the more mobile $^{99}$Tc was found in characterization borehole C4297. In addition to the high $^{137}$Cs at tank C-105, evidence from the historical record indicates that three unplanned near-surface release events (UPR 200-E-81, UPR-200-E-82, UPR-20-E-86) occurred on the southwest side of C Farm (Figure 3-36). These events are known to have made relatively significant contributions to vadose zone contamination (RPP-14430, "Subsurface Conditions Description of the C and A-AX Waste Management Area").

The UPR-200-E-81 event occurred near the 241-CR-151 diversion box and involved the loss of ~140,000 L (~36,000 gal) of waste. The UPR-200-E-82 event occurred near the 241-C-152 diversion box and involved the loss of ~10,000 L (~2,600 gal) of waste. The UPR-200-E-86 event occurred in a pipeline break near the southwest corner of C Farm and involved the loss of ~66,000 L (~17,400 gal) of waste. Other UPRs occurred within or near to WMA C (RPP-ENV-33418) and are the subject of further characterization efforts at WMA C (RPP-PLAN-39114). These other UPRs are also shown on Figure 3-36. The Phase 2 RCRA Facility Investigation (RPP-RPT-58339) found low levels of contaminants related to tank waste. However, the contaminant concentration levels found in the soil are so low that the areas in which they are found are not considered sources for the groundwater contamination at WMA C.

**3.1.9.2.4 Unconfined Aquifer – Monitoring.** Quarterly groundwater monitoring was initiated at WMA C in 1992 in accordance with WHC-SD-EN-AP-012, "Interim-Status Groundwater Monitoring Plan for the Single-Shell Tanks." The initial well network consisted of five wells: 299-E27-7, 299-E27-12, 299-E27-13, 299-E27-14, and 299-E27-15 (Figure 3-39). These wells were used for quarterly groundwater monitoring beginning in March 1992 and continued until the Fall of 1993. In the Spring of 1994, semi-annual sampling began for indicator parameter evaluation. Monthly sampling began in June 1998 to prepare for sluicing at tank C-106. The monthly sampling was scaled back to bi-monthly in 2000 and then returned to quarterly sampling in 2001. In 2001, a new monitoring plan, PNNL-13024, "RCRA Groundwater Monitoring Plan

for Single-Shell Tank Waste Management Area C at the Hanford Site," was initiated and required additional wells to ensure adequate monitoring network coverage for WMA C. Wells 299-E27-4, 299-E27-21, 299-E27-22, and 299-E27-23 (Figure 3-39) were subsequently added to the network.

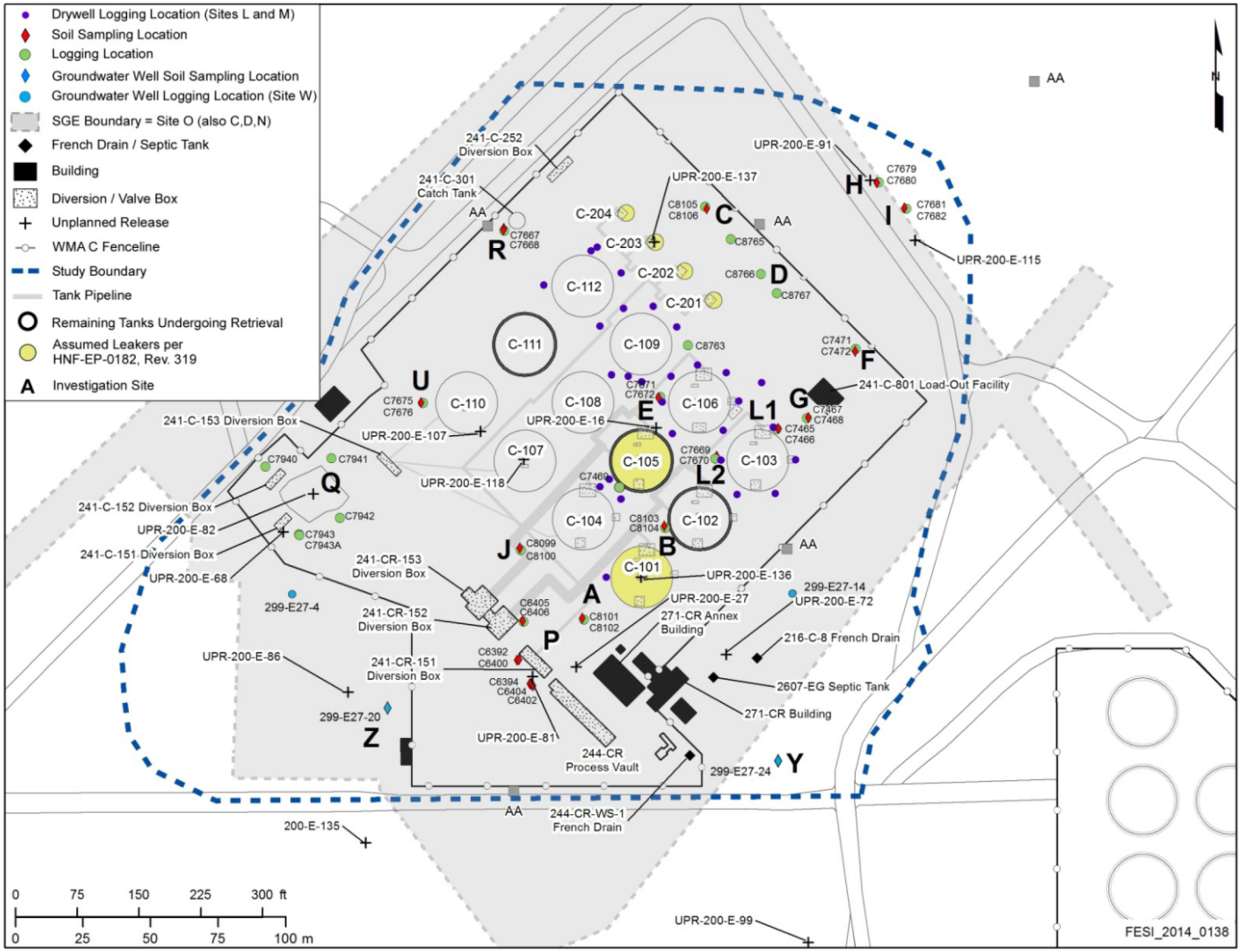
In 2009, WMA C was placed in assessment monitoring because of the exceedance of the critical mean for the indicator parameter specific conductance. In addition, the dangerous constituent cyanide has been found in groundwater beneath WMA C, albeit at levels much lower than the DWS. To meet quarterly RCRA assessment requirements, a new monitoring plan (DOE/RL-2009-77, Groundwater Quality Assessment Plan for the Single-Shell Tank Waste Management Area C) was developed which superseded PNNL-13024. Currently, assessment monitoring is being completed in accordance with DOE/RL-2009-77. Three wells (299-E27-24, 299-E27-25, and 299-E27-155; see Figure 3-39) were added to the network per DOE/RL-2009-77. Well 299-E27-25 is not shown on Figure 3-39; it is located ~170 m (~550 ft) northeast of the northeast fenceline of WMA C. The network now is composed of 12 WMA C monitoring network wells.

In addition to meeting the quarterly assessment requirements, quarterly monitoring is also done to meet the requirements of External letter 04-TPD-083, "Agreement on Content of Tank Waste Retrieval Work Plans," in which quarterly groundwater monitoring sample results are to be provided to Ecology during tank retrievals. To meet the sampling requirements, the groundwater monitoring analyses include RCRA and AEA constituents from the following: anions, cyanide, metals $^{99}$Tc, gross beta, total uranium, and low-level gamma scan. The most recent quarterly monitoring report is SGW-58561, "WMA C Quarterly October Through December 2014 Quarterly Groundwater Monitoring Report."

**3.1.9.2.5 Unconfined Aquifer – Groundwater Flow Conditions.** The water table or potentiometric surface lies ~60 m (~200 ft) below the bottom of the tank farm excavations within the undifferentiated $H_3/CC_u/RF$. The aquifer materials consist dominantly of sandy gravel or silty sandy gravel. The water table elevation beneath WMA C is ~122 m (400 ft) NGVD88 with ~77 m (255 ft) of vadose zone. The aquifer thickness, based on the top of basalt at 108 m (355 ft), is ~13.4 m (44 ft). Hydraulic conductivity values reported for the aquifer in this area vary considerably, ranging from 0.04 (silt lenses within the sandy gravel) to 6,900 m/day (1.6 in. to 22,600 ft). Additional hydraulic property data from aquifer testing at wells near WMA C is provided in RPP-RPT-46088.

Currently, the general groundwater flow direction in the unconfined aquifer beneath WMA C is to the south/southeast. The water table is very flat overall, with an estimated hydraulic gradient between $1 \times 10^{-5}$ to $2 \times 10^{-5}$ m/m; the estimated groundwater flow velocity ranges from 0.2 to 0.4 m/day (0.7 to 1.3 ft/day) (RPP-RPT-46088). Those hydraulic gradient estimates are also consistent with those recently reported in SGW-54165, "Evaluation of the Unconfined Aquifer Hydraulic Gradient Beneath the 200 East Area, Hanford Site" for the unconfined aquifer near the Integrated Disposal Facility (IDF) and PUREX cribs. Also coincident with the flow change are decreasing concentrations of other contaminants in monitoring wells west of C Farm, indicating a change in flow direction. These observations and other interpretations discussed in SGW-58561 provide sufficient evidence for the determination of a south to southeast flow direction at WMA C.

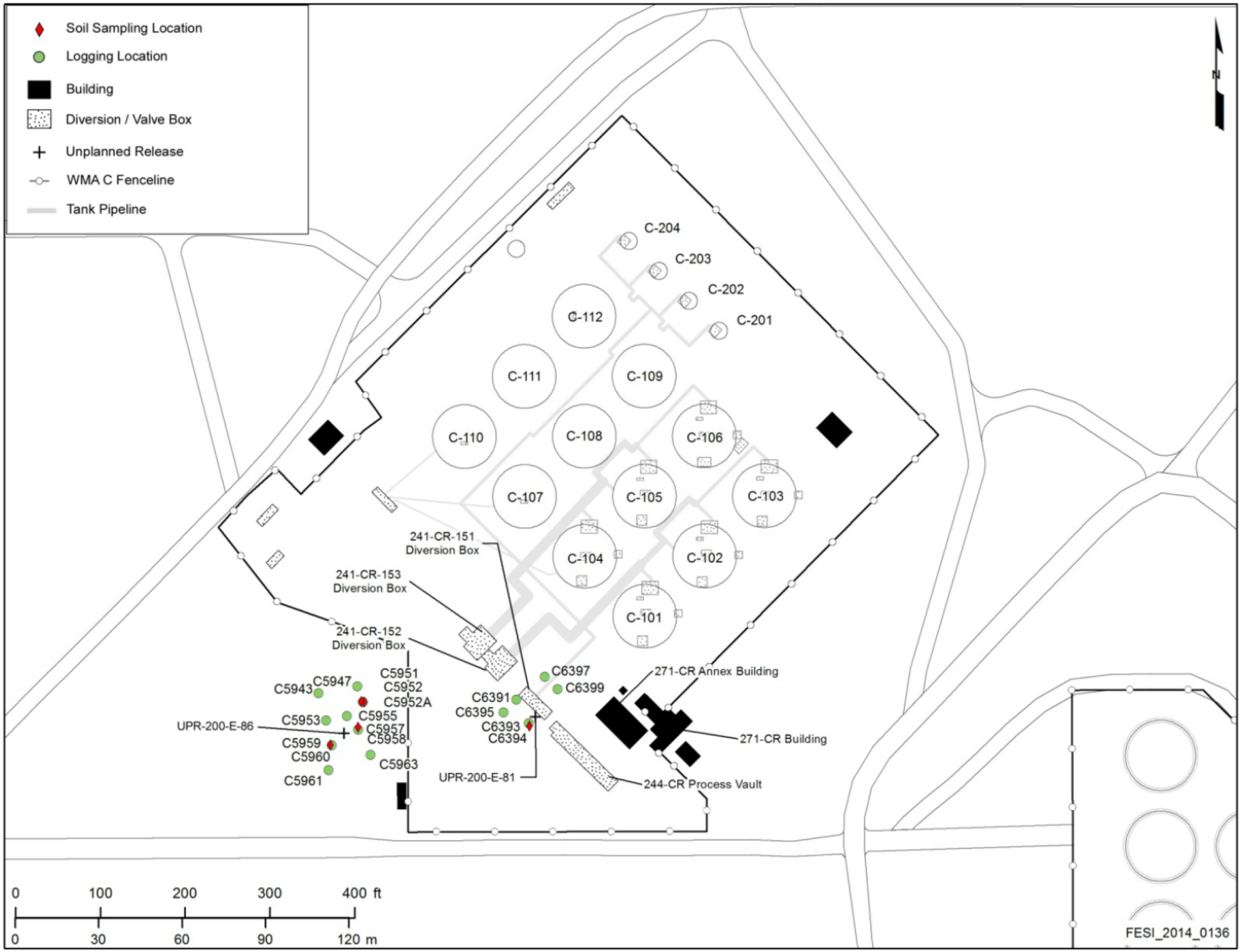
**Figure 3-40a. Completed Phase 2 RCRA Facility Investigation Characterization Locations.**




Reference: HNF-EP-0182, "Waste Tank Summary Report for Month Ending July 31, 2014," Rev. 319.

RCRA = Resource Conservation and Recovery Act of 1976, 42 USC 6901, et seq.
SGE = Surface Geophysical Exploration
WMA = Waste Management Area

**Figure 3-40b. Completed Transitional (Phase 1.5) Characterization Locations.**




WMA = Waste Management Area

**Table 3-3. Summary Statistics for Volumetric Moisture Content in the Lithologic Units Underlying Waste Management Area C.**

| Unit | Count of Wells | Count of Measurements | Minimum (Vol %) | Maximum (Vol %) | Average (Vol %) | Median (Vol %) | Mode (Vol %) | Standard Deviation | Variance |
|---|---|---|---|---|---|---|---|---|---|
| Backfill | 52 | 4,052 | 0.11 | 30.61 | 8.09 | 7.48 | 6.20 | 3.71 | 13.75 |
| H1 | 66 | 7,977 | 0.13 | 30.64 | 5.88 | 4.72 | 3.26 | 3.67 | 13.47 |
| H2 | 64 | 20,876 | 1.06 | 26.32 | 5.15 | 4.96 | 4.89 | 1.82 | 3.30 |
| H3 | 1 | 7 | 5.54 | 7.09 | 6.18 | 6.01 | Too Few | 0.65 | 0.43 |
| Waste Management Area C | 67 | 32,912 | 0.11 | 30.64 | 5.69 | 5.09 | 4.89 | 2.82 | 7.95 |

**Figure 3-41. Moisture Content (% Vol) Measurements in Vadose Zone at Waste Management Area C.**

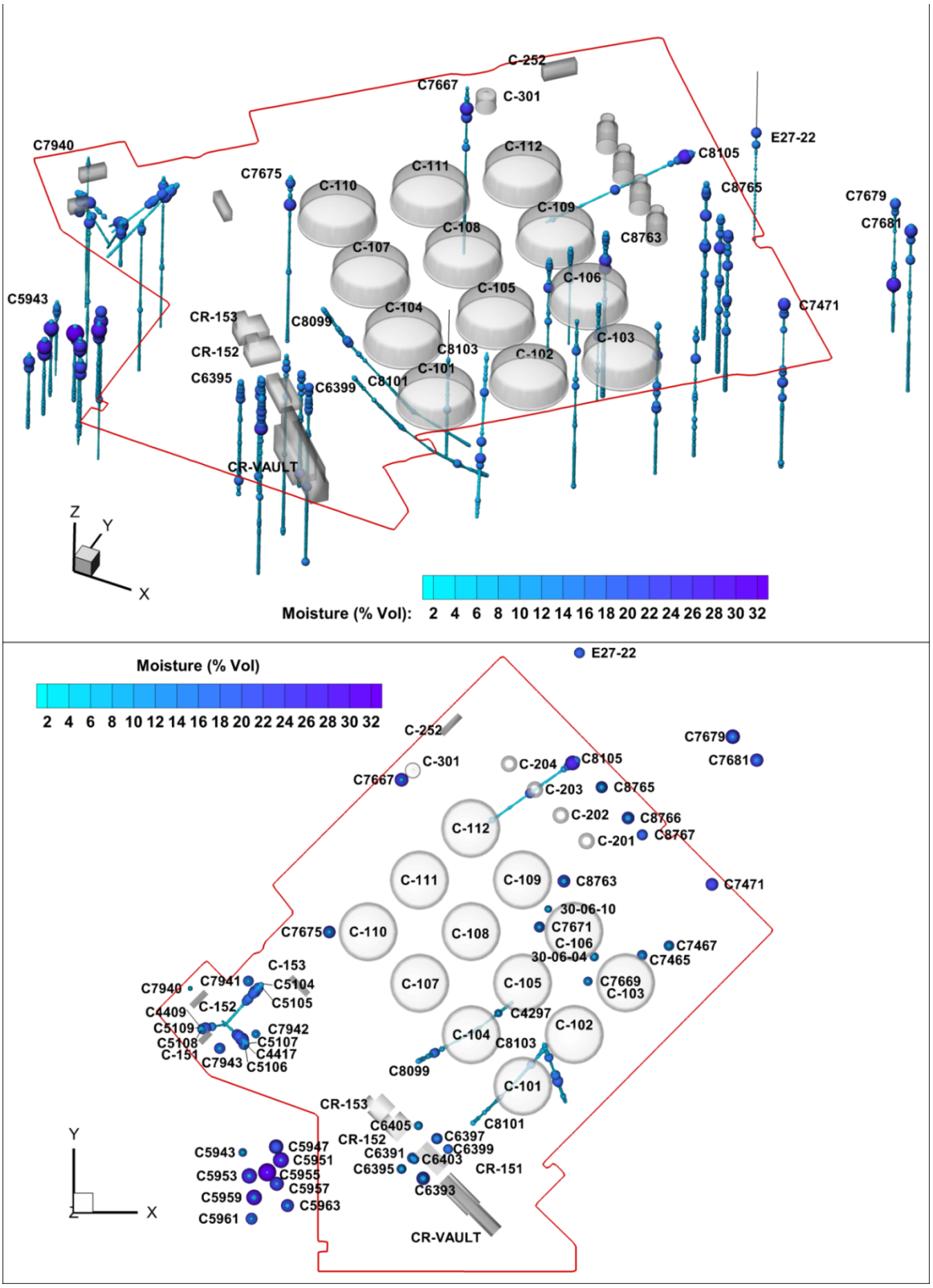
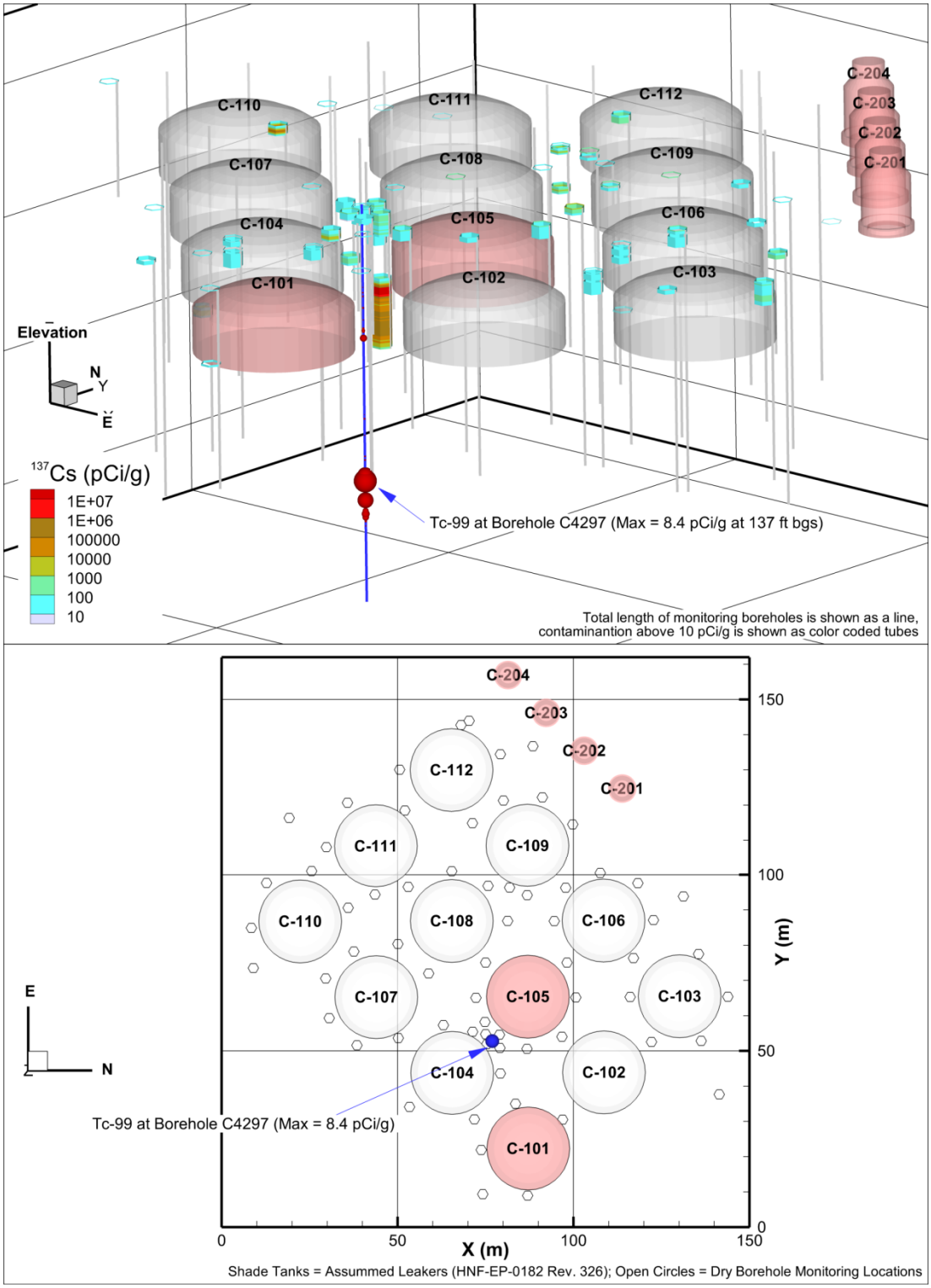


**Figure 3-42. Three-Dimensional Perspective of Waste Management Area C Tanks and Drywells Showing Occurrence of Significant (>10 pCi/g) Cesium-137 Contamination in the Vadose Zone along with Technetium-99 at Borehole C4297.**




Reference: HNF-EP-0182, "Waste Tank Summary Report for Month Ending February 28, 2015," Rev. 326.

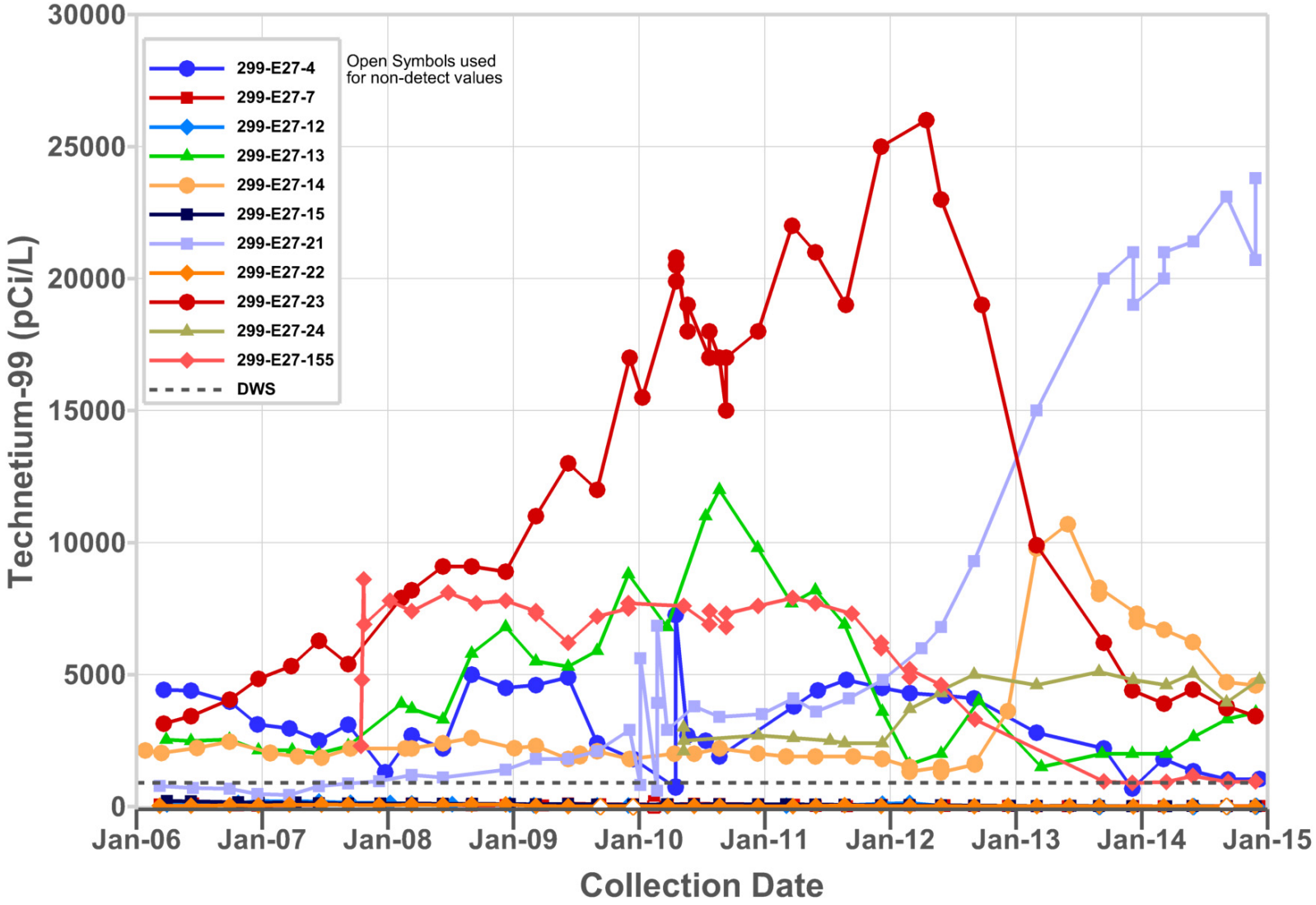
The discharge of large volumes of wastewater in the early 1950s to B Pond raised the water table in the vicinity of WMAs C and A-AX as much as 4.9 m (16 ft) above the pre-Hanford Site operations level (PNNL-14548, "Hanford Site Groundwater Monitoring for Fiscal Year 2003"). The corresponding flow direction underneath WMA C at this time was toward the southwest (DOE/ORP-2008-01 Appendix H). Water levels began to decline in the late 1980s when wastewater discharges were reduced. The decline has become even more pronounced since other effluent discharges throughout the 200 Areas ceased in 1995. Water levels are expected to continue declining within the region surrounding WMAs A-AX and C, with the flow direction changing to the southeast. With the change in flow direction, contamination originating in the B Complex in the northwest corner of 200 East may flow underneath WMA C in the not-too-distant future.

**3.1.9.2.6 Unconfined Aquifer – Contamination.** Observations of elevated concentrations of nitrate, sulfate, and $^{99}$Tc appear to be associated with past releases from WMA C because these constituents are much higher in the downgradient wells compared to upgradient wells, and they exceed their respective groundwater DWSs. Additionally, cyanide, which is a dangerous waste constituent, is also found in the aquifer at levels above the detection limit, but well below the DWS of 200 µg/L ($2.7 \times 10^{-5}$ oz/gal). The measured cyanide concentration was 13.9 µg/L ($1.9 \times 10^{-6}$ oz/gal) in December 2013 at well 299-E27-14. Only $^{99}$Tc and cyanide are discussed further in this section. Technetium-99 exceeded the DWS by a factor of almost 30 and cyanide is a dangerous waste constituent. For discussions and interpretations of the overall trends of other constituents in monitoring wells in the vicinity of WMA C, the reader is referred to SGW-58561.

In December 2014, $^{99}$Tc had concentrations exceeding the 900 pCi/L DWS in 7 of the 11 monitoring wells surrounding WMA C (Figure 3-43). However in 2006, only 4 of the 11 wells exceeded the DWS. Three of these wells (299-E27-4, 299-E27-13, and 299-E27-23) are located just outside the south-central region of WMA C (Figure 3-39). The other well that exceeded the DWS is 299-E27-14, located east of WMA C. Two new wells (299-E27-155 and 299-E27-4) placed to the south and east of WMA C after 2006 also showed $^{99}$Tc concentrations above the DWS when they were installed. The $^{99}$Tc in the groundwater in that region appears to be centered on well 299-E27-23 with the trend in that well increasing from ~5,000 pCi/L in late 2006 to ~26,000 pCi/L by April 2012. Since then, the trend at the well has been decreasing, falling to ~3,400 pCi/L by December 2014. This decline is associated with changes in the flow direction to the east and southeast. The resulting change in flow direction and sampling in downgradient wells (299-E27-21 and 299-E27-24) from 299-E27-23 show $^{99}$Tc increasing in these wells, indicating plume movement to the east-southeast. Finally, at well 299-E27-14, $^{99}$Tc values ranged between 1,500 and 2,600 pCi/L from 2006 to late 2012. However, in early 2013 they started increasing, peaking in June of 2013 at 10,700 pCi/L and decreasing since then; they had decreased to 6,200 pCi/L by December 2014. It is believed the $^{99}$Tc found at well 299-E27-14 is from a different source than $^{99}$Tc found in the south-central region of WMA C.

The specific source of $^{99}$Tc in the groundwater at WMA C has not been identified.

**Figure 3-43. Technetium-99 Concentrations in Waste Management Area C Wells from January 2006 through December 2014.**



The dangerous waste constituent cyanide was detected at four WMA C wells in December 2014 at concentrations far below the 200 µg/L DWS. A possible reason for the increased number of wells with detectable cyanide between June and December is that the detection limit for cyanide decreased from 4 to 1.67 µg/L ($5.3 \times 10^{-7}$ oz/gal to $2.2 \times 10^{-7}$ oz/gal). Three of the four wells (299-E27-7, 299-E27-14, and 299-E27-23) with detected cyanide were reported with concentrations between 3 and 4 µg/L ($4.0 \times 10^{-7}$ oz/gal to $5.3 \times 10^{-7}$ oz/gal). The other well (299-E27-4) was detected with 7.9 µg/L ($1.1 \times 10^{-6}$ oz/gal). Concentrations at well 299-E27-4 are generally near the detection level but were higher in December of 2009, 2011, and 2014 (10.4, 7.98, and 7.9 µg/L [$1.39 \times 10^{-6}$ oz/gal, $1.06 \times 10^{-6}$ oz/gal and $1.07 \times 10^{-6}$ oz/gal], respectively). Remnant levels of low cyanide concentrations appear to be present sporadically beneath the eastern and western portions of the C Farm facility, while more persistent concentrations exist to the southeast (wells 299-E27-14 and 299-E27-24) as can be seen in Figure 3-44. However, cyanide concentrations have appeared to diminish beneath C Farm. The highest cyanide concentration in December 2014 was 7.9 µg/L ($1.1 \times 10^{-6}$ oz/gal) at well 299-E27-4. As discussed in DOE/RL-2009-77, the source is likely be related to past releases from WMA C, but a specific source within WMA C has not been identified.

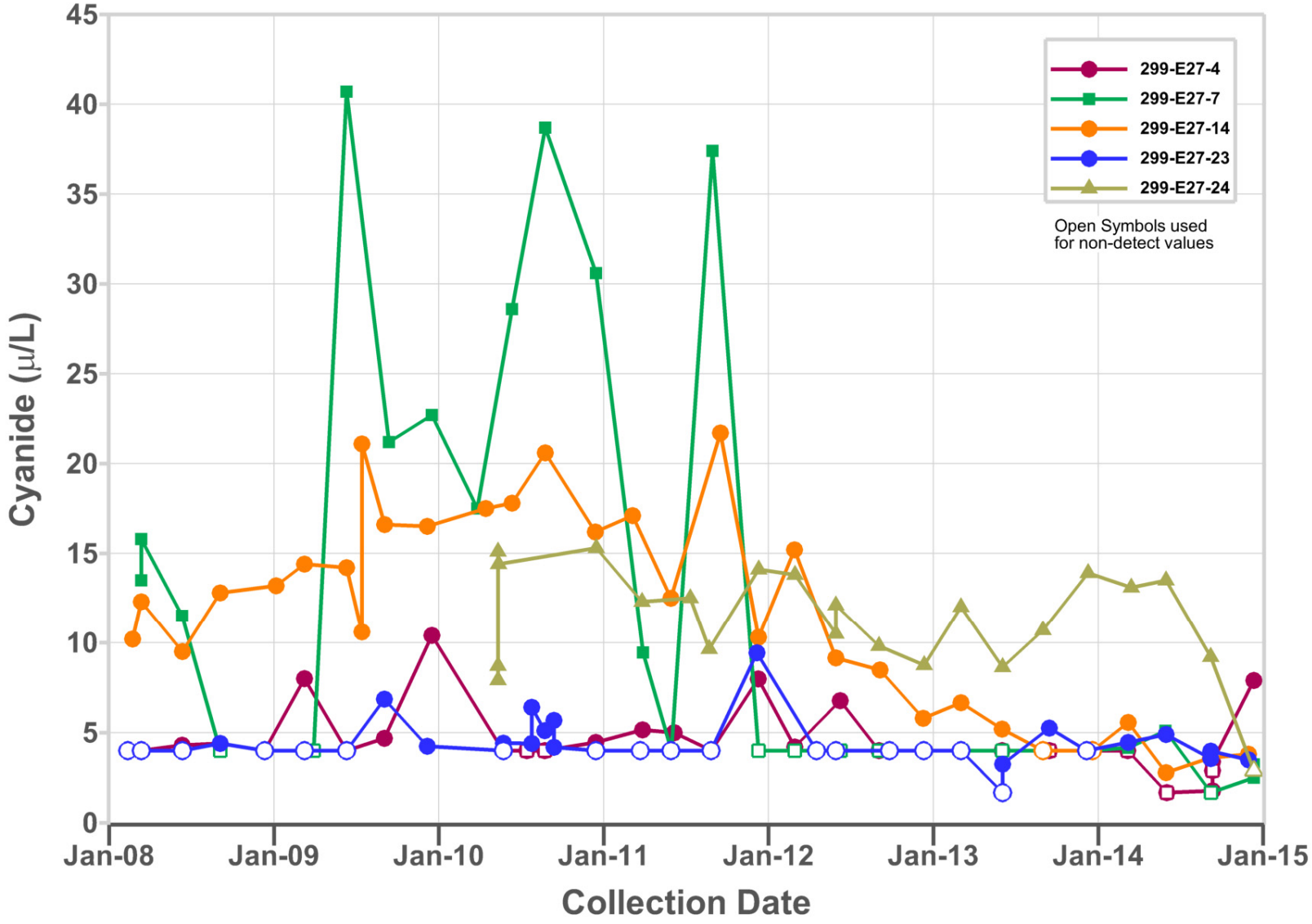
## 3.2 PRINCIPAL FACILITY DESIGN FEATURES

Waste Management Area C is part of the Hanford Site SST system consisting of 149 underground SSTs and processing equipment designed and constructed between 1940 and 1964 to transport and store radioactive and hazardous chemical wastes generated from irradiated nuclear fuel processing. The tanks, designed to store waste, vary in size from 190,000 to 3,800,000 L (50,000 gal to 1,000,000 gal) and contain a variety of solid and liquid waste. In addition to the tanks, a large amount of ancillary equipment associated with the system exists and, although not designed to store wastes, the ancillary equipment is contaminated through contact with the waste. Waste was routed to the tanks through a network of underground waste transfer piping, with interconnections provided in concrete pits that allowed changes to the routing through instrumentation. Processing vaults used during waste handling operations, evaporators used to reduce the waste stored in the system, and other miscellaneous structures used for a variety of waste handling operations are also included in the system. The SST system was taken out of service in 1980 and no additional waste has been added to the tanks.

For the landfill closure[1] of WMA C, site closure is assumed to occur at year 2020, at which time the tanks are assumed to be filled with grout and covered with a final closure cover. This section provides site-specific information for WMA C. It is a summary from the most recent documents that describe present conditions, geology and hydrology, subsurface contamination, and source terms. The list of these documents and what they contain is given in Appendix A. The majority of these documents were produced to support the working sessions for the WMA C PA that took place from February 2009 to May 2011. In addition to the data packages, several other documents have been produced after the working sessions that provide updated information on WMA C facility characteristics.

[1] 78 FR 75913, "Record of Decision: Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington" (December 13, 2013).

**Figure 3-44. Cyanide Concentrations in Waste Management Area C Wells from January 2006 through December 2014.**



### 3.2.1 Facility Description

Waste Management Area C is located in the east central portion of the 200 East Area (Figure 3-4) in land that is designated to be Industrial-Exclusive. Waste Management Area C is one of seven WMAs (A-AX, B-BX-BY, C, S-SX, T, TX-TY, and U) containing 149 SSTs built from 1943 to 1964 (Figure 3-2). In general, the WMA C boundary is represented by the fenceline surrounding the C Farm (Figure 3-3). Waste Management Area C contains twelve 100-series SSTs and four 200-series SSTs that were constructed in 1943 to 1944 along with associated ancillary equipment (i.e., diversion boxes, pipes). It was placed in service in 1946, and used to store and transfer waste until the mid-1980s. Additional ancillary equipment (244-CR vault and CR diversion boxes) were added in the early 1950s. Because of its long operational history, C Farm received waste generated by essentially all of the Hanford Site major chemical processing operations including bismuth phosphate fuel processing, uranium recovery, PUREX fuel processing, Hot Semiworks Facility pilot plant operations, fission product recovery, and tank farm interim stabilization and isolation activities.

Fifteen of the 16 WMA C SSTs were interim stabilized between 1981 and 2003 (HNF-SD-RE-TI-178, "Single-Shell Tank Interim Stabilization Record"). The interim stabilization process removed as much pumpable liquid as practicable. "Practicable" means pumping was continued until the pump rate was less than 0.19 L/min (0.05 gpm). Only tank C-106 was not interim stabilized. This tank went directly to retrieval. The waste in the WMA C tanks is currently in the process of being retrieved and transferred to Hanford's double-shell tanks. However, not all waste can be retrieved and estimates of the inventory of radionuclides and hazardous chemicals remaining in the tank residuals after closure are given in Section 3.2.2.

During its operational history, a number of confirmed or suspected waste loss events occurred in WMA C (Figure 3-36). These included suspected tank leaks and known waste losses from waste transfer piping systems. The current understanding of contaminant occurrences and environmental conditions at WMA C is described in RPP-ENV-33418 and DOE/ORP-2008-01. The primary contamination zones currently identified in WMA C include a localized high $^{137}Cs$ activity zone near the bottom of the southwest part of tank C-105 and three UPRs near pipelines and diversion boxes in the southwest part of WMA C. Furthermore, groundwater in the vicinity of WMA C contains $^{99}Tc$ at concentrations greater than 25 times the DWS of 900 pCi/L.

**3.2.1.1 Infrastructure.** This section summarizes the information given in the following data packages produced for the working sessions: RPP-RPT-44042, "Recharge and Waste Release within Engineered System in Waste Management Area C" and RPP-RPT-46879, "Corrosion and Structural Degradation within Engineered System in Waste Management Area C." Table 3-4 lists the WMA C infrastructure components that were included in the WMA C PA. Inventories of radionuclides and hazardous chemicals remaining in these components are provided in Section 3.2.2.

**3.2.1.1.1 Single-Shell Tanks.** The 241-C Tank Farm (C Farm, i.e., WMA C) contains 12 first-generation, reinforced concrete tanks with carbon steel liners covering the sides and bottoms. The 100-series tanks are 23 m (75 ft) in diameter, with a maximum 5-m (16-ft) depth and 2,006,000-L (530,000-gal) design capacity. The 200-series tanks are 6 m (20 ft) in diameter

with a maximum 7-m (24-ft) depth and 208,000-L (55,000-gal) design capacity. Typical tank configuration and dimensions are shown in Figure 3-45. The 100-series tanks sit below grade with at least 2 m (7 ft) of soil cover to provide shielding from radiation exposure to operating personnel. Tank pits are located on top of the 100-series tanks and provide access to the tank, pumps, and monitoring equipment.

The SSTs were constructed in place with carbon steel (ASTM A283/A283M-03, "Standard Specification for Low and Intermediate Tensile Strength Carbon Steel Plates") lining the bottom and sides of a reinforced concrete shell. The tanks have concave bottoms (i.e., center of tanks lower than the perimeter) and a curving intersection of the sides and bottom (Figure 3-46). The inlet and outlet lines are located near the top of the liners (Figure 3-45). The tanks are arranged in four rows of three tanks. The tanks in each row are piped together so that when the first tank fills, it overflows (cascades) into the second tank, and the second into the third. The four smaller 200-series tanks are piped to diversion box 241-C-252 (Figure 3-45). For additional history of types of waste that went into WMA C, please see RPP-RPT-44042.

The HFFACO Appendix H requires that tanks be retrieved to less than 10.2 $m^3$ (360 $ft^3$) for 100-series SSTs and 0.85 $m^3$ (30 $ft^3$) for 200-series SSTs or the limit of technology, whichever is lower. The thresholds of 10.2 $m^3$ (360 $ft^3$) and 0.85 $m^3$ (30 $ft^3$) were the average calculated residual volume left in each of the 100-series SSTs and 200-series, respectively, after 99% of the waste is retrieved. The C Farm will be the first tank farm at Hanford to be completely retrieved. Table 3-5 provides the current status of retrieval operations at WMA C as of February 28, 2015.

**3.2.1.1.2 Ancillary Equipment.** To support the transfer and storage of waste within the WMA C SSTs, a complex waste transfer system of pipelines (transfer lines), diversion boxes, vaults, valve pits, and other miscellaneous structures exists. Collectively, these are referred to as ancillary equipment, as shown in Figure 3-36. Multiple levels of piping were installed over time in WMA C. A time line of piping installations is described in RPP-7494. It is estimated that there are ~11 km (~7 mi) of waste transfer piping in C Farm (RPP-PLAN-47559). Estimated total volume of piping is given in Table 3-4; estimated volume of residuals remaining in pipes after closure is 5,962 L (1,575 gal) (RPP-PLAN-47559).

The 244-CR Process Tank Vault (244-CR vault) is located south of the tanks. The vault is a two-level, multi-cell, reinforced-concrete structure constructed below grade (DOE/RL-92-04, PUREX Source Aggregate Area Management Study Report), which contains four underground tanks along with overhead piping and equipment. This reference estimated a capacity of 170,343 L (45,000 gal) each for two tanks (TK-CR-001 and TK-CR-011) and a capacity of 55,494 L (14,700 gal) each for the other two tanks (TK-CR-002 and TK-CR-003). HNF-EP-0182 currently lists the capacities of TK-CR-001 and TK-CR-011 as 151,400 L (40,000 gal) each and the capacities of TK-CR-002 and TK-CR-003 as 56,775 L (15,000 gal) each. This vault and associated diversion boxes 241-CR-151, 241-CR-152, and 241-CR-153 were constructed in 1951 and ceased operating in 1988. Figure 3-47 shows the waste pH, temperature, and volume estimates in 2005. Approximately 98% of the liquid volume in the cells was removed in early 2010 (RPP-RPT-45845, "Completion of Pumpable Liquid Removal from 244-CR Vault"). In addition to the tanks in the 244-CR vault, a catch tank C-301 exists that was used to catch waste from the diversion boxes.

**Table 3-4. Operating Period and Capacities for Waste Management Area C Facilities Included in the Performance Assessment.***

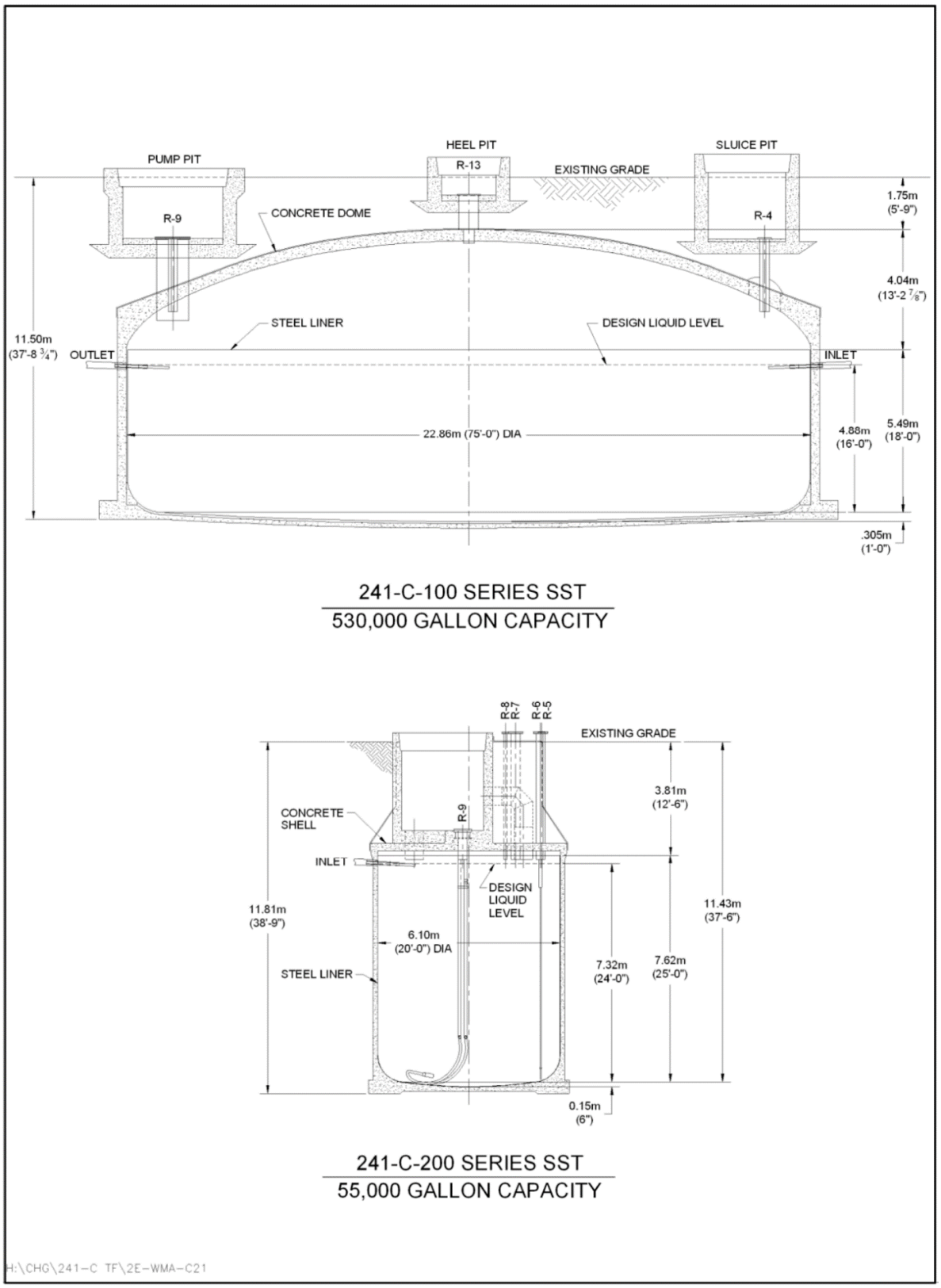
| Facility | Interim Stabilized | Constructed | Operating Capacity (gal) |
|---|---|---|---|
| ***Single-Shell Tanks*** | | | |
| 241-C-101 | 1983 | 1943 to 1944 | 530,000 |
| 241-C-102 | 1995 | 1943 to 1944 | |
| 241-C-103 | 2003 | 1943 to 1944 | |
| 241-C-104 | 1989 | 1943 to 1944 | |
| 241-C-105 | 1995 | 1943 to 1944 | |
| 241-C-106 | N/A | 1943 to 1944 | |
| 241-C-107 | 1995 | 1943 to 1944 | |
| 241-C-108 | 1984 | 1943 to 1944 | |
| 241-C-109 | 1983 | 1943 to 1944 | |
| 241-C-110 | 1995 | 1943 to 1944 | |
| 241-C-111 | 1984 | 1943 to 1944 | |
| 241-C-112 | 1990 | 1943 to 1944 | |
| 241-C-201 | 1982 | 1943 to 1944 | 55,000 |
| 241-C-202 | 1981 | 1943 to 1944 | |
| 241-C-203 | 1982 | 1943 to 1944 | |
| 241-C-204 | 1982 | 1943 to 1944 | |
| ***Miscellaneous Underground Storage Tanks*** | | | |
| **Facility** | **Removed From Service** | **Constructed** | **Operating Capacity (gal)** |
| 241-C-301 catch tank | 1988 | 1946 | 36,000 |
| 244-CR-001 vault tank** | 1988 (244-CR Process Tank Vault) | 1946 | 40,000 |
| 244-CR-002 vault tank** | | 1946 | 15,000 |
| 244-CR-003 vault tank** | | 1946 | 15,000 |
| 244-CR-011 vault tank** | | 1946 | 40,000 |
| ***Underground Waste Transfer Lines*** | | | |
| 241-C tank farm pipelines | N/A | 1943 to 1944 | ~26,700 |
| 241-C-151 | 1985 | 1946 | N/A |
| 241-C-152 | 1985 | 1946 | N/A |
| 241-C-153 | 1985 | 1946 | N/A |
| 241-C-252 | 1985 | 1946 | N/A |
| 241-CR-151 | 1985 | 1952 | N/A |
| 241-CR-152 | 1985 | 1952 | N/A |
| 241-CR-153 | 1985 | 1952 | N/A |

*Data on the facilities are from DOE-RL-88-30, Hanford Site Waste Management Units Report; RPP-15043, "Single-Shell Tank System Description"; RPP-PLAN-47559, Single-Shell Tank Waste Management Area C Pipeline Feasibility Evaluation."

**Capacity estimates for tanks associated with the 244-CR Vault are from HNF-EP-0182, Rev, 338, "Waste Tank Summary Report for Month Ending February 29, 2016"

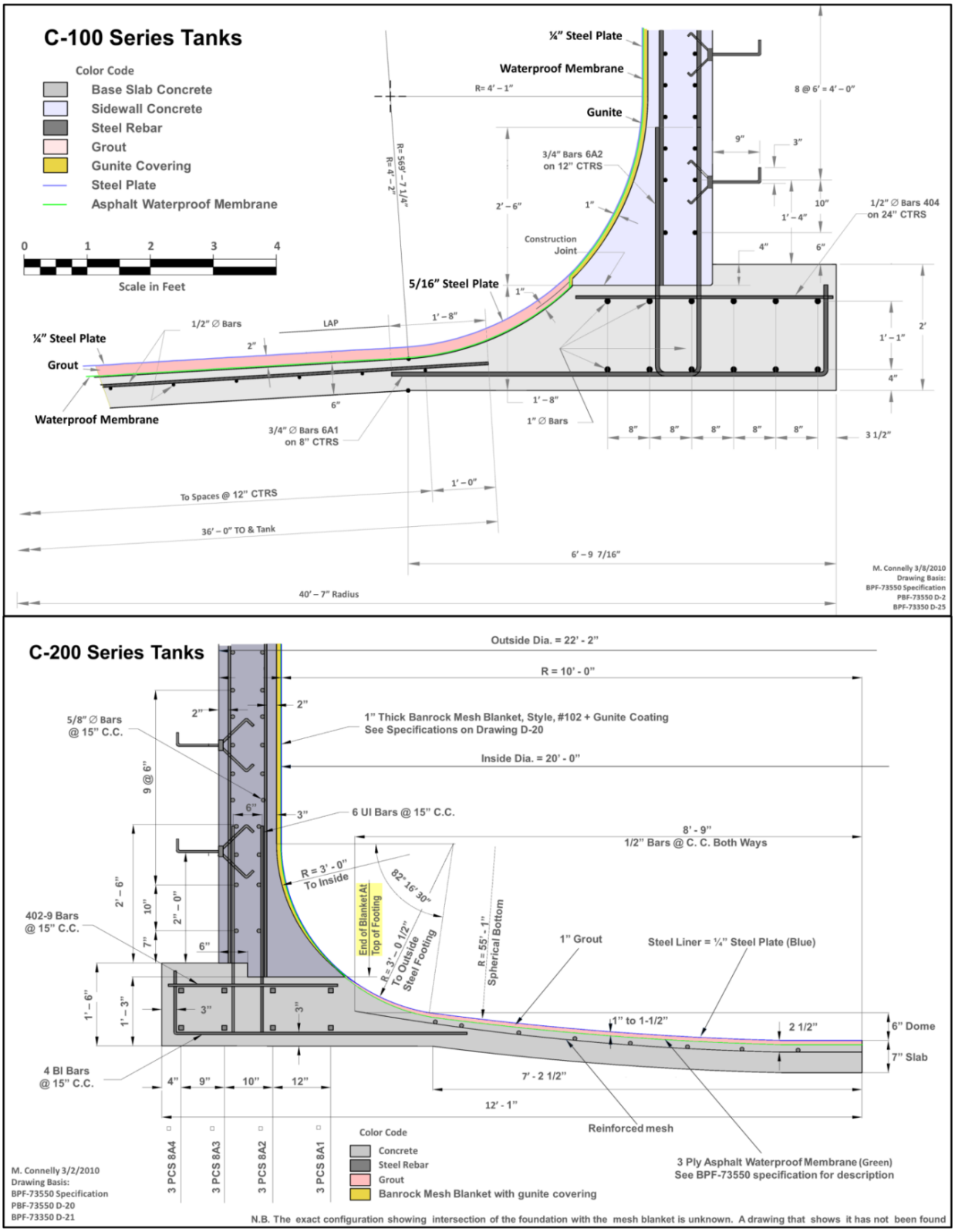
N/A = not applicable

**Figure 3-45. Waste Management Area C Tanks and Associated Tank Infrastructure.**




SST = single-shell tank

**Figure 3-46. Corner of Tank Floor with Tank Sides for the C-100 and C-200 Series Tanks.**




Reference: BPF-73550, "Specifications For Construction of Composite Storage Tanks Bldg. No. 241 Hanford Engineer Works Project 9536."

**Table 3-5. Single-Shell Tank Retrieval Status at Waste Management Area C as of May 31, 2014.[a] (2 sheets)**

| Tank Number | Status | Comments | Nominal Volume of Remaining Waste[b] | Reference |
|---|---|---|---|---|
| 241-C-101 | Complete | Declared "Retrieved to Limit of First and Second Retrieval Technologies," September 25, 2013 | 5.0 kgal | RPP-CALC-56434, "Post-Retrieval Camera/CAD Modeling System Waste Volume Estimate for Tank 241-C-101" |
| 241-C-102 | Ongoing | Retrieval in progress – retrieval initiated April 27, 2014 | 51.7 kgal | HNF-EP-0182, "Waste Tank Summary Report for Month Ending February 28, 2015," Rev. 326 Note. 10 |
| 241-C-103 | Complete | Declared "Retrieval Completed," August 23, 2006 | 2.5 kgal | RPP-RPT-33060, "Retrieval Data Report for Single-Shell Tank 241-C-103" |
| 241-C-104 | Complete | Declared "Retrieval Completed," August 17, 2012 | 1.9 kgal | RPP-CALC-54284, "Post-Hard Heel Retrieval Camera/CAD Modeling System Waste Volume Estimate for Tank 241-C-104" |
| 241-C-105 | Ongoing | Retrieval in progress – retrieval initiated June 11, 2014 | 131.3 kgal | HNF-EP-0182<br>Rev. 326 Note. 13 |
| 241-C-106 | Complete | Declared "Retrieval Completed," December 31, 2003 | 2.8 kgal | RPP-20577, "Stage II Retrieval Data Report for Single-Shell Tank 241-C-106" |
| 241-C-107 | Complete | Declared "Retrieved to Limit of Third Retrieval Technology," September 30, 2014 | 10.7 kgal | RPP-CALC-59985, "Post-Retrieval Camera/CAD Modeling System Waste Volume Estimate for Tank 241-C-107" |
| 241-C-108 | Complete | Declared "Retrieved to Limit of Modified Sluicing Technology," March 22, 2012 | 3.4 kgal | RPP-CALC-54266, "Post-Hard Heel Retrieval Camera/CAD Modeling System Waste Volume Estimate for Tank 241-C-108" |
| 241-C-109 | Complete | Declared "Retrieved to Limit of Modified Sluicing Technology," September 12, 2012 | 2.0 kgal | RPP-CALC-54759, "Post-Hard Heel Retrieval Camera/CAD Modeling System Waste Volume Estimate for Tank 241-C-109" |
| 241-C-110 | Complete | Declared "Retrieval Completed," October 30, 2013 | 1.8 kgal | RPP-CALC-56399, "Post-Hard Heel Retrieval Camera/CAD Modeling System Waste Volume Estimate for Tank 241-C-110" |
| 241-C-111 | Ongoing | Retrieval in progress – retrieval initiated September 14, 2010 | 32.8 kgal | HNF-EP-0182<br>Rev. 326 Note 19 |
| 241-C-112 | Ongoing | Declared "Retrieval Completed," May 29, 2014 | 12.7 kgal | RPP-CALC-56856, "Estimated Waste Volume Remaining in Single Shell Tank 241-C-112 after Hard Heel Retrieval" |

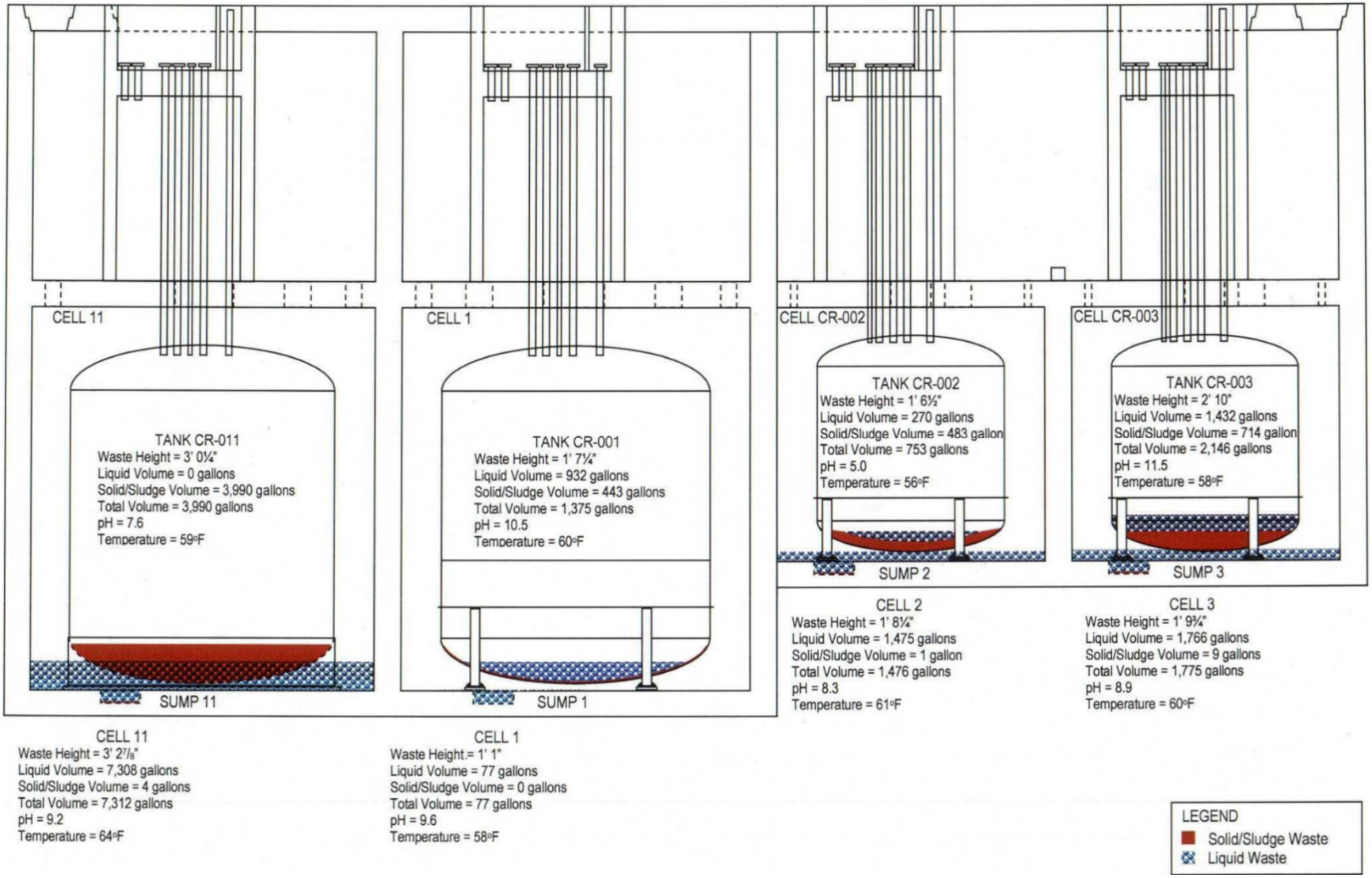
**Table 3-5. Single-Shell Tank Retrieval Status at Waste Management Area C as of May 31, 2014.[a] (2 sheets)**

| Tank Number | Status | Comments | Nominal Volume of Remaining Waste[b] | Reference |
|---|---|---|---|---|
| 241-C-201 | Complete | Declared "Retrieval Completed," March 23, 2006 | 0.14 kgal | RPP-29441, "Post-Retrieval Waste Volume Determination for Single-Shell Tank 241-C-201" |
| 241-C-202 | Complete | Declared "Retrieval Completed," August 11, 2005 | 0.15 kgal | RPP-RPT-29095, "Retrieval Data Report for Single-Shell Tank 241-C-202" |
| 241-C-203 | Complete | Declared "Retrieval Completed," March 24, 2005 | 0.14 kgal | RPP-RPT-26475, "Retrieval Data Report for Single Shell Tank 241-C-203" |
| 241-C-204 | Complete | Declared "Retrieval Completed," December 11, 2006 | 0.14 kgal | RPP-RPT-34062, "Retrieval Data Report for Single-Shell Tank 241-C-204" |

[a] Status taken from HNF-EP-0182, Rev 326.

[b] Nominal volume of waste inventory is the best estimate of residual volume. Retrieval Data Reports also provide 95% upper confidence level volume as the bounding estimate of remaining waste.

**Figure 3-47. 244-CR Process Tank Vault Waste pH, Temperature, and Volume Estimates in 2005.**




Source: RPP-RPT-24257, "244-CR Vault Liquid Level Assessment and Video Inspection Completion Report."

The routing of liquid waste from the operations buildings to the tank farms was accomplished using underground transfer lines, diversion boxes, and valve pits. The diversion boxes housed jumpers (remote pipeline connectors) where waste could be routed from one transfer line to another. The diversion boxes are below-ground, reinforced-concrete boxes that were designed to contain any waste that leaked from the HLW transfer line connections. Per INDC-356-VOL3, "Construction Hanford Engineer Works U.S. Contract Number W-7412-ENG-1 Du Pont Project 9536 History of the Project Volume III" (page 923), the interior surfaces of diversion boxes were coated with a chemically resistant paint. If waste leaked into a diversion box, it generally drained by gravity to nearby catch tanks where any spilled waste was stored and then pumped to SSTs (DOE/RL-92-04). The seven diversion boxes located within WMA C are labeled (241-) C-151, C-152, C-153, C-252, CR-151, CR-152, and CR-153 on Figure 3-36.

**3.2.1.2 Closure.** The TC&WM EIS ROD (78 FR 75913) was published on December 13, 2013. It states the following:

> "SST closure operations include filling the tanks and ancillary equipment with grout to immobilize the residual waste. Disposal of contaminated equipment and soil will occur on site. The tanks will be grouted and contaminated soil may be removed. The SSTs will be landfill-closed, which means they will be stabilized, and an engineered modified RCRA Subtitle C barrier put in place followed by post-closure care."

Waste Management Area C closure is anticipated to occur during the next decade (i.e., ~2020), at which time the tanks will be filled with grout and covered with a final closure cover. Although tank leaks and soil releases have been identified in C Farm, for a nominal modeling case it is assumed that at the time of closure the C Farm tank liners will be intact. This is because tank C-105 is the only C Farm tank currently assumed to have a breach in the liner, with ~40% probability (RPP-ASMT-46452, "Tank 241-C-105 Leak Assessment Completion Report"). There are several other sources of releases near this tank and a liner breach for this tank is not confirmed. Other releases were assessed to have occurred high on the tank wall or to be cascade line or spare inlet releases (tanks C-101, C-104, C-108 and C-110). Liquid level decreases in tank C-111 and in the C-200-series tanks were assessed to be caused by evaporation with no apparent releases to the soil (RPP-ENV-33418). Drywell and leak detection monitoring to date in the vicinity of tanks retrieved showed no evidence of leakage during retrieval (RPP-RPT-58386, "Retrieval Data Report for Single-Shell Tank 241-C-101"; RPP-RPT-33060, "Retrieval Data Report for Single-Shell Tank 241-C-103"; RPP-RPT-54072, "Retrieval Data Report for Single-Shell Tank 241-C-104"; RPP-20577, "Stage II Retrieval Data Report for Single-Shell Tank 241-C-106"; RPP-RPT-58295, "Retrieval Data Report for Single-Shell Tank 241-C-107"; RPP-RPT-55896, "Retrieval Data Report for Single-Shell Tank 241-C-108"; RPP-RPT-55284, "Retrieval Data Report for Single-Shell Tank 241-C-109"; RPP-RPT-56796, "Retrieval Data Report for Single-Shell Tank 241-C-110"; RPP-RPT-58490; RPP-RPT-26475, "Retrieval Data Report for Single-Shell Tank 241-C-203"; RPP-RPT-29095, "Retrieval Data Report for Single-Shell Tank 241-C-202"; RPP-RPT-30181, "Retrieval Data Report for Single-Shell Tank 241-C-201"; RPP-RPT-34062, "Retrieval Data Report for Single-Shell Tank 241-C-204"), indicating that the waste containment appears to be intact for these tanks. In addition, operational monitoring data to date, in the vicinity of remaining tanks undergoing

retrieval (C-102, C-105, and C-111), show no evidence of waste losses during the retrieval process (personal communication, Alan Olander, Washington River Protection Solutions, LLC; 05/03/2016). The monitoring data results collected during retrieval of tank C-105 call into question the hypothesis of a possible breach in the liner of tank C-105.

While the tanks most likely will be filled with grout following retrieval of the waste in the tanks, the final closure cover may be delayed because of the proximity to nearby single-shell and double-shell tanks just to the east and southeast of WMA C. With the presence of grout in tanks and the possible use of a suitable interim cover over the tank farm, the delay in placement of final closure cover is not expected to have a significant adverse impact on the potential contaminant releases to the groundwater pathway from the tank farm after closure. This section summarizes information provided in RPP-RPT-44042 and RPP-RPT-46879.

**3.2.1.2.1 Stabilization of Tank and Selected Components with Grout Fill.** After the retrieval of the residual waste, the SSTs and some of the ancillary equipment and components (i.e., C-301 catch tank, 244-CR vault, and diversion boxes but not pipelines) within WMA C will be filled with grout. Grout is a material formed from cement, fly ash, fine aggregate, sodium bentonite clay, and water to create a free-flowing material that can be used to fill the tanks after waste retrieval is completed. The grout hardens in the tanks to stabilize the residual waste and provide structural stability for landfill closure of the tank farms.

The closure plan approach to fill the tanks will provide a high quality grout throughout the tank (DOE/EIS-0391, 2012). Although the final formulation of the grout has not been developed, it is assumed the grout would be similar to the cold-cap grout formulation developed by USACE for the Hanford Grout Vault Program. This formulation exhibits a low-hydration heat and is free-flowing, self-leveling, and designed to generate little or no free water during curing (DOE/EIS-0391 Appendix E). Figure 3-48 shows the conceptual model of an SST shortly after the emplacement of the grout, while Figure 3-49 shows the conceptual model of an aged tank system. The modified RCRA C barrier is not shown in either of these figures.

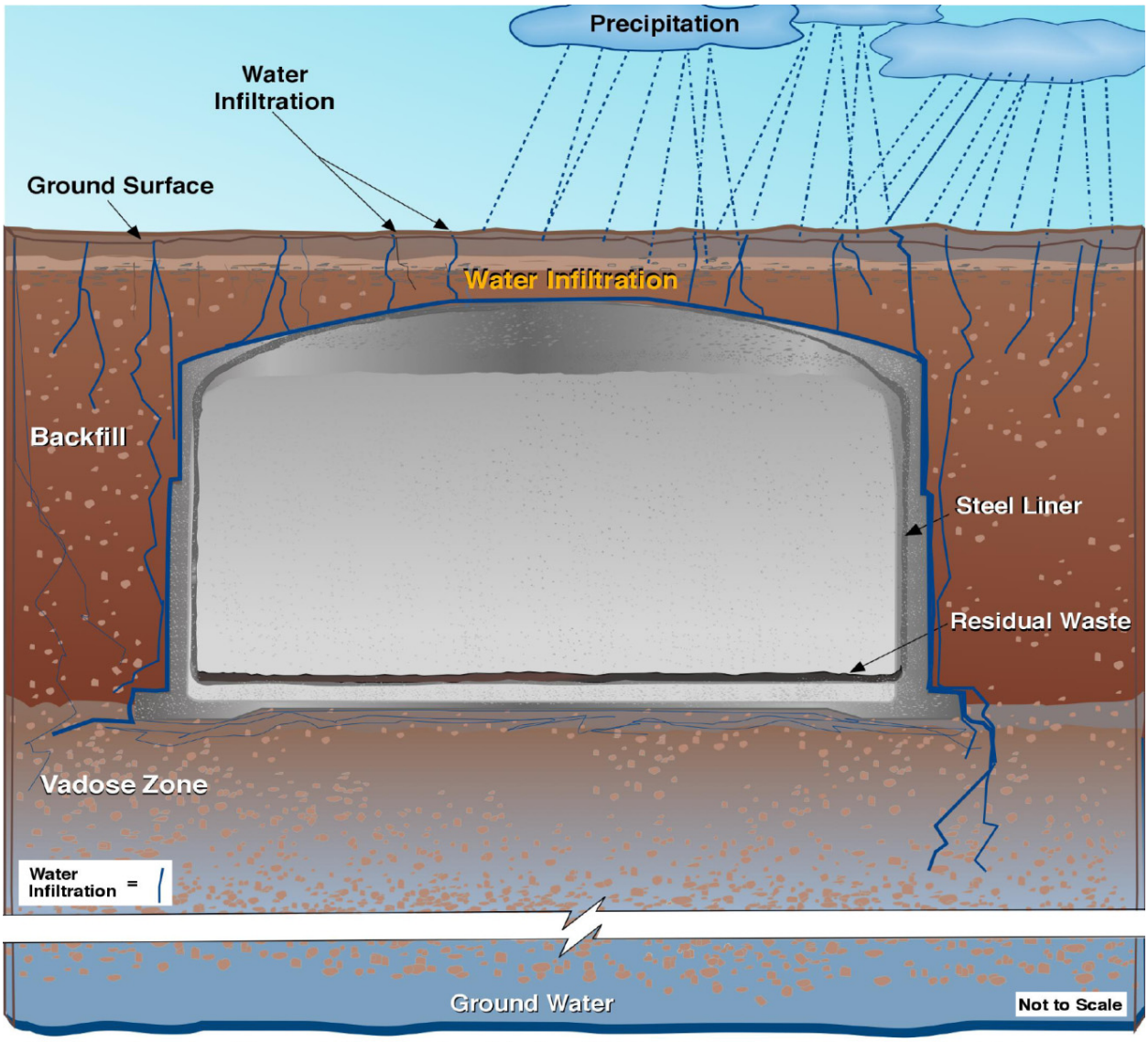
Pacific Northwest National Laboratory (PNNL) has conducted numerous studies to understand release of $^{99}$Tc, chromium, and uranium from residual waste left in the WMA C SSTs (C-103, C-104, C-106, C-108, C-202, C-203, and C-204) after closure using distilled water, as well as water in equilibrium with a young grout and with an aged grout. The results of these studies are given in Section 5.0 of this document.

The specific approach and implementation plans for stabilization of tanks and selected components will be developed and described in detail in closures plans required under RCRA closure requirements.

**3.2.1.2.2 Use of Modified RCRA C Barrier.** After the tank and ancillary equipment have been grouted, the closure plan approach would be to place an engineered modified RCRA C barrier over the site. DOE-RL-93-33, Focused Feasibility Study of Engineered Barriers for Waste Management Units in the 200 Areas provides the conceptual design criteria, regulatory requirements, technical guidance, and the conceptual baseline design of the modified RCRA C barrier. The surface cover does not currently exist, but the expected performance of the barrier

used in the PA comes from lysimeter studies, tracer tests, and computer simulations (PNNL-14744) as well as monitoring of the 200-BP-1 Prototype Hanford Barrier (PNNL-18845, "200-BP-1 Prototype Hanford Barrier – 15 Years of Performance Monitoring").

**Figure 3-48. Conceptual Model of Tank Filled with Cementitious Grout.**

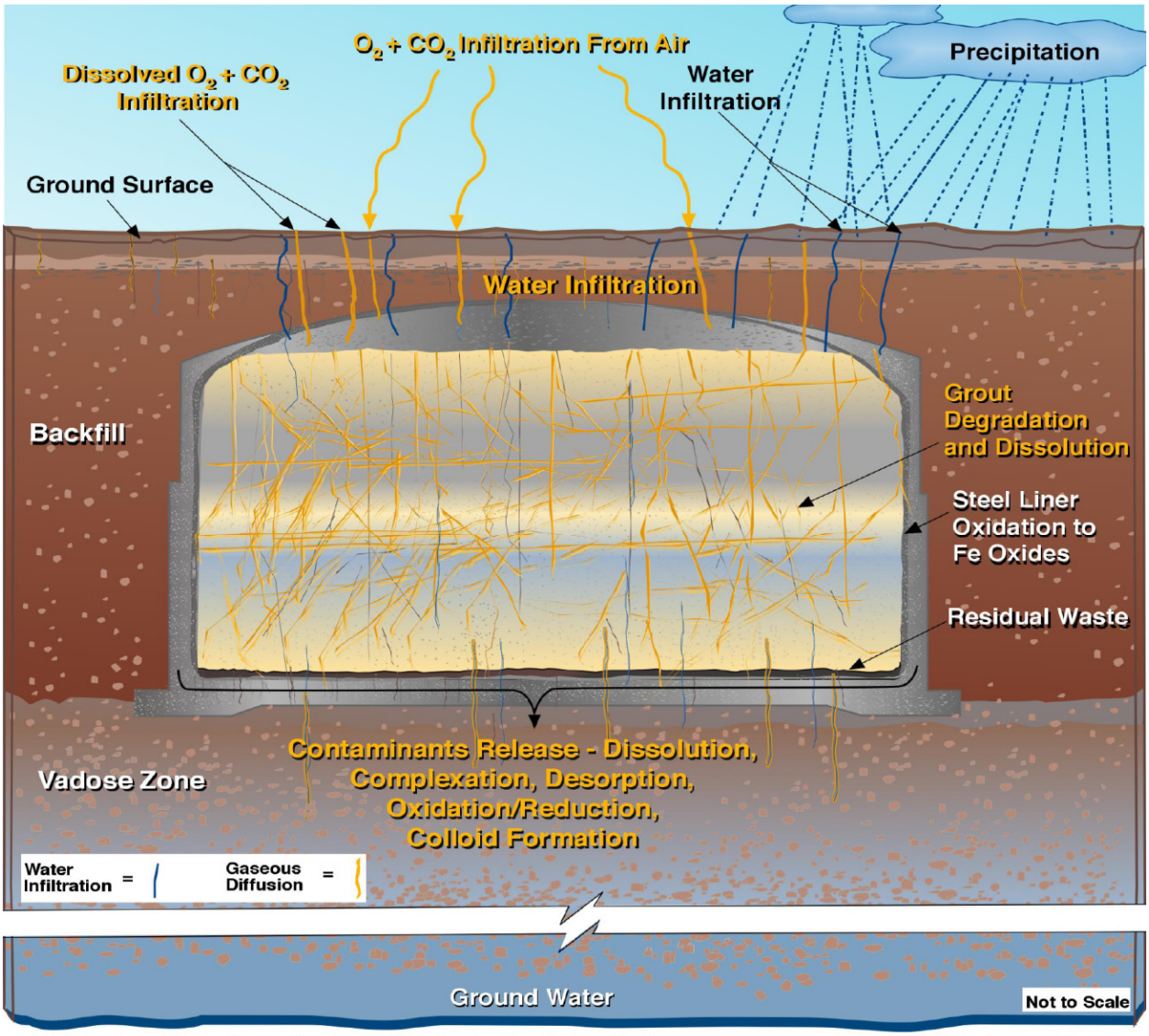



This is a schematic to illustrate infiltration of precipitation which is typically through slow gravitational drainage.

The modified RCRA Subtitle C barrier generally consists of a layer of clay, geo-membrane material, and sand and gravel. This RCRA-compliant barrier will be modified by the addition of ~4.6 m (15 ft) of soil to provide shielding from radioactive material and to deter intrusion. The cover includes a vegetated surface layer of fine-grained soils to retain moisture and encourage evapotranspiration, thereby minimizing infiltration and vadose zone transport of contaminants to groundwater. It is expected that thickness of the top layer of the barrier will be increased to provide additional defense-in-depth against direct contact exposure from a basement excavation

over the site. Prior to cover construction, specific closure cover designs will be evaluated and the most appropriate closure cover design will be selected for construction.

**Figure 3-49. Conceptual Model of Cementitious Grouted Tank Aging.**

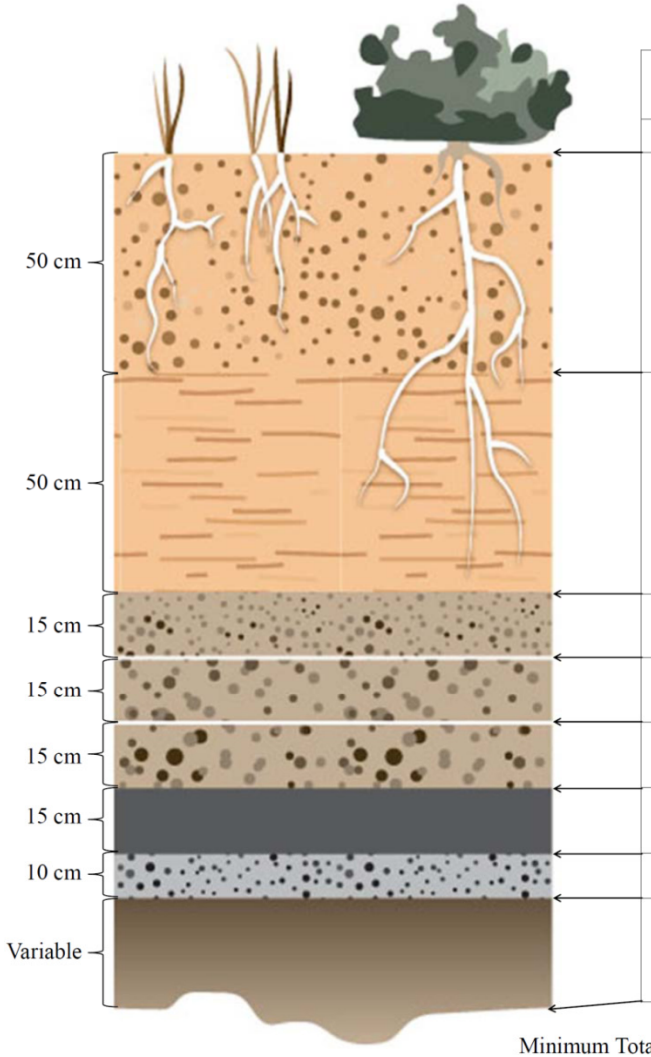



This is a schematic to illustrate the physical and chemical processes acting on grouted tank over time

Figure 3-50 provides the generic modified RCRA Subtitle C barrier baseline design from DOE/RL-93-33. The expected performance of this design configuration is used in building the fate and transport model. The performance of the barrier with regard to recharge comes from the upper one meter of the barrier which contains the silt loam layer. This layer collects and holds the precipitation that falls over the site during the winter months; then during the summer months, evapotranspiration takes place that removes the stored precipitation from an assumed silt loam layer.

**Figure 3-50. Generic Modified RCRA C Baseline Design from DOE/RL-93-33.**

## Modified RCRA C Barrier




| Layer Number | Thickness cm (in) | Layer Description | Function |
|---|---|---|---|
| 0 | N/A | Cover Vegetation | Mixed perennial grasses to enhance transpiration |
| 1 | 50 (20) | Silt loam with pea gravel admix | The topsoil material was identified for optimal water retention properties and should provide a good rooting medium for cover vegetation. The pea gravel is designed to minimize wind erosion of the silt loam without significantly affecting its moisture retention capabilities. (thickness may be increased to provided for protection against inadvertent intruder [DOE/RL-93-93 *Focused Feasibility Study of Engineered Barriers for Waste Management Units in the 200 Area*]) |
| 2 | 50 (20) | Compacted topsoil | Same as Layer 1. Layer 2 provides a supplemental soil moisture storage capacity. Compaction of this layer is intended to retard the rate of infiltration of soil moisture. The extended residence time of moisture in Layer 2 will increase the amount of moisture removed by evapotranspiration. (thickness may be increased to provided for protection against inadvertent intruder [DOE/RL-93-93]) |
| 3 | 15 (6) | Sand Filter | This layer is part of a two-layer graded filter designed to prevent the migration of topsoil particles into Layer 5. |
| 4 | 15 (6) | Gravel Filter | Same as Layer 3. |
| 5 | 15 (6) | Lateral drainage aggregate | The lateral drainage layer will intercept and divert moisture along a 2% slope to the margin of the cover for collection and/or discharge. |
| 6 | 15 (6) | Asphaltic concrete with spray applied asphalt coating | This layer will function as a hydrologic barrier and as a biointrusion barrier. |
| 7 | 10 (4) | Asphalt base course | The function of the material in this layer is to provide a stable base for placing and supporting the asphalt layer. |
| 8 | Variable | Grading Fill | This layer will provide a smooth, level subgrade for construction of the overlying layers. (thickness may be increased to provided for protection against inadvertent intruder [DOE/RL-93-93]) |

Minimum Total Thickness = 1.7 m

Reference: DOE/RL-93-33, Focused Feasibility Study of Engineered Barriers for Waste Management Units in the 200 Areas.

RCRA = Resource Conservation and Recovery Act of 1976, 42 USC 6901, et seq.

For a degraded surface barrier, a range of potential recharge rates can be envisioned. PNNL-14744 investigated the possibility of the most likely natural failure mechanisms (i.e., bioturbation of the silt loam layer, wind erosion, and accretion of windblown sand). With appropriate design considerations, PNNL-14744 argues that the failure possibility of these natural systems is quite low, and the emplaced silt-loam soils will continue to perform for as long as they remain in place. Based on these arguments, PNNL-14744 concluded that the long-term effectiveness of the surface barrier would continue to limit recharge rates to less than 0.1 mm/yr for thousands of years.

These arguments are further buttressed by the monitoring of the Hanford Barrier documented in PNNL-18845, which reports 15 years of data collection on the following:

- water-balance monitoring, consisting of precipitation, runoff, soil moisture storage, and drainage measurements with evapotranspiration calculated by difference
- stability monitoring, consisting of asphalt-layer-settlement, basalt-side-slope-stability, and surface-elevation measurements
- vegetation dynamics
- animal use.

The 200-BP-1 Prototype Hanford Barrier was installed in 1994 over the 216-B-57 Crib. Based on monitoring of the Prototype Hanford Barrier, it is expected that the barrier will continue to perform even after fires have burned off the vegetation (PNNL-18934, "The Effects of Fire on the Function of the 200-BP-1 Engineered Surface Barrier") and extreme precipitation events (PNNL-14143, "The Hanford Site 1000-Year Cap Design Test"). The lessons learned from the Prototype Hanford Barrier indicate that the cover design for the WMA C barrier will be very robust and will be able to continue to perform as designed for very long time frames, but to address potential uncertainties, cases are considered that address increased infiltration/recharge that could occur as a result of a variety of changes that may happen in the far future.

The modified RCRA-compliant closure cover being considered for WMA C will be designed to meet or exceed the regulatory requirements for applications at Category 1 LLW and Category 3 LLW (NRC Class C waste) facilities (see DOE/RL-93-93 for complete listing of regulatory requirements). The basis for the barrier design criteria is summarized in Table 3-6 (taken from DOE/RL-93-33, Table 2-5).

**Post-Closure - Erosion Protection.** Water and wind erosion surface cover material can impact the integrity of a surface cover. The low precipitation, the low intensity of precipitation events, the absence of surface run-on features at the Hanford Site, and stability monitoring (PNNL-18845) all support the assumption that water erosion will not be a significant factor at WMA C barrier. Wind erosion, however, has been observed at the Hanford Site, primarily in exposed sandy areas and in the sand dunes to the southeast of WMA C.

**Table 3-6. Summary of Design Criteria for the Modified RCRA C Barrier.**

| | |
|---|---|
| 1 | Minimize moisture infiltration through the cover. |
| 2 | Design a multilayer cover of materials that are resistant to natural degradation processes. |
| 3 | Design a durable cover that needs minimal maintenance during its design life. |
| 4 | Design a cover with a functional life of 500 years. |
| 5 | Prevent plants from accessing and mobilizing contamination (i.e., prevent root penetration into the waste zone). |
| 6 | Prevent burrowing animals from accessing and mobilizing contamination. |
| 7 | Ensure that the top of the waste is at least 5 m (16 ft) below final grade or include appropriate design provisions to limit inadvertent human intrusion. |
| 8 | Facilitate drainage and minimize surface erosion by wind and water. |
| 9 | Design the low-permeability layer of the cover to have a permeability less than or equal to any natural subsoil present. |
| 10 | Design the cover to prevent the migration and accumulation of topsoil material within the lateral drainage layer (i.e., clogging of the lateral drainage layer). |
| 11 | For frost protection, the lateral drainage layer and the low-permeability asphalt layer must be located at least 0.76 m (2.5 ft) below final grade. |

RCRA = Resource Conservation and Recovery Act of 1976, 42 USC 6901, et seq.

DOE/RL-99-11, 200-BP-1 Prototype Barrier Treatability Test Report evaluated the potential for wind erosion for surface barriers. DOE/RL-99-11 calculated that the worst-case potential erosion rate would be to lose 15 cm (6 in.) of silt loam in 500 years. The analysis method was derived for agricultural soils and did not consider the benefits of the pea gravel admix. Extensive wind tunnel studies performed at the Hanford Site 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 72, 90 and 108 km/hr (45, 56, and 67 mi/hr) (PNL-8478, "Soil Erosion Rates Caused by Wind and Saltating Sand Stresses in Wind Tunnel"; WHC-EP-0673, "Permanent Isolation Surface Barrier Development Plan"). With the lower reduction value (96%), the wind erosion potential would be 15 cm (6 in.) in 12,500 years. The experience at the Prototype Hanford Barrier ("Quest for the Perfect Cap" [Wing and Gee 1994]) suggests that wind erosion will be negligible within months after the barrier surface is vegetated. Therefore, for all intents and purposes, wind erosion of the silt loam should be minor and is assumed to be so for the WMA C vegetated, closure surface barrier.

The engineered cover system surface will be seeded and fertilized to promote plant growth. Vegetation will minimize erosion and accelerate removal of water from the water storage layer through transpiration. 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 Hanford disturbed areas.

**Post-Closure Inadvertent Intrusion Protection.** DOE/RL-93-33 included design criteria 4 and 7 listed in Table 3-6 as part of the design of the Modified RCRA Subtitle C Barrier to meet the

requirements of Title 10, Code of Federal Regulations (CFR), Part 61, "Licensing Requirements for Land Disposal of Radioactive Waste" (10 CFR 61), Subpart C—Performance Objectives, § 61.42, Protection of individuals from inadvertent intrusion and Subpart D—Technical Requirements for Land Disposal Facilities, § 61.52, Land disposal facility operation and disposal site closure for the protection of the inadvertent intruder. Additionally, to further 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 of the closed facility. The DOE is expected to maintain active control of the Hanford Site (using fences, patrols, alarms, and monitoring instruments). 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. Land-use restrictions and institutional controls will be placed on the closed WMA C facility and its adjacent buffer zone to permanently preclude development until unacceptable risk no longer remains at the site.

The closed WMA C facility will clearly delineate the boundaries of the surface barrier by providing a distinct contrast with the surrounding terrain. The side slopes are engineered structures that will be obvious that the structure had been built by humans. These distinct side slopes in combination with warning signs are intended to minimize the risk of human intrusion.

As discussed above, the WMA C engineered surface cover system also contains a bio-intrusion layer consisting of gravel. The function of this layer is to prevent small burrowing animals and rodents from penetrating the underlying cover components and the waste material. Barrier studies at Hanford have shown that a thin layer of gravel is effective in preventing animals and rodents from penetrating underlying waste materials (WHC-EP-0673). The bio-intrusion material will consist of gravel screened from the local available alluvium at the Hanford Site. The alluvium gravels at the Hanford Site are composed of granite, quartz, and other durable minerals that make it ideally suited for long-term applications.

### 3.2.2 Waste Inventory

This section summarizes residual waste inventory information and describes the methods and assumptions used to estimate the inventories and concentrations of radionuclides and chemicals in residual waste in the WMA C SSTs and ancillary equipment at closure. The ancillary equipment includes the C-301 catch tank, the 244-CR vault, diversion boxes and pits, and pipelines associated with WMA C. Detailed characteristic information of residual waste is provided in Section 5. A detailed report of the radiological and non-radiological inventory estimates for waste residuals in tanks and ancillary equipment in C Farm at the time of closure is provided in RPP-RPT-42323, "Hanford C-Farm Tank and Ancillary Equipment Residual Waste Inventory Estimates."

Tank waste inventories for the 25 chemicals and 46 radionuclides are tracked using a BBI process. A listing of these constituents is provided in Table 3-7. Available analytical data are evaluated to identify which data best represent the waste concentrations in a tank. When analytical data are not available for a chemical or radionuclide, waste concentrations are estimated based on waste process information. Waste volume estimates in the BBI are based on

waste-level measurements and/or waste transfer information. In addition to standard chemical and radionuclide BBI inventory estimates, after sampling tank residuals, inventories were developed for primary and secondary constituents in RPP-23403, "Single-Shell Tank Component Closure Data Quality Objectives."

**Table 3-7. Standard Best-Basis Inventory Constituents.**

| Chemicals | | Radionuclides | | |
|---|---|---|---|---|
| Al | Na | $^{3}H$ | $^{134}Cs$ | $^{234}U$ |
| Bi | Ni | $^{14}C$ | $^{137}Cs$ | $^{235}U$ |
| Ca | $NO_2$ | $^{59}Ni$ | $^{137m}Ba$ | $^{236}U$ |
| Cl | $NO_3$ | $^{60}Co$ | $^{151}Sm$ | $^{237}Np$ |
| $CO_3$ | Oxalate | $^{63}Ni$ | $^{152}Eu$ | $^{238}Pu$ |
| Cr | Pb | $^{79}Se$ | $^{154}Eu$ | $^{238}U$ |
| F | $PO_4$ | $^{90}Sr$ | $^{155}Eu$ | $^{239}Pu$ |
| Fe | Si | $^{90}Y$ | $^{226}Ra$ | $^{240}Pu$ |
| Hg | $SO_4$ | $^{93}Zr$ | $^{227}Ac$ | $^{241}Am$ |
| K | Sr | $^{93m}Nb$ | $^{228}Ra$ | $^{241}Pu$ |
| La | Total organic carbon | $^{99}Tc$ | $^{229Th}$ | $^{242}Cm$ |
| Mn | U-TOTAL | $^{106}Ru$ | $^{231}Pa$ | $^{242}Pu$ |
| | Zr | $^{113m}Cd$ | $^{232}Th$ | $^{243}Am$ |
| | | $^{125}Sb$ | $^{232}U$ | $^{243}Cm$ |
| | | $^{126}Sn$ | $^{233}U$ | $^{244}Cm$ |
| | | $^{129}I$ | | |

As of September 2014, waste was retrieved from 13 of 16 SSTs in C Farm (C-101, C-103, C-104, C-106, C-107, C-108, C-109, C-110, C-112, C-201, C-202, C-203, and C-204) and was in progress for the remaining 3 tanks (C-102, C-105 and C-111). Only BBI inventory estimates based on pre-retrieval samples and model estimates are currently available for the three unretrieved tanks (i.e., C-102, C-105, and C-111). After waste is retrieved, residual waste is sampled for constituents specified in RPP-23403. Tables 3-8 and 3-9 show primary chemical and radionuclide constituents in RPP-23403.

The following topics are discussed in this section:

- Major waste types

- Updated waste inventory estimates for tanks and ancillary equipment
  - Retrieved tanks with post-retrieval sampling
  - Retrieved tanks without post-retrieval sampling
  - Tanks undergoing retrieval
  - Ancillary equipment including C-301 catch tank, the 244-CR vault, pipelines, pits and diversion boxes
- Inventory uncertainties.

**Table 3-8. Primary Chemical Constituents.**

| **Inorganic Constituents** | | | |
|---|---|---|---|
| Acetate – $C_2H_3O_2^-$ | Chromium – Cr | Iron – Fe | pH |
| Aluminum – Al | Cobalt – Co | Lead – Pb | Selenium – Se |
| Ammonium – $NH_4^+$ | Copper – Cu | Manganese – Mn | Silver – Ag |
| Antimony – Sb | Cyanide – $CN^-$ | Mercury – Hg | Strontium – Sr |
| Arsenic – As | Ferrocyanide – $Fe(CN)_6^{4-}$ | Nickel – Ni | Thallium – Tl |
| Barium – Ba | Fluoride – $F^-$ | Nitrate – $NO_3^-$ | Uranium – U |
| Beryllium – Be | Formate – $CHO_2^-$ | Nitrite – $NO_2^-$ | Vanadium – V |
| Cadmium – Cd | Glycolate – $C_2H_3O_3^-$ | Oxalate – $C_2O_4^{2-}$ | Zinc – Zn |
| **Organic Constituents** | | | |
| 1,1,2-Trichloroethylene | 4-Methyl-2-pentanone (MIBK) | m-Xylene | Polychlorinated biphenyls |
| 2-Butanone (MEK) | Xylenes (Mixed isomers of o-, m-, and p-) | p-Xylene | |
| 2-Propanone (Acetone) | o-Xylene | Tributyl phosphate | |

Reference: RPP-23403, "Single-Shell Tank Component Closure Data Quality Objectives."

**3.2.2.1 Waste Inventory Assumptions.** Key enabling assumptions for current residual inventory estimates for C Farm SSTs and ancillary equipment include the following.

a. For tanks retrieved, the retrieval volumes and inventories documented in applicable retrieval data reports or residual inventory reports are the assumed inventories in WMA C SSTs at closure.

b. Radionuclides were decayed to January 1, 2020. Therefore, the radionuclide values presented differ from the 2014 BBI values, which are decayed to January 1, 2008.

c. For tanks not yet retrieved (i.e., C-102, C-105, and C-111), it was assumed that, for a lower bound estimate, the minimum volume remaining would be 10 kL (360 $ft^3$). This is the threshold goal for 100-series SSTs specified in the HFFACO.

d. The Hanford Tank Waste Operations Simulator (HTWOS) model is assumed to provide a lower bound estimate for threshold residual waste inventory estimates for tanks not yet retrieved (i.e., C-102, C-105, and C-111). This is because HTWOS assumes soluble constituents are mobilized during the retrieval process and largely removed when waste is retrieved to the threshold goal. The HTWOS assumptions are located in HNF-SD-WM-SP-012, "Tank Farm Contractor Operation and Utilization Plan."

e. The current BBI inventory is assumed to provide an upper bound estimate for tanks not yet retrieved (i.e., C-102, C-105, and C-111). These upper bound estimates presented for the tanks not yet retrieved reflect conditions in WMA C as of September 1, 2014.

f. Waste concentrations in ancillary equipment are assumed to be represented by the average concentration of waste in WMA C tanks that have been retrieved.

   This simplifying assumption is made because:

   - Little analytical data is available for waste in ancillary equipment,
   - Ancillary equipment was flushed, mobilizing soluble constituents similar to retrieval,
   - Ancillary equipment received waste to or from many of the tanks in a farm, and
   - Process history of waste types and volumes received by different ancillary equipment has not been developed and estimates would be highly uncertain.

g. It is assumed that waste in the C-301 catch tank and 244-CR vault will be retrieved prior to closure (no specific goals or limits have been established for these facilities). Retrieval of 90% of the waste was assumed for these facilities. The average residual concentrations for WMA C tanks retrieved to date was assumed for these facilities.

h. It was assumed that the waste was or will be flushed from pits and diversion boxes and the primary residual waste remaining at closure will be limited to waste adsorbed to concrete surfaces with waste penetration to a depth of 0.04 cm (0.0156 in.) (RPP-15043, "Single-Shell Tank System Description").

i. It was assumed that pipelines are 5% full of waste except for a plugged line and cascade lines which are assumed to be full. The technical basis for these assumptions and the associated pipeline lengths and estimated waste volumes are given in RPP-PLAN-47559.

**3.2.2.2 Major Waste Types.** The residual waste in WMA C at closure will be contained in tanks, vaults, pits/boxes, and pipelines. The waste originally stored in these tanks and ancillary

equipment consisted of supernate and sludge from the processing of irradiated uranium fuel. Supernate is free-standing liquid from the waste processing operations and sludge is precipitate from the supernate.

**Table 3-9. Primary Radiological Constituents.**

| | | |
|---|---|---|
| Cesium 137 – $^{137}$Cs | Technetium 99 – $^{99}$Tc | Plutonium 238 – $^{238}$Pu |
| Cobalt 60 – $^{60}$Co | Antimony 125 – $^{125}$Sb | Plutonium 239/240 – $^{239/240}$Pu |
| Europium 152 – $^{152}$Eu | Selenium 79 – $^{79}$Se | Plutonium 241 – $^{241}$Pu |
| Europium 154 – $^{154}$Eu | Tin 126 – $^{126}$Sn | Americium241 – $^{241}$Am |
| Europium 155 – $^{155}$Eu | Uranium 233 – $^{233}$U | Curium 242 – $^{242}$Cm |
| Carbon 14 – $^{14}$C | Uranium 234 – $^{234}$U | Curium 243 – $^{243}$Cm |
| Tritium – $^{3}$H | Uranium 235 – $^{235}$U | Curium 244 – $^{244}$Cm |
| Iodine 129 – $^{129}$I | Uranium 236 – $^{236}$U | Thorium 228 – $^{228}$Th |
| Nickel 63 – $^{63}$Ni | Uranium 238 – $^{238}$U | Thorium 230 – $^{230}$Th |
| Strontium 90 – $^{90}$Sr | Neptunium 237 – $^{237}$Np | Thorium 232 – $^{232}$Th |

Reference: RPP-23403, "Single-Shell Tank Component Closure Data Quality Objectives," Rev. 5.

Tables 3-10 and 3-11 show waste types and processes that generated wastes transferred to C Farm. These processes and the waste types generated are discussed in HNF-SD-WM-TI-740, "Standard Inventories of Chemicals and Radionuclides in Hanford Tank Wastes." Table 3-12 shows the principal types of sludge remaining in the C Farm tanks and ancillary equipment. The waste consists of a large array of chemicals and radionuclides. Process knowledge-based waste type composition estimates based on reactor fuel irradiation records and process plant records are provided in RPP-19822, "Hanford Defined Waste Model – Revision 5.0."

**3.2.2.3 Residual Waste Inventory Estimates**. Residual inventory estimates used in this RCA were determined based on information and conditions as of September 2014. Inventory estimates were developed for 1) residuals in retrieved tanks with post-retrieval sampling, 2) residuals in retrieved tanks without post-retrieval sampling, 3) residuals in tanks undergoing retrieval and 4) post-retrieval residual inventory estimates for ancillary equipment, including: C-301 catch tank, 244-CR vault tanks, and sumps, pits, diversion boxes, and waste transfer pipelines. These inventory estimates are reported in Tables 3-13, 3-14, 3-15, 3-16, and 3-17.

Inventory estimates for other constituents for which analytical results are available are reported in Appendix D of RPP-RPT-42323. These include primary analytes in RPP-23403 shown in Tables 3-8 and 3-9 and secondary constituents in the data quality objectives (DQO) document (RPP-23403). Additional discussion and details for current residual inventory estimates are provided in RPP-RPT-42323.

**Table 3-10. Waste Types Received into 241-C 100-series Tanks (1956 through 1978).**

| Year | C-101 | C-102 | C-103 | C-104 | C-105 | C-106 | C-107 | C-108 | C-109 | C-110 | C-111 | C-112 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1956 | TFeCN | | | CW | CW | | | | | OWW | OWW | TFeCN |
| 1957 | | | PSN | CW | CW | PSN/ OWW | | TFeCN | TFeCN | | CW/ TFeCN | TFeCN |
| 1958 | | | | CW | CW | | | | | | | |
| 1959 | | | | | CW | | | | CW | | CW | |
| 1960 | CW | CW | CW | | CW | | | CW | | | CW | CW |
| 1961 | | CW | | | | | CW | CW | | | CW | HS |
| 1962 | | CW | | | | | CW | | HS | | HS | HS |
| 1963 | PSN | CW | PSN | | PSN | PSN | | | | | HS | |
| 1964 | PSN | CW | | | | | HS | | HS | | HS | |
| 1965 | | CW | PSN | | | | HS | HS | HS | | | |
| 1966 | | TH/CW | PSN | | | | BNW/HS | | HS | | | |
| 1967 | | CW | | | | | HS | | | | | |
| 1968 | | CW/OWW | | | PSN | | | | | | | |
| 1969 | | OWW | | OWW | PSN | PSS | | | | | | |
| 1970 | | | IX | TH/OWW/PSN | PSN/RSN | PSS | IX | OWW/IX | IX | IX | | IX |
| 1971 | | | IX | CW/OWW | PSS | PSS | | | | | | |
| 1972 | | | CW/OWW | CW/OWW | PSS | | | | | IX | | |
| 1973 | | | Misc | Misc | PSS | | Misc | Misc | | | | |
| 1974 | | | Misc | Misc | PSS | BL | | | | | | |
| 1975 | | | Misc | Misc | PSS | BL | | | | | | |
| 1976 | | | Misc | Misc | PSS | BL | | | | | | |
| 1977 | | | | | | BL | | | | | | |
| 1978 | | | | | | BL | | | | | | |

Definitions:

Colors in table are used to highlight each waste type

BL B Plant strontium processing wastes and miscellaneous wastes

CW cladding (coating) waste from Plutonium Uranium Extraction (PUREX) or Reduction-Oxidation (REDOX) Plants

HS 201-C Hot Semiworks waste

IX cesium denuded waste from ion exchange process in B Plant

Misc Sources may include research waste from Battelle Northwest (i.e., BNW) which is now Pacific Northwest National Laboratory, reactor decontamination waste, etc.

OWW Organic Wash Waste from PUREX Plant

PSN PUREX high-level waste (HLW) supernate

PSS PUREX Sludge Supernate derived from washing PUREX HLW sludges in 244-AR Vault or 241-A and 241-AX tanks

RSN REDOX HLW Supernate

TFeCN Ferrocyanide waste from 244-CR vault treatment of tributyl phosphate waste

TH Thorium process waste from PUREX Plant

**Table 3-11. Waste Types in C-200 Series Tanks.**

| Waste Type | 241-C-201 | 241-C-202 | 241-C-203 | 241-C-204 |
|---|---|---|---|---|
| Metal Waste – Addition from B Plant | November 1947 – December 1948 | | | |
| Metal Waste Supernate – Removal to 241-C-106 | December 1953 | | | |
| Metal Waste Supernate – Removal to 241-C-104 | None | None | None | 7,000 gallons 11/1954 |
| Metal Waste Sluicing to 244-CR Process Tank Vault | 2/15/1954 – 3/17/1954 | 1/9/1954 – 1/14/1954 | 1/15/1954 – 1/28/1954 | 1/1955 – 2/1955 |
| Hot Semiworks – PUREX process waste (5/1955 – 3/1956)<br>Process equipment and facility flushes for modifications | 5/1955 – 11/1955 | 11/1955 – 5/1956 | 12/1955 – 11/1956<br>4/1956 – 11/1956 | 12/1955 – 11/1956<br>4/1956 – 11/1956 |
| Supernate Removal | | | 1/1970 – 3/1970 | |
| Supernate Removal | 4/1970 – 6/1970 | | | |
| Supernate Removal | | | | 7/1977 |
| Supernate Removal | 10/1980 | | | |

PUREX = Plutonium-Uranium Extraction (facility)

**Table 3-12. Current Waste Types in 241-C Farm Tanks.**

| Waste Type | Description | Tanks |
|---|---|---|
| AR | Water washed PUREX sludge (1967-1976) | C-103,1 06 |
| BL | B Plant Low activity waste (1963-1972) | C-106 |
| 1C | First cycle $BiPO_4$ coating waste (1944-1956) | C-107, 109, 110, 111, 112 |
| CWP1 | PUREX aluminum cladding waste (1956-1960) | C-101, 102, 103, 104, 105, 106, 111, 112 |
| CWP2 | PUREX aluminum cladding waste (1961-1972) | C-102, 104, 107, 112 |
| CWZr1 | PUREX/REDOX zirconium cladding waste (1968-1972) | C-102, 104 |
| HS | Hot Semiworks waste (1961-1968) | C-111, 112, 201, 202, 203, 204 |
| MW1 | $BiPO_4$ Metal Waste (1944-1949) | C-102 |
| OWW3 | PUREX organic wash waste (1968-1972) | C-104 |
| SRR | Strontium recovery waste (1969-1985) | C-107 |
| TBP (UR) | Tributyl phosphate /Uranium Recovery Waste (1952-1957) | C-101, 102, 105, 106 |
| TFeCN | Ferrocyanide sludge (1955-1958) | C-111, 112 |
| TH1 | Thoria process waste (1966) | C-102 |
| TH2 | Thoria process waste (1970) | C-104 |

$BiPO_4$ = bismuth phosphate
PUREX = Plutonium-Uranium Extraction (facility)
REDOX = Reduction-Oxidation (S Plant)

Concentrations for BBI constituents for the SSTs were calculated by dividing the inventories by associated volumes shown in the respective residual inventory tables (Tables 3-13 and 3-14). This calculation provides average concentrations for sludge, interstitial liquids and supernate and for multiple waste types in a tank. Where available, concentrations are based on analytical results. As of September 2014, analytical results were obtained for 10 of the 13 SSTs retrieved for constituents shown in Tables 3-8 and 3-9.

**3.2.2.3.1 Retrieved Tanks with Post-Retrieval Sampling.** Inventory estimates for the 10 SSTs (C-103, C-104, C-106, C-108, C-109, C-110, C-201, C-202, C-203, and C-204) for which retrieval operations have been completed and post-retrieval samples have been obtained are based on the BBI. As of September 2014, waste volume estimates were completed using a camera/computer-aided design (CAD) modeling system (CCMS) and post-retrieval residual sampling and analysis was completed for these 10 SSTs. In addition to standard chemical and radionuclide BBI inventory estimates, inventories were developed for many other constituents after sampling tank residuals.

The base case inventory for these tanks is the average BBI estimate and the upper bound inventory is the upper 95% confidence interval for the mean inventory. These inventories are provided in Tables 3-13 and 3-16.

**3.2.2.3.2 Retrieved Tanks without Post-Retrieval Sampling.** Inventory estimates for the three SSTs (C-101, C-107 and C-112) for which retrieval operations have been completed, but post-retrieval samples have not been obtained, are also based on the BBI and CCMS estimates. However, the basis for waste composition estimates for these tanks varies. For tanks C-101 and C-107 the BBI inventory estimates are based on pre-retrieval sample results, sample-based templates and process knowledge. For tank C-112, the BBI inventory estimates are based on in-process transfer samples representative of the C1 waste type and sample and process knowledge templates. Statistical uncertainties were not estimated for inventories based on process knowledge.

The base case inventory for retrieved tanks without post-retrieval sampling is the average BBI estimate. Because many of the constituents are not sample based, an upper bound inventory could not be estimated for many constituents for these tanks. It is believed that the concentration and inventory of soluble constituents will be significantly lower than currently estimated by the BBI. Inventory estimates for these tanks will be adjusted as needed, after post-retrieval sampling and analyses are completed. The inventories for tanks in this category are provided in Table 3-13; average waste concentrations are shown in Appendix B of RPP-RPT-42323.

**3.2.2.3.3 Tanks Undergoing Retrieval.** Future residual waste volumes are unknown for the three SSTs for which retrieval is in progress (C-102, C-105 and C-111); therefore, lower and upper bound residual inventories were estimated for these tanks (C-102, C-105, and C-111). These inventories are provided in Table 3-17.

The lower bound residual waste volume was assumed to be 360 $ft^3$ (the retrieval threshold goal) because it appears likely that more than 360 $ft^3$ of residual waste will be left in these tanks after retrieval.

**Table 3-13a. 241-C Tank Farm Residual Inventory Estimates for Retrieved Tanks with Post-Retrieval Sampling.**

| Tanks Retrieved (BBI average)[a] | 241-C-101[b] | 241-C-103 | 241-C-104 | 241-C-106 | 241-C-107[b] | 241-C-108 | 241-C-109 | 241-C-110 | 241-C-112[b] | 241-C-201 | 241-C-202 | 241-C-203 | 241-C-204 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Residual Volume (kL [kgal]) | 18.9 (4.99) | 9.57 (2.53) | 7.2 (1.90) | 10.49 (2.77) | 53 (14) | 12.9 (3.41) | 7.6 (2.01) | 8 (2.11) | 48 (12.68) | 0.6 (0.16) | 0.6 (0.16) | 0.5 (0.13) | 0.5 (0.13) |
| Total Chemicals (kg) | 2.00E+04 | 4.15E+03 | 4.79E+03 | 1.90E+03 | 2.74E+04 | 9.05E+03 | 4.97E+03 | 4.87E+03 | 2.64E+04 | 4.55E+02 | 3.96E+02 | 5.08E+02 | 4.57E+02 |
| Al | 7.93E+01 | 3.63E+03 | 1.14E+03 | 3.82E+02 | 1.98E+03 | 3.47E+03 | 2.15E+03 | 1.29E+03 | 3.32E+02 | 4.11E+00 | 8.48E+00 | 0.00E+00 | 5.88E+00 |
| Bi | 2.23E+01 | 9.49E-05 | 2.91E+00 | 2.94E+00 | 1.02E+03 | 7.56E+01 | 1.98E+00 | 3.63E+01 | 1.32E+03 | 6.10E-01 | 6.34E-01 | 1.29E+00 | 0.00E+00 |
| Ca | 1.15E+02 | 2.17E+01 | 1.35E+01 | 1.18E+02 | 5.04E+01 | 2.40E+01 | 1.56E+01 | 5.84E+00 | 6.44E+01 | 6.76E+00 | 7.12E+00 | 2.02E+00 | 5.90E-01 |
| Cl | 6.17E+01 | 1.94E-01 | 5.95E-01 | 6.14E+00 | 5.99E+01 | 9.01E-02 | 6.46E-02 | 6.26E-01 | 7.86E+01 | 2.93E-01 | 2.87E-01 | 5.86E-02 | 5.58E-03 |
| Cr | 7.23E+00 | 2.38E+00 | 3.06E+00 | 3.78E+00 | 5.54E+01 | 6.31E-01 | 1.76E-01 | 1.12E+00 | 5.78E+01 | 1.22E+01 | 9.09E+00 | 2.60E+00 | 1.36E+00 |
| F | 3.46E+01 | 1.62E-01 | 1.54E+01 | 5.43E-01 | 6.05E+02 | 1.21E+02 | 9.68E+01 | 1.38E+02 | 7.09E+02 | 2.69E+00 | 2.26E+00 | 1.64E+00 | 8.05E-03 |
| Fe | 8.77E+02 | 1.19E+02 | 3.24E+02 | 2.07E+02 | 4.37E+03 | 2.82E+02 | 9.28E+01 | 1.90E+02 | 7.02E+02 | 1.10E+02 | 8.70E+01 | 1.28E+01 | 3.21E+01 |
| Hg | 2.98E+00 | 1.06E+00 | 1.35E+00 | 1.93E+00 | 3.78E+00 | 2.03E-02 | 1.84E-02 | 1.07E-01 | 2.63E-02 | 1.07E-01 | 2.87E-01 | 2.23E-03 | 1.47E-01 |
| K | 8.68E+00 | 3.60E+00 | 1.31E+00 | 1.77E+01 | 2.58E+01 | 2.74E+00 | 2.61E-01 | 4.46E-01 | 2.21E+01 | 8.91E-01 | 9.09E-01 | 1.83E+00 | 2.02E+00 |
| La | 1.56E+00 | 1.82E-01 | 2.34E-02 | 2.44E+00 | 1.03E+01 | 1.32E-02 | 1.20E-01 | 9.98E-03 | 1.18E-01 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Mn | 7.14E+00 | 4.42E+00 | 4.29E+01 | 5.49E+02 | 1.93E+02 | 4.08E+00 | 5.63E-01 | 7.61E-01 | 6.52E+00 | 1.90E+01 | 1.69E+01 | 5.13E-01 | 2.39E-01 |
| Na | 4.80E+03 | 9.60E+01 | 1.15E+03 | 1.88E+02 | 6.13E+03 | 3.27E+03 | 1.30E+03 | 1.20E+03 | 6.90E+03 | 4.91E+01 | 4.58E+01 | 5.59E+01 | 3.33E+01 |
| Ni | 3.27E+00 | 4.58E+00 | 6.00E+00 | 3.02E+01 | 9.86E+01 | 7.45E+01 | 1.33E+01 | 4.13E-01 | 1.46E+00 | 6.15E+00 | 7.28E+00 | 2.04E-01 | 8.01E-01 |
| $NO_2$ | 5.64E+02 | 4.82E-01 | 5.06E+00 | 4.14E+01 | 2.15E+03 | 5.78E+00 | 3.83E+00 | 2.74E+00 | 6.75E+02 | 5.27E-01 | 4.52E-01 | 9.94E-01 | 3.13E-02 |
| $NO_3$ | 8.20E+03 | 8.71E-01 | 9.38E+00 | 3.48E+01 | 3.59E+03 | 9.16E+00 | 4.52E+00 | 6.73E+00 | 8.76E+03 | 1.35E+00 | 1.25E+00 | 3.76E+00 | 2.22E-02 |
| Pb | 2.07E+01 | 8.50E+00 | 6.48E+00 | 2.56E+01 | 3.62E+02 | 1.71E+01 | 5.39E+00 | 5.62E+00 | 1.36E+01 | 6.25E+00 | 5.84E+00 | 3.07E+00 | 1.02E+00 |
| $PO_4$ | 3.79E+03 | 2.99E+01 | 4.28E+01 | 9.00E+01 | 4.74E+03 | 1.18E+03 | 9.82E+02 | 1.40E+03 | 4.83E+03 | 5.46E+01 | 3.46E+01 | 7.24E+01 | 7.96E+01 |
| Si | 2.40E+01 | 1.27E+02 | 1.31E+02 | 1.60E+01 | 1.02E+02 | 8.78E+01 | 2.79E+01 | 2.05E+01 | 4.28E+02 | 6.99E+00 | 8.60E+00 | 2.01E+00 | 7.33E+00 |
| $SO_4$ | 7.71E+02 | 2.16E+00 | 1.15E+00 | 3.90E+00 | 5.17E+02 | 2.93E+00 | 2.86E+00 | 7.46E+00 | 9.32E+02 | 3.66E+00 | 4.01E-01 | 6.58E-01 | 1.28E-02 |
| Sr | 2.34E+01 | 2.41E+00 | 9.35E-01 | 1.83E+00 | 1.71E+01 | 1.97E+01 | 4.91E-01 | 5.63E+01 | 1.00E+01 | 9.09E-01 | 1.22E+00 | 2.30E-01 | 3.67E-01 |
| TIC as $CO_3$ | 6.57E+01 | 1.68E+01 | 4.77E+02 | 7.58E+01 | 6.45E+02 | 2.77E+02 | 2.03E+02 | 4.89E+02 | 4.12E+02 | 3.36E+01 | 3.43E+01 | 1.50E+01 | 1.41E+01 |
| TOC | 3.00E+01 | 1.25E+01 | 6.53E+01 | 9.07E+01 | 4.16E+01 | 3.96E+00 | 3.38E+01 | 1.20E+01 | 3.66E+01 | 2.43E+01 | 2.48E+01 | 4.47E+00 | 3.54E+01 |
| UTOTAL | 5.16E+02 | 4.91E+01 | 1.32E+03 | 2.70E+00 | 6.32E+02 | 1.21E+02 | 2.86E+01 | 5.49E+00 | 1.29E+02 | 1.11E+02 | 9.88E+01 | 3.26E+02 | 2.43E+02 |
| Zr | 3.79E-01 | 1.33E+01 | 2.49E+01 | 2.79E+00 | 2.80E+00 | 5.98E-01 | 7.05E+00 | 3.62E-01 | 9.53E+00 | 1.02E-02 | 9.45E-02 | 1.05E-01 | 0.00E+00 |

Source: RPP-RPT-42323, "Hanford C-Farm Tank and Ancillary Equipment Residual Waste Inventory Estimates."

[a] September 1, 2014 Best-Basis Inventory (BBI), includes tank 241-C-106 for which retrieval completion is under review. 95% Confidence Interval = Mean + 2 × Standard Deviation (Closure mean for tanks with closure reports, BBI mean for tanks 241-C-101, 241-C-107 and 241-C-112: no closure report). Difference between closure mean and BBI mean: Closure mean uses less than detect values in inventory estimates; BBI mean uses less than detect values or process knowledge estimate, whichever is lower. As a result, closure means may be higher than BBI means for some constituents.

[b] Inventories estimated without post-retrieval sampling.

**Table 3-13b. 241-C Tank Farm Residual Inventory Estimates for Retrieved Tanks with Post-Retrieval Sampling. (sheet 1 of 2)**

| Tanks Retrieved (BBI average)[a] | 241-C-101[b] | 241-C-103 | 241-C-104 | 241-C-106 | 241-C-107[b] | 241-C-108 | 241-C-109 | 241-C-110 | 241-C-112[b] | 241-C-201 | 241-C-202 | 241-C-203 | 241-C-204 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Residual Volume (kL [kgal]) | 18.9 (4.99) | 9.57 (2.53) | 7.2 (1.90) | 10.49 (2.77) | 53 (14) | 12.9 (3.41) | 7.6 (2.01) | 8 (2.11) | 48 (12.68) | 0.6 (0.16) | 0.6 (0.16) | 0.5 (0.13) | 0.5 (0.13) |
| Total Radionuclides (Ci)[c] | 7.30E+03 | 1.47E+04 | 1.43E+04 | 1.00E+05 | 6.37E+04 | 2.67E+03 | 4.75E+03 | 5.28E+03 | 1.92E+03 | 4.10E+02 | 7.25E+02 | 3.50E+02 | 2.33E+02 |
| $^{106}$Ru | 9.11E-20 | 1.72E-16 | 2.14E-10 | 8.59E-10 | 8.85E-17 | 7.01E-17 | 4.86E-17 | 1.38E-17 | 6.52E-17 | 2.82E-11 | 2.87E-11 | 2.35E-11 | 2.20E-11 |
| $^{113m}$Cd | 1.47E-03 | 1.49E-02 | 5.11E-02 | 2.13E+00 | 2.50E-03 | 1.97E-03 | 1.37E-03 | 3.89E-04 | 1.84E-03 | 5.77E-04 | 5.88E-04 | 4.80E-04 | 4.50E-04 |
| $^{125}$Sb | 9.36E-07 | 6.96E-07 | 9.60E-01 | 3.62E-03 | 1.31E-06 | 1.04E-06 | 7.20E-07 | 2.04E-07 | 9.70E-07 | 5.39E-05 | 5.49E-05 | 4.50E-05 | 4.21E-05 |
| $^{126}$Sn | 5.13E-04 | 5.27E-05 | 8.81E-03 | 1.76E+00 | 4.94E-04 | 3.91E-04 | 2.71E-04 | 2.38E-02 | 3.65E-04 | 1.10E-04 | 1.13E-04 | 9.21E-05 | 8.61E-05 |
| $^{129}$I | 5.55E-05 | 3.00E-03 | 4.84E-04 | 6.31E-04 | 4.07E-02 | 3.81E-05 | 2.65E-05 | 2.65E-04 | 3.57E-05 | 4.57E-07 | 7.35E-06 | 1.47E-05 | 3.57E-07 |
| $^{134}$Cs | 2.01E-09 | 3.78E-09 | 7.18E-06 | 1.54E-05 | 2.59E-10 | 2.05E-10 | 1.42E-10 | 4.04E-11 | 1.92E-10 | 4.13E-08 | 4.22E-08 | 3.46E-08 | 3.22E-08 |
| $^{137}$Cs | 3.61E+02 | 6.07E+02 | 6.22E+02 | 1.00E+03 | 2.32E+03 | 8.57E+01 | 4.31E+01 | 2.02E+01 | 7.66E+02 | 7.01E+00 | 6.18E+00 | 9.10E+00 | 4.13E+00 |
| $^{137m}$Ba | 3.22E+02 | 5.41E+02 | 5.54E+02 | 8.95E+02 | 2.06E+03 | 7.59E+01 | 3.84E+01 | 1.80E+01 | 6.80E+02 | 6.25E+00 | 5.51E+00 | 8.09E+00 | 3.67E+00 |
| $^{14}$C | 2.76E-03 | 6.99E-03 | 3.08E-03 | 8.21E-03 | 2.16E-02 | 8.18E-03 | 7.65E-04 | 1.51E-03 | 1.60E-02 | 7.64E-04 | 2.03E-04 | 1.66E-04 | 1.88E-04 |
| $^{151}$Sm | 4.00E+00 | 4.30E-01 | 3.17E+03 | 7.82E+03 | 1.04E+04 | 6.66E+00 | 4.65E+00 | 1.32E+00 | 6.25E+00 | 2.39E+01 | 2.43E+01 | 1.99E+01 | 1.86E+01 |
| $^{152}$Eu | 6.38E-05 | 2.58E-05 | 3.54E-02 | 2.02E+00 | 1.35E-04 | 1.07E-04 | 7.41E-05 | 2.11E-05 | 1.00E-04 | 2.10E-03 | 2.14E-03 | 1.75E-03 | 1.64E-03 |
| $^{154}$Eu | 2.77E-03 | 1.41E+00 | 1.57E+00 | 2.25E+01 | 5.70E-03 | 4.52E-03 | 3.13E-03 | 8.89E-04 | 4.22E-03 | 9.42E-02 | 9.61E-02 | 1.50E-02 | 5.62E-02 |
| $^{155}$Eu | 4.69E-04 | 4.37E-01 | 2.29E-01 | 7.65E+00 | 8.66E-04 | 6.84E-04 | 4.74E-04 | 1.35E-04 | 6.39E-04 | 1.45E-02 | 1.48E-02 | 1.81E-02 | 1.13E-02 |
| $^{226}$Ra | 5.90E-07 | 1.54E-08 | 3.24E-07 | 5.13E-04 | 5.95E-07 | 4.73E-07 | 3.26E-07 | 9.27E-08 | 4.40E-07 | 1.00E-09 | 1.02E-09 | 8.40E-10 | 7.86E-10 |
| $^{227}$Ac | 1.58E-06 | 6.39E-08 | 1.11E-05 | 1.74E-03 | 6.20E-06 | 7.78E-07 | 3.40E-06 | 9.62E-07 | 4.57E-06 | 3.45E-09 | 3.51E-09 | 2.87E-09 | 2.69E-09 |
| $^{228}$Ra | 2.64E-13 | 4.70E-05 | 8.73E-04 | 1.32E-04 | 9.70E-04 | 3.70E-06 | 2.06E-12 | 5.85E-13 | 2.78E-12 | 9.51E-07 | 9.70E-07 | 4.48E-07 | 3.35E-06 |
| $^{229}$Th | 1.33E-10 | 2.60E-11 | 8.56E-08 | 1.91E-05 | 1.89E-09 | 1.50E-09 | 1.04E-09 | 2.95E-10 | 1.40E-09 | 1.18E-11 | 1.20E-11 | 9.81E-12 | 9.17E-12 |
| $^{230}$Th[d] | — | — | — | 9.38E-04 | — | — | — | — | — | — | — | — | — |
| $^{231}$Pa | 2.48E-08 | 1.66E-07 | 7.47E-05 | 2.53E-03 | 3.83E-05 | 3.02E-05 | 2.10E-05 | 5.96E-06 | 2.82E-05 | 6.79E-09 | 6.93E-09 | 5.67E-09 | 5.30E-09 |
| $^{232}$Th | 1.12E-12 | 1.99E-04 | 3.70E-03 | 5.60E-04 | 4.11E-03 | 1.57E-05 | 8.72E-12 | 2.48E-12 | 1.18E-11 | 4.03E-06 | 4.11E-06 | 1.90E-06 | 1.42E-05 |
| $^{232}$U | 1.75E-06 | 4.29E-06 | 3.53E-02 | 4.87E-04 | 2.20E-06 | 4.50E-07 | 9.94E-08 | 1.91E-08 | 4.50E-07 | 2.25E-06 | 2.00E-06 | 6.60E-06 | 4.93E-06 |
| $^{233}$U | 1.71E-07 | 5.85E-03 | 2.18E+00 | 1.82E-03 | 2.15E-07 | 4.10E-08 | 9.69E-09 | 1.86E-09 | 4.39E-08 | 1.14E-05 | 1.02E-05 | 3.37E-05 | 2.51E-05 |
| $^{234}$U | 1.69E-01 | 1.36E-02 | 4.17E-01 | 9.40E-04 | 2.07E-01 | 3.25E-02 | 9.35E-03 | 2.64E-03 | 4.23E-02 | 3.65E-02 | 3.52E-02 | 1.13E-01 | 8.27E-02 |
| $^{235}$U | 7.54E-03 | 7.10E-04 | 1.98E-02 | 3.86E-05 | 9.24E-03 | 1.82E-03 | 4.01E-04 | 1.14E-04 | 1.89E-03 | 1.48E-03 | 1.42E-03 | 4.79E-03 | 3.42E-03 |
| $^{236}$U | 1.93E-03 | 3.74E-04 | 4.85E-03 | 1.73E-05 | 2.31E-03 | 2.85E-04 | 9.61E-05 | 2.93E-05 | 4.73E-04 | 5.23E-04 | 3.52E-04 | 8.33E-04 | 5.13E-04 |
| $^{237}$Np | 3.45E-04 | 1.35E-02 | 7.97E-02 | 5.41E-02 | 2.08E-04 | 2.17E-05 | 6.46E-04 | 1.09E-03 | 1.54E-04 | 3.42E-03 | 2.90E-03 | 2.70E-05 | 2.16E-02 |
| $^{238}$Pu | 1.13E-01 | 1.30E+00 | 5.89E-01 | 2.38E+00 | 8.05E-01 | 4.37E-03 | 1.56E-02 | 1.56E-02 | 3.59E-02 | 4.42E-01 | 3.99E-01 | 1.36E-02 | 2.76E-04 |
| $^{238}$U | 1.72E-01 | 1.64E-02 | 4.39E-01 | 9.02E-04 | 2.11E-01 | 4.03E-02 | 9.53E-03 | 2.59E-03 | 4.32E-02 | 3.69E-02 | 3.28E-02 | 1.09E-01 | 8.13E-02 |

**Table 3-13b. 241-C Tank Farm Residual Inventory Estimates for Retrieved Tanks with Post-Retrieval Sampling. (sheet 2 of 2)**

| Tanks Retrieved (BBI average)[a] | 241-C-101 | 241-C-103 | 241-C-104 | 241-C-106 | 241-C-107 | 241-C-108 | 241-C-109 | 241-C-110 | 241-C-112 | 241-C-201 | 241-C-202 | 241-C-203 | 241-C-204 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $^{239}$Pu | 1.83E+01 | 4.99E+00 | 5.15E+00 | 1.67E+01 | 1.30E+02 | 6.68E-01 | 4.01E-01 | 1.17E+00 | 5.79E+00 | 1.58E+01 | 1.43E+01 | 4.86E-01 | 9.84E-03 |
| $^{240}$Pu | 1.96E+00 | 1.04E+00 | 1.55E+00 | 3.57E+00 | 1.42E+01 | 7.27E-02 | 4.36E-02 | 1.27E-01 | 6.29E-01 | 3.40E+00 | 3.08E+00 | 1.05E-01 | 2.12E-03 |
| $^{241}$Am | 9.91E+00 | 4.83E+00 | 8.46E+00 | 6.38E+01 | 3.70E+02 | 9.46E-01 | 3.71E-01 | 4.94E-02 | 9.42E-01 | 2.46E+00 | 1.21E+00 | 3.16E-02 | 3.16E-03 |
| $^{241}$Pu | 1.54E+00 | 1.80E+00 | 1.14E+01 | 1.84E+01 | 1.10E+01 | 7.91E-02 | 5.09E-01 | 3.58E-01 | 4.91E-01 | 8.36E+00 | 7.52E+00 | 2.58E-01 | 5.21E-03 |
| $^{242}$Cm | 2.23E-03 | 5.73E-05 | 3.13E-02 | 1.45E-01 | 6.09E-02 | 1.59E-04 | 6.17E-05 | 8.75E-06 | 1.54E-04 | 8.30E-02 | 4.01E-02 | 1.04E-03 | 1.04E-04 |
| $^{242}$Pu | 2.70E-05 | 3.24E-05 | 1.97E-02 | 4.16E-04 | 1.97E-04 | 1.01E-06 | 6.07E-07 | 1.77E-06 | 8.76E-06 | 1.60E-04 | 1.45E-04 | 4.94E-06 | 9.98E-08 |
| $^{243}$Am | 1.43E-03 | 3.70E-05 | 5.25E-03 | 3.05E-03 | 3.86E-02 | 9.78E-05 | 3.91E-05 | 5.54E-06 | 9.72E-05 | 9.76E-04 | 4.71E-04 | 1.22E-05 | 1.22E-06 |
| $^{243}$Cm | 1.86E-05 | 7.66E-07 | 3.64E-03 | 5.55E-02 | 5.02E-04 | 1.50E-06 | 5.09E-07 | 7.22E-08 | 1.26E-06 | 3.10E-03 | 1.50E-03 | 3.88E-05 | 3.87E-06 |
| $^{244}$Cm | 3.32E-04 | 1.52E-05 | 6.69E-02 | 7.39E-01 | 8.95E-03 | 2.96E-05 | 9.09E-06 | 1.29E-06 | 2.25E-05 | 5.55E-02 | 2.68E-02 | 6.95E-04 | 6.95E-05 |
| $^{3}$H | 2.45E-02 | 3.98E-03 | 9.32E-03 | 4.17E-03 | 1.44E-02 | 1.94E-02 | 3.51E-03 | 1.80E-03 | 1.06E-02 | 1.57E-04 | 1.60E-04 | 1.31E-04 | 1.13E-04 |
| $^{59}$Ni | 7.23E-04 | 1.12E-01 | 8.64E-02 | 1.05E+01 | 1.18E-03 | 9.30E-04 | 6.46E-04 | 1.83E-04 | 8.69E-04 | 4.07E-03 | 4.16E-03 | 3.40E-03 | 3.18E-03 |
| $^{60}$Co | 1.76E-04 | 1.83E-02 | 4.66E-01 | 2.23E+00 | 9.14E-04 | 7.22E-04 | 5.02E-04 | 1.42E-04 | 6.75E-04 | 2.37E-03 | 2.44E-03 | 2.15E-03 | 1.86E-03 |
| $^{63}$Ni | 5.53E-02 | 1.86E+01 | 9.95E+01 | 6.53E+01 | 1.46E-01 | 2.80E+00 | 8.78E-01 | 4.08E-01 | 1.08E-01 | 8.33E-01 | 2.00E-01 | 5.54E-02 | 1.46E-02 |
| $^{79}$Se | 2.80E-04 | 2.64E-05 | 8.56E-03 | 9.57E-03 | 2.70E-04 | 1.62E-03 | 1.48E-04 | 4.21E-05 | 1.99E-04 | 5.49E-05 | 5.61E-05 | 4.58E-05 | 4.29E-05 |
| $^{90}$Sr | 3.29E+03 | 6.78E+03 | 4.89E+03 | 4.50E+04 | 2.42E+04 | 1.25E+03 | 2.33E+03 | 2.62E+03 | 2.28E+02 | 1.71E+02 | 3.31E+02 | 1.56E+02 | 1.03E+02 |
| $^{90}$Y | 3.29E+03 | 6.78E+03 | 4.89E+03 | 4.50E+04 | 2.42E+04 | 1.25E+03 | 2.33E+03 | 2.62E+03 | 2.28E+02 | 1.71E+02 | 3.31E+02 | 1.56E+02 | 1.03E+02 |
| $^{93m}$Nb | 1.83E-05 | 3.69E-04 | 3.16E-02 | 5.92E+00 | 8.45E-02 | 4.80E-02 | 4.64E-02 | 1.32E-02 | 6.26E-02 | 7.46E-04 | 7.64E-04 | 6.26E-04 | 5.84E-04 |
| $^{93}$Zr | 3.35E-05 | 7.03E-04 | 6.24E-02 | 1.04E+01 | 1.55E-01 | 1.22E-01 | 8.45E-02 | 2.41E-02 | 1.14E-01 | 1.46E-03 | 1.49E-03 | 1.22E-03 | 1.14E-03 |
| $^{99}$Tc | 4.34E-02 | 4.48E-02 | 3.04E-01 | 1.64E-01 | 2.14E+00 | 4.87E-02 | 8.77E-03 | 4.46E-02 | 1.69E+00 | 2.63E-03 | 2.50E-03 | 2.32E-03 | 3.18E-03 |

Source: RPP-RPT-42323, "Hanford C-Farm Tank and Ancillary Equipment Residual Waste Inventory Estimates."

[a] September 1, 2014 Best-Basis Inventory (BBI), includes tank 241-C-106 for which retrieval completion is under review. Note for: less than detect values; BBI mean uses less than detect values or process knowledge estimate, whichever is lower.

[b] Inventories estimated without post-retrieval sampling.

[c] Radionuclides are decayed to January 1, 2020 for 241-C Tank Farm closure assessments.

[d] Thorium-230 is not a standard BBI constituent but is included for Performance Assessment modeling estimates. Only the tank 241-C-106 nominal inventory based on analytical results is presented. Concentrations for other tanks sampled were below detection limits.

**Table 3-14a. 241-C Tank Farm Residual Inventory Estimates for Tanks Undergoing Retrieval.**

| Base Case for Tanks not Retrieved [a] | 241-C-102 | 241-C-105 | 241-C-111 |
|---|---|---|---|
| Residual Volume (kL [kgal]) | 10.2 (2.69) | 48.0 (12.7) | 132 (34.9) |
| Total Chemicals (kg) | 7.51E+03 | 2.76E+04 | 8.34E+04 |
| Al | 5.29E+03 | 1.49E+04 | 1.60E+04 |
| Bi | 4.53E+01 | 3.57E+01 | 1.55E+03 |
| Ca | 1.22E+02 | 1.90E+02 | 2.20E+03 |
| Cl | 2.62E-03 | 2.98E+01 | 2.21E+02 |
| Cr | 1.13E+01 | 3.70E+01 | 7.33E+01 |
| F | 6.06E-03 | 7.90E+01 | 8.07E+02 |
| Fe | 3.37E+02 | 3.92E+02 | 7.53E+03 |
| Hg | 7.55E-02 | 5.02E-01 | 4.69E+01 |
| K | 7.85E+00 | 8.26E+01 | 1.87E+02 |
| La | 2.26E+00 | 2.62E-01 | 5.68E+01 |
| Mn | 2.86E+01 | 1.82E+02 | 4.68E+01 |
| Na | 4.30E+02 | 3.66E+03 | 1.03E+04 |
| Ni | 1.20E+02 | 1.59E+02 | 2.65E+03 |
| $NO_2$ | 2.78E-02 | 6.46E+02 | 5.50E+03 |
| $NO_3$ | 9.54E-02 | 7.81E+02 | 1.47E+04 |
| Pb | 2.84E+01 | 3.45E+01 | 7.65E+02 |
| $PO_4$ | 6.12E+01 | 5.77E+02 | 1.20E+04 |
| Si | 5.49E+02 | 2.97E+03 | 1.42E+03 |
| $SO_4$ | 7.21E+00 | 2.80E+02 | 1.26E+03 |
| Sr | 2.38E+00 | 1.37E+01 | 3.58E+01 |
| TIC as $CO_3$ | 5.80E+01 | 1.26E+03 | 3.47E+03 |
| TOC | 2.18E+01 | 4.14E+02 | 1.46E+02 |
| UTOTAL | 2.93E+02 | 7.32E+02 | 2.36E+03 |
| Zr | 9.46E+01 | 1.56E+01 | 3.02E+01 |

Source: RPP-RPT-42323, "Hanford C-Farm Tank and Ancillary Equipment Residual Waste Inventory Estimates."

[a] Includes tanks 241-C-102, 241-C-105 and 241-C-111 for which retrieval is in progress as of September 1, 2014. Note: Based on retrieval results for other tanks and in-process results for these tanks, it appears that the retrieval goal of 360 $ft^3$ or less will not be met for these tanks. The base case reflects the assumed retrieval end state based on retrieval performance to date.

**Table 3-14b. 241-C Tank Farm Residual Inventory Estimates for Tanks Undergoing Retrieval. (2 sheets)**

| **Base Case for Tanks not Retrieved** [a] | **241-C-102** | **241-C-105** | **241-C-111** |
|---|---|---|---|
| Residual Volume (kL [kgal]) | 10.2 (2.69) | 48.0 (12.7) | 132 (34.9) |
| Total Radionuclides (Ci) [b] | 9.19E+02 | 6.74E+04 | 6.24E+05 |
| $^{106}$Ru | 1.71E-13 | 6.76E-16 | 7.13E-10 |
| $^{113m}$Cd | 1.78E-02 | 5.85E-02 | 5.99E-02 |
| $^{125}$Sb | 1.27E-05 | 2.89E-06 | 1.37E-03 |
| $^{126}$Sn | 1.83E-04 | 2.93E-04 | 6.72E-03 |
| $^{129}$I | 2.56E-03 | 8.93E-03 | 1.41E-02 |
| $^{134}$Cs | 1.54E-07 | 1.52E-08 | 1.42E-06 |
| $^{137}$Cs | 8.07E+01 | 5.07E+03 | 7.14E+03 |
| $^{137m}$Ba | 8.07E+01 | 4.52E+03 | 6.36E+03 |
| $^{14}$C | 9.88E-04 | 4.85E-02 | 1.04E-01 |
| $^{151}$Sm | 9.72E-01 | 2.36E+00 | 6.39E+02 |
| $^{152}$Eu | 1.26E-04 | 1.12E-04 | 5.38E-02 |
| $^{154}$Eu | 1.36E-01 | 4.67E-03 | 2.41E+00 |
| $^{155}$Eu | 2.62E-02 | 6.07E-04 | 3.70E-01 |
| $^{226}$Ra | 2.88E-07 | 1.59E-07 | 4.51E-06 |
| $^{227}$Ac | 1.93E-02 | 5.16E-07 | 1.82E-05 |
| $^{228}$Ra | 3.64E-01 | 2.36E-13 | 6.54E-12 |
| $^{229}$Th | 1.06E-02 | 1.25E-10 | 3.56E-09 |
| $^{231}$Pa | 2.12E-03 | 6.56E-07 | 4.99E-05 |
| $^{232}$Th | 2.29E-02 | 9.98E-13 | 2.77E-11 |
| $^{232}$U | 2.83E-02 | 8.61E-06 | 2.22E-05 |
| $^{233}$U | 2.17E+00 | 5.01E-07 | 4.80E-05 |
| $^{234}$U | 1.13E-01 | 2.38E-01 | 7.74E-01 |
| $^{235}$U | 4.27E-03 | 1.02E-02 | 3.37E-02 |
| $^{236}$U | 1.43E-03 | 5.16E-03 | 1.32E-02 |
| $^{237}$Np | 5.16E-05 | 1.93E-04 | 3.32E-03 |
| $^{238}$Pu | 1.48E+00 | 7.48E-01 | 1.70E+00 |
| $^{238}$U | 9.78E-02 | 2.44E-01 | 7.88E-01 |
| $^{239}$Pu | 6.49E+01 | 5.27E+01 | 9.45E+01 |

**Table 3-14b. 241-C Tank Farm Residual Inventory Estimates for Tanks Undergoing Retrieval. (2 sheets)**

| Base Case for Tanks not Retrieved [a] | 241-C-102 | 241-C-105 | 241-C-111 |
|---|---|---|---|
| $^{240}$Pu | 1.55E+01 | 1.04E+01 | 1.85E+01 |
| $^{241}$Am | 2.12E+01 | 2.83E+01 | 8.32E+01 |
| $^{241}$Pu | 4.87E+01 | 1.75E+01 | 3.54E+01 |
| $^{242}$Cm | 1.15E-03 | 1.01E-03 | 6.21E-02 |
| $^{242}$Pu | 9.00E-04 | 3.13E-04 | 6.54E-04 |
| $^{243}$Am | 7.93E-04 | 6.71E-04 | 1.15E-02 |
| $^{243}$Cm | 6.22E-05 | 9.09E-06 | 1.82E-03 |
| $^{244}$Cm | 1.28E-03 | 1.56E-04 | 3.26E-02 |
| $^{3}$H | 2.15E-05 | 4.08E+00 | 2.58E+00 |
| $^{59}$Ni | 1.62E-01 | 4.40E-01 | 1.40E+00 |
| $^{60}$Co | 2.14E-01 | 6.82E-01 | 1.03E-01 |
| $^{63}$Ni | 1.36E+01 | 3.61E+01 | 1.13E+02 |
| $^{79}$Se | 1.60E-06 | 1.51E-04 | 3.53E-03 |
| $^{90}$Sr | 2.94E+02 | 2.88E+04 | 3.05E+05 |
| $^{90}$Y | 2.94E+02 | 2.88E+04 | 3.05E+05 |
| $^{93m}$Nb | 1.10E-02 | 1.45E-03 | 9.78E-02 |
| $^{93}$Zr | 4.22E-03 | 2.76E-03 | 1.81E-01 |
| $^{99}$Tc | 3.56E-03 | 7.81E+00 | 2.19E+00 |

Source: RPP-RPT-42323, "Hanford C-Farm Tank and Ancillary Equipment Residual Waste Inventory Estimates."

[a] Includes tanks 241-C-102, 241-C-105 and 241-C-111 for which retrieval is in progress as of September 1, 2014. Note: Based on retrieval results for other tanks and in-process results for these tanks, it appears that the retrieval goal of 360 $ft^3$ or less will not be met for these tanks. The base case reflects the assumed retrieval end state based on retrieval performance to date.

[b] Radionuclides are decayed to January 1, 2020 for 241-C Tank Farm closure assessments.

**Table 3-15a. 241-C Tank Farm Residual Inventory Estimates for Ancillary Equipment.**

| Ancillary Equipment | Catch Tank 241-C-301 [a] | 244-CR Process Tank Vault [a] | Pits [b] | Diversion Boxes [b] | Pipelines [b] |
|---|---|---|---|---|---|
| Residual Volume (kL [kgal]) | 4.0 (1.06) | 4.1 (1.08) | 0.1 (0.03) | 0.2 (0.06) | 6.1 (1.6) |
| Total Chemicals (kg) | 2.64E+03 | 2.70E+03 | 7.98E+01 | 1.55E+02 | 3.99E+03 |
| Al | 5.28E+02 | 5.41E+02 | 1.60E+01 | 3.10E+01 | 7.99E+02 |
| Bi | 6.40E+00 | 6.56E+00 | 1.94E-01 | 3.75E-01 | 9.69E+00 |
| Ca | 1.94E+01 | 1.98E+01 | 5.86E-01 | 1.14E+00 | 2.93E+01 |
| Cl | 7.51E-01 | 7.70E-01 | 2.27E-02 | 4.40E-02 | 1.14E+00 |
| Cr | 1.79E+01 | 1.83E+01 | 5.41E-01 | 1.05E+00 | 2.70E+01 |
| F | 2.12E+01 | 2.18E+01 | 6.43E-01 | 1.25E+00 | 3.22E+01 |
| Fe | 2.21E+02 | 2.27E+02 | 6.70E+00 | 1.30E+01 | 3.35E+02 |
| Hg | 5.82E-01 | 5.96E-01 | 1.76E-02 | 3.41E-02 | 8.81E-01 |
| K | 5.30E+00 | 5.43E+00 | 1.60E-01 | 3.11E-01 | 8.02E+00 |
| La | 1.09E-01 | 1.12E-01 | 3.31E-03 | 6.40E-03 | 1.65E-01 |
| Mn | 4.82E+01 | 4.94E+01 | 1.46E+00 | 2.83E+00 | 7.30E+01 |
| Na | 4.40E+02 | 4.51E+02 | 1.33E+01 | 2.58E+01 | 6.65E+02 |
| Ni | 1.45E+01 | 1.48E+01 | 4.38E-01 | 8.49E-01 | 2.19E+01 |
| $NO_2$ | 3.87E+00 | 3.97E+00 | 1.17E-01 | 2.27E-01 | 5.86E+00 |
| $NO_3$ | 7.50E+00 | 7.69E+00 | 2.27E-01 | 4.40E-01 | 1.14E+01 |
| Pb | 1.41E+01 | 1.45E+01 | 4.28E-01 | 8.28E-01 | 2.14E+01 |
| $PO_4$ | 3.46E+02 | 3.55E+02 | 1.05E+01 | 2.03E+01 | 5.24E+02 |
| Si | 3.63E+01 | 3.72E+01 | 1.10E+00 | 2.13E+00 | 5.49E+01 |
| $SO_4$ | 4.16E+00 | 4.27E+00 | 1.26E-01 | 2.44E-01 | 6.30E+00 |
| Sr | 5.57E+00 | 5.71E+00 | 1.69E-01 | 3.27E-01 | 8.43E+00 |
| TIC as $CO_3$ | 1.42E+02 | 1.46E+02 | 4.31E+00 | 8.35E+00 | 2.16E+02 |
| TOC | 7.47E+01 | 7.66E+01 | 2.26E+00 | 4.38E+00 | 1.13E+02 |
| UTOTAL | 6.76E+02 | 6.93E+02 | 2.05E+01 | 3.97E+01 | 1.02E+03 |
| Zr | 2.61E+00 | 2.67E+00 | 7.89E-02 | 1.53E-01 | 3.95E+00 |

Source: RPP-RPT-42323, "Hanford C-Farm Tank and Ancillary Equipment Residual Waste Inventory Estimates."

[a] Assumes 90% retrieval for C-301 catch tank and 244-CR vault. Note: Current volumes and inventories for these tanks are 10 times the values shown in this table.

[b] Estimated waste volumes and inventories at closure for pits, diversion boxes and pipelines.

**Table 3-15b. 241-C Tank Farm Residual Inventory Estimates for Ancillary Equipment. (2 sheets)**

| Ancillary Equipment | Catch Tank 241-C-301 [a] | 244-CR Process Tank Vault [a] | Pits [b] | Diversion Boxes [b] | Pipelines [b] |
|---|---|---|---|---|---|
| Residual Volume (kL [kgal]) | 4.0 (1.06) | 4.1 (1.08) | 0.1 (0.03) | 0.2 (0.06) | 6.1 (1.6) |
| Total Radionuclides (Ci) [b] | 7.04E+03 | 7.22E+03 | 2.13E+02 | 4.13E+02 | 1.07E+04 |
| $^{106}$Ru | 1.19E-10 | 1.22E-10 | 3.60E-12 | 6.98E-12 | 1.80E-10 |
| $^{113m}$Cd | 8.63E-02 | 8.85E-02 | 2.61E-03 | 5.06E-03 | 1.31E-01 |
| $^{125}$Sb | 5.36E-02 | 5.50E-02 | 1.62E-03 | 3.15E-03 | 8.12E-02 |
| $^{126}$Sn | 6.91E-02 | 7.08E-02 | 2.09E-03 | 4.05E-03 | 1.05E-01 |
| $^{129}$I | 2.09E-04 | 2.15E-04 | 6.34E-06 | 1.23E-05 | 3.17E-04 |
| $^{134}$Cs | 1.10E-06 | 1.12E-06 | 3.32E-08 | 6.43E-08 | 1.66E-06 |
| $^{137}$Cs | 1.23E+02 | 1.26E+02 | 3.74E+00 | 7.24E+00 | 1.87E+02 |
| $^{137m}$Ba | 1.10E+02 | 1.13E+02 | 3.33E+00 | 6.46E+00 | 1.67E+02 |
| $^{14}$C | 2.07E-03 | 2.12E-03 | 6.28E-05 | 1.22E-04 | 3.14E-03 |
| $^{151}$Sm | 5.38E+02 | 5.51E+02 | 1.63E+01 | 3.16E+01 | 8.15E+02 |
| $^{152}$Eu | 8.45E-02 | 8.66E-02 | 2.56E-03 | 4.96E-03 | 1.28E-01 |
| $^{154}$Eu | 1.19E+00 | 1.22E+00 | 3.60E-02 | 6.98E-02 | 1.80E+00 |
| $^{155}$Eu | 3.66E-01 | 3.75E-01 | 1.11E-02 | 2.15E-02 | 5.54E-01 |
| $^{226}$Ra | 1.96E-05 | 2.01E-05 | 5.94E-07 | 1.15E-06 | 2.97E-05 |
| $^{227}$Ac | 6.72E-05 | 6.89E-05 | 2.04E-06 | 3.94E-06 | 1.02E-04 |
| $^{228}$Ra | 5.99E-05 | 6.14E-05 | 1.82E-06 | 3.52E-06 | 9.08E-05 |
| $^{229}$Th | 7.32E-07 | 7.51E-07 | 2.22E-08 | 4.30E-08 | 1.11E-06 |
| $^{231}$Pa | 1.03E-04 | 1.06E-04 | 3.12E-06 | 6.04E-06 | 1.56E-04 |
| $^{232}$Th | 2.54E-04 | 2.60E-04 | 7.69E-06 | 1.49E-05 | 3.85E-04 |
| $^{232}$U | 1.99E-03 | 2.04E-03 | 6.04E-05 | 1.17E-04 | 3.02E-03 |
| $^{233}$U | 1.21E-01 | 1.25E-01 | 3.68E-03 | 7.13E-03 | 1.84E-01 |
| $^{234}$U | 2.30E-01 | 2.35E-01 | 6.96E-03 | 1.35E-02 | 3.48E-01 |
| $^{235}$U | 9.72E-03 | 9.96E-03 | 2.94E-04 | 5.70E-04 | 1.47E-02 |
| $^{236}$U | 1.96E-03 | 2.01E-03 | 5.94E-05 | 1.15E-04 | 2.97E-03 |
| $^{237}$Np | 2.87E-02 | 2.94E-02 | 8.68E-04 | 1.68E-03 | 4.34E-02 |
| $^{238}$Pu | 7.52E-01 | 7.71E-01 | 2.28E-02 | 4.41E-02 | 1.14E+00 |
| $^{238}$U | 2.26E-01 | 2.31E-01 | 6.83E-03 | 1.32E-02 | 3.42E-01 |

**Table 3-15b. 241-C Tank Farm Residual Inventory Estimates for Ancillary Equipment. (2 sheets)**

| Ancillary Equipment | Catch Tank 241-C-301 [a] | 244-CR Process Tank Vault [a] | Pits [b] | Diversion Boxes [b] | Pipelines [b] |
|---|---|---|---|---|---|
| $^{239}$Pu | 2.17E+01 | 2.22E+01 | 6.57E-01 | 1.27E+00 | 3.28E+01 |
| $^{240}$Pu | 4.68E+00 | 4.79E+00 | 1.42E-01 | 2.74E-01 | 7.08E+00 |
| $^{241}$Am | 5.63E+00 | 5.77E+00 | 1.70E-01 | 3.30E-01 | 8.52E+00 |
| $^{241}$Pu | 1.23E+01 | 1.26E+01 | 3.71E-01 | 7.19E-01 | 1.86E+01 |
| $^{242}$Cm | 9.02E-02 | 9.25E-02 | 2.73E-03 | 5.29E-03 | 1.37E-01 |
| $^{242}$Pu | 1.32E-03 | 1.35E-03 | 3.99E-05 | 7.74E-05 | 2.00E-03 |
| $^{243}$Am | 1.39E-03 | 1.43E-03 | 4.21E-05 | 8.16E-05 | 2.11E-03 |
| $^{243}$Cm | 5.41E-03 | 5.55E-03 | 1.64E-04 | 3.17E-04 | 8.19E-03 |
| $^{244}$Cm | 8.74E-02 | 8.96E-02 | 2.65E-03 | 5.13E-03 | 1.32E-01 |
| $^{3}$H | 2.13E-03 | 2.18E-03 | 6.44E-05 | 1.25E-04 | 3.22E-03 |
| $^{59}$Ni | 4.21E-01 | 4.31E-01 | 1.27E-02 | 2.47E-02 | 6.37E-01 |
| $^{60}$Co | 1.18E-01 | 1.21E-01 | 3.58E-03 | 6.93E-03 | 1.79E-01 |
| $^{63}$Ni | 9.69E+00 | 9.93E+00 | 2.93E-01 | 5.69E-01 | 1.47E+01 |
| $^{79}$Se | 1.05E-03 | 1.07E-03 | 3.17E-05 | 6.14E-05 | 1.58E-03 |
| $^{90}$Sr | 3.11E+03 | 3.18E+03 | 9.40E+01 | 1.82E+02 | 4.70E+03 |
| $^{90}$Y | 3.11E+03 | 3.18E+03 | 9.40E+01 | 1.82E+02 | 4.70E+03 |
| $^{93m}$Nb | 2.34E-01 | 2.40E-01 | 7.08E-03 | 1.37E-02 | 3.54E-01 |
| $^{93}$Zr | 4.13E-01 | 4.24E-01 | 1.25E-02 | 2.43E-02 | 6.26E-01 |
| $^{99}$Tc | 3.70E-02 | 3.80E-02 | 1.12E-03 | 2.17E-03 | 5.61E-02 |

Source: RPP-RPT-42323, "Hanford C-Farm Tank and Ancillary Equipment Residual Waste Inventory Estimates."

[a] Assumes 90% retrieval for C-301 catch tank and 244-CR vault. Note: Current volumes and inventories for these tanks are 10 times the values shown in this table.

[b] Estimated waste volumes and inventories at closure for pits, diversion boxes and pipelines.

Note: Radionuclides are decayed to January 1, 2020 for 241-C Tank Farm closure assessments.

**Table 3-16a. 241-C Tank Farm Residual Inventory 95% Confidence Interval Estimates for Retrieved Tanks with Post-Retrieval Sampling. (2 sheets)**

| Tanks Retrieved (Best-Basis Inventory, 95% Confidence Intervals for Single-Shell Tanks with post-retrieval residual data)[a] | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **241-C-103** | **241-C-104** | **241-C-106** | **241-C-108** | **241-C-109** | **241-C-110** | **241-C-201** | **241-C-202** | **241-C-203** | **241-C-204** |
| Al | 4.34E+03 | 1.80E+03 | 4.89E+02 | 4.17E+03 | 2.94E+03 | 1.74E+03 | 5.50E+00 | 9.28E+00 | —[b] | 5.88E+00 |
| Bi | —[b] | 4.35E+00 | —[b] | —[b] | 2.49E+00 | 4.72E+01 | 1.08E+00 | 1.03E+00 | 1.52E+00 | —[b] |
| Ca | 2.65E+01 | 2.39E+01 | 1.53E+02 | 2.86E+01 | 2.26E+01 | 7.49E+00 | 1.02E+01 | 7.86E+00 | 2.45E+00 | 5.90E-01 |
| Cl | 4.97E-01 | 9.06E-01 | —[b] | —[b] | —[b] | —[b] | 6.15E-01 | 5.86E-01 | 7.36E-02 | 6.98E-03 |
| Cr | 3.02E+00 | 4.45E+00 | 4.85E+00 | 7.98E-01 | 2.45E-01 | 1.61E+00 | 2.52E+01 | 9.94E+00 | 3.70E+00 | 1.36E+00 |
| F | 2.02E-01 | 3.01E+01 | —[b] | 1.60E+02 | 1.20E+02 | 1.84E+02 | 4.97E+00 | 2.84E+00 | 2.20E+00 | 8.05E-03 |
| Fe | 1.62E+02 | 4.83E+02 | 2.65E+02 | 3.71E+02 | 1.41E+02 | 2.68E+02 | 2.01E+02 | 9.99E+01 | 1.90E+01 | 3.21E+01 |
| Hg | 1.71E+00 | 1.95E+00 | 2.86E+00 | 2.49E-02 | 3.03E-02 | 1.64E-01 | 1.53E-01 | 3.34E-01 | 2.98E-03 | 1.47E-01 |
| K | 4.46E+00 | 1.82E+00 | —[b] | — | —[b] | 6.73E-01 | —[b] | —[b] | —[b] | —[b] |
| La | 2.51E-01 | —[b] | 3.12E+00 | —[b] | 1.78E-01 | —[b] | —[b] | —[b] | —[b] | —[b] |
| Mn | 5.44E+00 | 8.90E+01 | 7.11E+02 | 6.73E+00 | 9.34E-01 | 1.04E+00 | 3.91E+01 | 1.86E+01 | 7.02E-01 | 2.39E-01 |
| Na | 1.14E+02 | 1.60E+03 | 2.43E+02 | 3.97E+03 | 1.91E+03 | 1.56E+03 | 7.03E+01 | 5.75E+01 | 6.64E+01 | 3.33E+01 |
| Ni | 5.60E+00 | 1.10E+01 | 3.99E+01 | 8.99E+01 | 1.97E+01 | 5.38E-01 | 1.28E+01 | 8.05E+00 | 3.01E-01 | 8.01E-01 |
| $NO_2$ | 6.13E-01 | 7.81E+00 | —[b] | 6.85E+00 | 4.49E+00 | —[b] | 8.86E-01 | 6.63E-01 | 2.98E+00 | 3.12E-02 |
| $NO_3$ | 1.10E+00 | 1.30E+01 | —[b] | 1.15E+01 | 5.79E+00 | 1.33E+01 | 2.11E+00 | 1.73E+00 | —[b] | 2.23E-02 |
| Pb | 1.08E+01 | 9.91E+00 | 3.31E+01 | 2.26E+01 | 6.39E+00 | 7.32E+00 | 8.93E+00 | 6.45E+00 | 4.00E+00 | 1.02E+00 |
| $PO_4$ | 4.81E-01 | 7.52E+01 | —[b] | 1.68E+03 | 1.49E+03 | 1.82E+03 | — | — | — | 7.96E+01 |
| Si | 1.53E+02 | 1.82E+02 | 2.07E+01 | 1.49E+02 | 5.12E+01 | 2.76E+01 | 1.14E+01 | 1.00E+01 | 2.90E+00 | 7.33E+00 |

**Table 3-16a. 241-C Tank Farm Residual Inventory 95% Confidence Interval Estimates for Retrieved Tanks with Post-Retrieval Sampling. (2 sheets)**

| Tanks Retrieved (Best-Basis Inventory, 95% Confidence Intervals for Single-Shell Tanks with post-retrieval residual data)[a] | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **241-C-103** | **241-C-104** | **241-C-106** | **241-C-108** | **241-C-109** | **241-C-110** | **241-C-201** | **241-C-202** | **241-C-203** | **241-C-204** |
| $SO_4$ | 2.27E-01 | 1.60E+00 | —[b] | 3.54E+00 | 3.62E+00 | 9.33E+00 | 5.41E+00 | 4.41E-01 | 1.98E+00 | 1.28E-02 |
| Sr | 3.16E+00 | 1.46E+00 | 2.34E+00 | 2.61E+01 | 7.52E-01 | 8.94E+01 | 1.68E+00 | 1.33E+00 | 2.78E-01 | 3.67E-01 |
| TIC as $CO_3$ | — | — | — | — | — | — | — | — | — | — |
| TOC | — | — | — | — | — | — | — | — | — | — |
| UTOTAL | 6.03E+01 | 1.99E+03 | —[b] | 1.48E+02 | 4.24E+01 | 7.51E+00 | 2.12E+02 | 1.54E+02 | 3.70E+02 | 3.04E+02 |
| Zr | 1.65E+01 | 5.55E+01 | 3.60E+00 | 7.57E-01 | — | 4.63E-01 | 2.19E-02 | 1.08E-01 | 1.25E-01 | —[b] |

Source: RPP-RPT-42323, "Hanford C-Farm Tank and Ancillary Equipment Residual Waste Inventory Estimates."

[a] September 1, 2014 Best-Basis Inventory (BBI), includes tank 241-C-106 for which retrieval completion is under review.
95% Confidence Interval = Mean + 2 × Standard Deviation (Closure mean for tanks with closure reports, BBI mean for C-101, C-107 and C-112: no closure report).

95% confidence intervals were not calculated for constituents with concentrations below analytical detection limits.

[b] Concentration less than analytical detection limit.

TIC = Total inorganic carbon

TOC = Total organic carbon

**Table 3-16b. 241-C Tank Farm Residual Inventory 95% Confidence Interval Estimates for Retrieved Tanks with Post-Retrieval Sampling. (3 sheets)**

| Tanks Retrieved (95% Confidence Interval with post-retrieval residual data)[a] | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **241-C-103** | **241-C-104** | **241-C-106** | **241-C-108** | **241-C-109** | **241-C-110** | **241-C-201** | **241-C-202** | **241-C-203** | **241-C-204** |
| $^{106}$Ru | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] |
| $^{113m}$Cd | — | — | — | — | — | — | — | — | — | — |
| $^{125}$Sb | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] |
| $^{126}$Sn | — | 1.68E-02 | — | —[b] | —[b] | 3.53E-02 | — | — | — | — |
| $^{129}$I | 3.81E-03 | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | 9.64E-06 | 3.84E-05 | —[b] |
| $^{134}$Cs | 2.08E-06 | — | —[b] | — | — | — | — | — | — | — |
| $^{137}$Cs | 7.40E+02 | 1.14E+03 | 1.35E+03 | 1.07E+02 | 5.55E+01 | 3.18E+01 | 9.13E+00 | 7.18E+00 | 1.09E+01 | 5.16E+00 |
| $^{137m}$Ba | 6.60E+02 | 9.99E+02 | 1.20E+03 | 9.52E+01 | 4.91E+01 | 2.83E+01 | 8.14E+00 | 6.40E+00 | 9.70E+00 | 4.60E+00 |
| $^{14}$C | —[b] | 4.64E-03 | —[b] | —[b] | —[b] | —[b] | 1.38E-03 | —[b] | —[b] | —[b] |
| $^{151}$Sm | — | — | — | — | — | — | — | — | — | — |
| $^{152}$Eu | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] |
| $^{154}$Eu | 1.89E+00 | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] |
| $^{155}$Eu | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] |
| $^{226}$Ra | — | —[b] | — | — | — | — | — | — | — | — |
| $^{227}$Ac | — | — | — | — | — | — | — | — | — | — |
| $^{228}$Ra | — | — | — | — | — | — | — | — | — | — |
| $^{229}$Th | — | — | — | — | — | — | — | — | — | — |
| $^{231}$Pa | — | —[b] | —[b] | —[b] | —[b] | —[b] | — | — | — | — |

**Table 3-16b. 241-C Tank Farm Residual Inventory 95% Confidence Interval Estimates for Retrieved Tanks with Post-Retrieval Sampling. (3 sheets)**

| Tanks Retrieved (95% Confidence Interval with post-retrieval residual data)[a] | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **241-C-103** | **241-C-104** | **241-C-106** | **241-C-108** | **241-C-109** | **241-C-110** | **241-C-201** | **241-C-202** | **241-C-203** | **241-C-204** |
| $^{230}$Th[c] | —[b] | —[b] | 1.45E-03 | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] |
| $^{232}$Th | 2.36E-04 | 7.21E-03 | 7.68E-04 | 1.99E-05 | 1.32E-05 | -- | 7.76E-06 | 7.75E-06 | 4.27E-06 | 2.52E-05 |
| $^{232}$U | — | — | — | — | — | — | — | — | — | — |
| $^{233}$U | 6.95E-03 | —[b] | 2.36E-03 | —[b] | —[b] | —[b] | 2.03E-07 | —[b] | —[b] | —[b] |
| $^{234}$U | 1.84E-02 | 6.08E-01 | 1.21E-03 | 4.72E-02 | —[b] | 3.80E-03 | 4.27E-04 | 4.44E-02 | 1.41E-01 | 1.07E-01 |
| $^{235}$U | 8.69E-04 | 2.99E-02 | 5.16E-05 | 2.20E-03 | 5.93E-04 | 1.53E-04 | 6.22E-09 | 1.75E-03 | 5.67E-03 | 4.26E-03 |
| $^{236}$U | 4.58E-04 | 7.30E-03 | 2.40E-05 | 5.12E-04 | 1.75E-04 | 3.72E-05 | 1.12E-07 | 4.90E-04 | 1.06E-03 | 6.57E-04 |
| $^{237}$Np | 2.52E+01 | —[b] | 1.03E-01 | —[b] | —[b] | 1.43E-03 | 7.33E+00 | 5.02E+00 | —[b] | 5.61E+01 |
| $^{238}$Pu | 2.19E+00 | 1.06E+00 | —[b] | 4.85E-03 | 2.12E-02 | 2.20E-02 | —[b] | —[b] | —[b] | —[b] |
| $^{238}$U | 2.01E-02 | 8.57E-01 | 1.30E-03 | 4.97E-02 | 1.41E-02 | — | 2.30E-08 | 4.00E-02 | 1.29E-01 | 1.01E-01 |
| $^{239}$Pu | 7.26E+00 | 9.01E+00 | 2.24E+01 | 7.83E-01 | 6.03E-01 | 1.69E+00 | 2.76E+01 | 1.63E+01 | 7.34E-01 | 1.23E-02 |
| $^{240}$Pu | 1.57E+00 | 2.71E+00 | 4.83E+00 | 8.52E-02 | 6.56E-02 | 1.85E-01 | 5.95E+00 | 3.52E+00 | 1.58E-01 | 2.64E-03 |
| $^{241}$Am | 6.90E+00 | 1.67E+01 | 8.13E+01 | 1.18E+00 | 4.41E-01 | 6.67E-02 | 4.06E+00 | 1.39E+00 | 4.16E-02 | 3.93E-03 |
| $^{241}$Pu | 3.08E+00 | 1.90E+01 | 2.04E+01 | 6.63E-02 | 6.05E-01 | 4.62E-01 | 1.10E+01 | 7.10E+00 | 3.71E-01 | 6.17E-03 |
| $^{242}$Cm | —[b] | 5.86E-02 | — | —[b] | —[b] | —[b] | — | —[b] | —[b] | —[b] |
| $^{242}$Pu | — | 3.54E-02 | — | 1.18E-06 | —[b] | 2.57E-06 | — | — | — | — |
| $^{243}$Am | — | — | — | — | — | — | — | — | — | — |
| $^{243}$Cm | 5.32E-02 | 8.10E-03 | 6.30E-01 | —[b] | —[b] | —[b] | 2.92E-02 | —[b] | —[b] | 2.41E-05 |
| $^{244}$Cm | 1.06E+00 | 1.48E-01 | 1.20E+01 | —[b] | —[b] | —[b] | 5.57E-01 | —[b] | —[b] | 4.78E-04 |

**Table 3-16b. 241-C Tank Farm Residual Inventory 95% Confidence Interval Estimates for Retrieved Tanks with Post-Retrieval Sampling. (3 sheets)**

| Tanks Retrieved (95% Confidence Interval with post-retrieval residual data)[a] | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **241-C-103** | **241-C-104** | **241-C-106** | **241-C-108** | **241-C-109** | **241-C-110** | **241-C-201** | **241-C-202** | **241-C-203** | **241-C-204** |
| $^{3}H$ | —[b] | —[b] | —[b] | —[b] | —[b] | 2.46E-03 | —[b] | —[b] | —[b] | —[b] |
| $^{59}Ni$ | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] |
| $^{60}Co$ | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] |
| $^{63}Ni$ | 2.26E+01 | 2.60E+02 | 8.78E+01 | 3.69E+00 | 1.08E+00 | 5.38E-01 | 1.27E+00 | 2.40E-01 | 6.90E-02 | 1.86E-02 |
| $^{79}Se$ | —[b] | —[b] | —[b] | 2.15E-03 | —[b] | —[b] | —[b] | —[b] | —[b] | —[b] |
| $^{90}Sr$ | 9.73E+03 | 9.74E+03 | 5.75E+04 | 1.77E+03 | 2.99E+03 | 3.69E+03 | 2.30E+02 | 3.60E+02 | 2.11E+00 | 1.29E+02 |
| $^{90}Y$ | 9.73E+03 | 9.74E+03 | 5.75E+04 | 1.77E+03 | 2.99E+03 | 3.69E+03 | 2.30E+02 | 3.60E+02 | 2.11E+00 | 1.29E+02 |
| $^{93m}Nb$ | — | — | — | — | — | — | — | — | — | — |
| $^{93}Zr$ | — | — | — | — | — | — | — | — | — | — |
| $^{99}Tc$ | 5.37E-02 | 4.65E-01 | 2.22E-01 | 6.12E-02 | 1.10E-02 | 7.08E-02 | 4.78E-03 | 3.88E-03 | 3.97E-03 | 4.03E-03 |

Source: RPP-RPT-42323, "Hanford C-Farm Tank and Ancillary Equipment Residual Waste Inventory Estimates."

[a] Analytical data as of September 1, 2014 Best-Basis Inventory (BBI) constituents only, includes tank 241-C-106 for which retrieval completion is under review. 95% confidence interval = Mean + 2 × Standard Deviation (Closure mean for tanks with closure reports, BBI mean for C-101, C-107 and C-112: no closure report). 95% confidence intervals are not included for constituents with concentrations below analytical detection limits.

[b] Concentration less than analytical detection limit.

[c] Thorium-230 is not a standard BBI constituent, but is included for Performance Assessment model estimates.

Radionuclides are decayed to January 1, 2020 for 241-C Tank Farm closure assessments.

**Table 3-17a. 241-C Tank Farm Residual Inventory Lower Bound and Upper Bound Estimates for Tanks Undergoing Retrieval.**

| | BBI – Upper Bound Estimate for Tanks not Retrieved as of September 1, 2014 * | | | HTWOS – Lower Bound Estimate for Tanks not Retrieved (assumes 360 $ft^3$ in tanks after retrieval) * | | |
|---|---|---|---|---|---|---|
| | **241-C-102** | **241-C-105** | **241-C-111** | **241-C-102** | **241-C-105** | **241-C-111** |
| Residual Volume (kL [kgal]) | 405 (107) | 500 (132) | 132 (34.9) | 10.2 (2.69) | 10.2 (2.69) | 10.2 (2.69) |
| Total Chemicals (kg) | 2.28E+05 | 2.86E+05 | 8.34E+04 | 7.51E+03 | 7.55E+03 | 1.017E+04 |
| Al | 9.45E+04 | 1.55E+05 | 1.60E+04 | 5.29E+03 | 5.14E+03 | 3.51E+03 |
| Bi | 8.23E+02 | 3.72E+02 | 1.55E+03 | 4.53E+01 | 1.09E+01 | 3.52E+02 |
| Ca | 2.25E+03 | 1.98E+03 | 2.20E+03 | 1.22E+02 | 6.49E+01 | 5.02E+02 |
| Cl | 6.09E+02 | 3.10E+02 | 2.21E+02 | 2.62E-03 | 9.07E-04 | 2.76E-04 |
| Cr | 2.19E+02 | 3.85E+02 | 7.33E+01 | 1.13E+01 | 2.42E+00 | 1.25E+01 |
| F | 1.41E+03 | 8.23E+02 | 8.07E+02 | 6.06E-03 | 2.41E-03 | 1.01E-03 |
| Fe | 5.98E+03 | 4.08E+03 | 7.53E+03 | 3.37E+02 | 1.35E+02 | 1.72E+03 |
| Hg | 2.06E+00 | 5.23E+00 | 4.69E+01 | 7.55E-02 | 1.53E-05 | 5.83E-05 |
| K | 4.08E+02 | 8.60E+02 | 1.87E+02 | 7.85E+00 | 1.86E+01 | 9.32E+00 |
| La | 4.01E+01 | 2.73E+00 | 5.68E+01 | 2.26E+00 | 9.05E-02 | 1.30E+01 |
| Mn | 5.10E+02 | 1.90E+03 | 4.68E+01 | 2.86E+01 | 6.22E+01 | 1.06E+01 |
| Na | 3.60E+04 | 3.81E+04 | 1.03E+04 | 4.30E+02 | 5.80E+02 | 2.42E+02 |
| Ni | 2.18E+03 | 1.66E+03 | 2.65E+03 | 1.20E+02 | 5.47E+01 | 6.05E+02 |
| $NO_2$ | 6.46E+03 | 6.73E+03 | 5.50E+03 | 2.78E-02 | 1.97E-02 | 6.86E-03 |
| $NO_3$ | 2.22E+04 | 8.14E+03 | 1.47E+04 | 9.54E-02 | 2.38E-02 | 1.83E-02 |
| Pb | 5.47E+02 | 3.59E+02 | 7.65E+02 | 2.84E+01 | 9.07E+00 | 1.75E+02 |
| $PO_4$ | 5.58E+03 | 6.01E+03 | 1.20E+04 | 6.12E+01 | 1.76E-02 | 1.37E+03 |
| Si | 1.20E+04 | 3.09E+04 | 1.42E+03 | 5.49E+02 | 1.02E+03 | 1.83E+02 |
| $SO_4$ | 2.45E+03 | 2.92E+03 | 1.26E+03 | 7.21E+00 | 8.55E-03 | 1.57E-03 |
| Sr | 5.24E+01 | 1.43E+02 | 3.58E+01 | 2.38E+00 | 4.59E+00 | 7.49E+00 |
| TIC as $CO_3$ | 2.57E+04 | 1.31E+04 | 3.47E+03 | 5.80E+01 | 1.18E+02 | 7.91E+02 |
| TOC | 6.32E+02 | 4.31E+03 | 1.46E+02 | 2.18E+01 | 8.78E+01 | 2.05E+01 |
| UTOTAL | 5.27E+03 | 7.63E+03 | 2.36E+03 | 2.93E+02 | 2.39E+02 | 5.38E+02 |
| Zr | 1.75E+03 | 1.62E+02 | 3.02E+01 | 9.46E+01 | 5.29E+00 | 6.49E+00 |

Source: RPP-RPT-42323, "Hanford C-Farm Tank and Ancillary Equipment Residual Waste Inventory Estimates."

*Inventory estimates based on retrievals through September 1, 2014 for tank 241-C-102, 241-C-105, and 241-C-111. These would be the residual inventories if no additional waste was retrieved from these tanks after September 1, 2014. Note: Based on retrieval results for other tanks and in-process results for these tanks, it appears that the retrieval goal of 360 $ft^3$ or less will not be met for these tanks. The base case reflects the assumed retrieval end state based on retrieval performance to date.

BBI = Best-Basis Inventory
HTWOS = Hanford Tank Waste Operations Simulator
TIC = Total inorganic carbon
TOC = Total organic carbon

**Table 3-17b. 241-C Tank Farm Residual Inventory Lower Bound and Upper Bound Estimates for Tanks Undergoing Retrieval. (2 sheets)**

| | BBI – Upper Bound Estimate for Tanks not Retrieved as of September 1, 2014 [a] | | | HTWOS – Lower Bound Estimate for Tanks not Retrieved (assumes 360 $ft^3$ in tanks after retrieval) [a] | | |
|---|---|---|---|---|---|---|
| | **241-C-102** | **241-C-105** | **241-C-111** | **241-C-102** | **241-C-105** | **241-C-111** |
| Residual Volume (kL [kgal]) | 405 (107) | 500 (132) | 132 (34.9) | 10.2 (2.69) | 10.2 (2.69) | 10.2 (2.69) |
| Total Radionuclides (Ci)[b] | 2.75E+04 | 7.02E+05 | 6.24E+05 | 9.19E+02 | 2.28E+04 | 1.39E+05 |
| $^{106}Ru$ | 1.13E-12 | 7.04E-15 | 7.13E-10 | 1.71E-13 | 2.33E-16 | 1.63E-10 |
| $^{113m}Cd$ | 3.24E-01 | 6.10E-01 | 5.99E-02 | 1.78E-02 | 1.30E-02 | 1.22E-02 |
| $^{125}Sb$ | 2.27E-04 | 3.01E-05 | 1.37E-03 | 1.27E-05 | 8.84E-07 | 3.12E-04 |
| $^{126}Sn$ | 3.54E-03 | 3.05E-03 | 6.72E-03 | 1.83E-04 | 7.72E-05 | 1.53E-03 |
| $^{129}I$ | 7.89E-02 | 9.30E-02 | 1.41E-02 | 2.56E-03 | 2.72E-07 | 1.75E-08 |
| $^{134}Cs$ | 1.09E-05 | 1.58E-07 | 1.42E-06 | 1.54E-07 | 4.81E-09 | 2.02E-12 |
| $^{137}Cs$ | 6.08E+03 | 5.29E+04 | 7.14E+03 | 8.07E+01 | 1.52E+03 | 8.40E-03 |
| $^{137m}Ba$ | 5.43E+03 | 4.71E+04 | 6.36E+03 | 8.07E+01 | 1.52E+03 | 8.40E-03 |
| $^{14}C$ | 4.89E-01 | 5.05E-01 | 1.04E-01 | 9.88E-04 | 5.54E-04 | 1.31E-07 |
| $^{151}Sm$ | 1.73E+01 | 2.46E+01 | 6.39E+02 | 9.72E-01 | 8.14E-01 | 1.46E+02 |
| $^{152}Eu$ | 2.24E-03 | 1.16E-03 | 5.38E-02 | 1.26E-04 | 3.85E-05 | 1.23E-02 |
| $^{154}Eu$ | 2.42E+00 | 4.86E-02 | 2.41E+00 | 1.36E-01 | 1.60E-03 | 5.50E-01 |
| $^{155}Eu$ | 4.66E-01 | 6.32E-03 | 3.70E-01 | 2.62E-02 | 2.09E-04 | 8.45E-02 |
| $^{226}Ra$ | 5.21E-06 | 1.66E-06 | 4.51E-06 | 2.88E-07 | 5.46E-08 | 1.03E-06 |
| $^{227}Ac$ | 2.90E-01 | 5.38E-06 | 1.82E-05 | 1.93E-02 | 4.89E-07 | 1.91E-05 |
| $^{228}Ra$ | 9.63E-02 | 2.45E-12 | 6.54E-12 | 3.64E-01 | 5.17E-12 | 1.14E-10 |
| $^{229}Th$ | 1.90E-01 | 1.30E-09 | 3.56E-09 | 1.06E-02 | 4.06E-11 | 8.12E-10 |
| $^{231}Pa$ | 3.77E-02 | 6.83E-06 | 4.99E-05 | 2.12E-03 | 2.23E-07 | 1.07E-05 |
| $^{232}Th$ | 4.08E-01 | 1.04E-11 | 2.77E-11 | 2.29E-02 | 3.25E-13 | 7.14E-12 |
| $^{232}U$ | 5.10E-01 | 8.97E-05 | 2.22E-05 | 2.83E-02 | 2.80E-06 | 5.06E-06 |
| $^{233}U$ | 3.91E+01 | 5.22E-06 | 4.80E-05 | 2.17E+00 | 1.63E-07 | 1.10E-05 |
| $^{234}U$ | 2.04E+00 | 2.48E+00 | 7.74E-01 | 1.13E-01 | 7.77E-02 | 1.77E-01 |
| $^{235}U$ | 7.68E-02 | 1.06E-01 | 3.37E-02 | 4.27E-03 | 3.33E-03 | 7.70E-03 |
| $^{236}U$ | 2.58E-02 | 5.37E-02 | 1.32E-02 | 1.43E-03 | 1.68E-03 | 3.02E-03 |
| $^{237}Np$ | 9.45E-04 | 2.01E-03 | 3.32E-03 | 5.16E-05 | 6.30E-05 | 7.58E-04 |

**Table 3-17b. 241-C Tank Farm Residual Inventory Lower Bound and Upper Bound Estimates for Tanks Undergoing Retrieval. (2 sheets)**

| | BBI – Upper Bound Estimate for Tanks not Retrieved as of September 1, 2014 [a] | | | HTWOS – Lower Bound Estimate for Tanks not Retrieved (assumes 360 ft$^3$ in tanks after retrieval) [a] | | |
|---|---|---|---|---|---|---|
| | 241-C-102 | 241-C-105 | 241-C-111 | 241-C-102 | 241-C-105 | 241-C-111 |
| $^{238}$Pu | 2.64E+01 | 7.79E+00 | 1.70E+00 | 1.48E+00 | 2.58E-01 | 3.89E-01 |
| $^{238}$U | 1.76E+00 | 2.54E+00 | 7.88E-01 | 9.78E-02 | 7.97E-02 | 1.80E-01 |
| $^{239}$Pu | 1.16E+03 | 5.49E+02 | 9.45E+01 | 6.49E+01 | 1.81E+01 | 2.16E+01 |
| $^{240}$Pu | 2.77E+02 | 1.08E+02 | 1.85E+01 | 1.55E+01 | 3.57E+00 | 4.21E+00 |
| $^{241}$Am | 3.50E+02 | 2.95E+02 | 8.32E+01 | 2.12E+01 | 1.00E+01 | 1.94E+01 |
| $^{241}$Pu | 8.68E+02 | 1.82E+02 | 3.54E+01 | 4.87E+01 | 6.01E+00 | 8.06E+00 |
| $^{242}$Cm | 2.09E-02 | 1.06E-02 | 6.21E-02 | 1.15E-03 | 3.50E-04 | 1.41E-02 |
| $^{242}$Pu | 1.60E-02 | 3.26E-03 | 6.54E-04 | 9.00E-04 | 1.08E-04 | 1.49E-04 |
| $^{243}$Am | 1.47E-02 | 6.99E-03 | 1.15E-02 | 7.93E-04 | 5.83E-05 | 2.62E-03 |
| $^{243}$Cm | 1.13E-03 | 9.47E-05 | 1.82E-03 | 6.22E-05 | 3.14E-06 | 4.13E-04 |
| $^{244}$Cm | 2.34E-02 | 1.62E-03 | 3.26E-02 | 1.28E-03 | 5.36E-05 | 7.39E-03 |
| $^{3}$H | 5.00E+00 | 4.25E+01 | 2.58E+00 | 2.15E-05 | 1.24E-04 | 3.22E-06 |
| $^{59}$Ni | 2.93E+00 | 4.58E+00 | 1.40E+00 | 1.62E-01 | 1.51E-01 | 3.20E-01 |
| $^{60}$Co | 3.90E+00 | 7.10E+00 | 1.03E-01 | 2.14E-01 | 2.27E-01 | 2.35E-02 |
| $^{63}$Ni | 2.46E+02 | 3.76E+02 | 1.13E+02 | 1.36E+01 | 1.24E+01 | 2.57E+01 |
| $^{79}$Se | 2.03E-03 | 1.57E-03 | 3.53E-03 | 1.60E-06 | 4.59E-09 | 4.80E-09 |
| $^{90}$Sr | 6.47E+03 | 3.00E+05 | 3.05E+05 | 2.94E+02 | 9.86E+03 | 6.95E+04 |
| $^{90}$Y | 6.47E+03 | 3.00E+05 | 3.05E+05 | 2.94E+02 | 9.86E+03 | 6.95E+04 |
| $^{93m}$Nb | 3.89E-02 | 1.51E-02 | 9.78E-02 | 1.10E-02 | 2.41E-03 | 1.04E-01 |
| $^{93}$Zr | 7.82E-02 | 2.88E-02 | 1.81E-01 | 4.22E-03 | 9.39E-04 | 3.90E-02 |
| $^{99}$Tc | 3.02E-01 | 8.14E+01 | 2.19E+00 | 3.56E-03 | 9.43E-01 | 5.49E-02 |

Source: RPP-RPT-42323, "Hanford C-Farm Tank and Ancillary Equipment Residual Waste Inventory Estimates."

[a] Inventory estimates based on retrievals through September 1, 2014 for tank 241-C-102, 241-C-105, and 241-C-111. These would be the residual inventories if no additional waste was retrieved from these tanks after September 1, 2014. Note: Based on retrieval results for other tanks and in-process results for these tanks, it appears that the retrieval goal of 360 ft$^3$ or less will not be met for these tanks. The base case reflects the assumed retrieval end state based on retrieval performance to date.

[b] Radionuclides are decayed to January 1, 2020 for 241-C Tank Farm closure assessments.

BBI = Best-Basis Inventory HTWOS = Hanford Tank Waste Operations Simulator

The HTWOS model was used to estimate residual inventories for the lower bound if tanks are retrieved to the threshold goal of 360 $ft^3$. The HTWOS model simulates retrieval operations considering the mobility and composition of waste and retrieval fluids to estimate the waste residual inventories after retrieval. As such, it provides a more rigorous approach to estimate residual inventories compared to estimates based on simple percentage of waste currently in the tanks and differentiates between soluble and insoluble constituents. However, if only a portion of the waste is retrieved and if soluble constituents are not washed from the waste, the inventories of soluble and insoluble constituents may be much different than that predicted by the HTWOS model.

The upper bound inventory was the BBI inventory on September 1, 2014 for each tank; this would be the residual inventory if no additional waste can be retrieved from these tanks. The BBI waste volumes and concentrations were used to calculate upper bound inventories for these tanks.

A base case estimate for the volume and concentration of residual waste that will remain after retrieval was also made based on characteristics of the waste and retrieval performance to date for these tanks. Base case estimates are presented in Table 3-14 and discussed in Section 3.2.2.4.3.

**3.2.2.3.4 Residual Inventory Estimates for Ancillary Equipment.** Because little information is available for waste in catch tanks and pipelines, it was assumed that the composition of waste in pipelines and catch tanks is the same as the average composition of waste in the BBI for C Farm SSTs. Waste volumes for C-301 catch tank and the 244-CR vault were based on measurements. However, the amount of waste remaining in pits, diversion boxes and pipelines is unknown. Based on operations information, most of the waste has been flushed from the pits, diversion boxes, and pipelines. Hence, the residual waste volume is expected to be small compared to catch tank and SST post-retrieval residuals. A volume estimate for pits and diversion boxes was developed based on the surface area of pits and diversion boxes in C Farm. A volume estimate for pipelines was developed based on the length and size of pipelines in C Farm.

The inventory estimates for the ancillary equipment are provided in Table 3-15.

**3.2.2.4 Inventory Uncertainty.** Table 3-18 shows different sources of uncertainties that must be considered for inventory estimates for retrieved and non-retrieved tanks and different types of ancillary equipment. The following sections address each of these uncertainties.

**3.2.2.4.1 Inventory Estimates for Retrieved Tanks with Post-Retrieval Sample Analyses.** The primary sources of uncertainty for retrieved tanks with post-retrieval samples and analysis are analytical uncertainty and residual waste volume uncertainty. Post-retrieval samples were collected in accordance with the SST Component Closure DQO (RPP-23403). Samples were collected at multiple locations in the residual waste in an attempt to provide a representative sample. Analytical uncertainty estimates are determined for each constituent and sample analyzed considering precision and accuracy of samples based on variability between primary and duplicate samples, and other quality controls specified in the DQO and sampling and

analysis plan. Differences between sample results from two or more locations provide a measure of spatial variability and representativeness of the tank samples.

**Table 3-18. Inventory Uncertainties.**

| Facility | Uncertainties |
|---|---|
| Retrieved tanks with post-retrieval sample analyses | • Analytical uncertainties.<br>• Waste volume measurement uncertainties. |
| Retrieved tanks without post-retrieval analyses | • Pre-retrieval analytical sample uncertainties.<br>• Process knowledge uncertainty for constituents without sample analysis.<br>• Uncertainty in waste composition changes after retrieval.<br>• Waste volume measurement uncertainties. |
| Tanks undergoing retrieval | • Uncertainty in waste volume that will be retrieved.<br>• Pre-retrieval analytical sample uncertainties.<br>• Process knowledge uncertainty for constituents without sample analysis.<br>• Uncertainty in waste composition changes after retrieval. |
| Catch Tank 241-C-301 and 244-CR Process Tank Vault | • Waste volume measurement uncertainties.<br>• Uncertainty in waste volume that will be retrieved.<br>• Limited sample data, inventories based on average composition of residual tank waste samples. |
| Pits, Diversion Boxes, and Pipelines | • Uncertainty in waste volume remaining in pipelines.<br>• Uncertainty in the number and length of pipelines.<br>• No sample data and limited process knowledge data. Inventories based on the average composition of residual tank waste samples. |

The median sample-based relative standard deviation (RSD) for the 10 tanks sampled was ~0.17. Radionuclides and chemical constituents with low concentrations tend to have higher RSDs than those with high concentrations. The RSDs by constituent for C Farm tanks are included in applicable retrieval data reports and in Appendix D.1 and D.2 of RPP-RPT-42323. Based on tank sample data and sample analytical reports, mean concentrations, RSDs of the mean and 95% upper confidence limit (UCL) values were calculated for the constituents in each waste phase. As shown in Appendix D.1, for some constituents analytical results were below detection levels for the method used. Nominal concentration estimates for these constituents are based on the detection limit or other estimates, whichever is lower. Upper bound inventories (Table 3-16) were not calculated for constituents with concentrations lower than analytical detection limits.

Waste volume measurements for retrieved tanks were performed using the CCMS. In-tank videos of SSTs were recorded following retrieval. The videos document the location of residual solids and liquid waste remaining in the tank. Using CAD 3-D software, a 3-D model of the SST was built, and video of the tank waste was reviewed. Knowledge of tank construction, plate lengths and heights, the size of debris in the tanks, and other measurable features were used as a guide to estimate the area and height of waste remaining in a tank. Based on CCMS estimates of sand piles with known volumes, a regression line was calculated to determine uncertainty for CCMS measurements. The regression equation was changed over time as additional data was obtained. Uncertainty equations and requirements for CCMS are specified in RPP-23403.

Tables 3-19 and 3-20 and Appendix D of RPP-RPT-42323 show volume uncertainty estimates for tanks retrieved to date.

**Table 3-19. 241-C Tank Farm Post-Retrieval Waste Volume Estimates (cubic feet).**

| Component | 241-C-103[a] | 241-C-106[b] | 241-C-201[c] | 241-C-202[d] | 241-C-203[e] | 241-C-204[f] |
|---|---|---|---|---|---|---|
| In dish bottom | 266 | 348 | 10.7 | 8.5 | 13.4 | 9.6 |
| In tank equipment | 3.6 | 4.8 | 3.4 | 6.1 | 0 | 3.4 |
| On stiffener rings and walls | 68.4 | 17 | 5.1 | 5.1 | 5.1 | 5.3 |
| Total | 338 | 370 | 19.2 | 19.7 | 18.5 | 18.3 |
| 95% upper confidence limit | 351[g] | 466[h] | 20.5 | 20.9 | 19.9 | 19.6 |

[a] RPP-RPT-33060, "Retrieval Data Report for Single-Shell Tank 241-C-103."

[b] RPP-20577, "Stage II Retrieval Data Report for Single-Shell Tank 241-C-106," and RPP-19866, "Calculation for the Post-Retrieval Waste Volume Determination for Tank 241-C-106."

[c] RPP-RPT-30181, "Retrieval Data Report for Single-Shell Tank 241-C-201."

[d] RPP-RPT-29095, "Retrieval Data Report for Single-Shell Tank 241-C-202."

[e] RPP-RPT-26475, "Retrieval Data Report for Single-Shell Tank 241-C-203."

[f] RPP-RPT-34062, "Retrieval Data Report for Single-Shell Tank 241-C-204."

[g] In accordance with RPP-23403, "Single-Shell Tank Component Closure Data Quality Objectives," Rev. 3, 1.04 × dish bottom volume + 0.85 + Equip + Rings + Wall.

[h] In accordance with RPP-13889, "Tank 241-C-106 Component Closure Action Data Quality Objectives."

**3.2.2.4.2 Inventory Estimates for Retrieved Tanks without Post-Retrieval Sample Analyses.** For tanks without post-retrieval analysis or for which analysis is in progress (C-101, C-107), current inventory estimates are based on pre-retrieval sample results, sample-based templates, or process knowledge. Sample results after bulk retrieval are included in the BBI for tank C-112; however, the closure inventory report and retrieval data report with the complete set of inventories and analytical results for constituents specified in the DQO was not available as of September 1, 2014.

For tanks C-101 and C-107, current BBI concentration estimates take no credit for soluble analytes that may have been washed out of the waste during retrieval processes. However, because the volume of waste remaining in these tanks was well above the retrieval goal of 10.2 $m^3$ (360 $ft^3$), it is unknown what portion of the soluble analytes were removed. Pre-retrieval sample results were not available for many of the constituents specified in the BBI and sample-based templates or process knowledge estimates were developed to fill these gaps.

Sample-based template values were developed from a review of sample data for tanks with similar process histories and at least one waste layer from the same waste process (i.e., same waste type). Table 3-21 lists waste type groupings for waste transferred to C Farm tanks. The decision to include tank data in a template was based on tank transfer records indicating the expected waste type and depth in a tank and a comparison with expected analytical

concentrations for a given waste type, and is documented in each update of the BBI for that tank. Although sample-based template RSDs fall between 0 and 1.0, template RSDs can be much larger (as large as 17.0 for uranium; most values are 5.0 or lower). These results have large uncertainties because some are based on tank averages which have large variability with few data points. Waste type templates and uncertainties are described in RPP-8847, "Best-Basis Inventory Template Compositions of Common Tank Waste Layers."

**Table 3-20. 241-C Tank Farm Post-Retrieval Waste Volume Estimates (cubic feet).**

| Component | 241-C-101[a] | 241-C-104[b] | 241-C-108[c] | 241-C-109[d] | 241-C-110[e] | 241-C-112[f] |
|---|---|---|---|---|---|---|
| In dish bottom | 511 | 190 | 305 | 192 | 224 | 1,657 |
| In tank equipment | 0 | 0 | 0 | 1.9 | 0 | 0 |
| On stiffener rings and walls | 156 | 26.6 | 91.9 | 35.7 | 13.4 | 42.9 |
| Total | 667 | 217 | 397 | 230 | 237 | 1,700 |
| Total Residual Volume[g] | 767 | 254 | 456 | 267 | 281 | 1,700 |

[a] RPP-CALC-56434, "Post-Retrieval Camera/CAD Modeling System Waste Volume Estimate for Tank 241-C-101."
[b] RPP-CALC-54284, "Post-Hard Heel Retrieval Camera/CAD Modeling System Waste Volume Estimate for Tank 241-C-104."
[c] RPP-CALC-54266, "Post-Hard Heel Retrieval Camera/CAD Modeling System Waste Volume Estimate for Tank 241-C-108."
[d] RPP-CALC-54759, "Post-Hard Heel Retrieval Camera/CAD Modeling System Waste Volume Estimate for Tank 241-C-109."
[e] RPP-CALC-56399, "Post-Hard Heel Retrieval Camera/CAD Modeling System Waste Volume Estimate for Tank 241-C-110."
[f] RPP-CALC-56856, "Estimated Waste Volume Remaining in Single Shell Tank 241-C-112 after Hard Heel Retrieval."
[g] In accordance with RPP-23403, "Single-Shell Tank Component Closure Data Quality Objectives," Rev. 5, 1.195 × dish bottom volume + 0.27 + Equip + Rings + Wall.

**Table 3-21. Sample-Based Template Waste Type Groups for 241-C Tank Farm.**

| Waste Type Group | Common Factors to Group |
|---|---|
| **1C**, 2C, 1CFeCN | Bismuth phosphate bearing waste generated by decontamination of the bismuth phosphate process plutonium product. |
| **CWP1, CWP2**, CWR1 | Wastes generated by the decladding of aluminum clad reactor fuel. |
| **TBP**, PFeCN, **TFeCN** | Wastes resulting from the retrieval of metal waste for uranium recovery (typically high fission product waste). |

Note: Bold text for waste types in 241-C Tank Farm.

1CFeCN = Ferrocyanide sludge from in-plant scavenging of T-Plant 1C waste (without coating waste)
2C = Second cycle bismuth phosphate decontamination waste
CWR1 = Reduction-Oxidation (S Plant) aluminum cladding waste
PFeCN = Ferrocyanide sludge from tributyl phosphate (TBP) in-plant scavenged supernate and co-disposed TBP sludge

Due to the uncertainty associated with modeling, process knowledge model results are generally only used in the BBI in the absence of analytical data or waste sample-based templates for a given waste type. The process knowledge results are model results from the Hanford Defined Waste Model (HDW) Rev. 5. In the 1990s, Steve Agnew of the Los Alamos National Laboratory developed the HDW model (WHC-SD-WM-TI-632, "Hanford Defined Wastes: Chemical and Radionuclide Compositions"). The HDW Rev. 4 uses radionuclide fuel production output from the Oak Ridge Isotope Generation and Depletion Code 2 (ORIGEN2) model (RPP-13489, "Activity of Fuel Batches Processed Through Hanford Separations Plants, 1944 Through 1989"), then models fuel transfers through various processing steps to estimate waste types and composition for each Hanford tank through 1994. In 2004, the ORIGEN2 and HDW models were updated and with new data and methods (RPP-19822, Rev. 0-A). The scope of HDW Rev. 5 was limited to estimating waste type compositions, because sample data and volume measurements appeared to provide better estimates for distribution of the waste types between the tanks and the volume of waste in the tanks. The uncertainty in HDW waste type composition estimates has not been quantified. RPP-26744 shows the range of variability for different waste types and constituents based on reactor production variability as a function of time. Although this is only one of several potential sources of uncertainty, variability ranges by over an order of magnitude for some constituents.

**3.2.2.4.3 Inventory Estimates for Tanks Undergoing Retrieval.** The basis for a base case estimate for post-retrieval residual inventories varies for each of the three tanks remaining to be retrieved (C-102, C-105 and C-111). The largest uncertainty is how much waste can be retrieved and the extent to which soluble analytes (such as $^{99}$Tc) will be removed.

**Base Case Estimate of Inventory**. For purposes of modeling, the following subjective base case estimates were made for each of the three tanks based on retrieval results to-date and based on remaining waste properties.

**Tank C-102:** The initial waste retrieval performance information shows that for tank C-102, through August 2014 waste removal has been tracking as for other similar waste type tanks for which retrievals were completed to below 10.2 m$^3$ (360 ft$^3$). Therefore, achieving a final waste volume of 10.2 m$^3$ (360 ft$^3$) and using HTWOS model estimates for the residual inventory seems to be a reasonable assumption for this tank.

**Tank C-105:** Initial waste retrieval performance information for tank C-105 indicates that equipment and waste characteristics limit the performance of the designated retrieval technology (Mobile Arm Vacuum Retrieval System) and that other waste retrieval technologies (e.g., sluicing), or equipment modifications would be required to remove additional waste from the tank. Application of sluicing (particularly hot water sluicing) is expected to result in additional retrieval from tank C-105. The waste types and waste transfer history for tank C-105 are unique but there are some similarities to other C Farm tanks. In an effort to establish a residual waste volume that would be plausible, it is assumed that the quantity of waste remaining in tank C-105 will be similar to the quantity remaining in tank C-112, ~1,700 ft$^3$, 48 kL (~12,700 gal) (the maximum quantity remaining in any of the C Farm tanks retrieved as of September 2014).

**Tank C-111:** Waste retrieval performance data indicates that it will be difficult to remove any additional waste from tank C-111. The waste physical characteristics are such that negligible waste was removed during modified sluicing. Additional waste retrieval technologies, caustic and water dissolution, are planned. However, because of the hard, low-permeability waste layer remaining in tank C-111, little or none of the remaining waste may be removed by waste retrieval operations. Therefore, the BBI provides a reasonable volume estimate for tank C-111.

**Lower-bound Estimates of Inventory.** As a lower bound, the HTWOS inventory estimates can be used. The HTWOS estimate assumes the retrieval goal of 10.2 $m^3$ (360 $ft^3$) will be met. It also factors in wash/leach processes to estimate the composition of residuals after retrieval.

A general idea of how well HTWOS predicts tank waste residual inventories can be shown by comparing the 2002 HTWOS residual concentration estimates for tank C-103 with post-retrieval measurements for the tank (Table 3-22). On average, the HTWOS overestimated the measured chemical values for concentrations greater than $10^{-3}$ g/L ($1.34 \times 10^{-4}$ oz/gal) by a factor of ~3 and underestimated measured radionuclide concentrations > $10^{-7}$ Ci/L by a factor of ~0.7. In general, the HTWOS estimates were closer to measured values for constituents with higher concentrations.

**Table 3-22. Comparison of Hanford Tank Waste Operations Simulator Pre-Retrieval Concentration Estimates for Tank 241-C-103 Residuals with Post-Retrieval Sample Results. (2 sheets)**

| Constituent | Units | HTWOS 2002 Residual Waste Estimate | 2014 Residual Data | Ratio of HTWOS 2002/ 2014 Residuals |
|---|---|---|---|---|
| **Al** | g/L | 2.45E+01 | 3.79E+02 | 6.47E-02 |
| **Ca** | g/L | 4.68E-01 | 2.27E+00 | 2.06E-01 |
| **Cl** | g/L | 8.22E-02 | 2.03E-02 | 4.05E+00 |
| **Cr** | g/L | 1.23E-01 | 2.49E-01 | 4.93E-01 |
| **F** | g/L | 1.29E-01 | 1.69E-02 | 7.64E+00 |
| **Fe** | g/L | 2.00E+00 | 1.24E+01 | 1.61E-01 |
| **Hg** | g/L | 2.52E-02 | 1.11E-01 | 2.27E-01 |
| **K** | g/L | 8.22E-02 | 3.76E-01 | 2.19E-01 |
| **La** | g/L | 2.59E-02 | 1.90E-02 | 1.36E+00 |
| **Mn** | g/L | 5.98E-02 | 4.62E-01 | 1.30E-01 |
| **Na** | g/L | 3.26E+00 | 1.00E+01 | 3.25E-01 |
| **Ni** | g/L | 5.48E-01 | 4.79E-01 | 1.15E+00 |
| **$NO_2$** | g/L | 1.99E+00 | 5.04E-02 | 3.96E+01 |
| **$NO_3$** | g/L | 1.94E-01 | 9.10E-02 | 2.13E+00 |
| **Pb** | g/L | 8.01E-02 | 8.88E-01 | 9.02E-02 |

**Table 3-22. Comparison of Hanford Tank Waste Operations Simulator Pre-Retrieval Concentration Estimates for Tank 241-C-103 Residuals with Post-Retrieval Sample Results. (2 sheets)**

| Constituent | Units | HTWOS 2002 Residual Waste Estimate | 2014 Residual Data | Ratio of HTWOS 2002/ 2014 Residuals |
|---|---|---|---|---|
| **$PO_4$** | g/L | 3.95E-01 | 3.12E+00 | 1.27E-01 |
| **Si** | g/L | 4.46E+00 | 1.33E+01 | 3.36E-01 |
| **$SO_4$** | g/L | 3.27E-01 | 2.26E-01 | 1.45E+00 |
| **Sr** | g/L | 3.99E-03 | 2.52E-01 | 1.58E-02 |
| **TIC as $CO_3$** | g/L | 3.27E+00 | 1.76E+00 | 1.86E+00 |
| **TOC** | g/L | 1.03E+00 | 1.31E+00 | 7.91E-01 |
| **Zr** | g/L | 1.45E+00 | 1.39E+00 | 1.04E+00 |
| **$^{137}Cs$** | Ci/L | 9.55E-03 | 6.35E-02 | 1.50E-01 |
| **$^{14}C$** | Ci/L | 5.94E-07 | 7.30E-07 | 8.14E-01 |
| **$^{154}Eu$** | Ci/L | 2.13E-04 | 1.47E-04 | 1.45E+00 |
| **$^{155}Eu$** | Ci/L | 3.69E-05 | 4.57E-05 | 8.07E-01 |
| **$^{234}U$** | Ci/L | 2.71E-07 | 1.42E-06 | 1.91E-01 |
| **$^{238}Pu$** | Ci/L | 1.02E-05 | 1.36E-04 | 7.50E-02 |
| **$^{238}U$** | Ci/L | 2.78E-07 | 1.71E-06 | 1.62E-01 |
| **$^{241}Am$** | Ci/L | 5.46E-04 | 5.04E-04 | 1.08E+00 |
| **$^{241}Pu$** | Ci/L | 2.60E-04 | 1.88E-04 | 1.38E+00 |
| **$^{60}Co$** | Ci/L | 1.06E-05 | 1.91E-06 | 5.56E+00 |
| **$^{63}Ni$** | Ci/L | 4.93E-04 | 1.94E-03 | 2.54E-01 |
| **$^{90}Sr$** | Ci/L | 3.43E-01 | 7.08E-01 | 4.84E-01 |
| **$^{99}Tc$** | Ci/L | 4.20E-06 | 4.68E-06 | 8.97E-01 |

HTWOS = Hanford Tank Waste Operations Simulator
TIC = Total inorganic carbon
TOC = Total organic carbon

For all tanks retrieved, the HTWOS concentration estimates for total chemicals (kg/L) were a factor of 1.8 times higher than post-retrieval measurements for tank C-106 and 0 to 10 times lower for other tanks. The HTWOS concentration estimates for total radionuclides (Ci/L) were 2 to 35 times lower than post-retrieval measurements.

**Upper-bound Estimates of Inventory**. The BBI, showing the current inventories for these tanks, provides the best available information for an upper-bound estimate for tanks undergoing retrieval. This would reflect a residual waste volume if no additional waste can be retrieved from the tanks. The BBI waste concentrations for these tanks are based on pre-retrieval

measurements and pre-retrieval process knowledge. Current BBI concentration estimates take no credit for soluble analytes that may have been washed out of the waste during retrieval processes to-date.

#### 3.2.2.4.4 Residual Inventory in Ancillary Equipment.

**Residual Inventory Volume in Catch Tank 241-C-301 and 244-CR Process Tank Vault.** For the base case an assumption was made that 90% of the waste will be retrieved from these tanks. Whether more or less waste is retrieved is unknown. Therefore, as an upper bound it should be assumed that no retrieval occurs and the current waste volume will remain at closure.

Although the C-301 tanks were sampled, few sample data were obtained. An estimate of waste types and contents could be made based on waste transfer sources, but the correlation of sources to residual waste remaining in C-301 would be highly speculative. Furthermore, some or all of the waste may have been diluted for transfer. Therefore, a simplifying assumption was made that the composition of waste in tank C-301 and in the 244-CR vault tanks and sumps is similar to the average composition of residual waste samples from the C Farm SSTs. Although there is high uncertainty in this assumption, if the waste was more dilute than tank waste, the actual composition should be lower. Nevertheless, it is recommended that improved characterization of the C-301 catch tank and the 244-CR vault should be included in the RCA maintenance plan.

**Residual Inventory Volume in Pits, Diversion Boxes and Pipelines**. Sources of volume uncertainty include the number and length of pits, diversion boxes and pipelines. For pits and pipelines another uncertainty is the thickness of waste adsorbed and whether any other residual waste remains in the tank. The volume of waste expected to be in the pits and diversion boxes is very small compared to the pipelines, and as a result, uncertainty in the waste inventory is of negligible importance for the RCA. As a result, no uncertainty evaluations are recommended. For the waste pipelines base case, the volume is from RPP-PLAN-47559 and assumes all pipelines are only 5% full except for a plugged line and cascade lines, which are assumed to be completely full. Studies suggest that the pipelines may be less than 5% full; however, it is possible that some pipelines contain more waste.

**Waste Composition (Same as Catch Tank 241-C-301 and 244-CR Process Tank Vault).** The waste composition was assumed to be similar to post-retrieval tank residuals because, like a retrieved tank, the pits, diversion boxes and pipelines are flushed. It could be argued that the waste, especially in plugged pipelines, is more similar to waste in tanks before retrieval than after. However, post-retrieval residual waste compositions were assumed given the relatively small length of plugged lines compared to unplugged lines, uncertainty in assumptions about the applicability of pre- or post-retrieval average waste composition for pipelines, and the fact that more analytical data for many of the closure DQO constituents is only available for post-retrieved tanks.

# 4.0 COMPARISON OF TANK RESIDUALS WITH WAC 173-340 SOIL CLEANUP LEVELS

This section provides additional risk management information related to concentrations of constituents remaining in waste residuals at WMA C. This section fulfills a request by Ecology to provide a comparison of residual waste concentrations in tanks and ancillary equipment against soil cleanup levels (CULs) as defined in the MTCA cleanup regulation WAC 173-340.

Per WAC 173-340-740, for soil CULs based on human exposure via direct contact or other exposure pathways where contact with the soil is required to complete the pathway, the point of compliance shall be established in the soils throughout the site from the ground surface to 4.6 m (15 ft) bgs (Figure 2-1). Under a closed configuration, residual waste is at a depth greater than the 4.6 m (15 ft) bgs; as a result, the direct contact pathway is considered incomplete.

For soil CULs based on the protection of groundwater, the point of compliance shall be established in the soils throughout the site. Under a closed configuration, residual waste remaining in WMA C tanks would be contained within a grout-filled tank, a steel tank liner, and an underlying concrete pad, and would not be immediately available for leaching by infiltrating water. RPP-PLAN-47559 previously provided to Ecology the comparison of the constituents in the pipeline residuals against the CULs.

## 4.1 CONSTITUENTS EVALUATED

Chemical BBI constituents and RPP-23403 primary constituents are identified in Section 3.2.2 of this document. Residual concentrations for retrieved tanks and ancillary equipment are given in RPP-RPT-42323, Appendix D-1. As of September 2014, waste was retrieved from 13 of 16 SSTs in C Farm (C-101, C-103, C-104, C-106, C-107, C-108, C-109, C-110, C-112, C-201, C-202, C-203, and C-204) and was in progress for the remaining three tanks (C-102, C-105, and C-111). For 10 of the 13 tanks retrieved as of September 2014, post-retrieval sample-based inventories for standard chemical BBI constituents and primary chemical constituents identified in RPP-23403 are available. The mean value of post-retrieval sample-based inventories is used to estimate residual waste concentrations for ancillary equipment. For tanks C-101, C-107 and C-112, inventory estimates based on post-retrieval sample data are pending laboratory analysis and are not yet available. For these tanks, BBI inventory/constituent concentration estimates are based on pre-retrieval samples or templates.

For the three unretrieved and in-process tanks (C-102, C-105, and C-111), at minimum and maximum residual inventory, constituent concentration estimates were evaluated. The HTWOS model residual inventory estimates were used at a minimum residual volume of 10.2 $m^3$ (360 $ft^3$), and the BBI and current residual volume for each tank was used as the maximum volume.

## 4.2 CALCULATION OF MODEL TOXICS CONTROL ACT METHOD B AND METHOD C CLEANUP LEVELS

The direct contact unrestricted land use CULs are calculated using equations and input parameters described in WAC 173-340-740, subsection (3) "Method B soil cleanup levels for unrestricted land use." The Standard Method B soil CULs for unrestricted land use are based on soil ingestion (non-petroleum constituents). These levels were calculated for noncarcinogens and carcinogens using equations 740-1 and 740-2, respectively. Default exposure parameters for calculating the CULs are described in ECF-Hanford-10-0444, "Documentation of Standard Method B Soil Cleanup Levels for Unrestricted Land Use." Standard Method B soil CULs for unrestricted land used are based on an acceptable cancer risk level of $1 \times 10^{-6}$ for carcinogens or a hazard quotient (HQ) of 1 for noncarcinogens.

The direct contact industrial land use CULs are calculated using equations and input parameters described in WAC 173-340-745, "Soil Cleanup Standards for Industrial Properties," subsection (5) "Method C industrial soil cleanup levels," item (b) "Standard Method C industrial soil cleanup levels." The Standard Method C industrial soil CULs are based on soil ingestion (non-petroleum constituents). These levels were calculated for noncarcinogens and carcinogens using equations 745-1 and 745-2, respectively. Default exposure parameters for calculating the CULs are described in ECF-HANFORD-10-0453, "Calculation of Standard Method C Direct Contact Soil Cleanup Levels for Industrial Land for the 100 Areas and 300 Area Remedial Investigation/Feasibility Study Reports." Standard Method C soil CULs for industrial properties used are based on an acceptable cancer risk level of $1 \times 10^{-5}$ for carcinogens or an HQ of 1 for noncarcinogens. Table 4-1 summarizes the MTCA soil CULs.

Reference dose (RFD) and carcinogenic potency factors are determined using the recommended reference hierarchy as described in OSWER Directive 9285.7-53, "Human Health Toxicity values in Superfund Risk Assessment." Methodology, inputs, assumptions, and results of the calculations are described in ECF-Hanford-10-0444 and ECF-HANFORD-10-0453.

### 4.2.1 Model Toxics Control Act Method B and Method C Direct Contact Equations

The following represents the Standard Method B and Standard Method C direct contact soil CUL equations for noncarcinogens and carcinogens.

**4.2.1.1 Noncarcinogens.** The equation below is obtained from WAC 173-340-740(3)(iii)(B)(I), Equation 740-1 and WAC 173-340-745(5)(b), Equation 745-1.

$$Soil\ CUL\left(\frac{mg}{kg}\right) = \frac{RfD \times ABW \times UCF \times HQ \times AT_{nc}}{SIR \times AB1 \times EF \times ED}$$

Where:

$RfD$ = reference dose (mg/kg-day)
$ABW$ = average body weight (kg)
$UCF$ = unit conversion factor (mg/kg)

$HQ$ = hazard quotient (unitless)
$AT_{nc}$ = averaging time – noncarcinogens (years)
$SIR$ = soil ingestion rate (mg/day)
$AB1$ = gastrointestinal absorption fraction (unitless)
$EF$ = exposure frequency (unitless)
$ED$ = exposure duration (years).

**4.2.1.2 Carcinogens.** The equation below is obtained from WAC 173-340-740(3)(iii)(B)(II), Equation 740-2 and WAC 173-340-745(5)(b), Equation 745-2.

$$Soil\ CUL\left(\frac{mg}{kg}\right) = \frac{Risk \times ABW \times AT_c \times UCF}{CPF \times SIR \times AB1 \times ED \times EF}$$

Where:

$Risk$ = reference dose (mg/kg-day)
$ABW$ = average body weight (kg)
$AT_c$ = averaging time – carcinogens (years)
$UCF$ = unit conversion factor (mg/kg)
$CPF$ = carcinogenic potency factor (kg-day/mg)
$SIR$ = soil ingestion rate (mg/day)
$AB1$ = gastrointestinal absorption fraction (unitless)
$ED$ = exposure duration (years)
$EF$ = exposure frequency (unitless).

## 4.3 MODEL TOXICS CONTROL ACT THREE-PHASE SOIL CONCENTRATIONS PROTECTIVE OF GROUNDWATER

Soil concentrations for groundwater protection are calculated using equations and input parameters described in WAC 173-340-747, subsection (4) “Fixed parameter three-phase partitioning model.” Distribution coefficients ($K_d$s) were calculated for organic constituents using Equation 747-2. Default input parameters for calculating soil concentration protective of groundwater are described in ECF-HANFORD-10-0442, “Calculation of Nonradiological Soil Concentrations Protective of Groundwater Using the Fixed Parameter 3-Phase Equilibrium Partitioning Equation for the 100 Areas and 300 Area.” The protective groundwater concentration is multiplied by a dilution factor (DF) that represents the reduction of soil leachate concentration caused by mixing in the aquifer, and then a standard linear equilibrium soil/water partitioning equation is used to calculate a soil concentration corresponding to the adjusted groundwater concentration.

**Table 4-1. Summary of Model Toxics Control Act Cleanup Levels. (3 sheets)**

| Analyte | Soil Method B Unrestricted Land Use[a] | | Soil Method C Industrial Land Use[b] | | Soil Concentration Protective of Groundwater[c] (mg/kg) |
|---|---|---|---|---|---|
| | $10^{-6}$ Carcinogen (mg/kg) | Noncarcinogen (mg/kg) | $10^{-5}$ Carcinogen (mg/kg) | Noncarcinogen (mg/kg) | |
| **Best-Basis Inventory Analytes** | | | | | |
| Aluminum | — | 80,000 | — | 3.50E+06 | 480,064 |
| Bismuth | — | — | — | — | — |
| Calcium | — | — | — | — | — |
| Chlorine | — | — | — | — | 1,000 |
| Chromium | — | 120,000 | — | 5.25E+06 | 2,000 |
| Fluoride | — | 4,800 | — | 210,000 | 2,884 |
| Iron | — | 56,000 | — | 2.45E+06 | 5,645 |
| Lanthanum | — | — | — | — | — |
| Lead | 1,000 | — | —[d] | —[d] | 3,000 |
| Manganese | — | 11,200 | — | 490,000 | 501 |
| Mercury | — | 24 | — | 1,050 | 2.1 |
| Nickel | — | 1,600 | — | 70,000 | 130 |
| Nitrate | — | 568,000 | — | 2.49E+07 | 180 |
| Nitrite | — | 24,000 | — | 1.05E+06 | 13 |
| Oxalate | — | — | — | — | — |
| Phosphate | — | — | — | — | — |
| Potassium | — | — | — | — | — |
| Silicon | — | — | — | — | — |
| Sodium | — | — | — | — | — |
| Strontium | — | 48,000 | — | 2.10E+06 | 6,758 |
| Sulfate | — | — | — | — | 1,000 |
| Total inorganic carbon as $CO_3$ | — | — | — | — | — |
| Total organic carbon | — | — | — | — | — |

**Table 4-1. Summary of Model Toxics Control Act Cleanup Levels. (3 sheets)**

| Analyte | Soil Method B Unrestricted Land Use[a] | | Soil Method C Industrial Land Use[b] | | Soil Concentration Protective of Groundwater[c] (mg/kg) |
|---|---|---|---|---|---|
| | $10^{-6}$ Carcinogen (mg/kg) | Noncarcinogen (mg/kg) | $10^{-5}$ Carcinogen (mg/kg) | Noncarcinogen (mg/kg) | |
| Uranium | — | 240 | — | 10,500 | 270 |
| Zirconium | — | — | — | — | — |
| **Primary Analytes and Required Organics (Source: RPP-23403, 2013, "Single-Shell Tank Component Closure Data Quality Objectives")** | | | | | |
| 1, 1, 2-Trichloroethylene (Trichloroethene) | 22 | 40 | 2,853 | 1,750 | 0.0036 |
| 2-Butanone | — | 48,000 | — | 2.10E+06 | 20 |
| 2-Propanone (Acetone) | — | 72,000 | — | 3.15E+06 | 29 |
| 4-Methyl-2-pentanone | — | 6,400 | — | 280,000 | 2.7 |
| Acetate | — | — | — | — | — |
| Ammonium | — | — | — | — | — |
| Aroclor-1016 | 1.43E+01 | 5.60E+00 | 1.88E+03 | 2.45E+02 | 1.1 |
| Aroclor-1221 | 5.00E-01 | — | 6.56E+01 | — | 0.0038 |
| Aroclor-1232 | 5.00E-01 | — | 6.56E+01 | — | 0.0038 |
| Aroclor-1242 | 5.00E-01 | — | 6.56E+01 | — | 0.069 |
| Aroclor-1248 | 5.00E-01 | — | 6.56E+01 | — | 0.067 |
| Aroclor-1254 | 5.00E-01 | 1.60E+00 | 6.56E+01 | 7.00E+01 | 0.11 |
| Aroclor-1260 | 5.00E-01 | — | 6.56E+01 | — | 0.72 |
| Antimony | — | 32 | — | 1,400 | 5.4 |
| Arsenic | 0.67 | 24 | 88 | 1,050 | 0.034 |
| Barium | — | 16,000 | — | 700,000 | 1,648 |
| Beryllium | — | 160 | — | 7,000 | 63 |
| Cadmium | — | 80 | — | 3,500 | 0.69 |
| Cobalt | — | 24 | — | 1,050 | 4.3 |
| Copper | — | 3,200 | — | 140,000 | 284 |

**Table 4-1. Summary of Model Toxics Control Act Cleanup Levels. (3 sheets)**

| Analyte | Soil Method B Unrestricted Land Use[a] | | Soil Method C Industrial Land Use[b] | | Soil Concentration Protective of Groundwater[c] (mg/kg) |
|---|---|---|---|---|---|
| | $10^{-6}$ Carcinogen (mg/kg) | Noncarcinogen (mg/kg) | $10^{-5}$ Carcinogen (mg/kg) | Noncarcinogen (mg/kg) | |
| Cyanide | — | 48 | — | 2,100 | 0.97 |
| Formate | — | — | — | — | — |
| Glycolate | — | — | — | — | — |
| m-Xylene | — | 16,000 | — | 700,000 | 14 |
| o-Xylene | — | 16,000 | — | 700,000 | 15 |
| Polychlorinated Biphenyls | 0.50 | — | 66 | — | — |
| Selenium | — | 400 | — | 17,500 | 5.2 |
| Silver | — | 400 | — | 17,500 | 14 |
| Thallium | — | — | — | — | 0.71 |
| Tributyl phosphate | 111 | 800 | 14,583 | 35,000 | 0.50 |
| Vanadium | — | 400 | — | 17,500 | 1,600 |
| Xylene (m & p) | — | 16,000 | — | 700,000 | 14 |
| Xylenes | — | 16,000 | — | 700,000 | 15 |
| Zinc | — | 24,000 | — | 1.05E+06 | 5,971 |

[a] ECF-Hanford-10-0444, "Documentation of Standard Method B Soil Cleanup Levels for Unrestricted Land Use."

[b] ECF-HANFORD-10-0453, "Calculation of Standard Method C Direct Contact Soil Cleanup Levels for Industrial Land Use for the 100 Areas and 300 Area Remedial Investigation/Feasibility Study Reports."

[c] ECF-HANFORD-10-0442, "Calculation of Nonradiological Soil Concentrations Protective of Groundwater Using the Fixed Parameter 3-Phase Equilibrium Partitioning Equation for the 100 Areas and 300 Area."

[d] The lead industrial land use cleanup level of 1,000 mg/kg is the Method A industrial soil cleanup level from Table 745-1 in Washington Administrative Code 173-340-745, "Soil Cleanup Standards for Industrial Properties," subsection (3) "Method A industrial soil cleanup levels."

### 4.3.1 Model Toxics Control Act Three-Phase Soil Concentrations Protective of Groundwater Equations

The following represent the fixed parameter three-phase equation used to derive soil concentrations for groundwater protection and the equation used to calculate chemical-specific $K_d$s for organic constituents.

The equation below is obtained from WAC 173-340-747(4)(b), Equation 747-1.

$$C_s = C_w(UCF)DF\left[K_d\frac{\theta_w + \theta_a H_{cc}}{\rho_b}\right]$$

Where:

$C_s$ = soil concentration (mg/kg)
$C_w$ = groundwater cleanup level (µg/L)
$UCF$ = unit conversion factor (1 mg/1,000 µg)
$DF$ = Dilution factor (dimensionless)
$K_d$ = Distribution coefficient (L/kg)
$\theta_w$ = water-filled soil porosity (mL water/mL soil)
$\theta_a$ = air-filled soil porosity (mL air/mL soil)
$H_{cc}$ = Henry's law constant (dimensionless)
$\rho_b$ = Dry soil bulk density (kg/L).

The equation below is obtained from WAC 173-340-747(4)(c)(i), Equation 747-2.

$$K_d = K_{oc} \times f_{oc}$$

Where:

$K_d$ = Distribution coefficient (L/kg)
$K_{oc}$ = Soil organic carbon-water partitioning coefficient (mL/g)
$f_{oc}$ = Soil fraction of organic carbon (g/g).

## 4.4 RESULTS OF THE COMPARISON TO WAC 173-340 CLEANUP LEVELS

Average concentrations for retrieved tanks for comparison against MTCA CULs for soil direct contact unrestricted land use (Method B), industrial land use (Method C), and soil concentrations protective of groundwater are summarized in Table 4-2. Table 4-3 provides comparisons of average concentrations for tanks without post-retrieval samples against MTCA soil Method B, Method C, and concentrations protective of groundwater. Tables 4-2 and 4-3 also provide Hanford Site-specific 90$^{th}$ percentile background concentration. A more detailed list of background concentrations and references is provided in Table E-18 of Appendix E. The ratios are obtained by dividing the analyte concentration by the soil direct contact CUL or the soil concentration protective of groundwater. The level of exceedance (ratio) corresponds to the

level of residual waste concentration that is above or below the CUL. A level of exceedance greater than 1 corresponds to a residual waste concentration greater than the CUL. Expanded lists of analytes that did not exceed respective CULs are provided in Tables E-1 through E-17 in Appendix E.

### 4.4.1 Comparison to Model Toxics Control Act Direct Contact Method B

The comparison results for retrieved and unretrieved tanks against MTCA Method B soil cleanup levels are discussed in the following sections. Table 4-4 provides a summary of analytes that exceed the MTCA Method B soil cleanup levels at each tank.

#### 4.4.1.1 Results for Retrieved Tanks with Post-Retrieval Sample-Based Inventory.

- For tank C-103, concentrations for five analytes (aluminum, arsenic, mercury, silver, and uranium) exceed Method B soil direct contact CULs. Levels of exceedance range from approximately 1.3 to 69 times greater than the soil CUL.

- For tank C-104, concentrations for seven analytes (aluminum, arsenic, cadmium, mercury, polychlorinated biphenyls, silver, and uranium) exceed Method B soil direct contact CULs. Levels of exceedance range from approximately 1 to 480 times greater than the soil CUL.

- For tank C-106, concentrations for six analytes (antimony, arsenic, manganese, mercury, nickel, and silver) exceed Method B soil direct contact CULs. Levels of exceedance range from approximately 1.1 to 270 times greater than the soil CUL.

- For tank C-108, concentrations for four analytes (aluminum, arsenic, nickel, and uranium) exceed Method B soil direct contact CULs. Levels of exceedance range from approximately 1.46 to 19 times greater than the soil CUL.

- For tank C-109, concentrations for four analytes (aluminum, arsenic, fluoride, and uranium) exceed Method B soil direct contact CULs. Levels of exceedance range from approximately 1.5 to 12 times greater than the soil CUL.

- For tank C-110, concentrations for four analytes (aluminum, arsenic, fluoride, and uranium) exceed Method B soil direct contact CULs. Levels of exceedance range from approximately 1.6 to 9 times greater than the soil CUL.

- For tank C-201, concentrations for nine analytes (antimony, aroclor-1232, arsenic, cobalt, iron, manganese, mercury, nickel, TBP, and uranium) exceed Method B soil direct contact CULs. Levels of exceedance range from approximately 1.8 to 600 times greater than the soil CUL.

- For tank C-202, concentrations for nine analytes (antimony, arsenic, cobalt, iron, manganese, mercury, nickel, TBP, and uranium) exceed Method B soil direct contact

CULs. Levels of exceedance range from approximately 1.6 to 500 times greater than the soil CUL.

- For tank C-203, concentrations for five analytes (antimony, arsenic, cobalt, TBP, and uranium) exceed Method B soil direct contact CULs. Levels of exceedance range from approximately 1.1 to 1,400 times greater than the soil CUL.

- For tank C-204, concentrations for seven analytes (antimony, arsenic, cobalt, mercury, selenium, TBP, and uranium) exceed Method B soil direct contact CULs. Levels of exceedance range from approximately 1.1 to 1,100 times greater than the soil CUL.

- For ancillary equipment, concentrations for eight analytes (aluminum, antimony, arsenic, cobalt, mercury, nickel, TBP, and uranium) exceed Method B soil direct contact CULs. Levels of exceedance range from approximately 1 to 420 times greater than the soil CUL.

#### 4.4.1.2 Results for Tanks with Pre-Retrieval Inventory.

- For tank C-101, based on BBI inventory, concentrations for two analytes (mercury and uranium) exceed Method B soil direct contact CULs. Levels of exceedance for mercury and uranium are approximately 2.7 and 47 times greater than the soil CUL, respectively.

- For tank C-102, based on BBI inventory, concentrations for three analytes (aluminum, nickel, and uranium) exceed Method B soil direct contact CULs. Levels of exceedance range from approximately 1.8 to 34 times greater than the soil CUL. For inventory based on HTWOS inventory at 10.2 $m^3$ (360 $ft^3$), four analytes (aluminum, chromium, iron, and uranium) exceed Method B soil direct contact CULs. Levels of exceedance range from approximately 4 to 610 times greater than the soil CUL.

- For tank C-105, based on BBI inventory, concentrations for three analytes (aluminum, nickel, and uranium) exceed Method B soil direct contact CULs. Levels of exceedance range from approximately 1.4 to 41 times greater than the soil CUL. For inventory based on HTWOS inventory at 10.2 $m^3$ (360 $ft^3$), six analytes (aluminum, chromium, iron, manganese, strontium, and uranium) exceed Method B soil direct contact CULs. Levels of exceedance range from approximately 4.1 to 650 times greater than the soil CUL.

- For tank C-107, based on BBI inventory, concentrations for four analytes (fluoride, mercury, nitrite, and uranium) exceed Method B soil direct contact CULs. Levels of exceedance range from approximately 1.1 to 32 times greater than the soil CUL.

- For tank C-111, based on BBI inventory, concentrations for four analytes (mercury, nickel, nitrite, and uranium) exceed Method B soil direct contact CULs. Levels of exceedance range from approximately 1.1 to 49 times greater than the soil CUL. For inventory based on HTWOS inventory at 10.2 $m^3$ (360 $ft^3$), six analytes (aluminum, chromium, iron, nickel, strontium, and uranium) exceed Method B soil direct contact CULs. Levels of exceedance range from approximately 1 to 20,000 times greater than the soil CUL.

- For tank C-112, based on BBI inventory, concentrations for two analytes (fluoride and uranium) exceed Method B soil direct contact CULs. Levels of exceedance for fluoride and uranium are approximately 2.2 and 7.8 times greater than the soil CUL, respectively.

### 4.4.2 Comparison to Model Toxics Control Act Direct Contact Method C

The comparison results for retrieved and unretrieved tanks against MTCA Method C soil cleanup levels are discussed in the following sections. Table 4-5 provides a summary of analytes that exceed the MTCA Method C soil cleanup levels at each tank.

#### 4.4.2.1 Results for Retrieved Tanks with Post-Retrieval Sample-Based Inventory.

- For tanks C-103, C-108, C-109, and C-110, no concentrations exceeded the industrial land use Method C soil direct contact CULs.

- For tank C-104, only uranium concentrations exceed Method C soil direct contact CULs. Uranium had a concentration 11 times greater than the soil CUL.

- For tank C-106, concentrations for two analytes (arsenic and lead) exceed Method C soil direct contact CULs. Levels of exceedance for arsenic and lead were approximately 2.1 and 1.6 times greater than the soil CUL, respectively.

- For tank C-201, concentrations for four analytes (arsenic, lead, TBP, and uranium) exceed Method C soil direct contact CULs. Levels of exceedance range from approximately 1.4 to 14 times greater than the soil CUL.

- For tank C-202, concentrations for three analytes (arsenic, lead, and uranium) exceed Method C soil direct contact CULs. Levels of exceedance range from approximately 1.1 to 12 times greater than the soil CUL.

- For tank C-203, concentrations for two analytes (arsenic, lead, and uranium) exceed Method C soil direct contact CULs. Levels of exceedance range from approximately 2.3 to 32 times greater than the soil CUL.

- For tank C-204, concentrations for four analytes (arsenic, lead, TBP, and uranium) exceed Method C soil direct contact CULs. Levels of exceedance range from approximately 1.1 to 26 times greater than the soil CUL.

- For ancillary equipment, concentrations for three analytes (arsenic, lead, and uranium) exceed Method C soil direct contact CULs. Levels of exceedance range from approximately 1.1 to 9.5 times greater than the soil CUL, respectively.

#### 4.4.2.2 Results for Tanks with Pre-Retrieval Inventory.

- Tanks C-102, C-105, and C-112 had no concentrations exceeding the industrial land use Method C soil direct contact CULs.

- For tank C-101, only uranium concentrations exceed the Method C soil direct contact CUL. The level of exceedance was approximately 1.1 times greater than the soil CUL.

- For tank C-102, based on HTWOS inventory at 10.2 $m^3$ (360 $ft^3$), concentrations for two analytes (iron and lead) exceed Method C soil direct contact CULs. Levels of exceedance for iron and lead were approximately 14 and 180 times greater than the soil CUL, respectively.

- For tank C-105, based on HTWOS inventory at 10.2 $m^3$ (360 $ft^3$), concentrations for two analytes (iron and lead) exceed Method C soil direct contact CULs. Levels of exceedance for iron and lead were approximately 15 and 250 times greater than the soil CUL, respectively.

- For tank C-107, only lead concentrations exceed the Method C soil direct contact CUL. The level of exceedance was approximately 4.4 times greater than the soil CUL.

- For tank C-111, based on BBI inventory, concentrations for two analytes (lead and uranium) exceed Method C soil direct contact CULs. Levels of exceedance for lead and uranium were approximately 1.1 and 3.8 times greater than the soil CUL, respectively. For inventory based on HTWOS inventory at 10.2 $m^3$ (360 $ft^3$), five analytes (chromium, iron, lead, strontium, and uranium) exceed Method C soil direct contact CULs. Levels of exceedance range from approximately 1.5 to 6,300 times greater than the soil CUL.

### 4.4.3 Comparison to Model Toxics Control Act Three-Phase Soil Concentrations Protective of Groundwater

The comparison results for retrieved and unretrieved tanks against MTCA three-phase soil concentrations protective of groundwater are discussed in the following sections. Table 4-6 provides a summary of analytes that exceed the MTCA three-phase soil concentrations protective of groundwater at each tank.

#### 4.4.3.1 Results for Retrieved Tanks with Post-Retrieval Sample Inventory.

- For tank C-103, 14 analytes (trichloroethene, antimony, arsenic, cadmium, cobalt, iron, mercury, nickel, nitrite, selenium, silver, thallium, TBP, and uranium) exceed MTCA three-phase concentrations protective of groundwater. Levels of exceedance range from approximately 1.4 to 1,300 times greater than the soil CUL.

- For tank C-104, 15 analytes (antimony, arsenic, cadmium, cyanide, iron, manganese, mercury, nickel, nitrate, nitrite, selenium, silver, thallium, TBP, and uranium) exceed MTCA three-phase concentrations protective of groundwater. Levels of exceedance range from approximately 1.7 to 430 times greater than the soil CUL.

- For tank C-106, 16 analytes (trichloroethene, antimony, arsenic, cadmium, cobalt, cyanide, iron, manganese, mercury, nickel, nitrate, nitrite, selenium, silver, sulfate, and

thallium) exceed MTCA three-phase concentrations protective of groundwater. Levels of exceedance range from approximately 2.3 to 5,300 times greater than the soil CUL.

- For tank C-108, 14 analytes (trichloroethene, antimony, arsenic, cadmium, cyanide, fluoride, iron, nickel, nitrate, nitrite, selenium, thallium, TBP, and uranium) exceed MTCA three-phase concentrations protective of groundwater. Levels of exceedance range from approximately 1.5 to 5,600 times greater than the soil CUL.

- For tank C-109, 13 analytes (antimony, arsenic, cadmium, cyanide, fluoride, iron, nickel, nitrate, nitrite, selenium, thallium, TBP, and uranium) exceed MTCA three-phase concentrations protective of groundwater. Levels of exceedance range from approximately 1.1 to 230 times greater than the soil CUL.

- For tank C-110, 13 analytes (antimony, arsenic, cadmium, copper, fluoride, iron, mercury, nitrate, nitrite, silver, thallium, TBP, and uranium) exceed MTCA three-phase concentrations protective of groundwater. Levels of exceedance range from approximately 1.1 to 180 times greater than the soil CUL.

- For tank C-201, 19 analytes (trichloroethene, antimony, arsenic, cadmium, chromium, cobalt, copper, cyanide, iron, lead, manganese, mercury, nickel, nitrate, nitrite, selenium, thallium, TBP, and uranium) exceed MTCA three-phase concentrations protective of groundwater. Levels of exceedance range from approximately 1.8 to 43,000 times greater than the soil CUL.

- For tank C-202, 19 analytes (trichloroethene, antimony, arsenic, cadmium, chromium, cobalt, copper, cyanide, iron, lead, manganese, mercury, nickel, nitrate, nitrite, selenium, thallium, TBP, and uranium) exceed MTCA three-phase concentrations protective of groundwater. Levels of exceedance range from approximately 1.1 to 11,000 times greater than the soil CUL.

- For tank C-203, 19 analytes (trichloroethene, antimony, arsenic, cadmium, chromium, cobalt, cyanide, iron, lead, manganese, mercury, nickel, nitrate, nitrite, selenium, silver, thallium, TBP, and uranium) exceed MTCA three-phase concentrations protective of groundwater. Levels of exceedance range from approximately 1.1 to 19,000 times greater than the soil CUL.

- For tank C-204, 13 analytes (trichloroethene, antimony, arsenic, cobalt, iron, mercury, nickel, nitrite, selenium, silver, thallium, TBP, and uranium) exceed MTCA three-phase concentrations protective of groundwater. Levels of exceedance range from approximately 1.7 to 150,000 times greater than the soil CUL.

**Table 4-2. Summary of Residual Tank Concentrations Compared Against Model Toxics Control Act Cleanup Level for Retrieved Tanks. (1 of 6 sheets)**

| Analyte | Residual Concentration[a] (mg/kg) | 90th Percentile Background (mg/kg) | Soil Method B Unrestricted Land Use[b] (mg/kg) | Soil Method C Industrial Land Use[c] (mg/kg) | 3-Phase Soil Concentration Protective of Groundwater[d] (mg/kg) | Ratio of Residual Waste Concentration to Soil Cleanup Levels | | | Above 90th Percentile Background? |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Method B | Method C | 3-Phase | |
| **Tank 241-C-103** | | | | | | | | | |
| 1, 1, 2-Trichloroethylene (Trichloroethene) | 0.011 | — | 22 | 1,750 | 0.0036 | 5.06E-04 | 6.29E-06 | ***3.06E+00*** | — |
| Aluminum | 261,000 | 11,800 | 80,000 | 3.50E+06 | 480,064 | ***3.26E+00*** | 7.46E-02 | 5.44E-01 | Yes |
| Antimony | 22 | 0.13 | 32 | 1,400 | 5.4 | 6.88E-01 | 1.57E-02 | ***4.06E+00*** | Yes |
| Aroclor-1221 | 1.36E-02 | — | 0.50 | 66 | 0.0038 | 2.72E-02 | 2.07E-04 | ***3.61E+00*** | — |
| Aroclor-1232 | 2.41E-01 | — | 0.50 | 66 | 0.0038 | 4.82E-01 | 3.67E-03 | ***6.41E+01*** | — |
| Arsenic | 46 | 6.5 | 0.67 | 88 | 0.034 | ***6.90E+01*** | 5.26E-01 | ***1.35E+03*** | Yes |
| Cobalt | 6.2 | 16 | 24 | 1,050 | 4.3 | 2.58E-01 | 5.90E-03 | ***1.43E+00*** | No |
| Cadmium | 70 | 0.56 | 80 | 3,500 | 0.69 | *8.75E-01* | 2.00E-02 | ***1.01E+02*** | Yes |
| Iron | 8,590 | 32,600 | 56,000 | 2.45E+06 | 5,645 | 1.53E-01 | 3.51E-03 | ***1.52E+00*** | No |
| Mercury | 76 | 0.013 | 24 | 1,050 | 2.1 | ***3.17E+00*** | 7.24E-02 | ***3.64E+01*** | Yes |
| Nickel | 329 | 19 | 1,600 | 70,000 | 130 | 2.06E-01 | 4.70E-03 | ***2.52E+00*** | Yes |
| Nitrite | 32 | — | 24,000 | 1.05E+06 | 13 | 1.33E-03 | 3.05E-05 | ***2.42E+00*** | — |
| Selenium | 50 | 0.78 | 400 | 17,500 | 5.2 | 1.25E-01 | 2.86E-03 | ***9.62E+00*** | Yes |
| Silver | 534 | 0.17 | 400 | 17,500 | 14 | ***1.34E+00*** | 3.05E-02 | ***3.93E+01*** | Yes |
| Thallium | 43 | 0.19 | — | — | 0.71 | — | — | ***6.04E+01*** | Yes |
| Tributyl phosphate | 74 | — | 111 | 14,583 | 0.50 | 6.66E-01 | 5.07E-03 | ***1.49E+02*** | — |
| Uranium | 3,530 | 3.2 | 240 | 10,500 | 270 | ***1.47E+01*** | 3.36E-01 | ***1.31E+01*** | Yes |
| **Tank 241-C-104** | | | | | | | | | |
| Aluminum | 100,000 | 11,800 | 80,000 | 3.50E+06 | 480,064 | ***1.25E+00*** | 2.86E-02 | 2.08E-01 | Yes |
| Antimony | 12 | 0.13 | 32 | 1,400 | 5.4 | 3.75E-01 | 8.57E-03 | ***2.21E+00*** | Yes |
| Arsenic | 9.9 | 6.5 | 0.67 | 88 | 0.034 | ***1.49E+01*** | 1.13E-01 | ***2.91E+02*** | Yes |
| Cadmium | 172 | 0.56 | 80 | 3,500 | 0.69 | ***2.15E+00*** | 4.91E-02 | ***2.49E+02*** | Yes |
| Cyanide | 1.6 | — | 48 | 2,100 | 0.97 | 3.33E-02 | 7.62E-04 | ***1.65E+00*** | — |
| Iron | 28,400 | 32,600 | 56,000 | 2.45E+06 | 5,645 | 5.07E-01 | 1.16E-02 | ***5.03E+00*** | No |
| Manganese | 3,770 | 512 | 11,200 | 490,000 | 501 | 3.37E-01 | 7.69E-03 | ***7.53E+00*** | Yes |
| Mercury | 118 | 0.013 | 24 | 1,050 | 2.1 | ***4.92E+00*** | 1.12E-01 | ***5.65E+01*** | Yes |
| Nickel | 528 | 19 | 1,600 | 70,000 | 130 | 3.30E-01 | 7.54E-03 | ***4.05E+00*** | Yes |
| Nitrate | 825 | 52 | 568,000 | 2.49E+07 | 180 | 1.45E-03 | 3.32E-05 | ***4.58E+00*** | Yes |
| Nitrite | 445 | — | 24,000 | 1.05E+06 | 13 | 1.85E-02 | 4.24E-04 | ***3.37E+01*** | — |
| Polychlorinated Biphenyls (high risk) | 0.51 | — | 0.50 | 66 | — | ***1.02E+00*** | 7.77E-03 | — | — |
| Selenium | 12 | 0.78 | 400 | 17,500 | 5.2 | 3.00E-02 | 6.86E-04 | ***2.31E+00*** | Yes |
| Silver | 1,440 | 0.17 | 400 | 17,500 | 14 | ***3.60E+00*** | 8.23E-02 | ***1.06E+02*** | Yes |
| Thallium | 12 | 0.19 | — | — | 0.71 | — | — | ***1.69E+01*** | Yes |
| Tributyl phosphate | 1.6 | — | 111 | 14,583 | 0.50 | 1.44E-02 | 1.10E-04 | ***3.23E+00*** | — |
| Uranium | 116,000 | 3.2 | 240 | 10,500 | 270 | ***4.83E+02*** | ***1.10E+01*** | ***4.29E+02*** | Yes |

**Table 4-2. Summary of Residual Tank Concentrations Compared Against Model Toxics Control Act Cleanup Level for Retrieved Tanks. (2 of 6 sheets)**

| Analyte | Residual Concentration[a] (mg/kg) | 90th Percentile Background (mg/kg) | Soil Method B Unrestricted Land Use[b] (mg/kg) | Soil Method C Industrial Land Use[c] (mg/kg) | 3-Phase Soil Concentration Protective of Groundwater[d] (mg/kg) | Ratio of Residual Waste Concentration to Soil Cleanup Levels | | | Above 90th Percentile Background? |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Method B | Method C | 3-Phase | |
| **Tank 241-C-106** | | | | | | | | | |
| 1, 1, 2-Trichloroethylene (Trichloroethene) | 0.010 | — | 22 | 1,750 | 0.0036 | 4.60E-04 | 5.71E-06 | ***2.78E+00*** | — |
| Antimony | 75 | 0.13 | 32 | 1,400 | 5.4 | ***2.34E+00*** | 5.36E-02 | ***1.38E+01*** | Yes |
| Aroclor-1221 | 2.35E-02 | — | 0.50 | 66 | 0.0038 | 4.70E-02 | 3.58E-04 | ***6.25E+00*** | — |
| Aroclor-1232 | 4.20E-01 | — | 0.50 | 66 | 0.0038 | 8.40E-01 | 6.40E-03 | ***1.12E+02*** | — |
| Aroclor-1242 | 7.62E-02 | — | 0.50 | 66 | 0.069 | 1.52E-01 | 1.16E-03 | ***1.11E+00*** | — |
| Aroclor-1254 | 1.47E-01 | — | 0.50 | 66 | 0.11 | 2.94E-01 | 2.24E-03 | ***1.29E+00*** | — |
| Arsenic | 182 | 6.5 | 0.67 | 88 | 0.034 | ***2.73E+02*** | ***2.08E+00*** | ***5.34E+03*** | Yes |
| Cadmium | 90.9 | 0.56 | 80 | 3,500 | 0.69 | ***1.14E+00*** | ***2.60E-02*** | ***1.32E+02*** | Yes |
| Cobalt | 24 | 16 | 24 | 1,050 | 4.3 | 1.00E+00 | 2.29E-02 | ***5.53E+00*** | Yes |
| Cyanide | 4.9 | — | 48 | 2,100 | 0.97 | 1.02E-01 | 2.33E-03 | ***5.05E+00*** | — |
| Iron | 13,000 | 32,600 | 56,000 | 2.45E+06 | 5,645 | 2.32E-01 | 5.31E-03 | ***2.30E+00*** | No |
| Lead | 1,620 | 10 | — | 1,000 [e] | 3,000 | — | ***1.62E+00*** | — | Yes |
| Manganese | 34,600 | 512 | 11,200 | 490,000 | 501 | ***3.09E+00*** | 7.06E-02 | ***6.91E+01*** | Yes |
| Mercury | 122 | 0.013 | 24 | 1,050 | 2.1 | ***5.08E+00*** | 1.16E-01 | ***5.84E+01*** | Yes |
| Nickel | 1,900 | 19 | 1,600 | 70,000 | 130 | ***1.19E+00*** | 2.71E-02 | ***1.46E+01*** | Yes |
| Nitrate | 2,900 | 52 | 568,000 | 2.49E+07 | 180 | 5.11E-03 | 1.17E-04 | ***1.61E+01*** | Yes |
| Nitrite | 2,610 | — | 24,000 | 1.05E+06 | 13 | 1.09E-01 | 2.49E-03 | ***1.98E+02*** | — |
| Selenium | 185 | 0.78 | 400 | 17,500 | 5.2 | 4.63E-01 | 1.06E-02 | ***3.56E+01*** | Yes |
| Silver | 494 | 0.17 | 400 | 17,500 | 14 | ***1.24E+00*** | 2.82E-02 | ***3.63E+01*** | Yes |
| Sulfate | 3,090 | 237 | — | — | 1,000 | — | — | ***3.09E+00*** | Yes |
| Thallium | 445 | 0.19 | — | — | 0.71 | — | — | ***6.25E+02*** | Yes |
| **Tank 241-C-108** | | | | | | | | | |
| 1, 1, 2-Trichloroethylene (Trichloroethene) | 0.0054 | — | 22 | 1,750 | 0.0036 | 2.48E-04 | 3.09E-06 | ***1.50E+00*** | — |
| Aluminum | 129,000 | 11,800 | 80,000 | 3.50E+06 | 480,064 | ***1.61E+00*** | 3.69E-02 | 2.69E-01 | Yes |
| Antimony | 12 | 0.13 | 32 | 1,400 | 5.4 | 3.75E-01 | 8.57E-03 | ***2.21E+00*** | Yes |
| Arsenic | 9.6 | 6.5 | 0.67 | 88 | 0.034 | ***1.44E+01*** | 1.10E-01 | ***2.82E+02*** | Yes |
| Cadmium | 2 | 0.56 | 80 | 3,500 | 0.69 | ***2.39E-02*** | 5.46E-04 | ***2.77E+00*** | Yes |
| Cyanide | 6.1 | — | 48 | 2,100 | 0.97 | 1.27E-01 | 2.90E-03 | ***6.29E+00*** | — |
| Fluoride | 4,480 | 2.8 | 4,800 | 210,000 | 2,884 | 9.33E-01 | 2.13E-02 | ***1.55E+00*** | Yes |
| Iron | 10,400 | 32,600 | 56,000 | 2.45E+06 | 5,645 | 1.86E-01 | 4.24E-03 | ***1.84E+00*** | No |
| Nickel | 2,760 | 19 | 1,600 | 70,000 | 130 | ***1.73E+00*** | 3.94E-02 | ***2.12E+01*** | Yes |
| Nitrate | 340 | 52 | 568,000 | 2.49E+07 | 180 | 5.99E-04 | 1.37E-05 | ***1.89E+00*** | Yes |
| Nitrite | 214 | — | 24,000 | 1.05E+06 | 13 | 8.92E-03 | 2.04E-04 | ***1.62E+01*** | — |
| Selenium | 12 | 0.78 | 400 | 17,500 | 5.2 | 3.00E-02 | 6.86E-04 | ***2.31E+00*** | Yes |
| Thallium | 3,970 | 0.19 | — | — | 0.71 | — | — | ***5.58E+03*** | Yes |
| Tributyl phosphate | 2.0 | — | 111 | 14,583 | 0.50 | 1.80E-02 | 1.37E-04 | ***4.03E+00*** | — |
| Uranium | 4,480 | 3.2 | 240 | 10,500 | 270 | ***1.87E+01*** | 4.27E-01 | ***1.66E+01*** | Yes |

**Table 4-2. Summary of Residual Tank Concentrations Compared Against Model Toxics Control Act Cleanup Level for Retrieved Tanks. (3 of 6 sheets)**

| Analyte | Residual Concentration[a] (mg/kg) | 90th Percentile Background (mg/kg) | Soil Method B Unrestricted Land Use[b] (mg/kg) | Soil Method C Industrial Land Use[c] (mg/kg) | 3-Phase Soil Concentration Protective of Groundwater[d] (mg/kg) | Ratio of Residual Waste Concentration to Soil Cleanup Levels | | | Above 90th Percentile Background? |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Method B | Method C | 3-Phase | |
| **Tank 241-C-109** | | | | | | | | | |
| Aluminum | 162,000 | 11,800 | 80,000 | 3.50E+06 | 480,064 | ***2.03E+00*** | 4.63E-02 | 3.37E-01 | Yes |
| Antimony | 5.9 | 0.13 | 32 | 1,400 | 5.4 | 1.84E-01 | 4.21E-03 | ***1.09E+00*** | Yes |
| Arsenic | 7.7 | 6.5 | 0.67 | 88 | 0.034 | ***1.16E+01*** | 8.80E-02 | ***2.26E+02*** | Yes |
| Cadmium | 1 | 0.56 | 80 | 3,500 | 0.69 | ***1.24E-02*** | 2.83E-04 | ***1.43E+00*** | Yes |
| Cyanide | 30 | — | 48 | 2,100 | 0.97 | 6.25E-01 | 1.43E-02 | ***3.09E+01*** | — |
| Fluoride | 7,320 | 2.8 | 4,800 | 210,000 | 2,884 | ***1.53E+00*** | 3.49E-02 | ***2.54E+00*** | Yes |
| Iron | 7,020 | 32,600 | 56,000 | 2.45E+06 | 5,645 | 1.25E-01 | 2.87E-03 | ***1.24E+00*** | No |
| Nickel | 1,010 | 19 | 1,600 | 70,000 | 130 | 6.31E-01 | 1.44E-02 | 7.75E+00 | Yes |
| Nitrate | 342 | 52 | 568,000 | 2.49E+07 | 180 | 6.02E-04 | 1.38E-05 | ***1.90E+00*** | Yes |
| Nitrite | 289 | — | 24,000 | 1.05E+06 | 13 | 1.20E-02 | 2.75E-04 | ***2.19E+01*** | — |
| Selenium | 5.9 | 0.78 | 400 | 17,500 | 5.2 | 1.48E-02 | 3.37E-04 | ***1.13E+00*** | Yes |
| Thallium | 6.7 | 0.19 | — | — | 0.71 | — | — | ***9.41E+00*** | Yes |
| Tributyl phosphate | 0.66 | — | 111 | 14,583 | 0.50 | 5.94E-03 | 4.53E-05 | ***1.33E+00*** | — |
| Uranium | 2,160 | 3.2 | 240 | 10,500 | 270 | ***9.00E+00*** | 2.06E-01 | ***8.00E+00*** | Yes |
| **Tank 241-C-110** | | | | | | | | | |
| Aluminum | 131,000 | 11,800 | 80,000 | 3.50E+06 | 480,064 | ***1.64E+00*** | 3.74E-02 | 2.73E-01 | Yes |
| Antimony | 6.1 | 0.13 | 32 | 1,400 | 5.4 | 1.91E-01 | 4.36E-03 | ***1.12E+00*** | Yes |
| Arsenic | 6.0 | 6.5 | 0.67 | 88 | 0.034 | ***9.00E+00*** | 6.86E-02 | ***1.76E+02*** | No |
| Cadmium | 1 | 0.56 | 80 | 3,500 | 0.69 | ***1.26E-02*** | 2.89E-04 | ***1.46E+00*** | Yes |
| Copper | 318 | 22 | 3,200 | 140,000 | 284 | 9.94E-02 | 2.27E-03 | ***1.12E+00*** | Yes |
| Fluoride | 14,000 | 2.8 | 4,800 | 210,000 | 2,884 | ***2.92E+00*** | 6.67E-02 | ***4.85E+00*** | Yes |
| Iron | 19,200 | 32,600 | 56,000 | 2.45E+06 | 5,645 | 3.43E-01 | 7.84E-03 | ***3.40E+00*** | No |
| Mercury | 11 | 0.013 | 24 | 1,050 | 2.1 | 4.58E-01 | 1.05E-02 | ***5.27E+00*** | Yes |
| Nitrate | 682 | 52 | 568,000 | 2.49E+07 | 180 | 1.20E-03 | 2.74E-05 | ***3.79E+00*** | Yes |
| Nitrite | 277 | — | 24,000 | 1.05E+06 | 13 | 1.15E-02 | 2.64E-04 | ***2.10E+01*** | — |
| Silver | 25 | 0.17 | 400 | 17,500 | 14 | 6.25E-02 | 1.43E-03 | ***1.84E+00*** | Yes |
| Thallium | 4.3 | 0.19 | — | — | 0.71 | — | — | ***6.04E+00*** | Yes |
| Tributyl phosphate | 10 | — | 111 | 14,583 | 0.50 | 9.00E-02 | 6.86E-04 | ***2.02E+01*** | — |
| Uranium | 556 | 3.2 | 240 | 10,500 | 270 | ***2.32E+00*** | 5.30E-02 | ***2.06E+00*** | Yes |
| **Tank 241-C-201** | | | | | | | | | |
| 1, 1, 2-Trichloroethylene (Trichloroethene) | 0.012 | — | 22 | 1,750 | 0.0036 | 5.52E-04 | 6.86E-06 | ***3.33E+00*** | — |
| Antimony | 95 | 0.13 | 32 | 1,400 | 5.4 | ***2.97E+00*** | 6.79E-02 | ***1.75E+01*** | Yes |
| Aroclor-1221 | 6.48E-02 | — | 0.50 | 66 | 0.0038 | 1.30E-01 | 9.87E-04 | ***1.72E+01*** | — |
| Aroclor-1232 | 1.17E+00 | — | 0.50 | 66 | 0.0038 | ***2.34E+00*** | 1.78E-02 | ***3.11E+02*** | — |
| Aroclor-1242 | 2.07E-01 | — | 0.50 | 66 | 0.069 | 4.14E-01 | 3.15E-03 | ***3.02E+00*** | — |
| Arsenic | 119 | 6.5 | 0.67 | 88 | 0.034 | ***1.79E+02*** | ***1.36E+00*** | ***3.49E+03*** | Yes |
| Cadmium | 10 | 0.56 | 80 | 3,500 | 0.69 | 1.22E-01 | 2.78E-03 | ***1.41E+01*** | Yes |
| Chromium | 12,900 | 19 | 120,000 | 5.25E+06 | 2,000 | 1.08E-01 | 2.46E-03 | ***6.45E+00*** | Yes |

**Table 4-2. Summary of Residual Tank Concentrations Compared Against Model Toxics Control Act Cleanup Level for Retrieved Tanks. (4 of 6 sheets)**

| Analyte | Residual Concentration[a] (mg/kg) | 90th Percentile Background (mg/kg) | Soil Method B Unrestricted Land Use[b] (mg/kg) | Soil Method C Industrial Land Use[c] (mg/kg) | 3-Phase Soil Concentration Protective of Groundwater[d] (mg/kg) | Ratio of Residual Waste Concentration to Soil Cleanup Levels | | | Above 90th Percentile Background? |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Method B | Method C | 3-Phase | |
| Cobalt | 90 | 16 | 24 | 1,050 | 4.3 | ***3.75E+00*** | 8.57E-02 | ***2.07E+01*** | Yes |
| Copper | 643 | 22 | 3,200 | 140,000 | 284 | 2.01E-01 | 4.59E-03 | ***2.26E+00*** | Yes |
| Cyanide | 2.2 | — | 48 | 2,100 | 0.97 | 4.58E-02 | 1.05E-03 | ***2.27E+00*** | — |
| Iron | 117,000 | 32,600 | 56,000 | 2.45E+06 | 5,645 | **2.09E+00** | 4.78E-02 | **2.07E+01** | Yes |
| Lead | 6,650 | 10 | — | 1,000 [e] | 3,000 | — | **6.65E+00** | ***2.22E+00*** | Yes |
| Manganese | 20,200 | 512 | 11,200 | 490,000 | 501 | **1.80E+00** | 4.12E-02 | ***4.03E+01*** | Yes |
| Mercury | 114 | 0.013 | 24 | 1,050 | 2.1 | 4.75E+00 | 1.09E-01 | ***5.46E+01*** | Yes |
| Nickel | 6,540 | 19 | 1,600 | 70,000 | 130 | ***4.09E+00*** | 9.34E-02 | ***5.02E+01*** | Yes |
| Nitrate | 1,440 | 52 | 568,000 | 2.49E+07 | 180 | 2.54E-03 | 5.79E-05 | ***8.00E+00*** | Yes |
| Nitrite | 560 | — | 24,000 | 1.05E+06 | 13 | 2.33E-02 | 5.33E-04 | ***4.24E+01*** | — |
| Selenium | 122 | 0.78 | 400 | 17,500 | 5.2 | 3.05E-01 | 6.97E-03 | ***2.35E+01*** | Yes |
| Thallium | 351 | 0.19 | — | — | 0.71 | — | — | ***4.93E+02*** | Yes |
| Tributyl phosphate | 21,200 | — | 111 | 14,583 | 0.50 | **1.91E+02** | ***1.45E+00*** | ***4.28E+04*** | — |
| Uranium | 143,000 | 3.2 | 240 | 10,500 | 270 | ***5.96E+02*** | ***1.36E+01*** | ***5.29E+02*** | Yes |
| **Tank 241-C-202** | | | | | | | | | |
| 1, 1, 2-Trichloroethylene (Trichloroethene) | 0.012 | — | 22 | 1,750 | 0.0036 | 5.52E-04 | 6.86E-06 | ***3.33E+00*** | — |
| Antimony | 95 | 0.13 | 32 | 1,400 | 5.4 | ***2.97E+00*** | 6.79E-02 | ***1.75E+01*** | Yes |
| Arsenic | 95 | 6.5 | 0.67 | 88 | 0.034 | ***1.43E+02*** | ***1.09E+00*** | ***2.79E+03*** | Yes |
| Cadmium | 18 | 0.56 | 80 | 3,500 | 0.69 | ***2.29E-01*** | ***5.23E-03*** | ***2.65E+01*** | Yes |
| Chromium | 9,480 | 19 | 120,000 | 5.25E+06 | 2,000 | 7.90E-02 | 1.81E-03 | ***4.74E+00*** | Yes |
| Cobalt | 80 | 16 | 24 | 1,050 | 4.3 | ***3.33E+00*** | 7.62E-02 | ***1.84E+01*** | Yes |
| Copper | 320 | 22 | 3,200 | 140,000 | 284 | 1.00E-01 | 2.29E-03 | ***1.13E+00*** | Yes |
| Cyanide | 4.1 | — | 48 | 2,100 | 0.97 | 8.54E-02 | 1.95E-03 | ***4.23E+00*** | — |
| Iron | 90,800 | 32,600 | 56,000 | 2.45E+06 | 5,645 | ***1.62E+00*** | 3.71E-02 | ***1.61E+01*** | Yes |
| Lead | 6,090 | 10 | — | 1,000 [e] | 3,000 | — | ***6.09E+00*** | ***2.03E+00*** | Yes |
| Manganese | 17,600 | 512 | 11,200 | 490,000 | 501 | ***1.57E+00*** | 3.59E-02 | ***3.51E+01*** | Yes |
| Mercury | 299 | 0.013 | 24 | 1,050 | 2.1 | ***1.25E+01*** | 2.85E-01 | ***1.43E+02*** | Yes |
| Nickel | 7,600 | 19 | 1,600 | 70,000 | 130 | ***4.75E+00*** | 1.09E-01 | ***5.83E+01*** | Yes |
| Nitrate | 1,300 | 52 | 568,000 | 2.49E+07 | 180 | 2.29E-03 | 5.23E-05 | ***7.22E+00*** | Yes |
| Nitrite | 471 | — | 24,000 | 1.05E+06 | 13 | 1.96E-02 | 4.49E-04 | ***3.57E+01*** | — |
| Selenium | 95 | 0.78 | 400 | 17,500 | 5.2 | 2.38E-01 | 5.43E-03 | ***1.83E+01*** | Yes |
| Thallium | 256 | 0.19 | — | — | 0.71 | — | — | ***3.60E+02*** | Yes |
| Tributyl phosphate | 5,530 | — | 111 | 14,583 | 0.50 | ***4.98E+01*** | 3.79E-01 | ***1.12E+04*** | — |
| Uranium | 121,000 | 3.2 | 240 | 10,500 | 270 | ***5.04E+02*** | ***1.15E+01*** | ***4.48E+02*** | Yes |
| **Tank 241-C-203** | | | | | | | | | |
| 1, 1, 2-Trichloroethylene (Trichloroethene) | 0.0097 | — | 22 | 1,750 | 0.0036 | 4.46E-04 | 5.54E-06 | ***2.69E+00*** | — |
| Antimony | 199 | 0.13 | 32 | 1,400 | 5.4 | ***6.22E+00*** | 1.42E-01 | ***3.67E+01*** | Yes |
| Aroclor-1221 | 1.33E-02 | — | 0.50 | 66 | 0.0038 | 2.66E-02 | 2.03E-04 | ***3.54E+00*** | — |

**Table 4-2. Summary of Residual Tank Concentrations Compared Against Model Toxics Control Act Cleanup Level for Retrieved Tanks. (5 of 6 sheets)**

| Analyte | Residual Concentration[a] (mg/kg) | 90th Percentile Background (mg/kg) | Soil Method B Unrestricted Land Use[b] (mg/kg) | Soil Method C Industrial Land Use[c] (mg/kg) | 3-Phase Soil Concentration Protective of Groundwater[d] (mg/kg) | Ratio of Residual Waste Concentration to Soil Cleanup Levels | | | Above 90th Percentile Background? |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Method B | Method C | 3-Phase | |
| Aroclor-1232 | 2.28E-02 | — | 0.50 | 66 | 0.0038 | 4.56E-02 | 3.47E-04 | ***6.06E+00*** | — |
| Aroclor-1254 | 1.94E-01 | — | 0.50 | 66 | 0.11 | 3.88E-01 | 2.96E-03 | ***1.70E+00*** | — |
| Arsenic | 199 | 6.5 | 0.67 | 88 | 0.034 | ***2.99E+02*** | ***2.27E+00*** | ***5.84E+03*** | Yes |
| Cadmium | 21 | 0.56 | 80 | 3,500 | 0.69 | ***2.63E-01*** | ***6.00E-03*** | ***3.04E+01*** | Yes |
| Chromium | 2,830 | 19 | 120,000 | 5.25E+06 | 2,000 | 2.36E-02 | 5.39E-04 | ***1.41E+00*** | Yes |
| Cobalt | 26 | 16 | 24 | 1,050 | 4.3 | ***1.08E+00*** | 2.48E-02 | ***5.99E+00*** | Yes |
| Cyanide | 4.5 | — | 48 | 2,100 | 0.97 | 9.38E-02 | 2.14E-03 | ***4.64E+00*** | — |
| Iron | 14,000 | 32,600 | 56,000 | 2.45E+06 | 5,645 | 2.50E-01 | 5.71E-03 | ***2.48E+00*** | No |
| Lead | 3,340 | 10 | — | 1,000 [e] | 3,000 | — | ***3.34E+00*** | ***1.11E+00*** | Yes |
| Manganese | 558 | 512 | 11,200 | 490,000 | 501 | 4.98E-02 | 1.14E-03 | ***1.11E+00*** | Yes |
| Mercury | 2.4 | 0.013 | 24 | 1,050 | 2.1 | 1.00E-01 | 2.29E-03 | ***1.15E+00*** | Yes |
| Nickel | 222 | 19 | 1,600 | 70,000 | 130 | 1.39E-01 | 3.17E-03 | ***1.70E+00*** | Yes |
| Nitrate | 4,090 | 52 | 568,000 | 2.49E+07 | 180 | 7.20E-03 | 1.65E-04 | ***2.27E+01*** | Yes |
| Nitrite | 1,080 | — | 24,000 | 1.05E+06 | 13 | 4.50E-02 | 1.03E-03 | ***8.18E+01*** | — |
| Selenium | 199 | 0.78 | 400 | 17,500 | 5.2 | 4.98E-01 | 1.14E-02 | ***3.83E+01*** | Yes |
| Silver | 24 | 0.17 | 400 | 17,500 | 14 | 6.00E-02 | 1.37E-03 | ***1.76E+00*** | Yes |
| Thallium | 398 | 0.19 | — | — | 0.71 | — | — | ***5.59E+02*** | Yes |
| Tributyl phosphate | 9,440 | — | 111 | 14,583 | 0.50 | ***8.50E+01*** | 6.47E-01 | ***1.90E+04*** | — |
| Uranium | 339,000 | 3.2 | 240 | 10,500 | 270 | ***1.41E+03*** | ***3.23E+01*** | ***1.25E+03*** | Yes |
| **Tank 241-C-204** | | | | | | | | | |
| 1, 1, 2-Trichloroethylene (Trichloroethene) | 0.012 | — | 22 | 1,750 | 0.0036 | 5.52E-04 | 6.86E-06 | ***3.33E+00*** | — |
| Antimony | 446 | 0.13 | 32 | 1,400 | 5.4 | ***1.39E+01*** | 3.19E-01 | ***8.22E+01*** | Yes |
| Aroclor-1221 | 1.42E-02 | — | 0.50 | 66 | 0.0038 | 2.84E-02 | 2.16E-04 | ***3.77E+00*** | — |
| Aroclor-1232 | 2.39E-02 | — | 0.50 | 66 | 0.0038 | 4.78E-02 | 3.64E-04 | ***6.35E+00*** | — |
| Aroclor-1254 | 2.03E-01 | — | 0.50 | 66 | 0.11 | 4.06E-01 | 3.09E-03 | ***1.78E+00*** | — |
| Arsenic | 271 | 6.5 | 0.67 | 88 | 0.034 | ***4.07E+02*** | ***3.10E+00*** | ***7.95E+03*** | Yes |
| Cadmium | 23 | 0.56 | 80 | 3,500 | 0.69 | ***2.81E-01*** | ***6.43E-03*** | ***3.26E+01*** | Yes |
| Cobalt | 45 | 16 | 24 | 1,050 | 4.3 | ***1.88E+00*** | 4.29E-02 | ***1.04E+01*** | Yes |
| Iron | 35,800 | 32,600 | 56,000 | 2.45E+06 | 5,645 | 6.39E-01 | 1.46E-02 | ***6.34E+00*** | Yes |
| Lead | 1,140 | 10 | — | 1,000 [e] | 3,000 | — | ***1.14E+00*** | 3.80E-01 | Yes |
| Mercury | 164 | 0.013 | 24 | 1,050 | 2.1 | ***6.83E+00*** | 1.56E-01 | ***7.85E+01*** | Yes |
| Nickel | 893 | 19 | 1,600 | 70,000 | 130 | 5.58E-01 | 1.28E-02 | ***6.85E+00*** | Yes |
| Nitrite | 35 | — | 24,000 | 1.05E+06 | 13 | 1.46E-03 | 3.33E-05 | ***2.65E+00*** | — |
| Selenium | 451 | 0.78 | 400 | 17,500 | 5.2 | ***1.13E+00*** | 2.58E-02 | ***8.67E+01*** | Yes |
| Silver | 23 | 0.17 | 400 | 17,500 | 14 | 5.75E-02 | 1.31E-03 | ***1.69E+00*** | Yes |
| Thallium | 451 | 0.19 | — | — | 0.71 | — | — | ***6.33E+02*** | Yes |
| Tributyl phosphate | 73,000 | — | 111 | 14,583 | 0.50 | ***6.57E+02*** | ***5.01E+00*** | ***1.47E+05*** | — |
| Uranium | 271,000 | 3.2 | 240 | 10,500 | 270 | ***1.13E+03*** | ***2.58E+01*** | ***1.00E+03*** | Yes |

**Table 4-2. Summary of Residual Tank Concentrations Compared Against Model Toxics Control Act Cleanup Level for Retrieved Tanks. (6 of 6 sheets)**

| Analyte | Residual Concentration[a] (mg/kg) | 90th Percentile Background (mg/kg) | Soil Method B Unrestricted Land Use[b] (mg/kg) | Soil Method C Industrial Land Use[c] (mg/kg) | 3-Phase Soil Concentration Protective of Groundwater[d] (mg/kg) | Ratio of Residual Waste Concentration to Soil Cleanup Levels | | | Above 90th Percentile Background? |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Method B | Method C | 3-Phase | |
| **Ancillary Equipment** | | | | | | | | | |
| 1, 1, 2-Trichloroethylene (Trichloroethene) | 0.0075 | — | 22 | 1,750 | 0.0036 | 3.45E-04 | 4.29E-06 | ***2.08E+00*** | — |
| Aluminum | 82,727 | 11,800 | 80,000 | 3.50E+06 | 480,064 | ***1.03E+00*** | 2.36E-02 | 1.72E-01 | Yes |
| Antimony | 97 | 0.13 | 32 | 1,400 | 5.4 | ***3.03E+00*** | 6.93E-02 | ***1.79E+01*** | Yes |
| Aroclor-1221 | 2.59E-02 | — | 0.50 | 66 | 0.0038 | 5.18E-02 | 3.94E-04 | ***6.88E+00*** | — |
| Aroclor-1232 | 3.76E-01 | — | 0.50 | 66 | 0.0038 | 7.51E-01 | 5.72E-03 | ***9.98E+01*** | — |
| Aroclor-1242 | 8.76E-02 | — | 0.50 | 66 | 0.069 | 1.75E-01 | 1.34E-03 | ***1.28E+00*** | — |
| Aroclor-1254 | 1.30E-01 | — | 0.50 | 66 | 0.11 | 2.59E-01 | 1.98E-03 | ***1.13E+00*** | — |
| Arsenic | 94 | 6.5 | 0.67 | 88 | 0.034 | ***1.41E+02*** | ***1.07E+00*** | ***2.76E+03*** | Yes |
| Cadmium | 40.8 | 0.56 | 80 | 3,500 | 0.69 | ***5.10E-01*** | ***1.17E-02*** | ***5.91E+01*** | Yes |
| Chromium | 2,756 | 19 | 120,000 | 5.25E+06 | 2,000 | 2.30E-02 | 5.25E-04 | ***1.38E+00*** | Yes |
| Cobalt | 28 | 16 | 24 | 1,050 | 4.3 | ***1.17E+00*** | 2.67E-02 | ***6.45E+00*** | Yes |
| Cyanide | 5.6 | — | 48 | 2,100 | 0.97 | 1.17E-01 | 2.67E-03 | ***5.78E+00*** | — |
| Fluoride | 3,421 | 2.8 | 4,800 | 210,000 | 2,884 | 7.13E-01 | 1.63E-02 | ***1.19E+00*** | Yes |
| Iron | 34,421 | 32,600 | 56,000 | 2.45E+06 | 5,645 | 6.15E-01 | 1.40E-02 | ***6.10E+00*** | Yes |
| Lead | 2,163 | 10 | — | 1,000 [e] | 3,000 | — | ***2.16E+00*** | 7.21E-01 | Yes |
| Manganese | 7,758 | 512 | 11,200 | 490,000 | 501 | 6.93E-01 | 1.58E-02 | ***1.55E+01*** | Yes |
| Mercury | 91 | 0.013 | 24 | 1,050 | 2.1 | ***3.79E+00*** | 8.67E-02 | ***4.36E+01*** | Yes |
| Nickel | 2,182 | 19 | 1,600 | 70,000 | 130 | ***1.36E+00*** | 3.12E-02 | ***1.67E+01*** | Yes |
| Nitrate | 1,200 | 52 | 568,000 | 2.49E+07 | 180 | 2.11E-03 | 4.83E-05 | ***6.67E+00*** | Yes |
| Nitrite | 601 | — | 24,000 | 1.05E+06 | 13 | 2.50E-02 | 5.72E-04 | ***4.55E+01*** | — |
| Selenium | 113 | 0.78 | 400 | 17,500 | 5.2 | 2.83E-01 | 6.46E-03 | ***2.17E+01*** | Yes |
| Silver | 257 | 0.17 | 400 | 17,500 | 14 | 6.43E-01 | 1.47E-02 | ***1.89E+01*** | Yes |
| Thallium | 594 | 0.19 | — | — | 0.71 | — | — | ***8.34E+02*** | Yes |
| Tributyl phosphate | 12,140 | — | 111 | 14,583 | 0.50 | ***1.09E+02*** | 8.32E-01 | ***2.45E+04*** | — |
| Uranium | 100,091 | 3.2 | 240 | 10,500 | 270 | ***4.17E+02*** | ***9.53E+00*** | ***3.71E+02*** | Yes |

Note: **Bolded** ratios indicate exceedances.

[a] RPP-RPT-42323, "Hanford C-Farm Tank and Ancillary Equipment Residual Waste Inventory Estimates," Appendix D-1.3, "Mean Concentration of C-Farm Sludge Residual Waste (for post retrieval tank samples)."

[b] ECF-Hanford-10-0444, "Documentation of Standard Method B Soil Cleanup Levels for Unrestricted Land Use."

[c] ECF-HANFORD-10-0453, "Calculation of Standard Method C Direct Contact Soil Cleanup Levels for Industrial Land Use for the 100 Areas and 300 Area Remedial Investigation/Feasibility Study Reports."

[d] ECF-HANFORD-10-0442, "Calculation of Nonradiological Soil Concentrations Protective of Groundwater Using the Fixed Parameter 3-Phase Equilibrium Partitioning Equation for the 100 Areas and 300 Area."

[e] The lead soil industrial cleanup value is the Method A industrial soil cleanup level from Table 745-1 in Washington Administrative Code 173-340-745, "Soil Cleanup Standards for Industrial Properties," subsection (3) "Method A industrial soil cleanup levels."

**Table 4-3. Summary of Residual Concentrations for Tanks Without Post-Retrieval Sample Inventory Compared Against Model Toxics Control Act Cleanup Levels. (1 of 2 sheets)**

| Analyte | Residual Concentration[a] (mg/kg) | 90th Percentile Background (mg/kg) | Soil Method B Unrestricted Land Use[b] (mg/kg) | Soil Method C Industrial Land Use[c] (mg/kg) | Soil Concentration Protective of Groundwater[d] (mg/kg) | Ratio of Residual Waste Concentrations to Soil Cleanup Levels | | | Above 90th Percentile Background? |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Method B | Method C | 3-Phase | |
| **Tank 241-C-101 Best-Basis Inventory** | | | | | | | | | |
| Iron | 19,106 | 32,600 | 56,000 | 2.45E+06 | 5,645 | 3.41E-01 | 7.80E-03 | ***3.38E+00*** | No |
| Mercury | 65 | 0.013 | 24 | 1,050 | 2.1 | ***2.71E+00*** | 6.19E-02 | ***3.11E+01*** | Yes |
| Nitrate | 178,642 | 52 | 568,000 | 2.49E+07 | 180 | 3.15E-01 | 7.19E-03 | ***9.92E+02*** | Yes |
| Nitrite | 12,287 | — | 24,000 | 1.05E+06 | 13 | 5.12E-01 | 1.17E-02 | ***9.31E+02*** | — |
| Sulfate | 16,797 | 237 | — | — | 1,000 | — | — | ***1.68E+01*** | Yes |
| Uranium | 11,241 | 3.2 | 240 | 10,500 | 270 | ***4.68E+01*** | ***1.07E+00*** | ***4.16E+01*** | Yes |
| **Tank 241-C-102 Best-Basis Inventory** | | | | | | | | | |
| Aluminum | 144,063 | 11,800 | 80,000 | 3.50E+06 | 480,064 | ***1.80E+00*** | 4.12E-02 | 3.00E-01 | Yes |
| Iron | 9,121 | 32,600 | 56,000 | 2.45E+06 | 5,645 | 1.63E-01 | 3.72E-03 | ***1.62E+00*** | No |
| Manganese | 777 | 512 | 11,200 | 490,000 | 501 | 6.94E-02 | 1.59E-03 | ***1.55E+00*** | Yes |
| Mercury | 3.1 | 0.013 | 24 | 1,050 | 2.1 | 1.29E-01 | 2.95E-03 | ***1.48E+00*** | Yes |
| Nickel | 3,322 | 19 | 1,600 | 70,000 | 130 | ***2.08E+00*** | 4.75E-02 | ***2.55E+01*** | Yes |
| Nitrate | 33,788 | 52 | 568,000 | 2.49E+07 | 180 | 5.95E-02 | 1.36E-03 | ***1.88E+02*** | Yes |
| Nitrite | 9,846 | — | 24,000 | 1.05E+06 | 13 | 4.10E-01 | 9.38E-03 | ***7.46E+02*** | — |
| Sulfate | 3,731 | 237 | — | — | 1,000 | — | — | ***3.73E+00*** | Yes |
| Uranium | 8,032 | 3.2 | 240 | 10,500 | 270 | ***3.35E+01*** | 7.65E-01 | ***2.97E+01*** | Yes |
| **Tank 241-C-102 Hanford Tank Waste Operations Simulator Inventory** | | | | | | | | | |
| Aluminum | 319,991 | 11,800 | 80,000 | 3.50E+06 | 480,064 | ***4.00E+00*** | 9.14E-02 | 6.67E-01 | Yes |
| Chromium | 2.66E+06 | 19 | 120,000 | 5.25E+06 | 2,000 | ***2.22E+01*** | 5.07E-01 | ***1.33E+03*** | Yes |
| Iron | 3.43E+07 | 32,600 | 56,000 | 2.45E+06 | 5,645 | ***6.13E+02*** | ***1.40E+01*** | ***6.08E+03*** | Yes |
| Lead | 183,886 | 10 | — | 1,000 | 3,000 | — | ***1.84E+02*** | ***3.13E+01*** | Yes |
| Manganese | 7,797 | 512 | 11,200 | 490,000 | 501 | 6.96E-01 | 1.59E-02 | ***1.56E+01*** | Yes |
| Nickel | 173 | 19 | 1,600 | 70,000 | 130 | 1.08E-01 | 2.47E-03 | ***1.33E+00*** | Yes |
| Nitrate | 2,118 | 52 | 568,000 | 2.49E+07 | 180 | 3.73E-03 | 8.52E-05 | ***1.18E+01*** | Yes |
| Uranium | 8,300 | 3.2 | 240 | 10,500 | 270 | ***3.46E+01*** | 7.90E-01 | ***3.07E+01*** | Yes |
| **Tank 241-C-105 Best-Basis Inventory** | | | | | | | | | |
| Aluminum | 201,299 | 11,800 | 80,000 | 3.50E+06 | 480,064 | ***2.52E+00*** | 5.75E-02 | 4.19E-01 | Yes |
| Manganese | 2,468 | 512 | 11,200 | 490,000 | 501 | 2.20E-01 | 5.04E-03 | ***4.93E+00*** | Yes |
| Mercury | 6.8 | 0.013 | 24 | 1,050 | 2.1 | 2.83E-01 | 6.48E-03 | ***3.26E+00*** | Yes |
| Nickel | 2,156 | 19 | 1,600 | 70,000 | 130 | 1.35E+00 | 3.08E-02 | ***1.65E+01*** | Yes |
| Nitrate | 10,571 | 52 | 568,000 | 2.49E+07 | 180 | 1.86E-02 | 4.25E-04 | ***5.87E+01*** | Yes |
| Nitrite | 8,740 | — | 24,000 | 1.05E+06 | 13 | 3.64E-01 | 8.32E-03 | ***6.62E+02*** | — |
| Sulfate | 3,792 | 237 | — | — | 1,000 | — | — | ***3.79E+00*** | Yes |
| Uranium | 9,909 | 3.2 | 240 | 10,500 | 270 | ***4.13E+01*** | 9.44E-01 | ***3.67E+01*** | Yes |
| **Tank 241-C-105 Hanford Tank Waste Operations Simulator Inventory** | | | | | | | | | |
| Aluminum | 327,286 | 11,800 | 80,000 | 3.50E+06 | 480,064 | ***4.09E+00*** | 9.35E-02 | 6.82E-01 | Yes |
| Chromium | 1.73E+06 | 19 | 120,000 | 5.25E+06 | 2,000 | ***1.44E+01*** | 3.30E-01 | ***8.65E+02*** | Yes |
| Iron | 3.64E+07 | 32,600 | 56,000 | 2.45E+06 | 5,645 | ***6.50E+02*** | ***1.49E+01*** | ***6.45E+03*** | Yes |
| Lead | 247,646 | 10 | — | 1,000 | 3,000 | — | ***2.48E+02*** | ***8.25E+01*** | Yes |
| Manganese | 446,615 | 512 | 11,200 | 490,000 | 501 | ***3.99E+01*** | 9.11E-01 | ***8.92E+02*** | Yes |
| Nitrate | 785 | 52 | 568,000 | 2.49E+07 | 180 | 1.38E-03 | 3.16E-05 | ***4.36E+00*** | Yes |
| Strontium | 348,540 | — | 48,000 | 2.10E+06 | 6,758 | ***7.26E+00*** | 1.66E-01 | ***5.16E+01*** | — |
| Uranium | 1,764 | 3.2 | 240 | 10,500 | 270 | ***7.35E+00*** | 1.68E-01 | ***6.53E+00*** | Yes |

**Table 4-3. Summary of Residual Concentrations for Tanks Without Post-Retrieval Sample Inventory Compared Against Model Toxics Control Act Cleanup Levels. (2 of 2 sheets)**

| Analyte | Residual Concentration[a] (mg/kg) | 90th Percentile Background (mg/kg) | Soil Method B Unrestricted Land Use[b] (mg/kg) | Soil Method C Industrial Land Use[c] (mg/kg) | Soil Concentration Protective of Groundwater[d] (mg/kg) | Ratio of Residual Waste Concentrations to Soil Cleanup Levels | | | Above 90th Percentile Background? |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Method B | Method C | 3-Phase | |
| **Tank 241-C-107 Best-Basis Inventory** | | | | | | | | | |
| Fluoride | 7,367 | 2.8 | 4,800 | 210,000 | 2,884 | ***1.53E+00*** | 3.51E-02 | ***2.55E+00*** | Yes |
| Iron | 53,145 | 32,600 | 56,000 | 2.45E+06 | 5,645 | 9.49E-01 | 2.17E-02 | ***9.41E+00*** | Yes |
| Lead | 4,405 | 10 | — | 1,000 | 3,000 | — | ***4.41E+00*** | — | Yes |
| Manganese | 2,343 | 512 | 11,200 | 490,000 | 501 | 2.09E-01 | 4.78E-03 | ***4.68E+00*** | Yes |
| Mercury | 46 | 0.013 | 24 | 1,050 | 2.1 | ***1.92E+00*** | 4.38E-02 | ***2.20E+01*** | Yes |
| Nickel | 1,200 | 19 | 1,600 | 70,000 | 130 | 7.50E-01 | 1.71E-02 | ***9.20E+00*** | Yes |
| Nitrate | 43,679 | 52 | 568,000 | 2.49E+07 | 180 | 7.69E-02 | 1.76E-03 | ***2.43E+02*** | Yes |
| Nitrite | 26,151 | — | 24,000 | 1.05E+06 | 13 | ***1.09E+00*** | 2.49E-02 | ***1.98E+03*** | — |
| Sulfate | 6,289 | 237 | — | — | 1,000 | — | — | ***6.29E+00*** | Yes |
| Uranium | 7,695 | 3.2 | 240 | 10,500 | 270 | ***3.21E+01*** | 7.33E-01 | ***2.85E+01*** | Yes |
| **Tank 241-C-111 Best-Basis Inventory** | | | | | | | | | |
| Chlorine | 1,101 | 100 | — | — | 1,000 | — | — | ***1.10E+00*** | Yes |
| Fluoride | 4,022 | 2.8 | 4,800 | 210,000 | 2,884 | 8.38E-01 | 1.92E-02 | ***1.39E+00*** | Yes |
| Iron | 37,530 | 32,600 | 56,000 | 2.45E+06 | 5,645 | 6.70E-01 | 1.53E-02 | ***6.65E+00*** | Yes |
| Lead | 3,813 | 10 | — | 1,000 | 3,000 | — | ***3.81E+00*** | ***1.27E+00*** | Yes |
| Mercury | 234 | 0.013 | 24 | 1,050 | 2.1 | ***9.75E+00*** | 2.23E-01 | ***1.12E+02*** | Yes |
| Nickel | 13,208 | 19 | 1,600 | 70,000 | 130 | ***8.26E+00*** | 1.89E-01 | ***1.01E+02*** | Yes |
| Nitrate | 73,266 | 52 | 568,000 | 2.49E+07 | 180 | 1.29E-01 | 2.95E-03 | ***4.07E+02*** | Yes |
| Nitrite | 27,412 | — | 24,000 | 1.05E+06 | 13 | ***1.14E+00*** | 2.61E-02 | ***2.08E+03*** | — |
| Sulfate | 6,280 | 237 | — | — | 1,000 | — | — | ***6.28E+00*** | Yes |
| Uranium | 11,762 | 3.2 | 240 | 10,500 | 270 | ***4.90E+01*** | 1.12E+00 | ***4.35E+01*** | Yes |
| **Tank 241-C-111 Hanford Tank Waste Operations Simulator Inventory** | | | | | | | | | |
| Aluminum | 226,677 | 11,800 | 80,000 | 3.50E+06 | 480,064 | ***2.83E+00*** | 6.48E-02 | 4.72E-01 | Yes |
| Chromium | 2.99E+07 | 819 | 120,000 | 5.25E+06 | 2,000 | ***2.49E+02*** | ***5.70E+00*** | ***1.49E+04*** | Yes |
| Iron | 1.12E+09 | 32,600 | 56,000 | 2.45E+06 | 5,645 | ***2.00E+04*** | ***4.57E+02*** | ***1.98E+05*** | Yes |
| Lead | 6.26E+06 | 10 | — | 1,000 | 3,000 | — | ***6.26E+03*** | ***2.09E+03*** | Yes |
| Manganese | 540 | 512 | 11,200 | 490,000 | 501 | 4.82E-02 | 1.10E-03 | ***1.08E+00*** | Yes |
| Nickel | 1,641 | 19 | 1,600 | 70,000 | 130 | ***1.03E+00*** | 2.34E-02 | ***1.26E+01*** | Yes |
| Nitrate | 1,760 | 52 | 568,000 | 2.49E+07 | 180 | 3.10E-03 | 7.08E-05 | ***9.78E+00*** | Yes |
| Strontium | 3.14E+06 | — | 48,000 | 2.10E+06 | 6,758 | ***6.54E+01*** | ***1.50E+00*** | ***4.65E+02*** | — |
| Uranium | 17,262 | 3.2 | 240 | 10,500 | 270 | ***7.19E+01*** | ***1.64E+00*** | ***6.39E+01*** | Yes |
| **Tank 241-C-112 Best-Basis Inventory** | | | | | | | | | |
| Fluoride | 10,329 | 2.8 | 4,800 | 210,000 | 2,884 | ***2.15E+00*** | 4.92E-02 | ***3.58E+00*** | Yes |
| Iron | 10,227 | 32,600 | 56,000 | 2.45E+06 | 5,645 | 1.83E-01 | 4.17E-03 | ***1.81E+00*** | No |
| Nitrate | 127,622 | 52 | 568,000 | 2.49E+07 | 180 | 2.25E-01 | 5.14E-03 | ***7.09E+02*** | Yes |
| Nitrite | 9,834 | — | 24,000 | 1.05E+06 | 13 | 4.10E-01 | 9.37E-03 | ***7.45E+02*** | — |
| Sulfate | 13,578 | 237 | — | — | 1,000 | — | — | ***1.36E+01*** | Yes |
| Uranium | 1,879 | 3.2 | 240 | 10,500 | 270 | ***7.83E+00*** | 1.79E-01 | ***6.96E+00*** | Yes |

Note: **Bolded** ratios indicate exceedances.

[a] RPP-RPT-42323, "Hanford C-Farm Tank and Ancillary Equipment Residual Waste Inventory Estimates," Appendix B-2, "2014 BBI Inventory for SSTs and Appendix C-2, 2014 Residual Inventory."

[b] ECF-Hanford-10-0444, "Documentation of Standard Method B Soil Cleanup Levels for Unrestricted Land Use."

[c] ECF-HANFORD-10-0453, "Calculation of Standard Method C Direct Contact Soil Cleanup Levels for Industrial Land Use for the 100 Areas and 300 Area Remedial Investigation/Feasibility Study Reports."

[d] ECF-HANFORD-10-0442, "Calculation of Nonradiological Soil Concentrations Protective of Groundwater Using the Fixed Parameter 3-Phase Equilibrium Partitioning Equation for the 100 Areas and 300 Area."

**Table 4-4. Summary of Analytes that Exceed Model Toxics Control Act Soil Method B Cleanup Levels.**

| Tank | Analytes |
|---|---|
| **Post-Retrieval Sample Based Inventory[a]** | |
| 241-C-103 | aluminum, arsenic, mercury, silver, and uranium |
| 241-C-104 | aluminum, arsenic, cadmium, mercury, polychlorinated biphenyls, silver, and uranium |
| 241-C-106 | antimony, arsenic, cadmium, manganese, mercury, nickel, and silver |
| 241-C-108 | aluminum, arsenic, nickel, and uranium |
| 241-C-109 | aluminum, arsenic, fluoride, and uranium |
| 241-C-110 | aluminum, arsenic, fluoride, and uranium |
| 241-C-201 | antimony, aroclor-1232, arsenic, cobalt, iron, manganese, mercury, nickel, tributyl phosphate, and uranium |
| 241-C-202 | antimony, arsenic, cobalt, iron, manganese, mercury, nickel, tributyl phosphate, and uranium |
| 241-C-203 | antimony, arsenic, cobalt, tributyl phosphate, and uranium |
| 241-C-204 | antimony, arsenic, cobalt, mercury, selenium, tributyl phosphate, and uranium |
| Ancillary Equipment | aluminum, antimony, arsenic, cobalt, mercury, nickel, tributyl phosphate, and uranium |
| **Pre-Retrieval Inventory** | |
| 241-C-101 | mercury and uranium |
| 241-C-102[b] | aluminum, nickel, and uranium |
| 241-C-102[c] | aluminum, chromium, iron, and uranium |
| 241-C-105[b] | aluminum, nickel, and uranium |
| 241-C-105[c] | aluminum, chromium, iron, manganese, strontium, and uranium |
| 241-C-107 | fluoride, mercury, nitrite, and uranium |
| 241-C-111[b] | mercury, nickel, nitrite, and uranium |
| 241-C-111[c] | aluminum, chromium, iron, nickel, strontium, and uranium |
| 241-C-112 | fluoride and uranium |

[a] Post-retrieval residual inventory estimates based on Best-Basis Inventory sample based inventory.

[b] Maximum pre-retrieval residual inventory estimates based on Best-Basis Inventory and current residual volume.

[c] Minimum pre-retrieval residual inventory estimates based on Hanford Tank Waste Operations Simulator model at a volume of 10.2 $m^3$ (360 $ft^3$).

For ancillary equipment, 19 analytes (trichloroethene, antimony, arsenic, cadmium, chromium, cobalt, cyanide, fluoride, iron, manganese, mercury, nickel, nitrate, nitrite, selenium, silver, thallium, TBP, and uranium) exceed MTCA three-phase concentrations protective of

groundwater. Levels of exceedance range from approximately 1.2 to 25,000 times greater than the soil CUL.

**Table 4-5. Summary of Analytes that Exceed Model Toxics Control Act Soil Method C Cleanup Levels.**

| Tank | Analytes |
|---|---|
| **Post-Retrieval Sample Based Inventory[a]** | |
| 241-C-103 | — |
| 241-C-104 | uranium |
| 241-C-106 | arsenic and lead |
| 241-C-108 | — |
| 241-C-109 | |
| 241-C-110 | |
| 241-C-201 | arsenic, lead, tributyl phosphate, and uranium |
| 241-C-202 | arsenic, lead, and uranium |
| 241-C-203 | arsenic, lead, and uranium |
| 241-C-204 | arsenic, lead, tributyl phosphate, and uranium |
| Ancillary Equipment | arsenic, lead, and uranium |
| **Pre-Retrieval Inventory** | |
| 241-C-101 | uranium |
| 241-C-102[b] | — |
| 241-C-102[c] | iron and lead |
| 241-C-105[b] | — |
| 241-C-105[c] | iron and lead |
| 241-C-107 | lead |
| 241-C-111[b] | lead and uranium |
| 241-C-111[c] | chromium, iron, lead, strontium, and uranium |
| 241-C-112 | — |

[a] Post-retrieval residual inventory estimates based on Best-Basis Inventory sample based inventory.

[b] Maximum pre-retrieval residual inventory estimates based on Best-Basis Inventory and current residual volume.

[c] Minimum pre-retrieval residual inventory estimates based on Hanford Tank Waste Operations Simulator model at a volume of 10.2 $m^3$ (360 $ft^3$).

**Table 4-6. Summary of Analytes that Exceed Model Toxics Control Act Three-Phase Soil Concentrations Protective of Groundwater. (2 sheets)**

| Tank | Analytes |
|---|---|
| **Post-Retrieval Sample Based Inventory[a]** | |
| 241-C-103 | trichloroethene, antimony, aroclor-1221, aroclor-1232, arsenic, cadmium, cobalt, iron, mercury, nickel, nitrite, selenium, silver, thallium, tributyl phosphate, and uranium |
| 241-C-104 | antimony, arsenic, cadmium, cyanide, iron, manganese, mercury, nickel, nitrate, nitrite, selenium, silver, thallium, tributyl phosphate, and uranium |
| 241-C-106 | trichloroethene, antimony,aroclor-1221, aroclor-1232, aroclor-1242, aroclor-1254, arsenic, cadmium, cobalt, cyanide, iron, manganese, mercury, nickel, nitrate, nitrite, selenium, silver, sulfate, and thallium |
| 241-C-108 | trichloroethene, antimony, arsenic, cadmium, cyanide, fluoride, iron, nickel, nitrate, nitrite, selenium, thallium, tributyl phosphate, and uranium |
| 241-C-109 | antimony, arsenic, cadmium, cyanide, fluoride, iron, nickel, nitrate, nitrite, selenium, thallium, tributyl phosphate, and uranium |
| 241-C-110 | antimony, arsenic, cadmium, copper, fluoride, iron, mercury, nitrate, nitrite, silver, thallium, tributyl phosphate, and uranium |
| 241-C-201 | trichloroethene, antimony, aroclor-1221, aroclor-1232, aroclor-1242, arsenic, cadmium, chromium, cobalt, copper, cyanide, iron, manganese, mercury, nickel, nitrate, nitrite, selenium, thallium, tributyl phosphate, and uranium |
| 241-C-202 | trichloroethene, antimony, arsenic, cadmium, chromium, cobalt, copper, cyanide, iron, lead, manganese, mercury, nickel, nitrate, nitrite, selenium, thallium, tributyl phosphate, and uranium |
| 241-C-203 | trichloroethene, antimony, aroclor-1221, aroclor-1232, aroclor-1242, arsenic, cadmium, chromium, cobalt, cyanide, iron, manganese, mercury, nickel, nitrate, nitrite, selenium, silver, thallium, tributyl phosphate, and uranium |
| 241-C-204 | trichloroethene, antimony, aroclor-1221, aroclor-1232, aroclor-1242, arsenic, cadmium, cobalt, iron, mercury, nickel, nitrate, nitrite, selenium, silver, thallium, tributyl phosphate, and uranium |
| Ancillary Equipment | trichloroethene, antimony, aroclor-1221, aroclor-1232, aroclor-1242, aroclor-1254, arsenic, cadmium, chromium, cobalt, cyanide, fluoride, iron, manganese, mercury, nickel, nitrate, nitrite, selenium, silver, thallium, tributyl phosphate, and uranium |
| **Pre-Retrieval Inventory** | |
| 241-C-101 | iron, mercury, nitrate, nitrite, sulfate, and uranium |
| 241-C-102[b] | iron, manganese, mercury, nickel, nitrate, nitrite, sulfate, and uranium |
| 241-C-102[c] | chromium, iron, lead, manganese, nickel, nitrate, and uranium |
| 241-C-105[b] | manganese, mercury, nickel, nitrate, nitrite, sulfate, and uranium |
| 241-C-105[c] | chromium, iron, manganese, nitrate, strontium, and uranium |
| 241-C-107 | fluoride, iron, lead, manganese, mercury, nickel, nitrate, nitrite, sulfate, and uranium |
| 241-C-111[b] | chlorine, fluoride, iron, lead, mercury, nickel, nitrate, nitrite, sulfate, and uranium |

**Table 4-6. Summary of Analytes that Exceed Model Toxics Control Act Three-Phase Soil Concentrations Protective of Groundwater. (2 sheets)**

| Tank | Analytes |
|---|---|
| 241-C-111[c] | chromium, iron, lead, manganese, nickel, nitrate, strontium, and uranium |
| 241-C-112 | fluoride, iron, nitrate, nitrite, sulfate, and uranium |

[a] Post-retrieval residual inventory estimates based on Best-Basis Inventory sample based inventory.

[b] Maximum pre-retrieval residual inventory estimates based on Best-Basis Inventory and current residual volume.

[c] Minimum pre-retrieval residual inventory estimates based on Hanford Tank Waste Operations Simulator model at a volume of 10.2 $m^3$ (360 $ft^3$).

#### 4.4.3.2 Results for Tanks with Pre-Retrieval Inventory.

- For tank C-101, based on BBI inventory, concentrations for six analytes (iron, mercury, nitrate, nitrite, sulfate, and uranium) exceed MTCA three-phase concentrations protective of groundwater. Levels of exceedance range from approximately 3.4 to 930 times greater than the soil CUL.

- For tank C-102, based on BBI inventory, concentrations for eight analytes (iron, manganese, mercury, nickel, nitrate, nitrite, sulfate, and uranium) exceed MTCA three-phase concentrations protective of groundwater. Levels of exceedance range from approximately 1.5 to 750 times greater than the soil CUL. For inventory based on HTWOS inventory at 10.2 $m^3$ (360 $ft^3$), seven analytes (chromium, iron, lead, manganese, nickel, nitrate, and uranium) exceed MTCA three-phase concentrations protective of groundwater. Levels of exceedance range from approximately 1.3 to 6,100 times greater than the soil CUL.

- For tank C-105, based on BBI inventory, concentrations for seven analytes (manganese, mercury, nickel, nitrate, nitrite, sulfate, and uranium) exceed MTCA three-phase concentrations protective of groundwater. Levels of exceedance range from approximately 3.3 to 660 times greater than the soil CUL. For inventory based on HTWOS inventory at 10.2 $m^3$ (360 $ft^3$), seven analytes (chromium, iron, lead, manganese, nitrate, strontium, and uranium) exceed MTCA three-phase concentrations protective of groundwater. Levels of exceedance range from approximately 4.4 to 6,500 times greater than the soil CUL.

- For tank C-107, based on BBI inventory, concentrations for 10 analytes (fluoride, iron, lead, manganese, mercury, nickel, nitrate, nitrite, sulfate, and uranium) exceed MTCA three-phase concentrations protective of groundwater. Levels of exceedance range from approximately 1.5 to 2,000 times greater than the soil CUL.

- For tank C-111, based on BBI inventory, concentrations for 10 analytes (chlorine, fluoride, iron, lead, mercury, nickel, nitrate, nitrite, sulfate, and uranium) exceed MTCA three-phase concentrations protective of groundwater. Levels of exceedance range from

approximately 1.3 to 2,100 times greater than the soil CUL. For inventory based on HTWOS inventory at 10.2 $m^3$ (360 $ft^3$), eight analytes (chromium, iron, lead, manganese, nickel, nitrate, strontium, and uranium) exceed MTCA three-phase concentrations protective of groundwater. Levels of exceedance range from approximately 1.1 to 200,000 times greater than the soil CUL.

- For tank C-112, based on BBI inventory, concentrations for six analytes (fluoride, iron, nitrate, nitrite, sulfate, and uranium) exceed MTCA three-phase concentrations protective of groundwater. Levels of exceedance range from approximately 1.8 to 750 times greater than the soil CUL.

## 4.5 CONCLUSIONS

With regard to MTCA direct contact Method B (soil cleanup levels for unrestricted land use), all 16 tanks had waste residuals containing contaminants that exceeded the MTCA Method B soil cleanup levels. For MTCA direct contact Method C (soil cleanup levels for industrial land use), 12 of the 16 tanks along with the ancillary equipment had at least one contaminant in the tank residual waste that exceeded the MTCA Method C soil cleanup levels. Four tanks did not exceed MTCA Method C soil cleanup levels for direct contact. This comparison to MTCA direct contact Methods B and C soil cleanup levels is for informational purposes only, because the tank residuals are located below point of compliance for direct contact (4.5 m [15 ft] bgs). No further analysis of the direct contact pathway is made in this document.

All 16 tanks, along with the ancillary equipment, had contaminants in the residuals that exceeded MTCA three-phase soil concentrations protective of groundwater. However, as noted earlier, the MTCA three-phase soil cleanup levels protective of groundwater are for contaminants that are in contaminated soil.

At closure, the tank residual waste is enclosed within a tank structure that consists of a steel liner supported by a concrete structure (Figures 3-46 and 3-47) and is not in contact with soil. Prior to closure of the tank farm, the tanks will also be filled with grout. Additional analyses need to be made to understand the release of the contaminants remaining in the tank residual wastes via the groundwater pathway from source through the environmental media (vadose zone and unconfined aquifer) and uptake at a well located downgradient from WMA C to assess the risk and hazard impacts to a human receptor using the groundwater.

The rest of this document describes the analysis of tank residual waste impacts along the groundwater pathway. While there is no specific guidance in WAC 173-303-610, WAC 173-303-640(8), or WAC 173-303-665(6) as to what should be included in this analysis, relevant guidance that may be applicable to this effort can be found in WAC 173-303-665 subsection (2) “Design and operating requirements” (b) which allows Ecology to exempt the

owner or operator from the requirement for a landfill liner WAC 173-303-665 (2)(a) under certain conditions. The exemption under WAC 173-303-665 (2)(b) is

> "… based on a demonstration by the owner or operator, that alternative design and operating practices, together with location characteristics, will prevent the migration of any dangerous constituents into the groundwater or surface water at any future time. In deciding whether to grant an exemption, the department will consider:
>
> (i) The nature and quantity of the wastes *[see Sections 3.2.2 Waste Inventory and Section 5.0 Constituent Identification, Section 6 Waste Characteristics]*;
> (ii) The proposed alternate design and operation *[see Section 3.2.1.2 Closure for assumed closure configuration]*;
> (iii) The hydrogeologic setting of the facility, including the attenuative capacity and thickness of the liners and soils present between the landfill and groundwater or surface water; and *[see Sections: 3.1 Site Characteristics and Section 7.0 Analysis of Hazards and Impacts (provides the conceptual and mathematical models used for the analysis), Section 8.0 Results]*
> (iv) All other factors which would influence the quality and mobility of the leachate produced and the potential for it to migrate to groundwater or surface water. *[see Section 9.0 Sensitivity Analysis for Groundwater Pathway]*"

WAC 173-303-665 (2)(b) does not specifically apply to tank systems, but because WMA C does not have a liner and/or leachate collection system, it is being brought forward to assist in determining what data and information Ecology might need to support closure decisions. The RCA puts together the information requested in WAC 173-303-665 (2)(b)(i) – (iv) in a variety of modeling approaches to understand contaminant levels in the leachate migrating out of the tank and ancillary equipment as a result of the residual contamination left behind, and its subsequent transport through the vadose zone into the unconfined aquifer and uptake by a human receptor in order to make better closure and post-closure care decisions.

# 5.0 CONSTITUENT IDENTIFICATION

Chemical constituents of potential concern (COPCs) were identified for the groundwater modeling portion of the RCA using two types of COPC identification evaluations: 1) an evaluation that considered inventory-related information including constituent-specific availability of toxicity information and mass estimates, and 2) an evaluation that considered information on the groundwater pathway including travel times to the accessible environment and constituent-specific mobility. These evaluations and their results are described in the following sections.

## 5.1 CONSTITUENT IDENTIFICATION BASED ON INVENTORY-RELATED INFORMATION

The approach taken for identifying specific chemical constituents for more detailed analysis in the RCA based on evaluation of inventory-related information is discussed below.

- The evaluation began with all chemicals for which WMA C tank inventory information is available in the BBI within the official Tank Waste Information Network System (TWINS) database. The BBI contains inventory estimates for 24 chemicals.

- The next step in the evaluation process considered known toxicity information. Chemicals tracked in the BBI with no known toxicity information were excluded as COPCs. Twelve constituents (Bi, Ca, Cl, K, La, Na, $PO_4$, Si, $SO_4$, total inorganic carbon, total organic carbon, and Zr) were excluded from further consideration.

The results of this overall COPC identification process identified a total of 12 chemical COPCs (Al, Cr, F, Fe, Hg, Mn, Ni, $NO_2$, $NO_3$, Pb, Sr, and total Uranium) for further evaluation in the RCA.

An additional evaluation was conducted to identify any supplemental analytes in residual inventory estimates for retrieved tanks that were not included in the BBI but may be of interest for the RCA calculations. Residual inventory estimates for retrieved tanks were obtained from RPP-RPT-42323, Table D-1. A comprehensive list of C Farm analytes is provided in RPP-RPT-42323, Table D-1; this list of analytes was reduced to identify supplemental analytes based on the following exclusion criteria:

- analytes not required to be sampled in RPP-23403,

- analytes without known toxicity information,

- analytes with nominal inventories less than 0.1 kg at each retrieved tank, as such small inventories were judged to have insignificant effect on the system performance, and

- analytes with $K_d$ values greater than 2 mL/g (see Sections 6.3.2.3 and 7.2.1)[1].

The process of identifying supplemental analytes, resulted in six analytes (B, Co, CN, Se, Sn, and TBP) being identified for further evaluation in the RCA.

## 5.2 SUMMARY OF CHEMICAL CONSTITUENT OF POTENTIAL CONCERN IDENTIFICATION

In summary, the total number of chemical COPCs identified for more detailed analysis in the RCA is 18. The final set of chemicals used for the more detailed analysis in the RCA are presented in Table 5-1.

**Table 5-1. List of Chemicals Considered for the RCRA Closure Analysis.**

| Number | Species ID | Description | Atomic Weight |
|---|---|---|---|
| 1 | Al | Aluminum | 26.98 |
| 2 | Cr | Chromium | 51.99 |
| 3 | F | Fluoride | 18.99 |
| 4 | Fe | Iron | 55.85 |
| 5 | Hg | Mercury | 200.6 |
| 6 | Mn | Manganese | 54.94 |
| 7 | Ni | Nickel | 58.7 |
| 8 | $NO_2$ | Nitrite | 46 |
| 9 | $NO_3$ | Nitrate | 62 |
| 10 | Pb | Lead | 207.2 |
| 11 | Sr | Strontium | 87.6 |
| 12 | UTOTAL | Total Uranium | 238.03 |
| 13 | B | Boron | 10.8 |
| 14 | Co | Cobalt | 58.9 |
| 15 | CN | Cyanide | 26 |
| 16 | Se | Selenium | 78.9 |
| 17 | Sn | Tin | 118.7 |
| 18 | TBP | Tributyl phosphate | 266.3 |

RCRA = Resource Conservation and Recovery Act of 1976

Furthermore, the residual inventory of pits is not considered due to very small estimated residual volume, which is a factor of 50 smaller than that estimated for the pipeline. The final best estimate inventory for chemicals considered in the RCA is presented in Table 5-2.

[1] Additional COPC identification was performed using the 3-D STOMP©-based flow and transport model to determine the maximum $K_d$ value of COPCs in the WMA C tank residuals that are capable of reaching the water table in 1,000 and 10,000 years. Methodology used in that COPC identification analysis is presented in Section 6.3.2.3, and results are provided in Section 7.2.1.

**Table 5-2. Estimated Inventory of Chemicals (in Kilograms) at Closure at Waste Management Area C Used in the RCRA Closure Analysis Calculations.**

| Tank/ Equipment | Al | Cr | F | Fe | Hg | Mn | Ni | $NO_2$ | $NO_3$ | Pb | Sr | U_Total | B | Co | CN | Se | Sn | TBP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **241-C-101** | 7.93E+01 | 7.23E+00 | 3.46E+01 | 8.77E+02 | 2.98E+00 | 7.14E+00 | 3.27E+00 | 5.64E+02 | 8.20E+03 | 2.07E+01 | 2.34E+01 | 5.16E+02 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| **241-C-102** | 9.45E+04 | 2.19E+02 | 1.41E+03 | 5.98E+03 | 2.06E+00 | 5.10E+02 | 2.18E+03 | 6.46E+03 | 2.22E+04 | 5.47E+02 | 5.24E+01 | 5.27E+03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| **241-C-103** | 3.63E+03 | 2.38E+00 | 1.62E-01 | 1.19E+02 | 1.06E+00 | 4.42E+00 | 4.58E+00 | 4.82E-01 | 8.71E-01 | 8.50E+00 | 2.41E+00 | 4.91E+01 | 1.95E-01 | 8.63E-02 | 1.12E-02 | 6.90E-01 | 1.14E+00 | 1.04E+00 |
| **241-C-104** | 1.14E+03 | 3.06E+00 | 1.54E+01 | 3.24E+02 | 1.35E+00 | 4.29E+01 | 6.00E+00 | 5.06E+00 | 9.38E+00 | 6.48E+00 | 9.35E-01 | 1.32E+03 | 0.00E+00 | 2.05E-02 | 1.05E-02 | 7.73E-02 | 2.13E-01 | 1.06E-02 |
| **241-C-105** | 1.49E+04 | 3.70E+01 | 7.92E+01 | 3.92E+02 | 5.03E-01 | 1.83E+02 | 1.60E+02 | 6.47E+02 | 7.83E+02 | 3.45E+01 | 1.38E+01 | 7.34E+02 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| **241-C-106** | 3.82E+02 | 3.78E+00 | 5.43E-01 | 2.07E+02 | 1.93E+00 | 5.49E+02 | 3.02E+01 | 4.14E+01 | 3.48E+01 | 2.56E+01 | 1.83E+00 | 2.70E+00 | 1.19E+00 | 3.75E-01 | 7.80E-02 | 2.94E+00 | 2.40E+00 | 0.00E+00 |
| **241-C-107** | 1.98E+03 | 5.54E+01 | 6.05E+02 | 4.37E+03 | 3.78E+00 | 1.93E+02 | 9.86E+01 | 2.15E+03 | 3.59E+03 | 3.62E+02 | 1.71E+01 | 6.32E+02 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| **241-C-108** | 3.47E+03 | 6.31E-01 | 1.21E+02 | 2.82E+02 | 2.03E-02 | 4.08E+00 | 7.45E+01 | 5.78E+00 | 9.16E+00 | 1.71E+01 | 1.97E+01 | 1.21E+02 | 4.20E-02 | 4.20E-02 | 1.34E-01 | 2.52E-01 | 1.26E-01 | 4.42E-02 |
| **241-C-109** | 2.15E+03 | 1.76E-01 | 9.68E+01 | 9.28E+01 | 1.84E-02 | 5.63E-01 | 1.33E+01 | 3.83E+00 | 4.52E+00 | 5.39E+00 | 4.91E-01 | 2.86E+01 | 1.12E-02 | 1.12E-02 | 3.37E-01 | 6.72E-02 | 3.36E-02 | 7.42E-03 |
| **241-C-110** | 1.29E+03 | 1.12E+00 | 1.38E+02 | 1.90E+02 | 1.07E-01 | 7.61E-01 | 4.13E-01 | 2.74E+00 | 6.73E+00 | 5.62E+00 | 5.63E+01 | 5.49E+00 | 2.33E-02 | 2.35E-02 | 8.12E-03 | 3.99E-02 | 8.42E-01 | 1.01E-01 |
| **241-C-111** | 1.60E+04 | 7.33E+01 | 8.07E+02 | 7.53E+03 | 4.69E+01 | 4.68E+01 | 2.65E+03 | 5.50E+03 | 1.47E+04 | 7.65E+02 | 3.58E+01 | 2.36E+03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| **241-C-112** | 3.32E+02 | 5.78E+01 | 7.09E+02 | 7.02E+02 | 2.63E-02 | 6.52E+00 | 1.46E+00 | 6.75E+02 | 8.76E+03 | 1.36E+01 | 1.00E+01 | 1.29E+02 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| **241-C-201** | 4.11E+00 | 1.22E+01 | 2.69E+00 | 1.10E+02 | 1.07E-01 | 1.90E+01 | 6.15E+00 | 5.27E-01 | 1.35E+00 | 6.25E+00 | 9.09E-01 | 1.11E+02 | 4.69E-02 | 8.56E-02 | 2.08E-03 | 1.16E-01 | 1.32E-01 | 2.02E+01 |
| **241-C-202** | 8.48E+00 | 9.09E+00 | 2.26E+00 | 8.70E+01 | 2.87E-01 | 1.69E+01 | 7.28E+00 | 4.52E-01 | 1.25E+00 | 5.84E+00 | 1.22E+00 | 9.88E+01 | 2.78E-02 | 7.84E-02 | 4.04E-03 | 9.27E-02 | 3.84E-01 | 5.41E+00 |
| **241-C-203** | 0.00E+00 | 2.60E+00 | 1.64E+00 | 1.28E+01 | 2.23E-03 | 5.13E-01 | 2.04E-01 | 9.94E-01 | 3.76E+00 | 3.07E+00 | 2.30E-01 | 3.26E+02 | 6.03E-02 | 2.64E-02 | 4.59E-03 | 2.01E-01 | 1.61E-01 | 9.54E+00 |
| **241-C-204** | 5.88E+00 | 1.36E+00 | 8.05E-03 | 3.21E+01 | 1.47E-01 | 2.39E-01 | 8.01E-01 | 3.13E-02 | 2.22E-02 | 1.02E+00 | 3.67E-01 | 2.43E+02 | 1.24E-01 | 4.13E-02 | 7.06E-04 | 4.13E-01 | 2.07E-01 | 6.69E+01 |
| **C-301** | 5.20E+02 | 1.76E+01 | 2.09E+01 | 2.18E+02 | 5.73E-01 | 4.75E+01 | 1.42E+01 | 3.81E+00 | 7.38E+00 | 1.39E+01 | 5.48E+00 | 6.65E+02 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| **CR-Vault** | 9.44E+02 | 3.19E+01 | 3.80E+01 | 3.96E+02 | 1.04E+00 | 8.63E+01 | 2.59E+01 | 6.92E+00 | 1.34E+01 | 2.52E+01 | 9.96E+00 | 1.21E+03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| **Pipelines** | 7.99E+02 | 2.70E+01 | 3.22E+01 | 3.35E+02 | 8.81E-01 | 7.30E+01 | 2.19E+01 | 5.86E+00 | 1.14E+01 | 2.14E+01 | 8.43E+00 | 1.02E+03 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |

RCRA = Resource Conservation and Recovery Act of 1976 TBP = tributyl phosphate

# 6.0 WASTE CHARACTERISTICS

The WMA C tanks and ancillary equipment received a wide range of waste streams produced from processing of spent nuclear fuel and selective extraction of isotopes of concern to support the Hanford operations. Table 3-12 summarizes the current waste types (primarily sludge) present in various WMA C tanks. The wastes consist of a large array of chemicals and radionuclides and their inventory is estimated on a tank-by-tank basis. As of September 2014, waste has been retrieved from 13 of 16 SSTs in WMA C and is in progress for the remaining 3 tanks (C-102, C-105, and C-111).

Following retrieval of tanks, post-retrieval sampling of the residual waste has been conducted for various constituents as indicated in Section 3.2.2 to estimate the residual inventory and volume. RPP-23403 also requested that in addition to collecting sample material to address the analytical requirements of the DQO, additional solid waste material be obtained to conduct release rate test for risk assessment calculations.

At a number of tanks following retrieval, sufficient material was collected for waste characterization and release rate estimates. As part of these waste characterization efforts, analytical methods are used to measure the chemical and radiological constituents in the waste sludge and to understand their composition, their solid-phase characteristics, and the leachability of primary contaminants of interest. Several detailed characterization reports are available for various tank residuals (e.g., PNNL-16738, “Hanford Tank 241-C-103 Residual Waste Contaminant Release Models and Supporting Data”; PNNL-15187, “Hanford Tank 241-C-106: Residual Waste Contaminant Release Model and Supporting Data,”; PNNL-14903, “Hanford Tanks 241-C-203 and 241-C-204: Residual Waste Contaminant Release Model and Supporting Data,”; PNNL-16229, “Hanford Tanks 241-C-202 and 241-C-203: Residual Waste Contaminant Release Model and Supporting Data”).

“Hanford tank residual waste – Contaminant source terms and release models” (Deutsch et al. 2011) summarized the characterization information of solid phases from four WMA C tank residuals (C-103, C-106, C-202, and C-203). Multiple samples of residual waste from each tank were received. The samples represent composite samples of solids collected from several locations in each storage tank. The photographs of the samples are shown in Figure 6-1. The yellowish color of the tank C-203 residual sample is due to presence of uranium at a concentration of about 50 wt.% while the color of the tank C-106 sample is likely due to presence of high manganese concentration resulting from oxalate reaction with the metals in the waste solids. Tank C-106 is the only tank from which waste was removed using oxalic acid.

The average reported composition (µg/g dry weight) for selected elements, primary contaminants of interest, and anions in bulk residual waste, developed from laboratory analysis of selected tank waste residual samples used for waste release studies by Deutsch et al. (2011), are presented in Table 6-1. Concentrations of certain contaminants and elements differ by orders of magnitude, indicating large variability. For example, the uranium concentration for adjacent tanks C-202 and C-203 are relatively high (207,000 and 505,000 µg/g [7,302 and 17,813 oz/ton], respectively) while they are relatively low for tanks C-103 and C-106 (3,730 and 310 µg/g [132 and 11 oz/ton], respectively). On the other hand, the trend in aluminum concentrations is

reversed, being relatively high for tanks C-103 and C-106 compared to tanks C-202 and C-203. The iron (Fe) concentration for tank C-202 is 122,000 µg/g (4,300 oz/ton) and for tank C-203 is 16,300 µg/g (575 oz/ton). These compositional differences between tanks are due to 1) the mixing of various types of waste disposed over the decades when they were in use, 2) the chemical reactions within the tanks from heating and evaporation, and 3) the effects of various waste retrieval methods (sluicing of wastes using tank supernates, groundwater, and/or oxalic acid). Additional information on average composition of selective constituents in waste residuals developed from inventory estimates in RPP-RPT-42323 is summarized in Tables 3-13 through 3-17.

The mineralogy of solid phases from the retrieved tanks has been summarized by Deutsch et al. (2011) and provided in Table 6-2. Gibbsite [$Al(OH)_3$] is a common mineral in tanks with high aluminum concentrations, while non-crystalline U–Na–C–O–P ± H phases are common in the uranium-rich residual wastes from tanks C-202 and C-203. Iron oxides/hydroxides have been identified in all residual waste samples studied to date. Figure 6-2 shows the electron micrograph of typical solids present in unleached tank C-103 residual waste.

Technetium was identified by scanning electron microscopy/energy dispersive spectroscopy (SEM/EDS) associated with iron oxide/hydroxide particles in tank C-103 residual waste at concentration from ~0.6 to 1.0 wt.%, providing direct evidence of technetium in solid phases. No iodine-containing phases could be identified, perhaps due to low mass concentrations. In tank C-106, due to leaching with oxalate, the manganese-bearing mineral phases are dominant; however, the presence of aluminum and iron-bearing mineral phases exists. The majority of the manganese occurs as Mn(II). Spectral analysis of tank C-106 samples indicate that uranium occurs primarily in the hexavalent oxidation state [U(VI)]; however, a small fraction may be present as U(IV). The majority of the chromium appears to be in the reduced trivalent [Cr(III)] oxidation state, while the iron is present in the oxidized trivalent [Fe(III)] state.

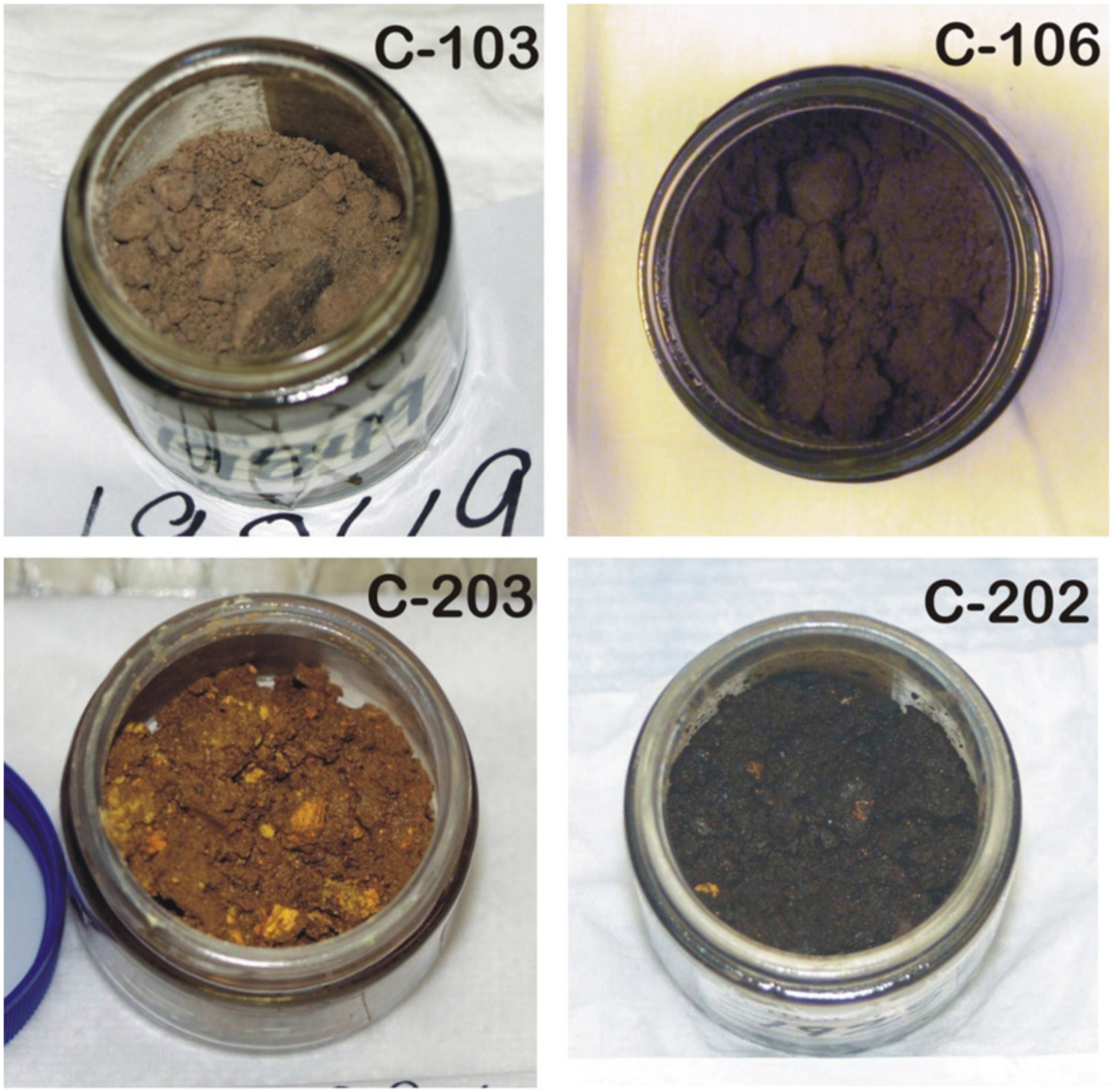
The residual waste in tanks C-202 and C-203 contains mostly amorphous solids of U-Na-C-O-P ± H and iron oxide/hydroxide as shown in Figure 6-3. No phases containing iodine or technetium were detected, most likely due to low concentration of these contaminants.

Recently, "Single-pass flow-through test elucidation of weathering behavior and evaluation of contaminant release models for Hanford tank residual radioactive waste" (Cantrell et al. 2013) provided an analysis of solid phases in the residual waste following leaching with three different leachates, namely the deionized (DI) water, $CaCO_3$ saturated solution, and 0.005 M $Ca(OH)_2$ solution that represent a range of possible water types contacting the residual waste. In general, the nature of the leachate did not have a large impact on the phases that were positively and tentatively identified. For the tank C-103 samples, the only phase identified was gibbsite, regardless of the leachate used. In the tank C-202 samples, calcite was positively identified, while for tank C-203 samples, calcite and schoepite were positively identified. Besides these, some possible (tentative) phases identified for tanks C-202 and C-203 included hydroxylapatite, $CaUO_4$, soddyite, studtite, $Na_2U_2O_7.6H_2O$, and boltwoodite.

The general trends in uranium leachate concentrations for the C-103, C-202, and C-203 tank residual wastes are very similar. The results are presented for tank C-202 in Figure 6-4. The

leached uranium concentration using DI water and $CaCO_3$ saturated solution are significantly higher than those in the 0.005 M $Ca(OH)_2$ leachates. This is attributed to the formation of Ca-rich precipitates (Ca phosphate and calcite) on the surfaces of the waste particles when using $Ca(OH)_2$ leachate, inhibiting dissolution of the underlying uranium phases in the waste. Since the tanks are planned to be grouted prior to the closure, the primary leachate is expected to be $Ca(OH)_2$ solution, which is likely to reduce the leaching of uranium.

**Figure 6-1. Photographs of As-Received, Post-Final Retrieval Residual Waste Samples from Tanks 241-C-103, 241-C-106, 241-C-202, and 241-C-203.**




Source: "Hanford tank residual waste – Contaminant source terms and release models" (Deutsch et al. 2011).

**Table 6-1. Average Composition (µg/g dry weight) for Selected Elements, Primary Contaminants of Interest, and Anions in Bulk Residual Waste from Some Waste Management Area C Tanks.**

| Analyte | 241-C-103 (µg/g dry wt.) | 241-C-106 (µg/g dry wt.) | 241-C-202 (µg/g dry wt.) | 241-C-203 (µg/g dry wt.) |
|---|---|---|---|---|
| Al | 136,000 | 81,699 | 13,600 | <710 |
| Ba | 181 | 914 | 208 | <142 |
| Ca | 616 | 46,490 | 14,500 | 3,140 |
| Cr | 193 | (727)[a] | 13,200 | 5,910 |
| Fe | 12,000 | 36,663 | 122,000 | 16,300 |
| K | Below detection limit | 8,526 | <15,800 | <355,000 |
| Mg | -42 | 3,162 | 2,560 | -729 |
| Mn | 470 | 108,069 | 25,700 | 956 |
| Na | 7,840 | 46,720 | 58,800 | 95,800 |
| Ni | 420 | 5,373 | 9,070 | 510 |
| Pb | 892 | 4,814 | 7,980 | 5,630 |
| Si | 9,070 | (4,895)[a] | 25,000 | 3,490 |
| Sr | 90.7 | (493)[a] | 1,510 | 409 |
| $^{238}U$ | 3,730 | 310 | 207,000 | 505,000 |
| $^{99}Tc$ | 0.231 | 1.14 | 0.149 | (0.0947)[a] |
| $^{129}I$ | (1.11E-5)[a] | Not available | Not available | Not available |
| $F^-$ | (31)[a] | 33 | 6,030 | 2,760 |
| $Cl^-$ | (5.4)[a] | 87 | 161 | 201 |
| $NO_2^-$ | (59)[a] | <73 | 485 | 610 |
| $NO_3^-$ | (250)[a] | <70 | 3,540 | 4,840 |
| $CO_3^{2-}$ | Below detection limit | 39,500 | 12,200 | 49,900 |
| $SO_4^{2-}$ | Below detection limit | <66 | 334 | 288 |
| $PO_4^{3-}$ | (66)[a] | <91 | 17,700 | 43,300 |
| Oxalate | — | 63,900 | 32,400 | 1,500 |

[a] Value in parenthesis is the estimated quantification limit.

Average radionuclide compositions can be found in RPP-ENV-58782.

Modified from "Hanford tank residual waste – Contaminant source terms and release models" (Deutsch et al. 2011).

**Table 6-2. Solid Phases Identified in Tank Residual Waste Samples.**

| Tank Number | Solid Phases | | Comments |
|---|---|---|---|
| | Major | Minor/trace | |
| 241-C-103 | Gibbsite [$Al(OH)_3$]; hematite (a-$Fe_2O_3$) | Two Fe oxide/hydroxides; cancrinite [$Na_6CaAl_6Si_6(CO_3)O_{24}$_$2H_2O$]; oxides of Ag ± Hg, U, Ca–P, Na–Ca–U, Si–Al–Mg–Na–Fe, Zr, and Th | Tc in three Fe oxide/hydroxide particles |
| 241-C-106 | Lindbergite ($MnC_2O_4.2H_2O$); whewellite ($CaC_2O_4.2H_2O$); gibbsite; böhmite [AlO(OH)]; dawsonite [$NaAlCO_3(OH)_2$]; hematite; rhodochrosite [$MnCO_3$]; possible Ag–Hg phase | Mn–Al–Fe–Na–P–Si–Ca–O ± C ± H; Mn–O–P ± Al ± C± H; Si–Al–Na–O ± C ±H; REE-rich oxide; Ca–Si–Al–O ± C ± H; $Ag^0$; Pb-containing phase | Tank leached with 0.9 M oxalic acid ($H_2C_2O_4$) during waste retrieval |
| 241-C-202 | Amorphous (non-crystalline) solids of either U Na–C–O–P ± H or Fe oxide/hydroxide | Trace amounts of Mn and Cr and sometimes Pb | No crystalline phases identified |
| 241-C-203 | Amorphous solids of primarily U Na–C–O–P ± H | Amorphous solids of Fe oxide/ hydroxide with trace amounts of Mn, Cr, Pb, and/or Cu | No crystalline phases identified; Similar to C-202 |

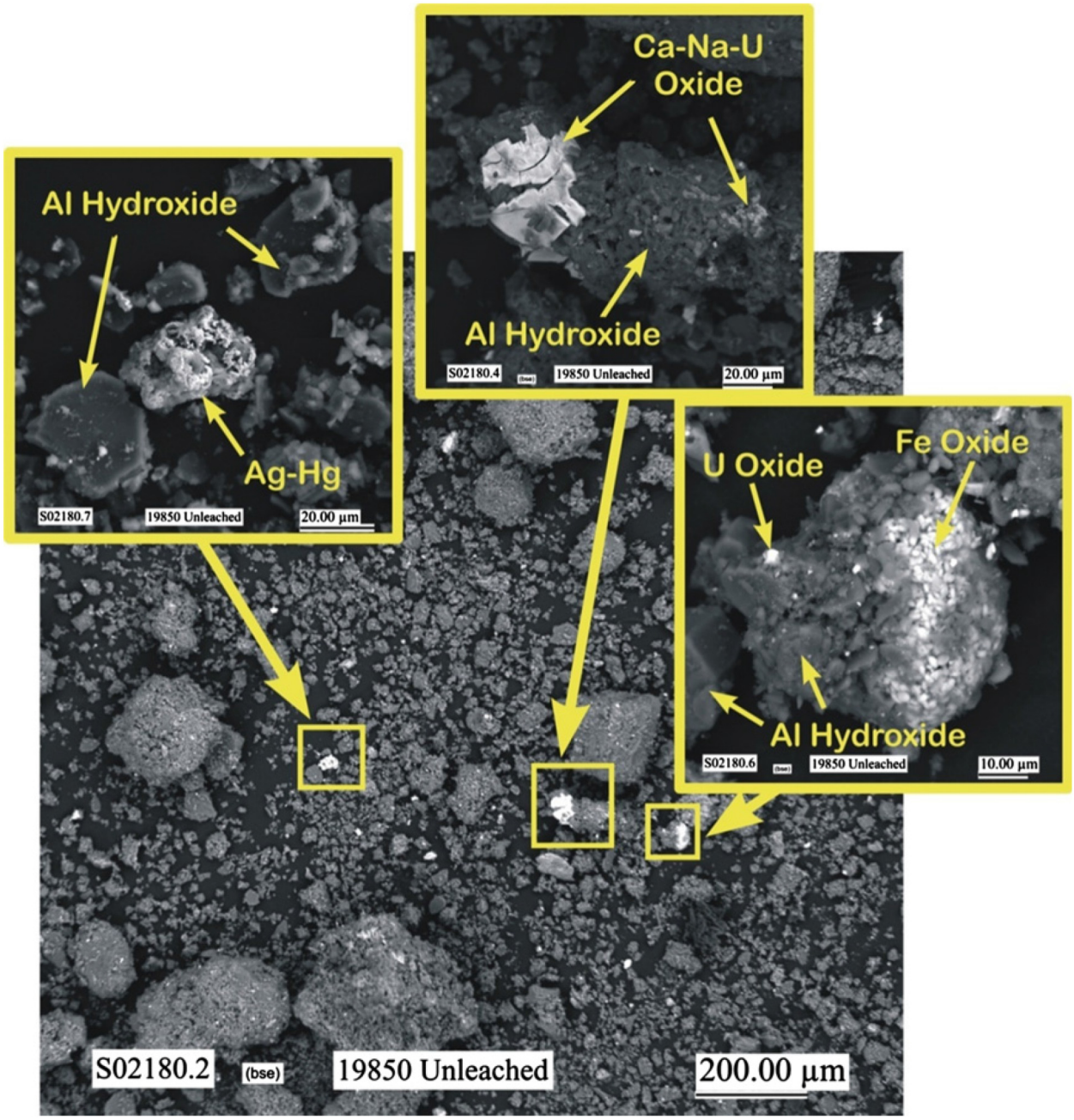
Modified from "Hanford tank residual waste – Contaminant source terms and release models" (Deutsch et al. 2011).

To investigate this leaching behavior, thermodynamic equilibrium modeling was conducted to calculate the mineral saturation indices and to identify solid phases potentially in equilibrium with the leachate composition. The saturation index is defined as SI = log ($Q/K_{sp}$), where Q is the activity product and $K_{sp}$ is the mineral solubility product at equilibrium at the temperature of interest. Minerals with SI values near zero (within ± 0.5) are generally considered to be at or near equilibrium, more positive values are considered oversaturated, and more negative values are considered undersaturated with respect to the solution composition. The SI calculated for the tank C-202 single-pass flow-through test (SPFT) effluents for the three leachates indicated that DI water and $CaCO_3$ saturated leachate give similar SI results while the $Ca(OH)_2$ leachate-based SI results are quite different. Results from DI water and $CaCO_3$ saturated leachates indicate that $NaUO_2PO_4.xH_2O$ is near equilibrium while Ca-containing phases (such as calcite and hydroxylapatite) were all undersaturated. The SI results for the $Ca(OH)_2$ leachates indicate all uranium-bearing phases to be highly undersaturated, but near saturated or oversaturated with respect to Ca-containing phases. Calcite was near saturation while hydroxylapatite and flourapatite were consistently highly oversaturated. These results are consistent with the observed leaching behavior of uranium. It is hypothesized that precipitation of Ca-rich phases resulted in coatings on the waste particles that could have temporarily inhibited dissolution and attainment of equilibrium for any uranium phase in contact with $Ca(OH)_2$ leachate solutions.

These results indicate that as long as the infiltrating water though the tank passes through the infill grout material, it will be conditioned to be similar to a dilute $Ca(OH)_2$ leachate solution and the uranium dissolution will remain inhibited. At some distant time in the future when the tank is assumed to be sufficiently degraded such that large open fractures develop that do not allow appreciable residence time for infiltrating waters to contact the grout material, the leachate would

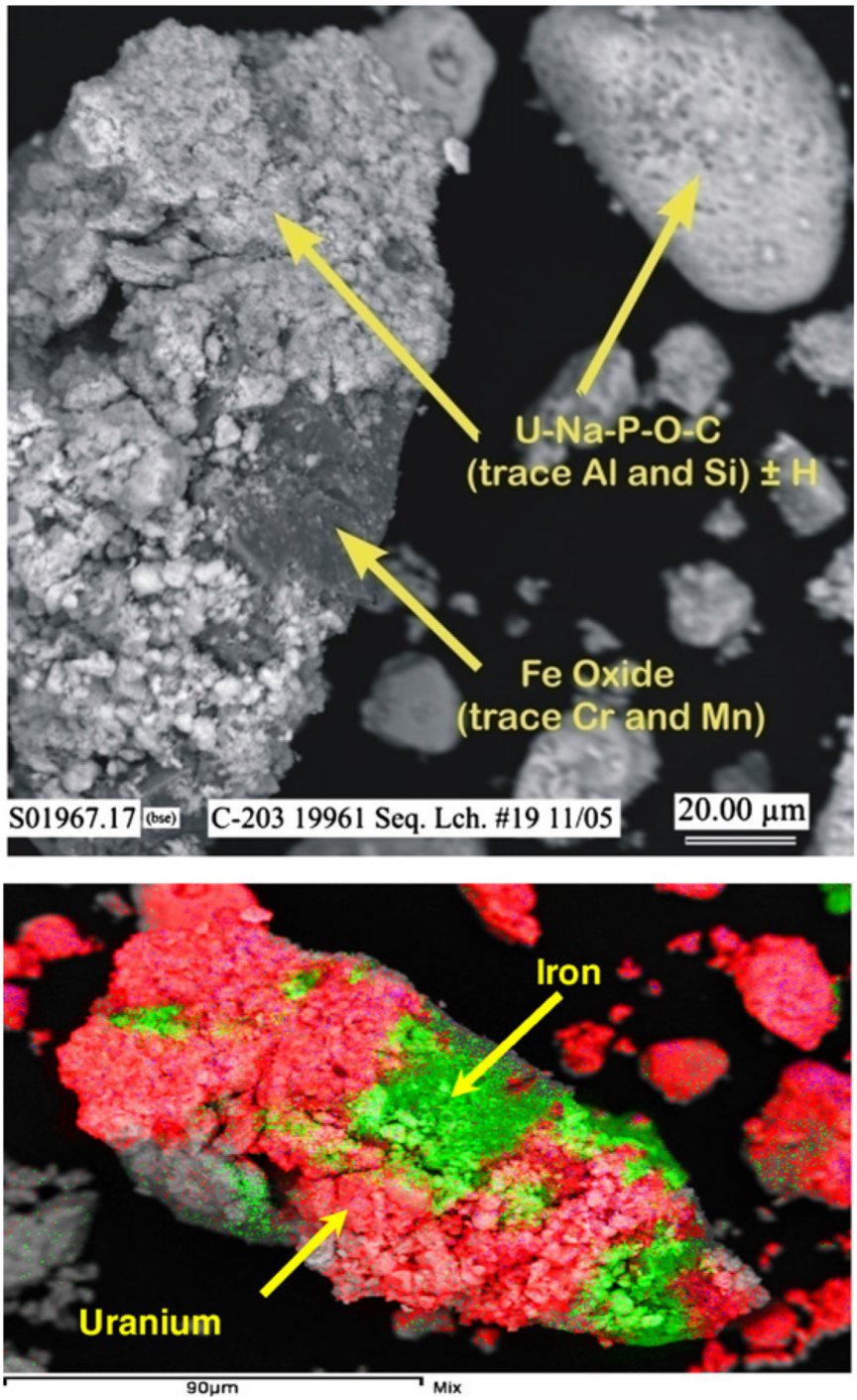
be similar to the $CaCO_3$ saturated water, and at that time, the uranium concentrations may increase when the residual waste is contacted.

**Figure 6-2. Low- and High-Magnification Electron Micrographs of Typical Solids Present in Unleached Tank 241-C-103 Residual Waste.**



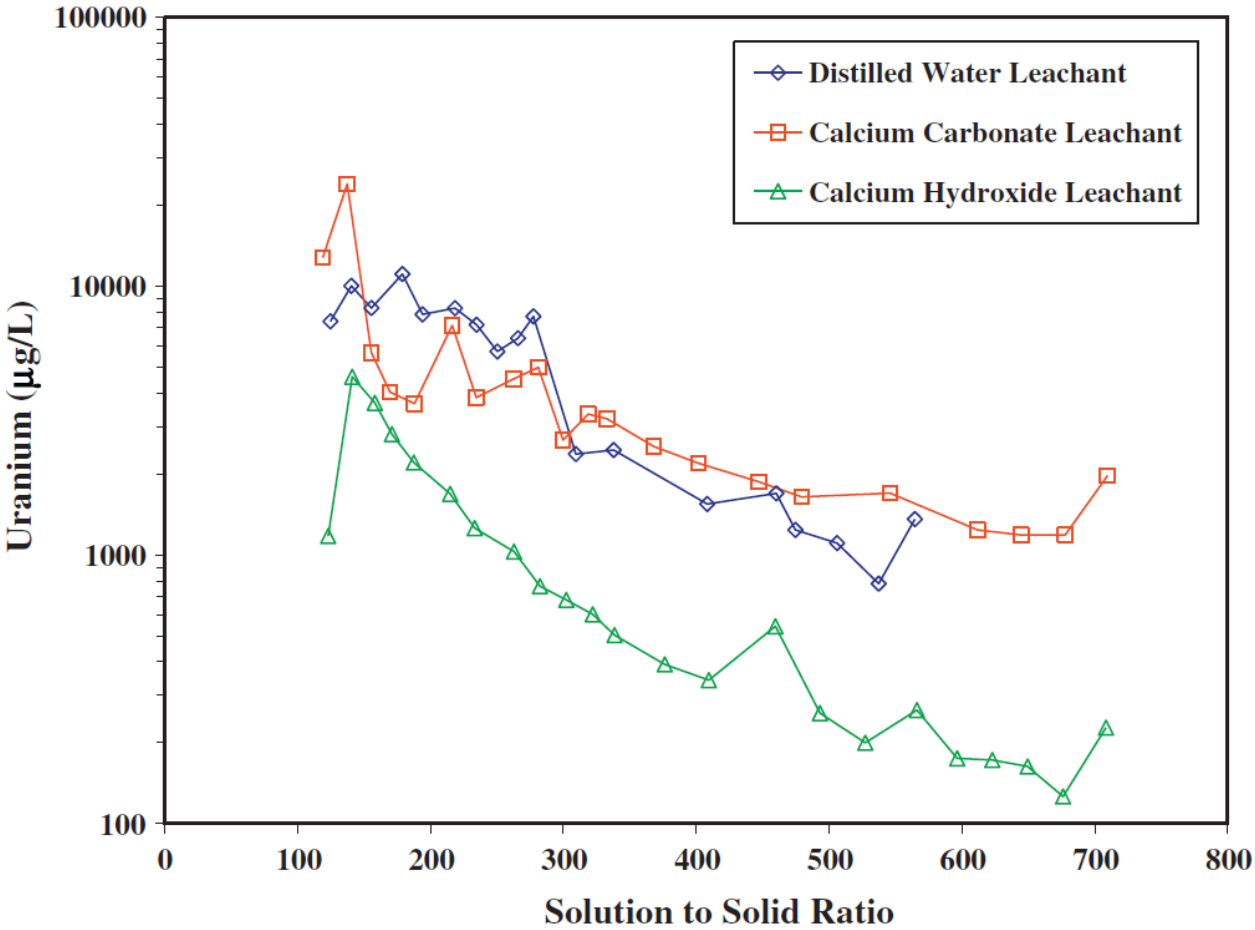

Reference: PNNL-16738, "Hanford Tank 241-C-103 Residual Waste Contaminant Release Models and Supporting Data."

**Figure 6-3. Electron Micrograph (top) and Multi-Element Energy Dispersive Spectroscopy Map (bottom) for an Aggregate of U-Na-C-O-P ± H and Fe Oxide/Hydroxide Particles Present in Sequential-Leached Water Extraction Sample of Tank 241-C-203 Residual Waste.**
**(The large aggregate at the center of the colored element distribution map is the same large aggregate, but rotated 45 degree counterclockwise, shown in the electron micrograph).**




Reference: PNNL-16229, "Hanford Tanks 241-C-202 and 241-C-203: Residual Waste Contaminant Release Models and Supporting Data."

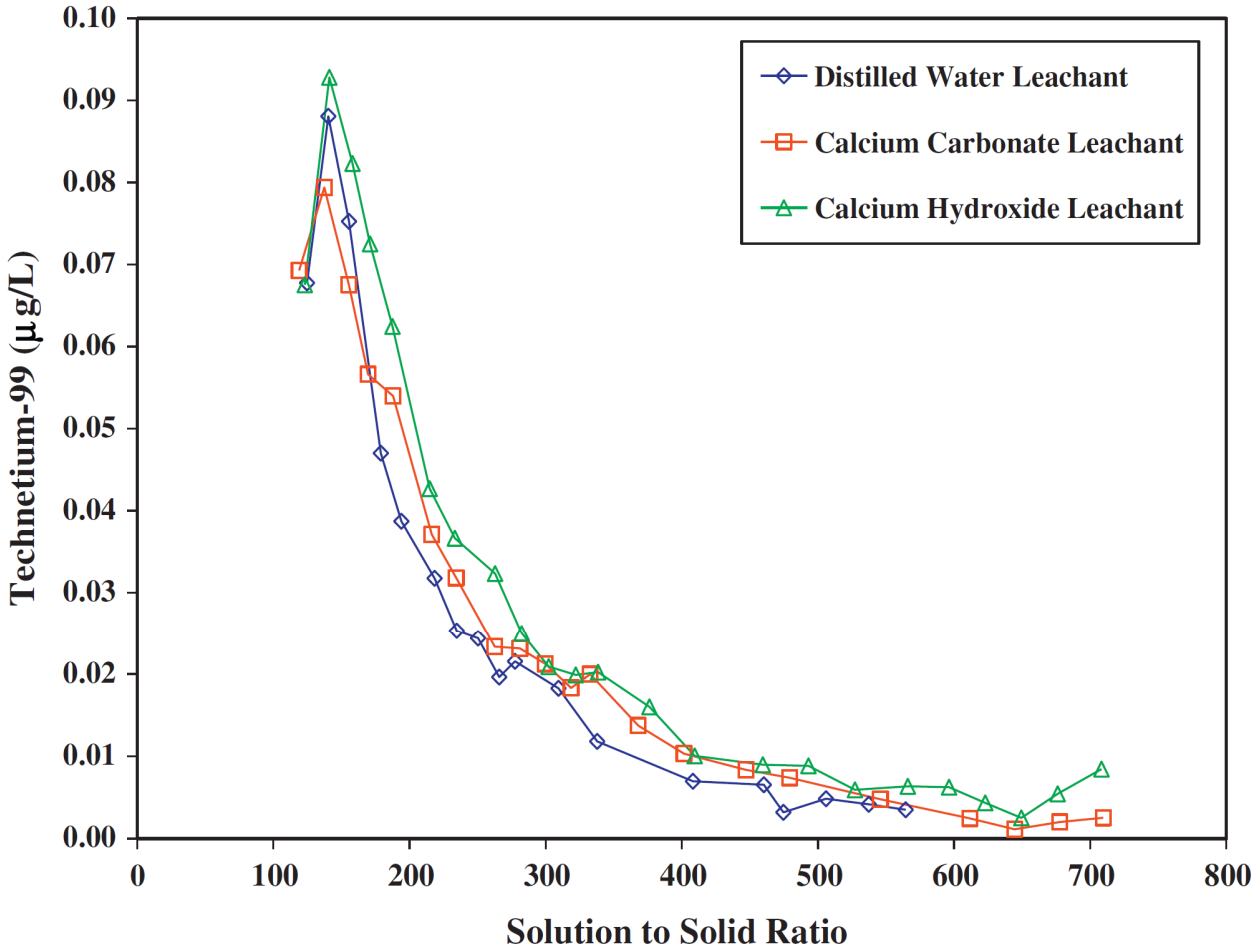
**Figure 6-4. Uranium Concentrations in Tank 241-C-202 Single-Pass Flow-Through Leachates as a Function of the Total Volume of Leachate that has Contacted the Waste in Terms of Leachate/Solid (Initial) Weight Ratio.**




Reference: "Single-pass flow-through test elucidation of weathering behavior and evaluation of contaminant release models for Hanford tank residual radioactive waste" (Cantrell et al. 2013).

Similar SPFT experiments, as indicated above to evaluate the uranium leaching, were conducted by Cantrell et al. (2013) to evaluate the leaching characteristics of $^{99}$Tc and chromium from tank C-202. Figures 6-5 and 6-6 indicate the $^{99}$Tc and chromium concentrations in tank C-202 SPFT leachates for the three leachate solutions as a function of solution to solid ratio. Figure 6-5 indicates that the $^{99}$Tc concentrations in all three leachates are very similar, with concentrations dropping near exponentially with increasing solution to solid ratio. Results for tanks C-203 and C-103 are very similar to tank C-202, although the magnitudes of the concentrations vary as a function of the residual inventory. The actual release mechanism for $^{99}$Tc remains indeterminate; however, it is likely that $^{99}$Tc is adsorbed onto and/or co-precipitated with iron oxides/hydroxides (Cantrell et al. 2013), and may slowly leach from dissolution of iron oxides/hydroxides mineral phases. This is consistent with the observation where technetium was identified by SEM/EDS associated with iron oxide/hydroxide particles in tank C-103 residual waste at concentration from ~0.6 to 1.0 wt.%.

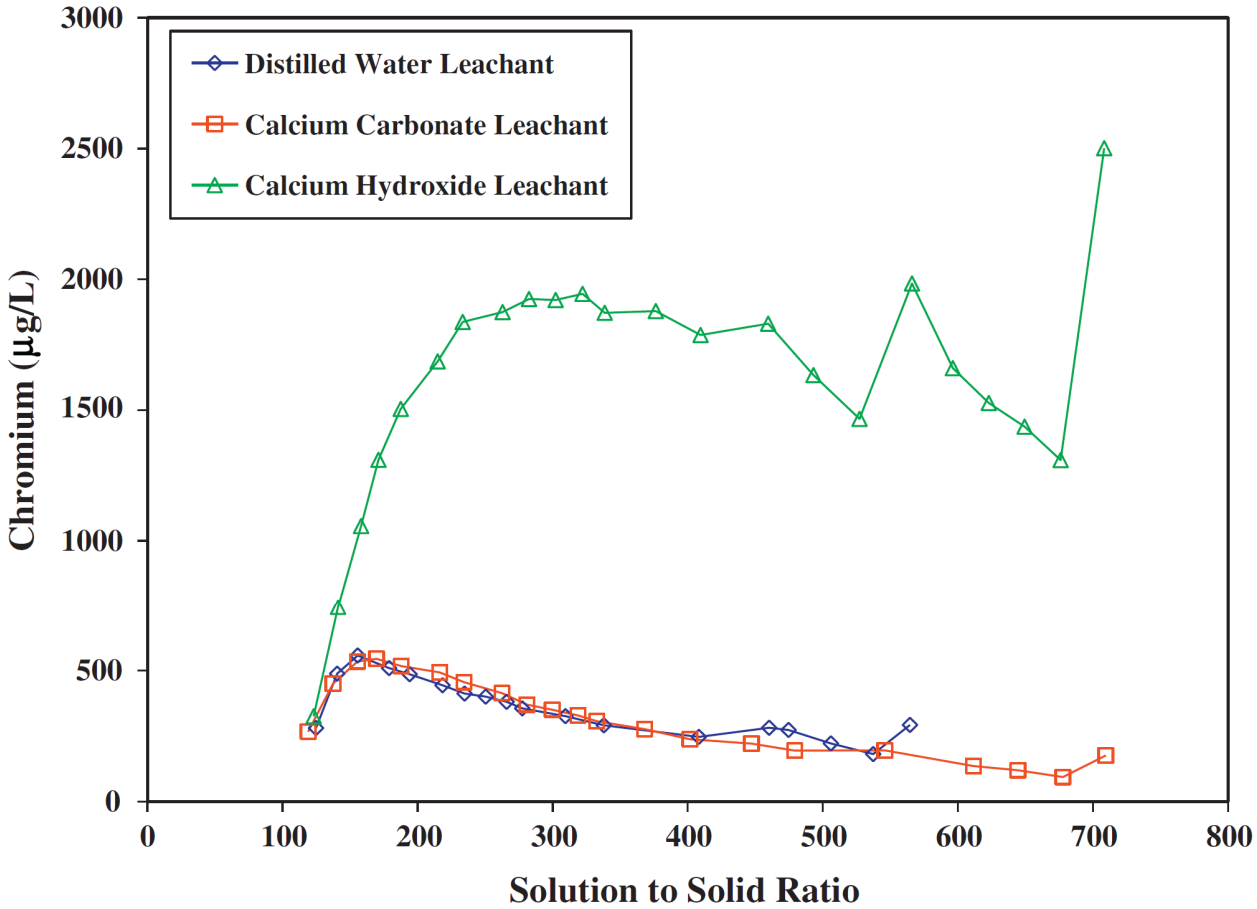
**Figure 6-5. Technetium-99 Concentration in Tank 241-C-202 Single-Pass Flow-Through Leachates as a Function of the Total Volume of Leachate that has Contacted the Waste in Terms of Leachate/Solid (Initial) Weight Ratio.**




Reference: "Single-pass flow-through test elucidation of weathering behavior and evaluation of contaminant release models for Hanford tank residual radioactive waste" (Cantrell et al. 2013).

Chromium in the SPFT leachates for tank C-202 residual waste (Figure 6-6) shows relatively high release concentrations initially, with concentrations in the $Ca(OH)_2$ leachates being much higher than those of the DI water and $CaCO_3$ leachates. The relatively high concentrations of chromium in $Ca(OH)_2$ leachate were not found for tank C-203, and the reason for this difference is not readily apparent. The leachate concentrations from C-103 tank residual waste were below the detection limit of 5 ppb. These results indicate large variations in the chromium release characteristics, and perhaps reflect the variability in the chromium present in trivalent and hexavalent oxidation states along with association with iron oxides/hydroxides. It is also possible that some chromate may also have been co-precipitated with phosphate in $NaUO_2PO_4.xH_2O$. As residual waste is leached with $Ca(OH)_2$ and portions of $NaUO_2PO_4.xH_2O$ are converted to $CaUO_4$, both $PO_4$ and $CrO_4$ are slowly released.

**Figure 6-6. Chromium Concentration in Tank 241-C-202 Single-Pass Flow-Through Leachates as a Function of the Total Volume of Leachate that has Contacted the Waste in Terms of Leachate/Solid (Initial) Weight Ratio.**




Reference: "Single-pass flow-through test elucidation of weathering behavior and evaluation of contaminant release models for Hanford tank residual radioactive waste" (Cantrell et al. 2013).

The total percentages of uranium and $^{99}$Tc leached from the residual waste samples during the course of the SPFT experiments were calculated and are presented in Table 6-3. The percent uranium leached varies from 0.3 % to 9.4%, while the percent $^{99}$Tc leached ranges from 4.5% to 15%. The percentage of uranium leached varies by the leachate type, with greater amount leached using DI water and $CaCO_3$ saturated water and significantly less with the $Ca(OH)_2$ leachate. In contrast, the percentage of $^{99}$Tc leached does not vary by the leachate type, but is influenced more by the particular sample.

**Table 6-3. Percentages of Total Uranium and Technetium-99 Leached from Tanks 241-C-202, 241-C-203, and 241-C-103 Residual Wastes during the Single-Pass Flow-Through Experiments.**

| Tank | Leachate | Percent Uranium Leached | Percent Technetium-99 Leached |
|---|---|---|---|
| 241-C-202 | Deionized water | 1.3 | 7.8 |
| 241-C-202 | $CaCO_3$ | 1.7 | 8.3 |
| 241-C-202 | $Ca(OH)_2$ | 0.3 | 9.0 |
| 241-C-203 | Deionized water | 2.5 | 6.2 |
| 241-C-203 | $CaCO_3$ | 2.1 | 7.4 |
| 241-C-203 | $Ca(OH)_2$ | 0.22 | 4.5 |
| 241-C-103 | Deionized water | 5.4 | 15 |
| 241-C-103 | $CaCO_3$ | 9.4 | 15 |
| 241-C-103 | $Ca(OH)_2$ | 3.5 | 12 |

Reference: "Single-pass flow-through test elucidation of weathering behavior and evaluation of contaminant release models for Hanford tank residual radioactive waste" (Cantrell et al. 2013).

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# 7.0 ANALYSIS OF RISK AND HAZARD IMPACTS

This RCA provides an assessment of the long-term human health and environmental impacts following the closure of the WMA C facility in the 200 East Area of the Hanford Site. This section provides an overview of the methodology developed to assess the scenarios and pathways and describes the conceptual models of facility performance and the development and implementation of the mathematical models used to estimate the impacts from the proposed closure action. It also integrates the information presented in earlier sections that forms the basis for the conceptual and mathematical model of the WMA C facility following closure. This information is presented in the following subsections:

- 7.1 Overview of Analysis
- 7.2 Conceptual Model of Facility Performance
- 7.3 Mathematical Models
- 7.4 Model Validation.

## 7.1 OVERVIEW OF ANALYSIS

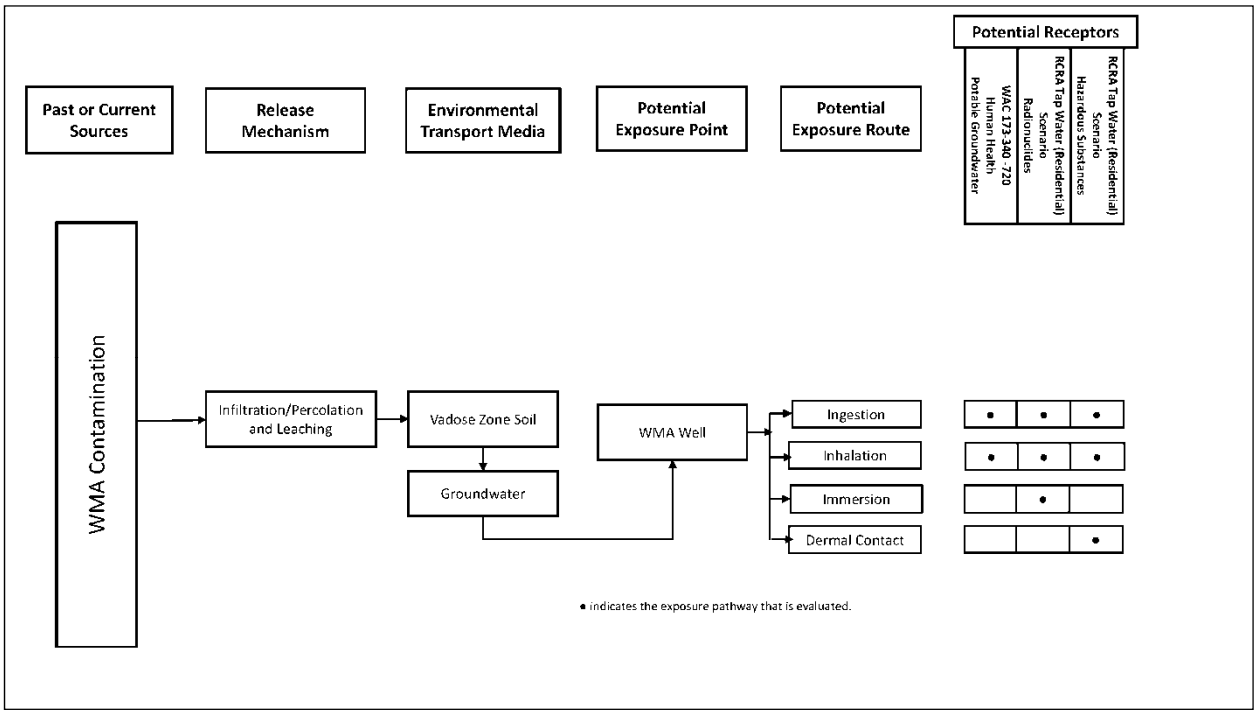
The safety concept of the closed tank farm is that various features of the closed facility have specific attributes that contribute to the ability of the system to meet performance measures. The analysis incorporates key elements of the disposal system called *safety functions* (Section 1.4) that are deemed important in assessing the system performance. The safety concept of the closed tank farm is that various features of the closed facility have specific attributes that contribute to the ability of the system to meet performance objectives. These attributes are called *safety functions* in this RCA. Safety functions are identified from basic understanding of the projected behavior of the system in the post-closure period. These safety functions and their behavior are used to identify specific analysis cases that show the robustness and defense-in-depth of the closed facility. These analysis cases, and the way in which they evaluate and explore the uncertainties in the post-closure period, form the structure of the RCA.

Facility performance is defined in terms of the onsite and offsite exposures using both carcinogenic risk and noncarcinogenic hazard from hazardous chemicals that may be inadvertently contacted and/or that might migrate from the disposal facility. All of the calculated exposures in this assessment are hypothetical, and depend on a future member of the public engaging in activities on the Central Plateau without knowledge of the prior existence of the Hanford Site and its disposal activities. Exposure calculated in this way is higher and occurs at earlier times than potential exposures off the Hanford Site, and therefore provides a more conservative set of exposure conditions than potential offsite exposures.

The conceptual exposure model for EPA tap water (residential scenario) and the 2007 MTCA potable groundwater cleanup levels are illustrated in Figure 7-1. The most important exposure pathway for hydrologic transport is groundwater use for drinking water and biotic transport. In the groundwater pathway, the analysis is focused on meteoric water from rain and snowfall, which enters the subsurface, contacts contaminants that have diffused from the grouted residual waste, and carries these contaminants to the unconfined aquifer. The surface water pathway is

omitted from this RCA because surface water does not exist within the 100-m point of analysis distance from the WMA C boundary. The main focus of this RCA is on evaluating the groundwater pathway. The analysis of the groundwater pathway comprises evaluations directed at two different performance measures. The first is a comparison of groundwater concentrations to Federal and State maximum contaminant levels (MCLs) and 2007 MTCA potable groundwater cleanup levels. The second is an assessment of cancer risk and non-cancer hazards for hazardous substances and cancer risk for radionuclides and in groundwater using the EPA tap water (residential) scenario.

**Figure 7-1. Conceptual Exposure Model for the EPA Tap Water (Residential) Scenario and the 2007 MTCA Potable Groundwater Cleanup Levels.**




EPA = U.S. Environmental Protection Agency MTCA = Model Toxics Control Act

The strategy for the WMA C RCA is to define and analyze both a base case and a suite of sensitivity cases. The base case is a single deterministic evaluation of future risk and hazard to the public as a result of the anticipated retrieval and closure actions taken at WMA C. It represents the situation in which the safety functions behave as expected as the facility evolves into the future. The base case assumptions and parameters generally are based on best available information, but some parameter estimates related to future conditions may have conservative bias. The results of the base case are used to evaluate compliance with performance measures. Additional sensitivity cases were defined to explore the effect of uncertainties in the models, assumptions, and data on the calculated consequences. The sensitivity cases were defined to evaluate the consequences associated with the loss of part or all of a safety function. In this way, the RCA is specifically structured to evaluate the key elements of the disposal system that contribute to its long-term safety. Uncertainty analyses were conducted as required under DOE O 435.1 and were included in the WMA C PA (RPP-ENV-58782, Section 8.1 Uncertainty

Analysis). These uncertainty analyses were conducted to evaluate the effect of parameter uncertainty on the results calculated for the base case using probabilistic tools (e.g., Monte Carlo analysis). While sensitivity analysis is included in this document, however, the uncertainty analysis is not because WAC 173-340-708, "Human Health Risk Assessment Procedures," subsection (11) "Probabilistic risk assessment" states the following:

> "Probabilistic risk assessment methods may be used under this chapter only on an informational basis for evaluating alternative remedies. Such methods shall not be used to replace cleanup standards and remediation levels derived using deterministic methods under this chapter until the department has adopted rules describing adequate technical protocols and policies for the use of probabilistic risk assessment under this chapter."

Confidence in the data, assumptions, and methods used in the analysis was developed through the following approaches:

- Many data were based on WMA C-specific site characterization, sampling, measurements and interpretations, including those for contaminant inventory, geology, hydrology and geochemistry. When data specific to WMA C were not available, data from nearby sites or comparable conditions, such as vadose zone hydraulic data and information developed from soil samples collected in the vicinity of the IDF, were used.

- Data were upscaled to represent field-scale processes using approaches that have been published in peer-reviewed journals. Upscaling techniques use information from small, core-scale measurements to develop parameters that are applicable to large, field-scale models.

- The process-based modeling software, STOMP© code (PNNL-11216, "STOMP Subsurface Transport Over Multiple Phases Application Guide"; PNNL-12030, "STOMP Subsurface Transport Over Multiple Phases Version 2.0 Theory Guide"), has been benchmarked and deemed suitable for use in this RCA. The STOMP© code is the pre-authorized modeling software at the Hanford Site for vadose zone and near-field groundwater modeling (Internal memorandum 1301789, "Modeling to Support Regulatory Decisionmaking at Hanford"). The STOMP© code has previously been qualified for simulation use at Hanford by CH2M HILL Plateau Remediation Company (CHRPC) (CHPRC-00269, "STOMP Requirements Traceability Matrix CHPRC Build 4").

- The system-level modeling software, GoldSim© ("GoldSim Contaminant Transport Module User's Guide" [GoldSim Technology Group 2014a]; "GoldSim Distributed Processing Module User's Guide" [GoldSim Technology Group 2014b]; "GoldSim Probabilistic Simulation Environment User's Guide" [GoldSim Technology Group 2014c]) has been deemed suitable based on its wide usage and acceptance in the various DOE O 435.1 PAs across the DOE complex. GoldSim© was the main modeling code used for systems-level modeling in this RCA effort. The GoldSim© software is an

example of additional simulation software that may be used at Hanford so long as DOE and Environmental Management software quality requirements are met.

- Sensitivity analyses were conducted to evaluate the effect of parameter uncertainties on the base case model and to build confidence in the expected future dose.

Results using the models and values are presented in Section 8.0 for the groundwater pathway and in Section 9.0 for the sensitivity analysis. Section 10.0 provides the results for the EPA tap water (residential) scenario, and a comparison of peak predicted groundwater concentrations to Federal and State MCLs and 2007 MTCA potable groundwater risk-based criteria, as well as a summary of the sensitivity analysis.

## 7.2 CONCEPTUAL MODEL OF FACILITY PERFORMANCE

The WMA C RCA methodology uses conceptual models that are based on the physical system and expected contaminant migration pathways.

Figure 7-2 provides a schematic representation of both WMA C as it will exist at closure and the contaminant migration pathways evaluated in this RCA. The WMA C is composed of man-made and natural components. The man-made components of the system that influence contaminant migration include a closure surface barrier, the WMA C tanks, pipelines, and infrastructure, and the distribution of waste in those components. The natural components of the system that influence contaminant migration are a number of mostly horizontal stratigraphic layers within the vadose zone and an underlying stratigraphic layer that is part of the unconfined aquifer. Figure 7-3 illustrates the stratigraphy for the WMA C site that has a deep vadose zone ranging from 75 to 85 m (246 to 280 ft) thick. The water table is located within the undifferentiated Hanford formation and Cold Creek gravels with a predominantly south/southeastwardly groundwater flow.

Figure 7-4 shows an aerial view of WMA C, and surrounding disturbed, undisturbed, and resurfaced areas. Also shown is the location of A Complex, where the 100 m (328 ft) point of analysis downgradient of WMA C is located. This location represents the assumed location of a hypothetical well that supplies water for drinking EPA tap water (residential) scenario calculations.

Several key safety functions and related Features, Events, and Processes (FEPs) characterize the conceptual models for release and transport of hazardous chemicals in WMA C and are discussed in Appendix H (Safety Functions and Features, Events, and Processes) for the post-closure period. The conceptual models and relevant parameters for fate and transport modeling are developed for the following four time periods:

- Pre-operations and initial construction period (before 1945) representing the time when the tank farm ground remained undisturbed from the Hanford Manhattan Project mission

- Operations period representing tank farm construction, current, and immediate future conditions of the tank farm (1945 to 2020)

- Closure and post-closure period during the assumed design life of the intact surface barrier (2020 to 2520) when the tanks become grouted and hazardous chemicals begin to diffuse out of the grout

- Post-closure period beyond assumed design life of the surface barrier (2520 to 12120) when the performance of the surface barrier is assumed to degrade.

A 1,000-year post-closure period is evaluated in the WMA C RCA to be consistent with the time frames of analysis being evaluated in the DOE O 435.1 PA; a 10,000-year post-closure period is considered for the purpose of evaluating uncertainty in the results because of the slow travel time through the vadose zone under post-closure conditions.

In the WMA C RCA analysis, net infiltration is controlled by the modified RCRA Subtitle C surface barrier. This barrier has a design life of 500 years, and this time period is used in the base case. However, the surface barrier may potentially last longer or shorter than the design life, depending on how the site evolves in the post-closure period. Sensitivity analysis cases evaluate alternative future behavior patterns in the infiltration rate due to uncertainty in the design life. Contact of infiltrating water with the residual waste is also limited by the tank structure, by the grout infill, and by the tank shell. There is substantial uncertainty about how long the tank wall may last before physical and chemical degradation occurs and allows water to flow through it. However, the tank structure and infill grout together will form a low permeability barrier to flow. Evaluations of the durability of this material and the longevity of its function to reduce water flow indicate very long lifetimes for the cementitious features of the tanks, such that they produce very low flow rates through the residual wastes for more than 10,000 years. Under these conditions, releases from the residual wastes only occur by diffusion through the base mat and into the vadose zone below the tanks. Sensitivity analysis cases evaluate alternative conditions when the grout allows flow to begin at earlier times.

For WMA C vadose zone modeling, small-scale laboratory measurements provide the basis for hydraulic properties used to predict the large, field-scale flow behavior (Appendix B). Each heterogeneous geologic unit is replaced by an equivalent homogeneous medium (EHM) with macroscopic flow properties. With each heterogeneous unit assigned its upscaled or effective hydraulic properties, the simulated flow fields predict the bulk or mean flow behavior at the field scale. Upscaling, in effect, accounts for the differences in scale between small, core-scale measurements and large, field-scale modeling. The hazardous chemicals travel through the vadose zone until they reach the water table and the unconfined aquifer. For the RCA modeling, the unconfined aquifer is treated as an EHM, and an equivalent saturated hydraulic conductivity is estimated for the undifferentiated Hanford gravels (Appendix C). In the final step of the analysis, the estimated groundwater concentrations at a 100 m (328 ft) downgradient location are used to calculate an HQ and cancer risk for each contaminant in order to calculate a total hazard index and excess lifetime cancer risk.

**Figure 7-2. Schematic Conceptual Representation of Waste Management Area C and Various Pathways.**

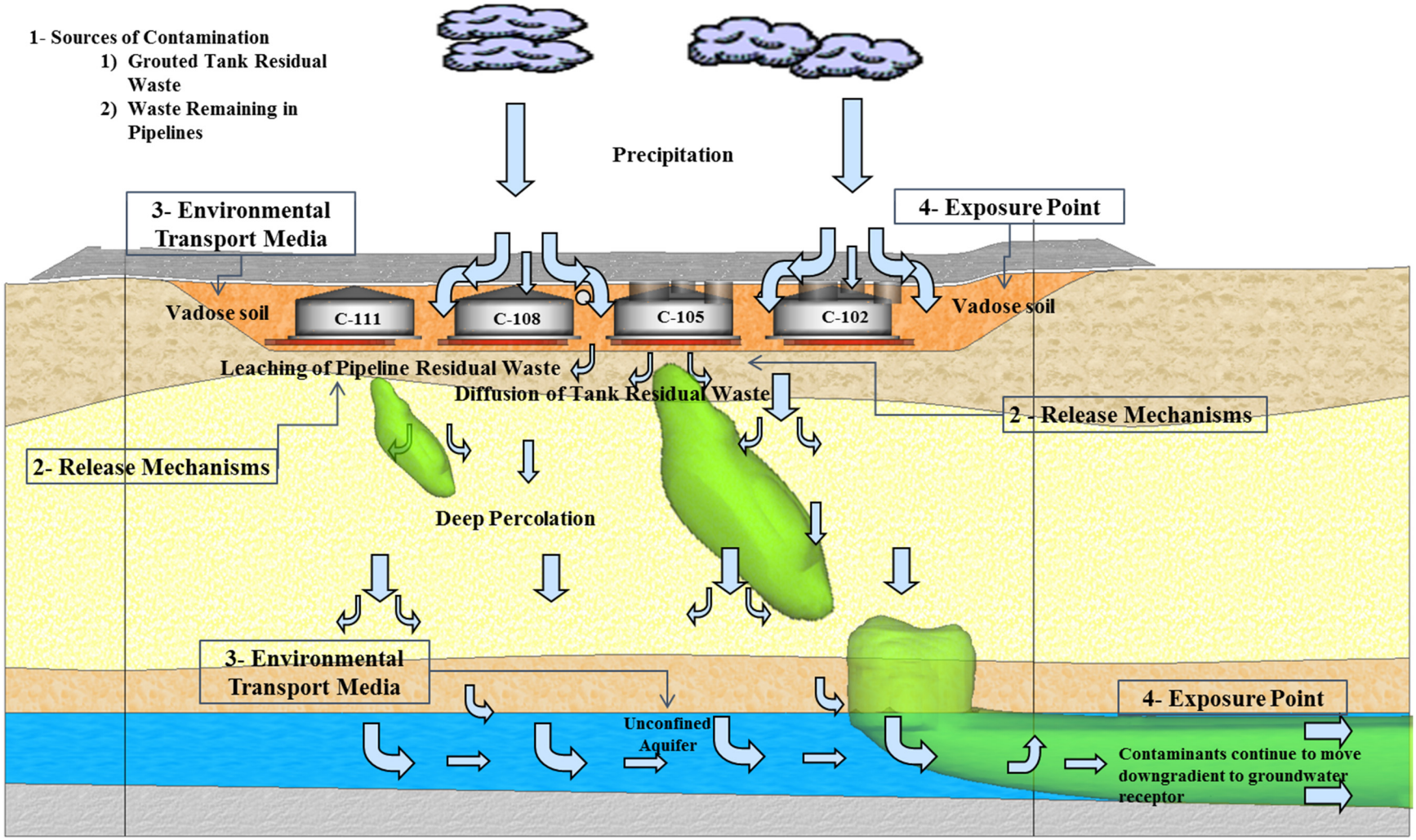


**Figure 7-3. Conceptual Model of the Waste Management Area C Site Showing Stratigraphy.**

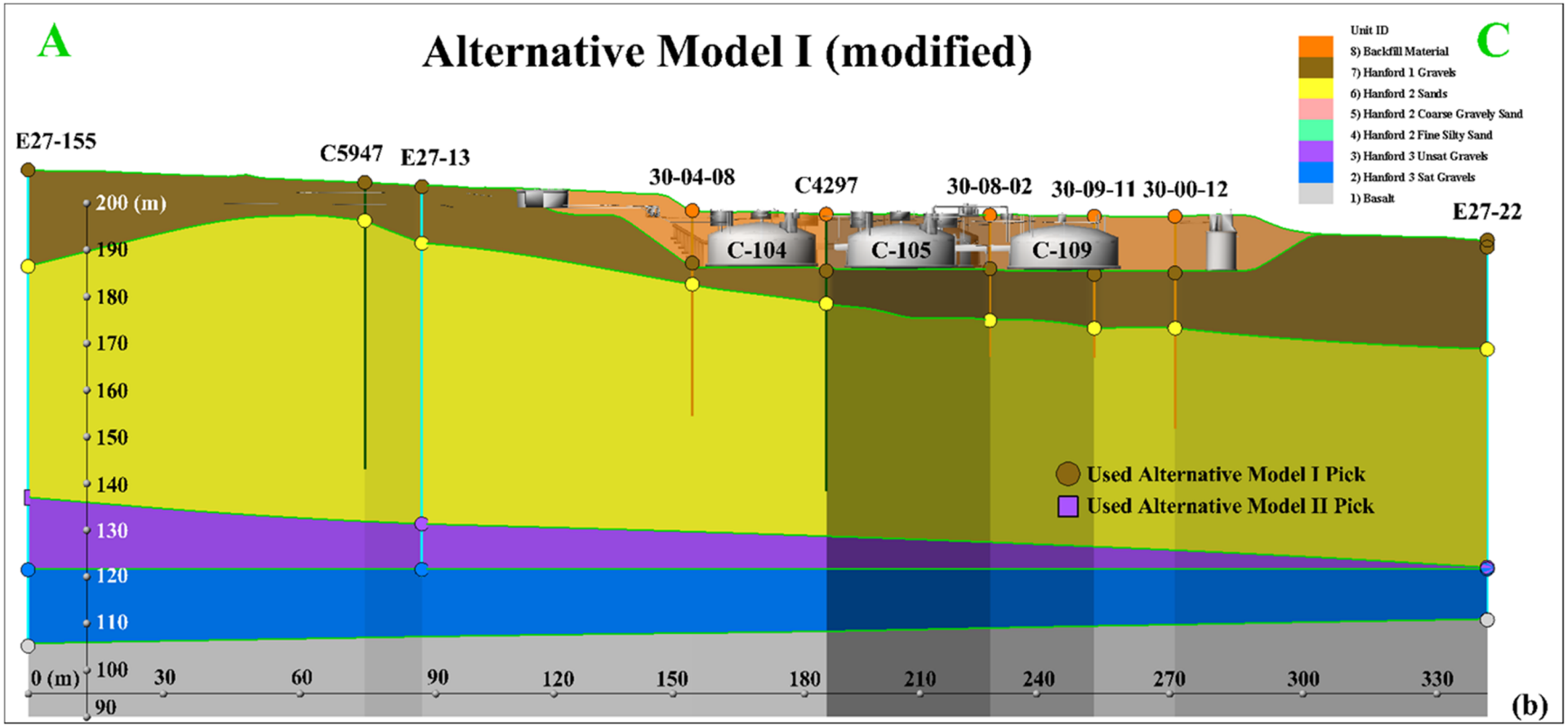


**Figure 7-4. Aerial View of Waste Management Area C Showing Surface Features and the Surrounding Area.**

WMA = Waste Management Area

### 7.2.1 Source Term and Engineered Features

The source term considers processes associated with release of contaminants from residual waste into the natural environment. Separate source terms are considered for each of the twelve 100-series tanks, four 200-series tanks, C-301 catch tank, 244-CR vault, and pipelines, resulting in 19 separate source terms. The inventory used in the source term model includes the current estimate of the inventory and residual volume (Tables 3-13 through 3-15). Source terms for pits and diversion boxes are not explicitly considered but are incorporated as part of the pipeline source term.

Both mineral phase solubility-limited and matrix degradation rate-limited processes are considered for release of contaminant from the waste. These conceptual models are based on observations made through multi-year leaching tests and identification of mineral phases as presented in Section 6. The only constituent-specific release model considered in the RCA is based on empirical evidence of dissolved concentration limits for chromium.

Note that release models for $^{99}$Tc and uranium are identified for use in the WMA C PA (RPP-ENV-58782, Sections 6.3.1.1 Source Release Model for Technetium-99 and 6.3.1.2 Source Release Model for Uranium).

The engineered features that are considered in the source term calculations are the tank structure, pipeline area,[1] infill grout material, and the emplaced surface cover at closure. The modified RCRA cover reduces the net infiltration that will eventually percolate to the buried tank structures and ancillary equipment. The infill grout material provides not only structural stability to the tank configuration, but also provides a relatively impermeable barrier to flow leading to flow diversion around the tank, as long as the grout is not physically degraded. The infill grout material also controls the chemical conditions of the pore water that contacts the residual waste through mineral phase dissolution and precipitation (e.g., dissolution of portlandite and precipitation of calcite).

The source term processes that are considered in the post-closure period include releases of contaminants from residual waste, and their transport to the underlying vadose zone via either diffusion or advection. The key processes that are expected to affect release of contaminants from tank residuals include:

- Leaching of contaminants from the tank waste residual layer into the pore water associated with the tank residuals
- Diffusive transport of contaminants through the tank wall grout and concrete layer, along the tortuous continuous connections, to vadose zone soil outside the tank
- Ongoing chemical and physical degradation of the tank wall concrete and grout layer

[1] Individual pipelines are not treated as separate sources. Instead, the inventory associated with the pipeline source term is distributed uniformly over the area at WMA C that contains pipelines.

- Ongoing dissolution and degradation of emplaced grout in the tank leading to eventual formation of cracks

- Once a sufficient number of cracks form in the engineered barriers, the potential exists for advective flow of water to begin to influence the source term.

Not all processes that are considered conceptually are included in the numerical models. Data from laboratory testing on the concrete samples provide a basis for the degradation of the concrete structure.

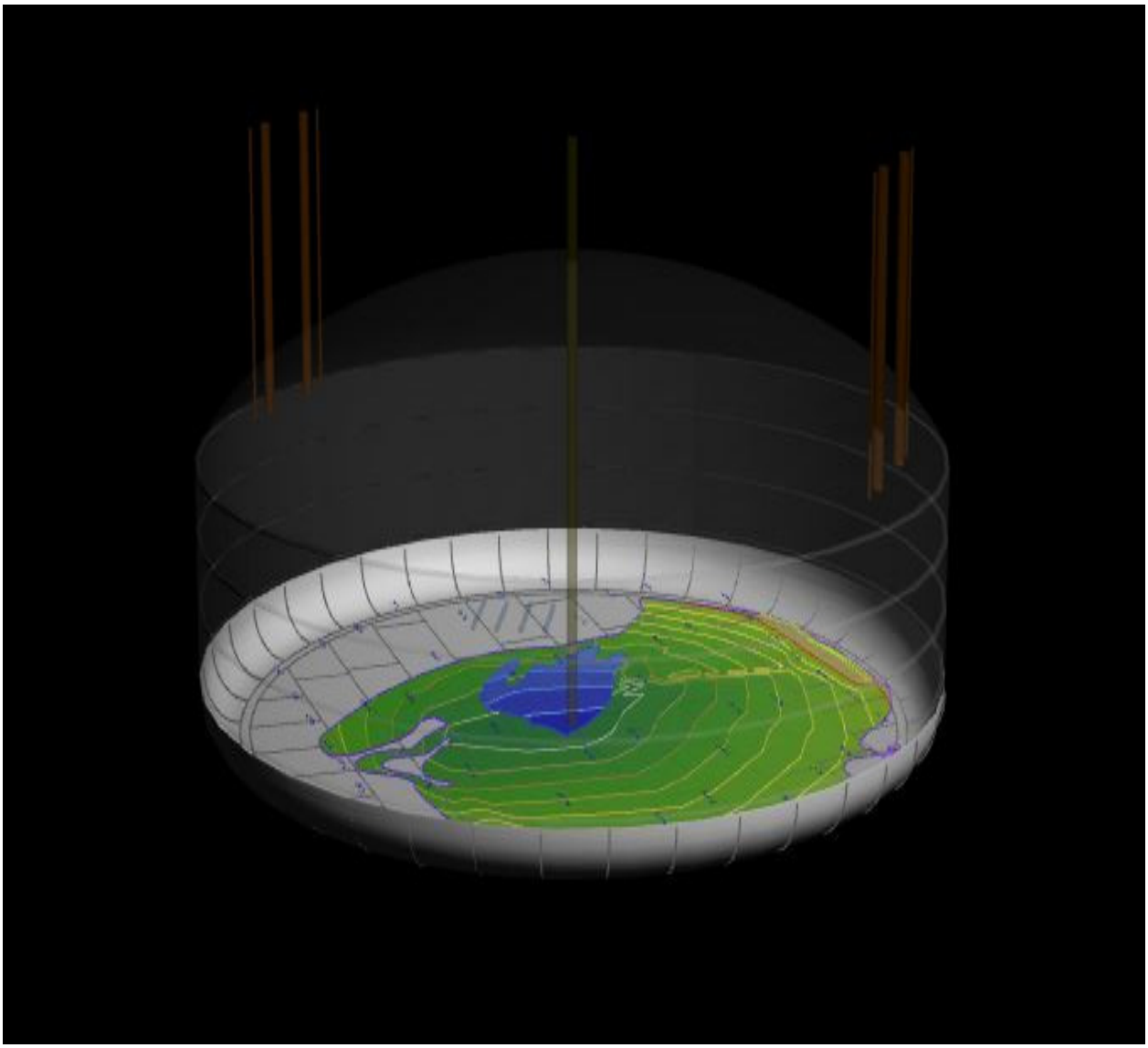
**7.2.1.1 Conceptualization of Source Term.** The distribution of residual waste volume within the retrieved tanks has been estimated by a variety of techniques that have involved video observations and computer/CAD modeling (e.g., RPP-CALC-54266, "Post-Hard Heel Retrieval Camera/CAD Modeling System Waste Volume Estimate for Tank 241-C-108"). The result of one such attempt is presented in Figure 7-5. Spatial distribution of residual waste volumes are estimated for the tank dish bottom, tank walls and stiffener rings, and in-tank equipment for the retrieved tanks, and are summarized in RPP-RPT-42323, Rev. 3. The estimates indicate that the majority of residual waste is located in the tank dish bottom (>80% for the 100-series tanks and >50% for the 200-series tanks), with minor amounts associated with the in-tank equipment.

For the purpose of developing a source release model for tanks and 244-CR vault, the residual waste volume is conceptualized to be present as a thin layer at the base of the tank (Figure 7-6). The estimated residual waste volume is assumed to be spread across the circular tank dish bottom area. The residual waste is conceptualized to be sludge-like, with a texture similar to a hardened paleosol. It is assumed to be fully saturated with a porosity of 40% based on evaluation of sludge waste phase from the retrieved tanks. The variability associated with residual volume is considered in the uncertainty analysis provided as part of the WMA C PA (RPP-ENV-58782, Section 8.1.3.2 Uncertainty in Residual Inventory Estimates.).

While the tank is intact, it will divert any water that infiltrates through the surface cover. Therefore, the transport mechanism for release of contaminants from the residual tank waste to the underlying vadose zone is primarily diffusive. The dissolved concentration of contaminants in the residual waste pore volume is controlled by the waste characteristics, such as waste form degradation and dissolution of solubility controlling mineral phases. The presence of continuous water connections is assumed across the grout and concrete layers for the diffusive transport to occur in the aqueous phase.

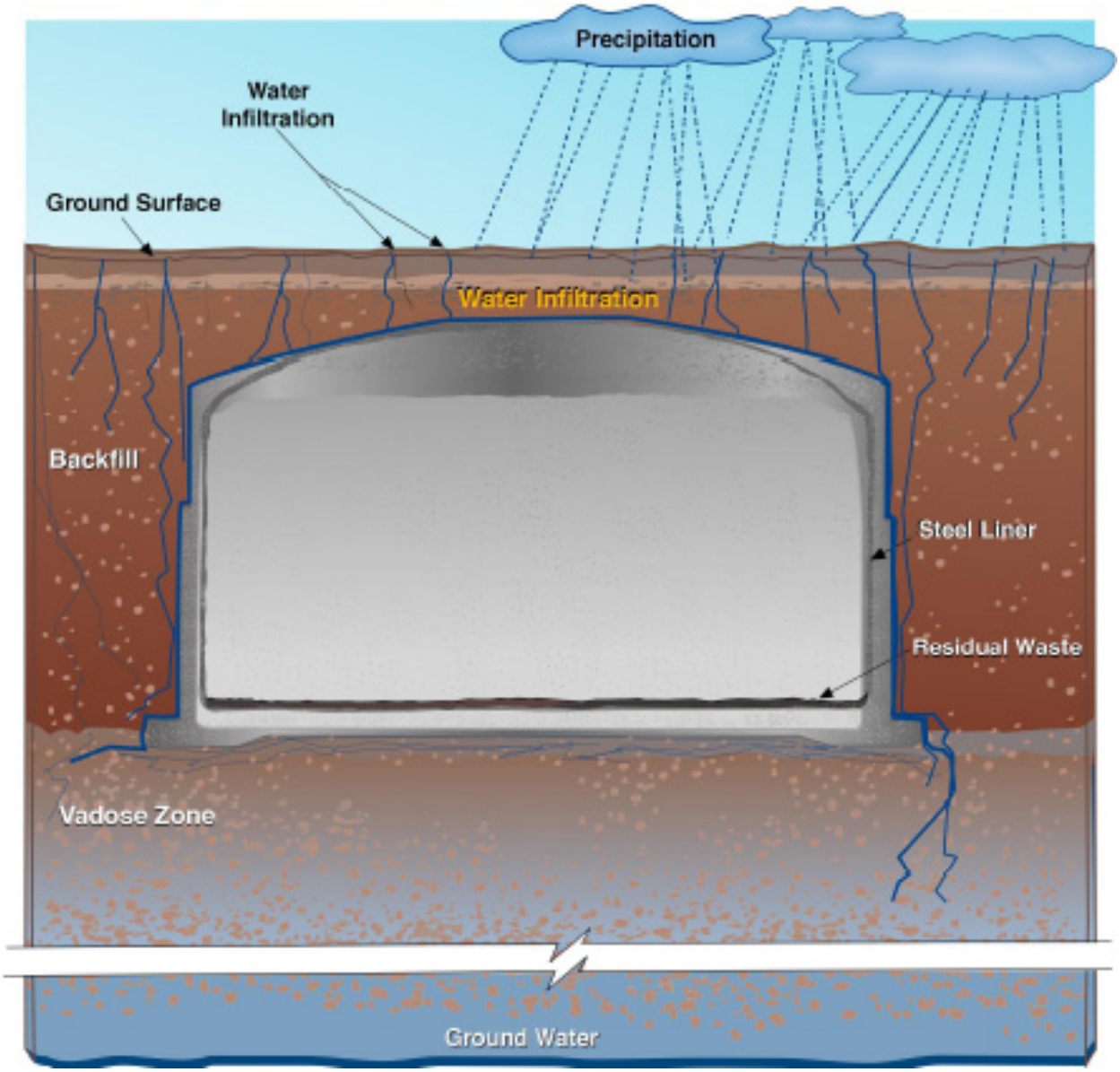
The source release model for the pipelines is quite different from the tanks. Instead of modeling discrete source terms, a single source area reflective of the approximate areal distribution of the waste transfer pipelines is considered. This is the assessed area of the tank farm where pipelines are generally present. The estimated residual inventory is uniformly spread over this area. Unlike tanks, the pipelines are assumed not to be filled with grout at closure, and due to limited information on the condition of the pipeline material, no credit is taken for the structural integrity of the pipeline. Therefore, both advective and diffusive releases are considered from the pipelines. More details related to the source conceptualization are discussed below.

**Figure 7-5. Computer Aided Modeling Results Showing Distribution of Residual Waste for a Retrieved Tank.**



**7.2.1.1.1 100-Series Tanks.** The C-100-series tanks consist of a concrete base slab with a steel-plate lining. They have an inside diameter of 22.9 m (75 ft) and an internal height of 5.5 m (18 ft) from the bottom of the steel tank liner to the top of the steel tank liner, which is also the spring line for the dome. The tanks are buried underground with approximately 2.1 m (7 ft) of backfill over the top of the dome to provide shielding from radiation exposure. The details of the engineered structure at the base of the C-100-series tanks are shown in Figures 7-7 and 7-8. The structures were built by installing a reinforced concrete base that is at least 0.15 m (6 in.) thick followed by 0.05 m (2 in.) of additional grout on top, over which carbon steel liner was emplaced. Following the completion of the bottom of the tank, the sidewalls of the metal liner were welded together and the liner was encased in sidewall concrete approximately 0.3 m (1 ft) thick. A concrete dome approximately 0.38 m (1.25 ft) thick was erected on top of the tank with a 3-ply waterproof membrane applied to the top of the dome.

**Figure 7-6. Conceptual Model of Tank after Site Closure.**




The carbon steel liner thickness varies, from 0.95 cm (0.375 in.) thick at the base of the tank to 0.64 cm (0.25 in.) thick along the sides. As shown in Figure 7-6, the residual waste layer is conceptualized to be located on top of the carbon steel liner. Although the carbon steel liner was designed to hold the waste in place and act as a barrier to transport of contaminants, no credit is taken for the liner due to lack of information on its present condition. Recent studies related to characterization of the corrosion behavior of the carbon steel liner (WHC-EP-0772, "Characterization of the Corrosion Behavior of the Carbon Steel Liner in Hanford Site Single-Shell Tanks") determined several likely corrosion processes within the tank environment that could lead to degradation of steel. Some of the likely corrosion processes are pitting and crevice corrosion, stress corrosion cracking, general corrosion, and galvanic cell corrosion. These are discussed in more detail in RPP-RPT-46879. These processes lead to uncertainties

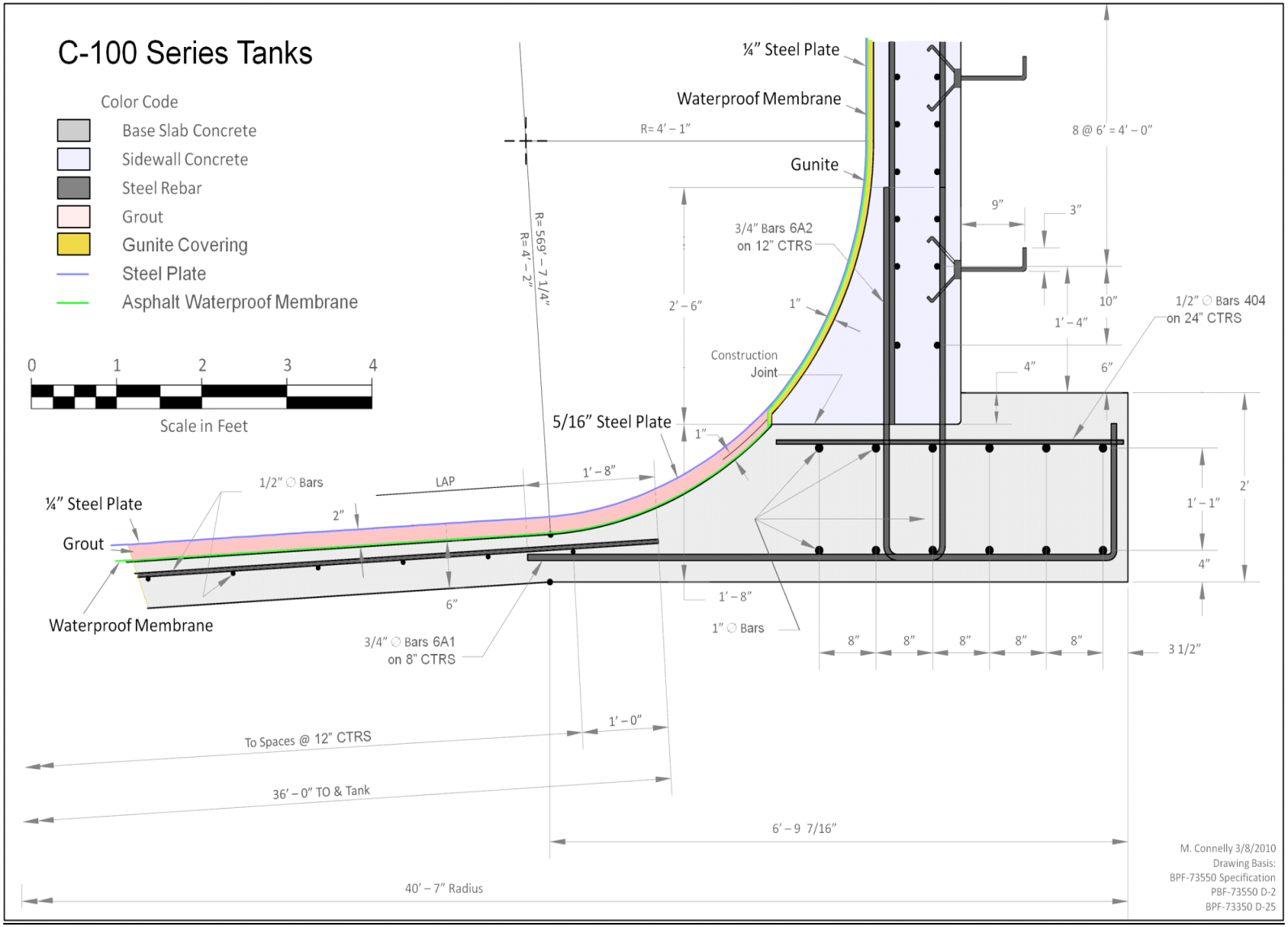
regarding the state of the carbon steel liner; consequently, no credit is taken in the source-term model for its presence. As a result, the residual waste layer is conceptualized to overlie the 0.05-m (2-in.)-thick grout layer that is underlain by the 0.15-m (6-in.)-thick base slab concrete layer. The source term model represents the shortest possible vertical diffusive transport path length from residual waste layer to outside of the tank, which is the combined thickness of grout and base slab concrete layer of 0.2 m (8 in.). The diffusive area is taken to be the base area of the tank. The aqueous concentration of contaminants in the residual waste provide the upstream boundary concentration for diffusive transport with a zero concentration boundary being applied in the far-field (at the water table depth). The source term release calculations are performed using the system model.

**7.2.1.1.2 200-Series Tanks.** The details of the engineered structure at the base of the C-200-series tanks is presented in Figure 7-9. The 200-series tanks have an internal diameter of 6.1 m (20 ft) and an operating depth of 7.3 m (24 ft). Other than the changed dimensions, the basic construction of the 200-series tanks is similar to the 100-series tanks. The 200-series tanks also have a base concrete slab over which a grout layer and a steel liner is present. The thickness of the base concrete slab is 0.15 m (6 in.), while the grout layer is 0.025 m (1 in.), leading to a combined thickness of 0.175 m (7 in.). Because the thickness differences are minor between the 100-series and 200-series tanks, a constant thickness of 0.2 m (8 in.) is applied to all the tanks for simplifying the diffusive transport calculations. Note that this thickness is conservative for diffusive release calculations as it ignores thickness of overlying steel liner (or steel corrosion products) and the residual waste (sludge) layer.

**7.2.1.1.3 244-CR Process Tank Vault.** The configuration of the 244-CR vault that is located in the southwest corner of the C Farm complex is shown in Figure 7-10. The vault is a two-level, underground, reinforced concrete structure. The lower level consists of four cells, each equipped with a concrete sump. The exterior walls and dividing walls between the cells are 0.61 m (2 ft) thick, with each cell housing a steel tank. The cells housing tanks CR-011 and CR-001 are each 7.9 m (26 ft) long by 6.7 (22 ft) wide. The cells housing tanks CR-002 and CR-003 are each 6.1 (20 ft) long by 4.9 m (16 ft) wide. Although the cells are distinct, for the purpose of source term modeling their inventory is assumed to be uniformly distributed over the rectangular footprint of the 244-CR vault of ~28 m (92 ft) length and 5.8 m (19 ft) width. The residual waste layer is conceptualized to be present over the grouted base of the tank, and the diffusive thickness is conservatively taken to be 0.2 m (8 in.) to be consistent with the path lengths assumed for the 100-series and 200-series tanks.

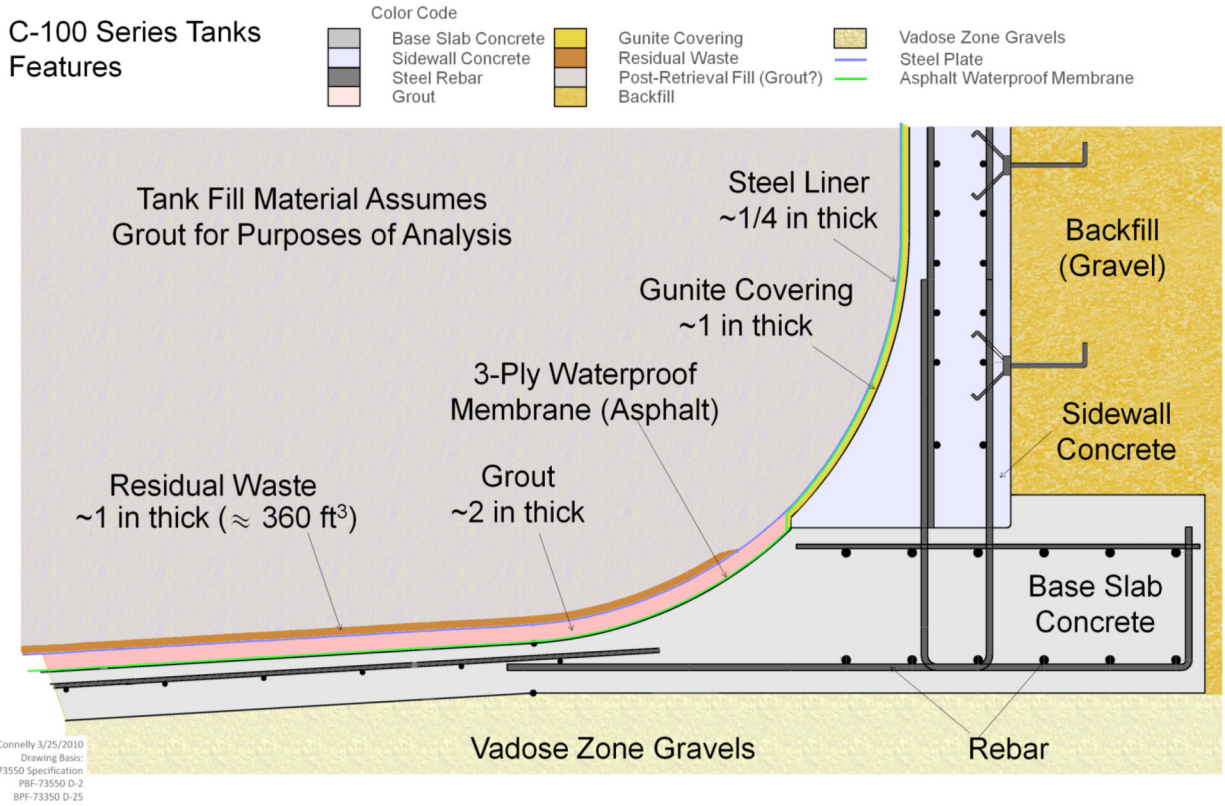
**7.2.1.1.4 Pipelines.** An extensive network of transfer lines connects the various components of the tank farms. These pipelines carried a variety of process wastes, typically in a slurry form. The initial tank farm waste-transfer pipelines installed in 1944 to 1945 were direct-buried (not encased) pipelines, with some on concrete slabs. Typical burial depth was 1 m (3 ft). After 1947, all pipelines installed either were concrete encased or pipe-in-pipe encased. The primary pipe used was typically carbon or stainless steel. Figure 7-11 shows the areal extent of active and existing pipelines in WMA C during the 1961 to 1978 time period.

**Figure 7-7. Engineered Structure at the Base of the C-100-Series Tank.**




Reference: BPF-73550, "Specifications For Construction of Composite Storage Tanks Bldg. No. 241 Hanford Engineer Works Project 9536."

**Figure 7-8. C-100-Series Tank Corner Features.**

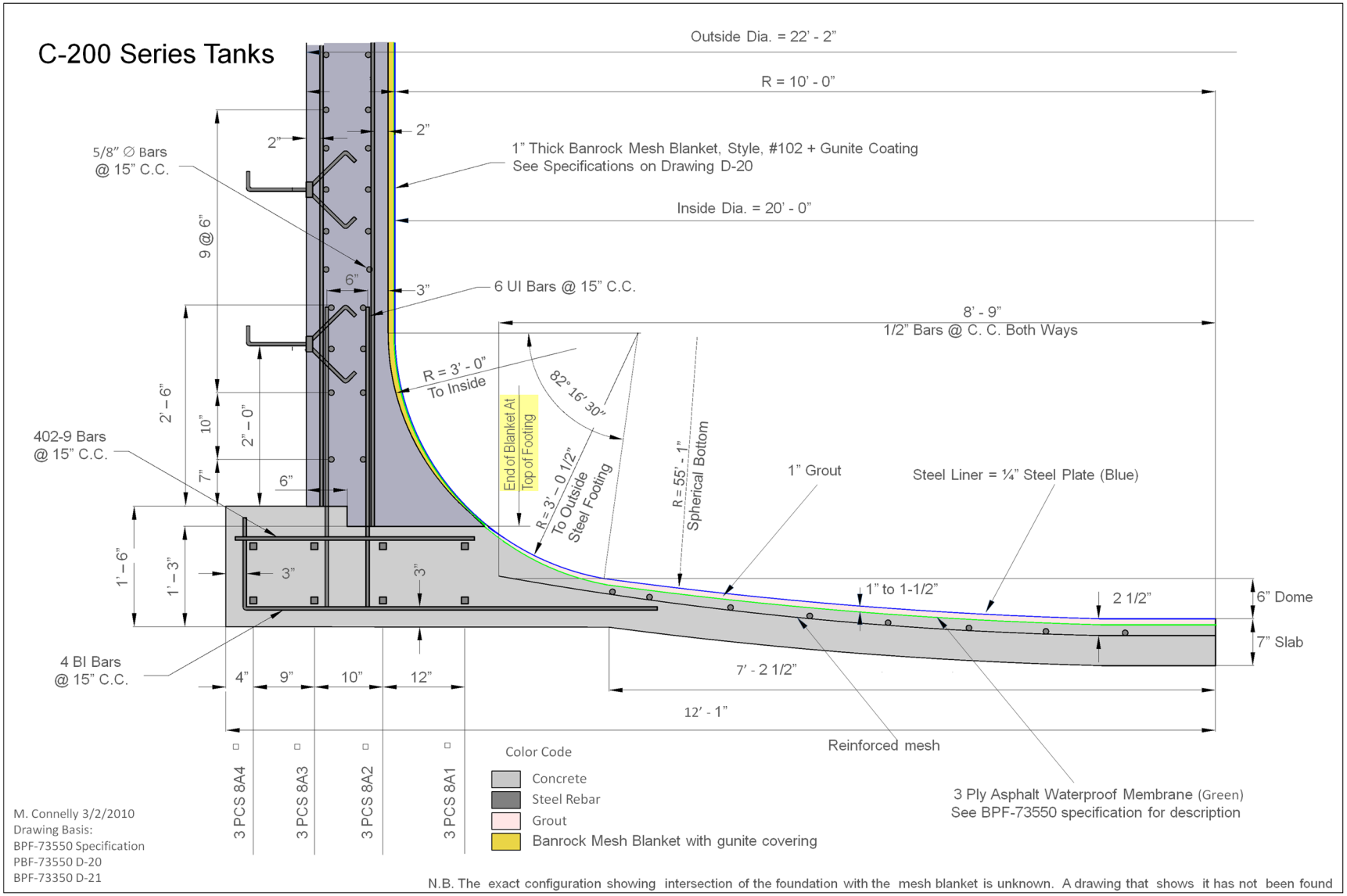



Reference: BPF-73550, "Specifications For Construction of Composite Storage Tanks Bldg. No. 241 Hanford Engineer Works Project 9536."

As discussed in RPP-PLAN-47559, approximately 11.2 km (7 mi) and 200 separate pipelines with different diameters and lengths comprise the abandoned pipelines in WMA C. Appendix A of RPP-PLAN-47559 compiles the information on various pipeline segments, indicating that the pipeline diameters typically vary from 0.05 m (2 in.) to 0.15 m (6 in.), with 0.076 m (3 in.) pipe diameter being the most common.

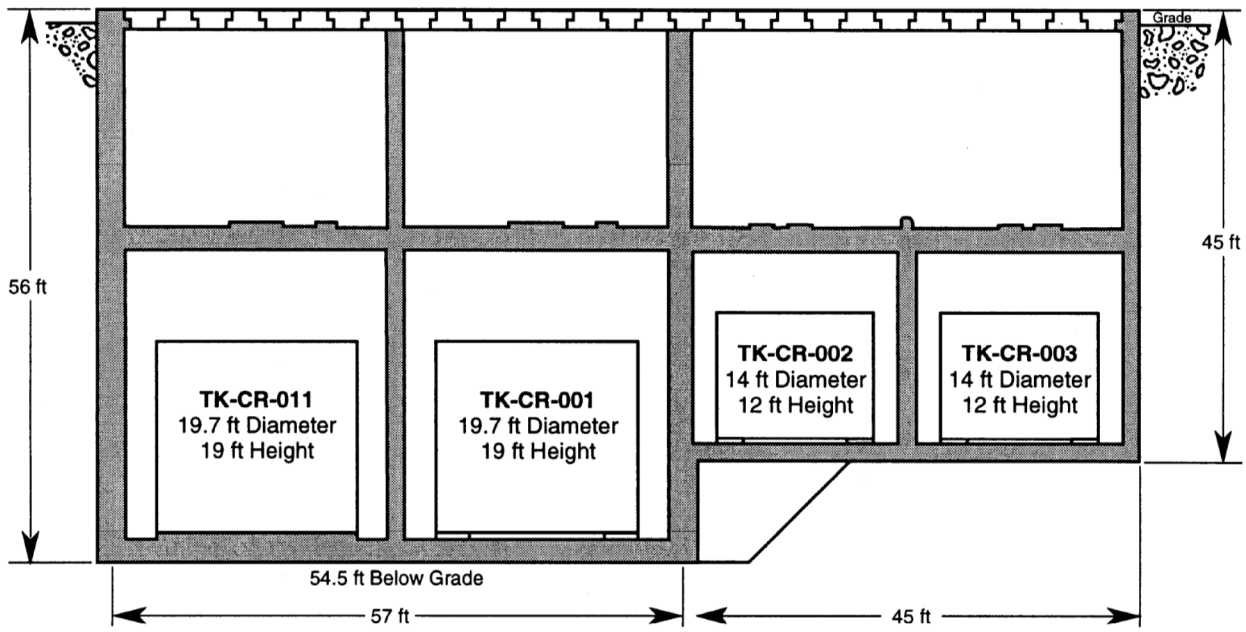
The residual pipeline inventory is based on the assumption of eight fully plugged cascade lines, one known plugged pipeline, and remaining pipelines assumed to be 5% full (RPP-PLAN-47559). Although the source inventory within the pipeline is spatially variable, for the purpose of the source release calculations the pipeline residual inventory is assumed to be uniformly distributed over a square area of side length 150 m (492 ft). This square area of areal extent 225,000 $m^2$ (0.09 $mi^2$) roughly coincides with the pipeline extent area shown in Figure 7-11. The contaminated thickness in the vertical direction is 0.076 m (3 in.), which is the most common pipeline diameter. The residual inventory is uniformly distributed within this volume mixed in with the bulk soil (backfill). Even though the pipeline material (carbon steel or stainless steel) or any grout-fill (that may occur in the future) may act as a barrier it is not considered in the model and the release from the pipeline is both advective and diffusive.

**Figure 7-9. C-200-Series Tank Cross-Section.**




Reference: BPF-73550, "Specifications For Construction of Composite Storage Tanks Bldg. No. 241 Hanford Engineer Works Project 9536."

**Figure 7-10. Schematic of the 244-CR Process Tank Vault in Waste Management Area C.**




**7.2.1.2 Evaluation of Tank Stability.** At closure, the tanks will be filled in with grout to provide structural and chemical stability and low permeability. During the placement of grout, the tank structure itself acts as a form into which the grout is poured. If the placement is not significantly interrupted, and if the grout mixes meet the placement specifications, the result will be a large monolith of emplaced grout. For the purpose of the RCA, the thickness of the infill grout is assumed to be 5 m (16.4 ft).

As the grout is not yet specified, reasonable assumptions are made about its likely composition and behavior. A possible tank fill is described in WSRC-TR-2005-00195, "Summary of Grout Development and Testing for Single Shell Tank Closure at Hanford" as consisting of three layers of grout: free flowing layer, structural stability layer, and a high compressive strength layer. The grout is anticipated to be formulated to meet the following core functions of the tank fill materials:

1. To confine residual waste through limitation of flow and through chemical stabilization of the residual material

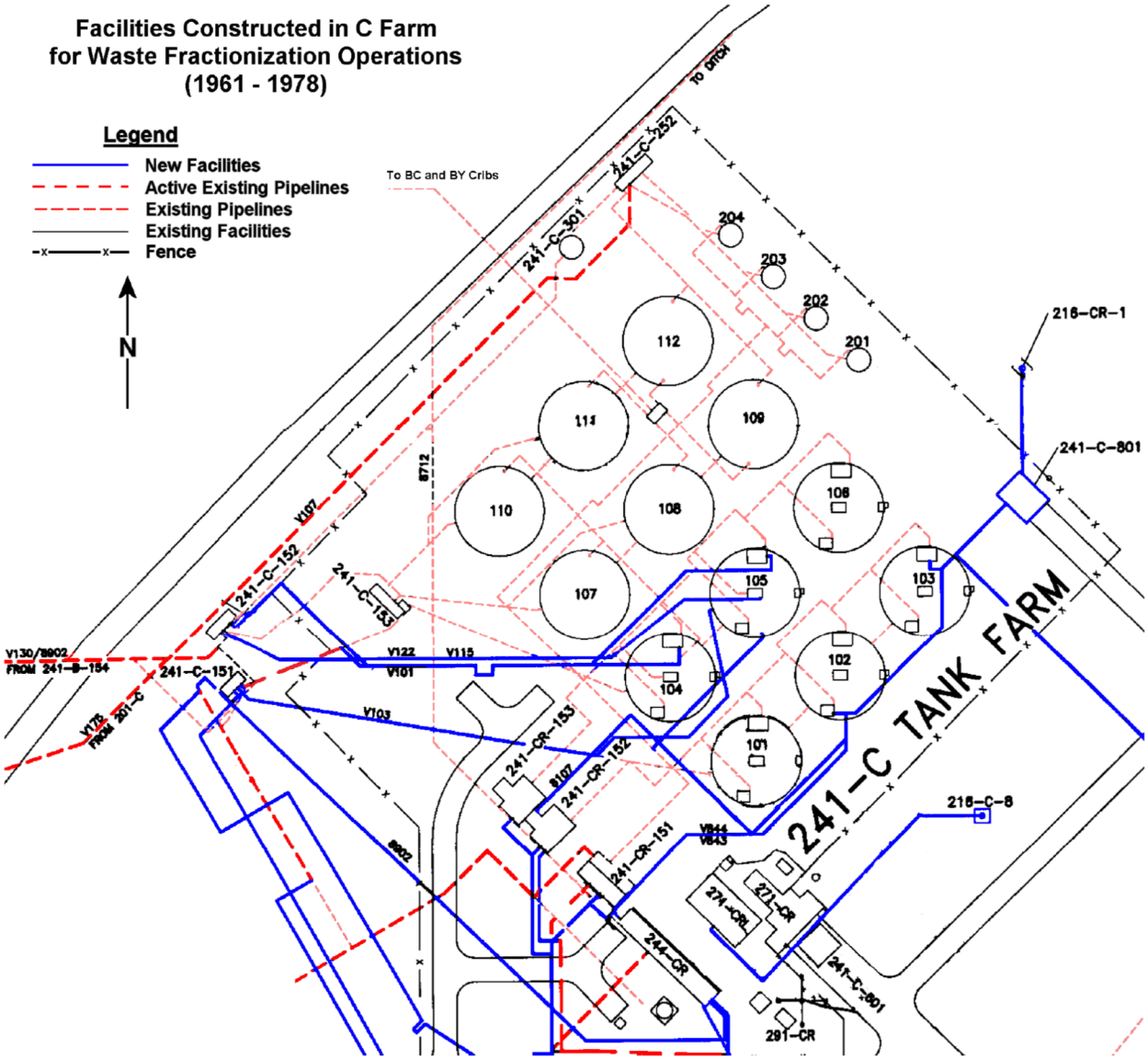
2. To provide stability and minimize maintenance

3. To reduce potential for infiltration or inadvertent intrusion.

The exact composition of grout is currently unknown, but it is likely to provide a significant barrier to flow through the tank, thereby restricting the release from the residual waste to be diffusive controlled. Once the grout meets compressive strength to resist deformation, limited physical damage is expected since the tank structure is below ground and surrounded by the soil

that will provide lithostatic (overburden) pressure. Degradation due to freezing and thawing is not likely to be significant either, due to depth of the tanks and ancillary equipment being below the freeze zone (deeper than 0.61 m [24 in.]). In addition, the geochemical conditions in the Hanford vadose zone are benign to concrete degradation. The Hanford soil pore waters are alkaline and are at or near saturation with calcite; therefore, any meaningful decalcification (acid attack) is not possible. The tank wall and grouted infill material is expected to undergo slow chemical and physical degradation. Therefore, the monolith is likely to remain an effective hydrologic barrier for a very long time.

**Figure 7-11. Location of Active and Existing Pipelines Along with New and Existing Facilities for Waste Fractionization Operations (1961 to1978).**

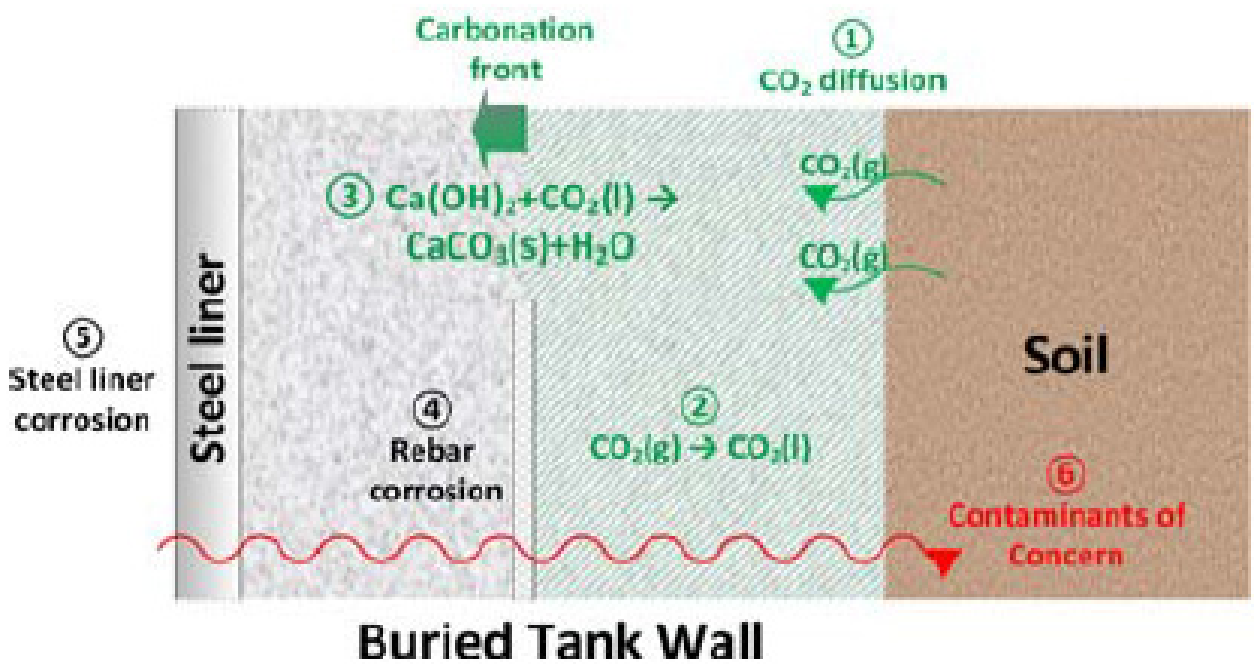



**7.2.1.2.1 Grout Degradation.** After closure, the tank concrete and grout is exposed to a combination of physical and chemical processes. Some processes may be beneficial (for

example, continuing hydration and self-sealing of cracks), while others may create deleterious changes, such as shrinkage and thermal cracking. Although the geochemical conditions at the Hanford Site are favorable to preventing grout and concrete degradation, there are potential chemical degradation mechanisms that under certain conditions could lead to degradation of grout and concrete forming the tank wall and the infill grout material. These key chemical degradation mechanisms are discussed and evaluated below along with the reasoning as to why these mechanisms are not carried forward into the numerical modeling.

**Carbonation.** Carbonation is the process where the $CO_2$ available in the soil-gas reacts with the calcium hydroxide in concrete to form calcium carbonate. This process is shown in Figure 7-12, where the $CO_2$ (g) is supplied by gaseous diffusion through the soil column. The carbonation reaction front is defined as the interface where the $Ca(OH)_2$ actively reacts with $CO_2$ gas and where the pH transitions from >12 [reflecting $Ca(OH)_2$ equilibrated pore water] to pH of 9 (reflecting $CaCO_3$ equilibrated pore water). Carbonation of concrete is a slow and continuous process that progresses from the outer surface inwards but slows down with increasing diffusive length. Detailed studies have indicated that movement of a carbonation front is typically proportional to the square root of exposure time. Carbonation has two effects: it increases mechanical strength of concrete by reducing permeability and reducing porosity (calcite has higher molar volume than portlandite), but is also decreases alkalinity, which is essential for corrosion prevention of the steel liner and other reinforcement steel. Below a pH of 10, the steel's thin layer of surface passivation dissolves and corrosion is promoted. Depending on the amount of steel present and its role in maintaining structural integrity of the tank, the stability of the tank can be compromised. Unlike normal reinforced concrete where significant amounts of rebar are present, the WMA C SSTs have relatively little equipment (and therefore steel) incorporated into the grout.

**Figure 7-12. Carbonation Process Acting on the Buried Tank Wall.**



The process of carbonation continues until all of the $Ca(OH)_2$ is dissolved. At this point, the dissolution chemistry is controlled by other hydrated calcium silicate and aluminate phases. When all of the $Ca(OH)_2$ has been leached away, other constituents become exposed to chemical decomposition. This decomposition eventually leaves behind silica and alumina compounds, which have little or no strength.

**Sulfate attack.** Sulfate attack represents a complex set of chemical and physical processes where the hydrated and unreacted phases in portland cement react with sulfate ions to form solid phases. This can lead to increased cracking due to formation of sulfate-bearing phases such as ettringite and gypsum, with considerable local expansion. Sulfate attack is typically managed by minimizing the reactive component (tricalcium aluminate) in the cement. The source of sulfate can be external (infiltrating water) or internal (from the concrete/cement itself). Delayed ettringite can form from an internal sulfate source such as sulfate present in the tank residuals. Although there may be some sulfate in the tank residuals, this amount is generally small (compared to the amount of grout infill) due to extensive washing and cleaning steps undertaken to remove the sludge. In addition, the grout is produced using low sulfate water with aggregate (fine sand) that is low in sulfate. The external source of sulfate is going to be slowly infiltrating waters, which have low sulfate content. Due to limited availability of sulfate, the impact from sulfate attack is not expected to be important for grout degradation in Hanford SSTs.

**Alkali-aggregate Attack.** The alkali-aggregate reaction occurs when aggregates containing reactive silica react with sodium and potassium oxides in the portland cement to form an alkali-silica gel. This gel can absorb water, which in turn can lead to expansion and cracking of the grout. In the mixes for Hanford tank fill, non-reactive quartz sand will likely be used. In addition, it is known that substitution of fly ash and blast furnace slag for some of the portland cement will mitigate the impact of the alkali-aggregate reactions. Finally, portland cements produced today intentionally have low amounts of alkali content to avoid alkali-aggregate reaction. Therefore, it appears unlikely that cracking due to alkali-aggregate reaction would occur in the Hanford SSTs.

**Acid Leaching (Decalcification)**. Acid leaching or decalcification refers to leaching of calcium ions (coupled with hydroxide ions) from pore solutions and dissolution of calcium hydroxide, C-S-H, and hydrated calcium aluminate phases in cementitious materials (WSRC-STI-2007-00607). This form of degradation occurs when concrete is in contact with acidic water for long periods of time. The ultimate residue produced by decalcification consists of hydrous forms of silica (silica gel), alumina (alumina gel), and iron oxide. The rate of attack depends on the flow rate and the chemistry of water. Since ambient Hanford pore waters have high alkalinity and are at near saturation with calcite mineral phase, the process of decalcification is likely to be very slow, if it occurs at all.

Current evaluations of chemical conditions inside the tank (based on residual waste chemistry) and outside the tank (based on pore water chemistry) indicate very benign conditions with regard to chemical degradation of concrete and tank-fill grout material. Consequently, the degradation due to chemical processes will progress at a very slow rate. Among the processes evaluated, carbonation was identified as the most likely chemical degradation mechanism, which will proceed naturally due to availability of $CO_2$ via gaseous diffusion.

**7.2.1.2.2 Grout Monolith Stability.** During scale-up testing for tank infill material, two monolith structures were created and tested for strength. The details are presented in WSRC-TR-2005-00195. Figure 7-13 shows the two monolith structures produced by placing three layers of grout into (4.6-m) 15-ft diameter swimming pools during scale-up testing. These monoliths remained after the swimming pool structures were removed. The layered monoliths displayed significant strength, as demonstrated by the difficulty encountered in breaking them apart. In fact, the bulldozer and the heavy-duty forklift shown in the figure were unable to turn over the monoliths. Both monoliths were repeatedly lifted on one side and dropped without breaking. Eventually, the bulldozer was able to break the monoliths along horizontal planes by ramming the bulldozer blade at the level of the interfacial areas. These tests indicate substantial increase in strength even though these monoliths were in initial phase of curing (only 5 days after the capping grout had been poured, and about 8 total days since the pouring of the first stabilization layer). Compressive strength measurements confirmed this and indicate that significant strengthening likely continues to occur out to 90 days of curing.

**7.2.1.2.3 Hanford Tank Concrete Evaluation.** As part of the initiative to evaluate the structural integrity of the tanks (called Single-Shell Tank Integrity Project or SSTIP), a 1.4-m (55-in.)-diameter reinforced concrete dome "Plug" was removed from tank C-107 in December 2010. More recently, an 11.6-m (38-ft) sidewall concrete core was removed from 241-A-106 tank (located in WMA A-AX south of WMA C) in May 2014. Results from inspection, physical testing, and petrographic examination of the concrete cores are reported in RPP-RPT-50934, "Inspection and Test Report for the Removed 241-C-107 Dome Concrete," and RPP-RPT-58254, "Concrete Core Testing Report for the Single-Shell Tank 241-A-106 Sidewall Coring Project." These analyses are very important in predicting the tank wall degradation because they provide direct empirical evidence on the state of concrete wall material after being left underground for 60 to 70 years. The results of analyses that are relevant for the RCA are discussed below.

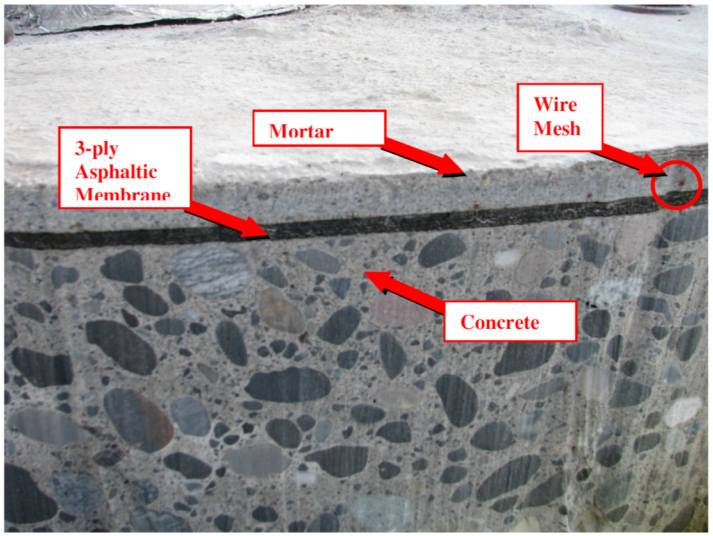
The 1.4-m (55-in.)-diameter concrete section ("Plug") removed from the center of the dome of tank C-107 is shown in Figure 7-14. It was removed using a combination of high pressure water and garnet abrasive. Fourteen cores were taken from the concrete "Plug," each 10.7 cm (4.2 in.) in diameter. Of those 14 cores, 12 underwent mechanical testing and 2 underwent petrographic examination. No cracks or large air voids were found during the inspection process. Additionally, the protective asphaltic membrane and mortar layers that were laid out during the construction were found to be intact. The average compressive strength of all of the tested cores was about 55,158 kPa (8,000 psi), more than 2.5 times the original 28-day design strength specified at the time of construction. Based on the results of petrographic examination, the concrete represented by the cores was in good condition. No distress (cracking or excessive microcracking) was observed in either core. The concrete showed no evidence of chemical attack, significant alkali-aggregate reactions, or other deleterious mechanisms involving aggregates and/or paste constituents. The concrete in both cores exhibited good physical paste properties. Apart from localized softer paste at the immediate top surface, the paste in the cores was hard and dense through the depth of the concrete. Distribution of aggregates and other paste constituents was uniform. Macroscopically, the cores were well consolidated (no large voids). The cement was nearly completely hydrated. The depth of carbonation from the top surface of both cores was reported to be 1 to 2 mm (0.04 to 0.08 in.).

**Figure 7-13. Demolition of (a) Pool 1 Monolith and (b) Pool 2 Monolith after Only 5 Days after the Capping Layer had been Poured.**
**Note that monolith from Pool 2 is in the foreground in (a). Also note the vertical crack in the Pool 2 monolith that occurred during the demolition.**

(a)

(b)

**Figure 7-14. Evaluation of 55-inch Diameter Reinforced Concrete Dome Plug from Tank 214-C-107.**

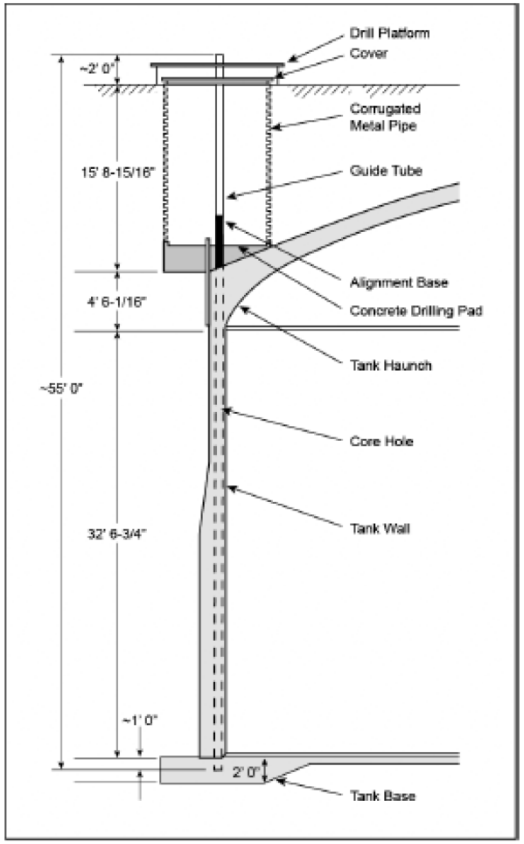


Sidewall coring of tank 241-A-106 was completed over two weeks in May 2014. Over 11.6 m (38 ft) of concrete core (8.4-cm [3.3-in. diameter]) was successfully removed to a depth approximately halfway through the tank footing. This tank was chosen due to its high heat load history and concerns over the thermal degradation of the concrete from heat exposure. The collected concrete cores are shown in Figure 7-15. Physical testing for structural integrity indicated favorable results, with values generally greater, and in many cases significantly greater, than expected. It is concluded that the effects of thermal degradation on the mechanical properties of the concrete appear to be negligible. No deficiencies were found with regard to the structural integrity of the tank. Petrographic analyses determined that the concrete is in overall good condition, with a minor amount of microcracking and minor evidence of deleterious mechanisms that do not appear to have significantly affected the overall quality and integrity of the concrete. The concrete was composed of siliceous natural gravel coarse aggregate and natural sand fine aggregate uniformly distributed in a portland cement paste binder. The paste appeared to be of good quality, although some degree of paste alteration (leaching of calcium hydroxide from the paste) was observed, along with a small amount of secondary ettringite mineral, possibly from sulfate containing impurities in the paste. Only one crack and very few microcracks were observed in the examined core segments. A very minor degree of alkali-silica reaction (ASR) had occurred in the concrete; however, no deterioration (no associated cracks or microcracks) was observed. Given the age of the concrete and current degree of ASR, further reaction and/or associated expansion is deemed unlikely. The depth of carbonation was found to be shallow and about 1 to 4 mm from outer surface in some core segments.

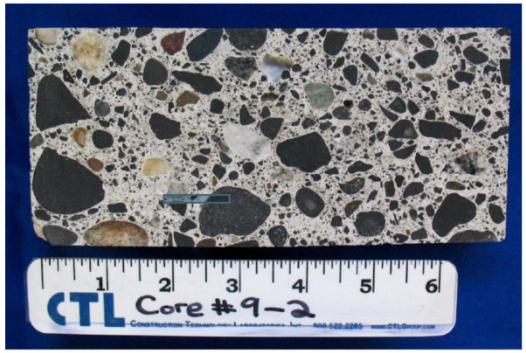
Results of material properties tests of concrete cores from the haunch and wall of tank 241-SX-115 (SX-115) and 202-A PUREX Canyon Building have been evaluated and documented in RHO-RE-CR-2, "Strength and Elastic Properties Tests of Hanford Concrete Cores – 241-SX-115 Tank and 202-A Purex Canyon Building." Both structures were built in the 1953 to 1954 time frame using the same concrete mix design. Compression strength and tensile strength tests on concrete samples taken from tank SX-115 in year 1981 indicated a pattern of possible decreasing strength with depth, but all samples were above the design value (compressive strength of 20,680 kPa [3,000 psi]). Material property tests were conducted on 17 specimens from the 202-A PUREX Building under three temperature conditions: unheated, heated to 93.3 °C (200 °F), and heated to 93.3 °C (200 °F) and then cooled to ambient temperature. The rate of heating was set at 23.9 °C/day (75 °F/day) to determine if the heat-up rate was significant in affecting the strength. The compressive strength for samples tested after heating to 93.3 °C (200 °F) showed a small decline compared to the unheated samples. However, for samples that were heated to 93.3 °C (200 °F) and then allowed to cool to ambient temperature, some strength recovery was observed with values falling well within the range of strengths measured for the unheated concrete. The compressive strengths of the 202-A PUREX Building concrete specimens were in excess of 20,680 kPa (3,000 psi) design value in all cases.

Visual inspection of 37 concrete core samples from tank SX-115 and 17 concrete core samples from 202-A PUREX Building indicated that most of the samples had no visible signs of concrete deterioration. However, four tank farm cores and two PUREX Building cores were found to have visible cracks, ranging from approximately 5 to 25 cm (2 to 10 in.) in length, possibly from coring activities.

**Figure 7-15. Evaluation of Sidewall Concrete Core from Tank 241-A-106.**



Side view of Core #3 [Length = 12½ in.], No significant voids present



A number of tests have been performed to evaluate the strength and elastic properties of the Hanford Tank Farm concrete core materials for temperatures varying from 22.2 °C to 121.1 °C (72 °F to 250 °F) (RHO-RE-CR-2). These tests were conducted on 7.6 cm by 15.2 cm (3 in. by 6 in.) cylinders fabricated from core materials from the 241-A, 241-S, 241-T, and 241-U Tank Farms. The 241-A Tank Farm concrete compressive and tensile strengths were about 45% greater than those values obtained from tank SX-115 concrete; however, the elastic properties were essentially equal. This could be due to variations between concrete batches or the fact that SX-115 tank wall concrete was subjected to higher temperatures during tank farm operations than the dome concrete in the 241-A Tank Farm. In no case did compressive strength of any tank SX-115 specimen fall below 20,680 kPa (3,000 psi). The lowest strength measured was 26,372 kPa (3,825 psi).

These results indicate that the concrete walls within WMA C tanks are likely to be structurally stable and in relatively good condition. The elevated temperatures experienced due to heat generated from radioactive decay and chemical reactions within the tank are unlikely to cause any appreciable decline in strength of the concrete in the tank walls.

**Aboveground Concrete Structure Evaluation.** In addition to the concrete samples taken from SST, some information on chemical degradation is also available from concrete cores taken from aboveground concrete structures on the Hanford Site. PNNL-23841, "Radionuclide Migration through Sediment and Concrete: 16 Years of Investigations" summarizes the characteristics of three concrete cores from aboveground structures that have been exposed to Hanford weather for 14, 28, and 57 years. The characterization summary is presented in Table 7-1. A minor degree of microcracking is noticeable, along with a moderately tight paste-aggregate bond. Ettringite is observed in the void spaces. The depth of carbonation increases with increasing age of the concrete. In the oldest specimen (213J), the carbonation had extended about 50 mm (1.97 in.) into the concrete wall. Given the limited data, the rate of carbonation of concrete at the Hanford Site can be estimated at approximately 0.3 to 0.9 mm (0.1 to 0.04 in.) per year. This carbonation rate provides an upper bound value that can be expected for a concrete under Hanford Site conditions.

Observations of the cores for buried Hanford tanks indicate the carbonation depth ranges from 1 to 4 mm (0.04 to 0.16 in.). Considering about 60 to 70 years of burial time, the carbonation rates are calculated to be about 0.01 to 0.07 mm/yr (0.0004 to 0.0028 in./yr). For the aboveground concrete structure, the carbonation rate is expectedly much higher and calculated to be about 0.3 to 0.9 mm/yr (0.01 to 0.04 in.). However, the rate of carbonation would be affected by several factors, such as concrete composition, porosity, and the degree of exposure to weathering.

Simplifying carbonation as a sharp moving front, a simple analytical expression for the location $x_c$ (mm) of the carbonation front when Relative Humidity exceeds 50% can be given as follows (Brown et al. 2013, "Modeling Carbonation of High-Level Waste Tank Integrity and Closure"):

$$x_c = A\sqrt{t}$$

where $A$ is proportionality constant and a function of initial $CO_2$ concentration, effective diffusivity of $CO_2$, etc., while $t$ is exposure time.

**Table 7-1. Characteristics of Concrete Cores from Aboveground Structures at the Hanford Site.**

| Characteristic | Field Lysimeter Test Facility Sample | 622C Sample | 213J Sample |
|---|---|---|---|
| Age | 14 | 28 | 57 |
| Carbonation Depth (mm) | 1 – 10 | 2 – 8 | 48 – 53 |
| Air Content (%) | 4 – 5 | 2 – 4 | 1 – 2 |
| Water/Cement Ratio | 0.5 – 0.55 | 0.5 – 0.55 | 0.52 – 0.57 |
| Secondary Deposits | Abundant ettringite lining voids | Ettringite lining voids | None in outer 50 mm – minor ettringite lining voids |
| Microcracks | Minor | Minor | Common in outer 50 mm |
| Steel | #4 ~103 mm cover | None | #4 ~80 mm cover |
| Unit Weight (pcf) | 153 | 152 | 148 |
| Aggregates | Well-graded siliceous gravel, 19 mm top size | Well-graded siliceous gravel, 23 mm top size | Well-graded siliceous gravel, 21 mm top size |
| Paste-Aggregate Bond | Moderately tight | Moderately tight | Moderately tight to moderately weak |

Reference: PNNL-23841, "Radionuclide Migration through Sediment and Concrete: 16 Years of Investigations."

Experimental results have confirmed this non-linear relationship between the carbonation front and square root of exposure time. For the sake of simplicity, and in order to do a bounding calculation, one can assume that the maximum depth of carbonation within the buried concrete tank structure is 10 mm (0.39 in.) (instead of the observed 1 to 4 mm [0.039 to 0.157 in.]). Next, considering 70 years of exposure time (burial time of SST in WMA C), the proportionality constant ($A$) can be calculated from the above equation to be 1.2 mm (0.05 in.) per square root of time in year. This Hanford Site-specific proportionality constant can then be used to calculate the depth of carbonation front as a function of time. Depths of carbonation front are calculated for arbitrary time periods in Table 7-2. Considering that a 0.2 m (8 in.) minimum thickness of concrete (and grout) layer exists at the base of the tank, the time for the carbonation front to propagate through this thickness will take over 20,000 years. The actual time frames would be even longer, since the observed depth of carbonation is 1 to 4 mm (0.039 to 0.157 in.) instead of assumed 10 mm (0.39 in.) for this calculation.

The above calculated time does not include carbonation through the infill grout material, which will also have to undergo chemical degradation (likely carbonation) before tank integrity can be assumed to be lost. A simple calculation—using 5.5 m (18 ft) grout thickness in the tank, and assuming carbonation front propagating from both top and bottom directions, and assuming a bounding 0.1 mm/yr (0.004 in./yr) linear carbonation rate—shows that the grout will not be fully degraded for another 27,500 years. As a result, the total time for the carbonation front to move through both the concrete wall and the infill grout can easily exceed 50,000 years. Results from recent modeling conducted by Brown et al. (2013) under Hanford subsurface conditions

(assuming 2.4% $CO_2$ in soil gas at 90% concrete saturations) indicates that the carbonation front propagation rate is < 0.1 mm/yr (0.004 in./yr).

**Table 7-2. Bounding Depth of Carbonation for Buried Concrete Calculated for Different Exposure Times Under Hanford Specific Conditions.**

| Elapsed Time (yr) | Depth (mm) | Depth (inches) |
|---|---|---|
| 1,000 | 37.8 | 1.5 |
| 5,000 | 84.5 | 3.3 |
| 10,000 | 119.5 | 4.7 |
| 20,000 | 169.0 | 6.7 |
| 50,000 | 267.3 | 10.5 |
| 100,000 | 378.0 | 14.9 |

The information presented above indicates that it is highly unlikely for the tank degradation to occur within the modeled time period of 10,000 years. As a result, the water entry in the tank is likely to be very slow or nonexistent altogether. For the purpose of the RCA, the infill grout is conceptualized to be located above the thin residual waste layer and separated from the grout/concrete layer at the base of the tank. While the infill grout is intact, no water can flow through the residual waste, and therefore the primary contaminant transport pathway is by diffusion through water in the pore spaces to the base of the tank and into the underlying vadose zone.

**Natural Analogues.** A way to gain insight into the longevity (durability) of grout, concrete, and mortar is through consideration of some of the well-studied ancient structures such as the Pantheon in Rome, Hadrian's Wall in Scotland, the Roman Aqueducts system, etc. Their durability is discussed in WSRC-TR-2005-00195. Such ancient structures that use pozzolanic materials in conjunction with hydrated lime [$Ca(OH)_2$] best simulate modern day concrete, grout, and mortar. Some of these ancient structures have existed for over 2,000 years despite being subjected to weather, abrasion, wars, and neglect. The longevity of these ancient structures, which is attributable to materials selection and placement techniques, suggests that the lifetimes for the grout monoliths within the protected, underground SSTs at Hanford could also extend into the thousands of years.

### 7.2.2 Chemical Transport

This section discusses the conceptual model of the projected transport of chemicals from the source term through the environment to the points of exposure and identifies the mechanisms included in the analysis for groundwater and biotic transport pathways.

**7.2.2.1 Conceptual Model for Groundwater Pathway.** This section provides an overview of major features that affect flow and transport of chemicals within the vadose zone and saturated zone underlying WMA C. Estimates of chemical concentrations in environmental media are

used to estimate doses to a hypothetical individual based on an assumed exposure scenario. Analysis of performance risk and hazard impacts therefore requires estimates of (1) the inventory of chemicals in the facility, (2) the release rates of these chemicals from the tank and pipeline residual waste, and (3) the migration rates and concentrations of chemicals released from the residual waste in environmental media (soil and water).

The conceptual model of the groundwater pathway considers a diffusion-controlled release of chemicals from the grouted tanks and ancillary equipment and an advection-controlled release from the pipelines, vertical transport through the thick vadose zone to the water table, and then transport laterally through the aquifer to a hypothetical well located 100 m (328 ft) downgradient. These features and processes reflect safety functions that serve as barriers to exposure in the context of defense in depth for protection of hypothetical receptors. The grouting of the tanks represents an engineered safety function or barrier to exposure, because one of the purposes of the grout is to limit the release of hazardous chemicals from the tanks to the vadose zone. The surface barrier (surface cover) represents a hybrid barrier to exposure, because while it is an engineered structure it eventually evolves into part of the natural system. The vadose zone beneath WMA C can also be viewed as a natural barrier. Once contaminants enter the vadose zone, the low recharge (infiltration rate) controlled by the surface cover system, the thickness of the vadose zone between the base of the tanks and the unconfined aquifer, and the soil-contaminant interaction, prevent all but the least-reactive contaminants from reaching the unconfined aquifer for thousands of years. The saturated zone (aquifer) beneath WMA C can be viewed as a natural barrier, because as recharge containing contaminants enters the aquifer, the leachate mixes with groundwater and becomes more dilute. This dilution in concentration lowers the exposure point concentration and consequent dose to a receptor. Thus the transport of hazardous chemicals to the groundwater is a complicated process that depends on data and assumptions relevant to the following physical systems: (1) engineered features of WMA C, (2) surface features of WMA C, (3) the vadose zone beneath WMA C, and (4) the saturated zone (groundwater) beneath WMA C.

First, this section describes the facility features important to modeling the release of contaminants from the source areas. This is followed by descriptions of the temporal evolution of the WMA C surface, the vadose zone stratigraphy, and the geochemical effects that impact chemical transport. Next is an overview discussing the basis for the saturated zone flow and transport used in the WMA C RCA. The final section provides a detailed justification of important assumptions and simplifications of the vadose zone flow and transport model.

**7.2.2.1.1 Waste Management Area C Facility Structures.** Section 3.2.1 provides a description of WMA C and the planned surface engineered cover system. The physical system includes the closure barrier and the complex structures that make up the closed facility. The WMA C sources consist of twelve 2,006,000-L (530,000-gal) 100-series tanks, four 208,000-L (55,000-gal) 200-series tanks, a 136,000-L (36,000-gal) catch tank, a vault with two 57,000-L (15,000-gal) and two 151,000-L (40,000-gal) tanks, and an estimated ~11 km (~7 mi) of pipeline

(RPP-PLAN-47559). RPP-RPT-49701 identifies the following four phases associated with the closure of WMA C.

- Facility Closure – All below-grade tanks and equipment are grouted to stabilize residual waste and void spaces.

- Demolition and Decommissioning (D&D) Activities – All above-grade facilities, equipment, utilities, and tank farm features are dispositioned, and all drywells and groundwater wells are decommissioned.

- Closure Cap Construction – The long-term surface barrier over the tank farm is constructed.

- Post Closure Monitoring and Maintenance – Monitoring continues as necessary to ensure the performance of the closure cap and to provide verification that the tank farm closure is satisfying the performance measures and requirements under WAC 173-303-610, WAC 173-303-610, and WAC 173-303-665.

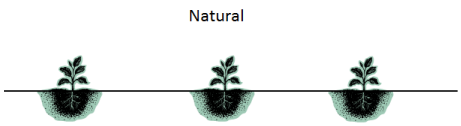
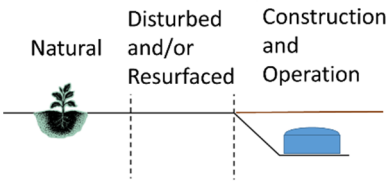
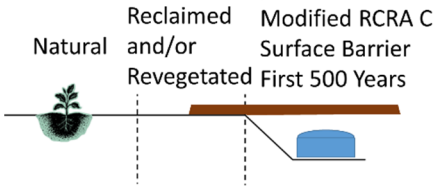
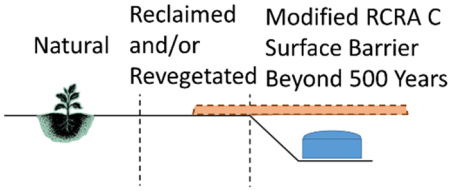
The grouting of the tanks and ancillary equipment is intended to stabilize these structures (prevent collapse/subsidence) and to minimize the release of hazardous chemicals by keeping the release controlled by diffusion processes. Contaminant releases from the grouted tanks and ancillary equipment are expected to remain diffusive, with no advection (or negligible) occurring through the tanks and ancillary equipment because sufficient degradation of the tank-wall and infill grout material is unlikely to occur within the simulated time period of 10,000 years. Chemical degradation rates are expected to be same as carbonation rates, and it is estimated that for the carbonation front to propagate through the minimum wall thickness of a tank (~200 mm [~8 in.]), it will take approximately 30,000 years. This calculated time excludes grout material inside the tank, which will also have to undergo carbonation before tank integrity could be assumed to be lost.

**7.2.2.1.2 Temporal Evolution of Waste Management Area C Surface.** Net infiltration, deep percolation, and recharge of water are the major transport mechanisms for moving contaminants from the closed system to the groundwater. In arid and semiarid regions with thick vadose zones, such as the Hanford Site, long-term factors like climate change, changes in the annual precipitation rates, and changes in vegetation structure and community are required to influence the deep vertical water fluxes. In these regions, large seasonal fluctuations in soil water potential are generally contained within the upper few meters of soil, and the spatially and temporally varying moisture fluxes even out within the deep subsurface above the water table.

With expected changes to the land cover over time due to growth of vegetation, several time periods have been conceptualized (Table 7-3) to represent the changes in recharge rates and hydrologic conditions at WMA C. Each of these time periods is characterized by a different recharge rate that will be discussed in Section 6.3.2. Following is a discussion of two assumptions that pertain to recharge: (1) that net infiltration through the thick, heterogeneous vadose zone in the 200 Areas dampens the effect of discrete events, and therefore episodic precipitation events can be replaced by an average annual recharge rate; and (2) that

impacts resulting from plausible climate change that may occur during the evaluation period do not adversely impact the performance of the surface or vadose zone as a barrier.

**Table 7-3. Timeline Considered for Representing the Evolution of Waste Management Area C.**

| Phase | Conditions | Duration | Conceptual Half Cross Section of the Waste Management Area C Area |
|---|---|---|---|
| Pre-operations | Before construction of Waste Management Area C | Until steady-state moisture conditions are achieved for the year. |  |
| Construction and Operations | Current conditions | 1945 to 2020 |  |
| Early Post-Closure | Transition to conditions of restricted recharge due to Modified RCRA C surface barrier | 2020 to 2520 |  |
| Late Post-Closure | Degraded surface barrier conditions | 2520 to 12020 |  |

RCRA = Resource Conservation and Recovery Act of 1976

Multi-year evaluations of soil moisture content data collected from vegetated desert soils throughout the United States indicate that water potentials remain very low and relatively invariant below depths of 2 to 5 m (6.6 to 16.4 ft) ("Ecohydrological Control of Deep Drainage in Arid and Semiarid Regions" [Seyfried et al. 2005]). In response to intermittent years of elevated precipitation such as those caused by El Nino in the southwestern United States, the biomass usage of water by deep-rooted xeric vegetation increases, depleting the excess water, and no net increase in groundwater recharge occurs ("Global synthesis of groundwater recharge in semiarid and arid regions" [Scanlon et al. 2006], Analysis of Techniques for Estimating Potential Recharge and Shallow Unsaturated Zone Water Balance near Yucca Mountain, Nevada [Leary 1990]). Simulation results representing the impact of a 20-year period of temporally varying precipitation on a surface barrier and a clean, graveled surface indicate that the temporal variation in drainage can effectively be ignored, and that an average value can be used with little

loss of accuracy (WHC-EP-0332, "Simulations of Infiltration of Meteoric Water and Contaminant Plume Movement in the Vadose Zone at Single-Shell Tank 241-T-106 at the Hanford Site," pp. 18-21).

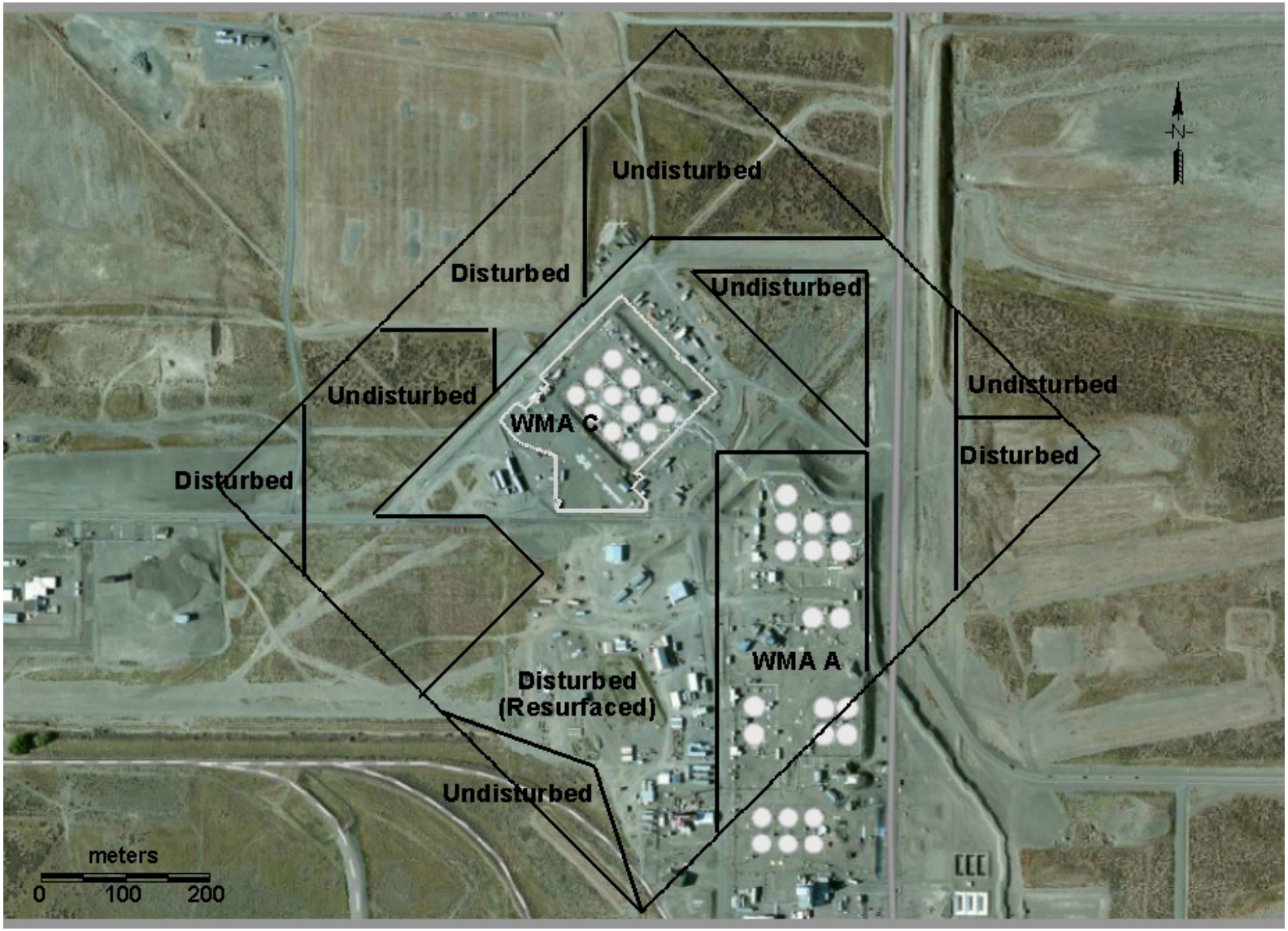
The sensitivity period of analysis extends to 10,000 years. Therefore, impacts to the performance of the vadose zone as a barrier caused by climate change during the evaluation period are plausible. However, climate change is not likely to affect the performance of the vadose zone as a barrier appreciably. Recharge rates applied to the design and post-design periods of the modeling are likely to remain unchanged, even if the precipitation increases as a consequence of climate change. Long-term climate studies (see Section 3.1.2.6, Climate Change) indicate that for the last 10,000 years precipitation ranged from 0% to 50% less than current levels, and ranged between 75% and 128% of modern levels during the glacial period before the Holocene (PNNL-13033). The average annual precipitation (172.2 mm [6.78 in.]) at the Hanford Site for 1981 to 2010 is actually less than the lower end of the range typically associated with sagebrush-dominated ecosystems (200 to 500 mm/yr [7.87 to 19.69 in.], U.S. Department of Agriculture, Natural Resources Conservation Service, Queried 12/18/2015, [Fact Sheets & Plant Guides/*Artemisia tridentata* ssp. tridentata], http://plants.usda.gov/plantguide/pdf/pg_artrt.pdf). Thus, the sagebrush community appears capable of exploiting any increases in soil moisture caused by increases in the annual precipitation consistent with or even in excess of the previous glacial period.

**Pre-operations.** Hydrologic conditions prior to the facility construction (1945) control the initial moisture content and the matric potential in the vadose zone. To estimate the initial conditions, a pre-operations phase is considered, which produces initial moisture conditions for subsequent temporal changes conceptualized at WMA C. A vegetation cover representative of natural conditions is assumed over the whole domain during this period.

**Construction and Operations.** The operations period (current condition) is considered to represent the WMA C construction phase along with operations until closure of the WMA. This period starts in 1945 and is assumed to end in 2020 when a surface barrier is placed over the facility. A distinct recharge rate will be assigned to the following four different zones during this period (Figure 7-16):

- The undisturbed zone around the facility characterized by a native vegetation cover
- The disturbed zone around the facility that has scant, deep-rooted vegetation but extensive grass cover
- The resurfaced zone around the facility that has no vegetation cover
- The WMA A-AX zone that corresponds to the tank farm gravel backfill that is not covered by vegetation
- The WMA C zone that corresponds to the tank farm gravel backfill that is not covered by vegetation.

**Figure 7-16. Surface Conditions In and Around Waste Management Area C during the Construction and Operations Period.**




WMA = Waste Management Area

**Early Post-Closure.** At the end of the construction period, the early post-closure period is considered to represent the time when the modified RCRA C barrier functions according to its design specifications for 500 years according to DOE/RL-93-33. The closure barrier functions to limit the flow of infiltrating moisture into the system by its water storage capacity and built-in engineered capillary breaks. During this period, distinct recharge rates are assigned to five spatially distinct zones (Figure 7-17):

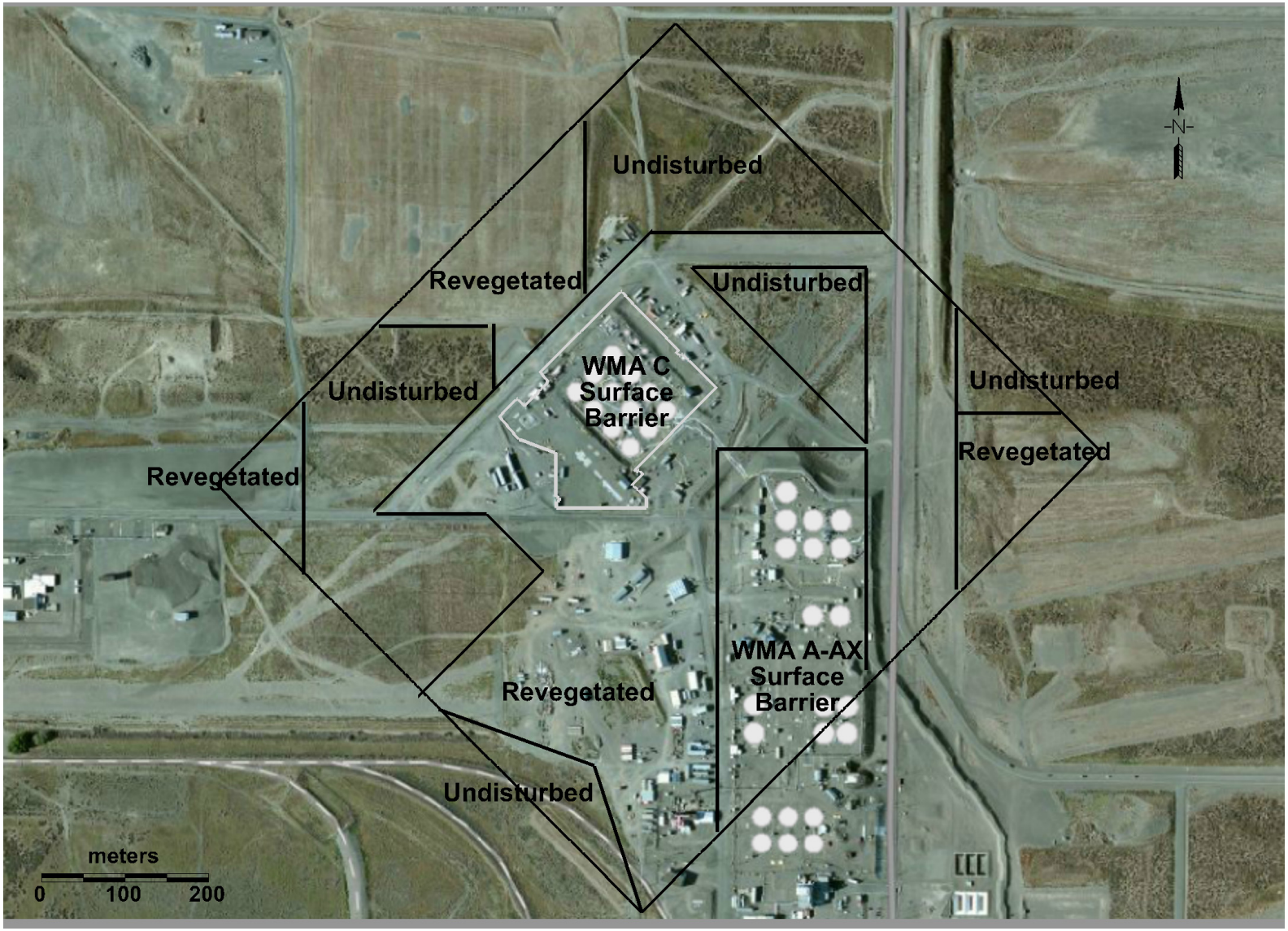
- The undisturbed zone, away from the WMA C surface barrier and the surrounding berm, characterized by an undisturbed native vegetation cover
- The disturbed zone, away from the WMA C surface barrier and the surrounding berm, characterized by an artificially introduced vegetation cover attempting to reclaim the surface with native vegetation species
- The resurfaced zone, away from the WMA C surface barrier and the surrounding berm, characterized by an artificially introduced vegetation cover attempting to reclaim the surface with native vegetation species
- The zone beneath the extent of the WMA A-AX surface barrier that is designed to minimize infiltration of meteoric waters
- The zone beneath the extent of the WMA C surface barrier that is designed to minimize infiltration of meteoric waters.

**Late Post-Closure.** Finally, a late post-closure period is considered to represent the functioning of a degraded surface barrier. This period will start at the end of its assumed design life expectancy of the surface barrier (year 2520) and will continue through the rest of the simulated time period. A distinct recharge rate will be assigned to three different zones during this period (Figure 7-17):

- The undisturbed, disturbed, and resurfaced zones away from the WMA C barrier characterized by undisturbed or reclaimed native vegetation cover
- The degraded WMA A-AX surface barrier fully covered with vegetation that has undergone reclaiming soil and ecological processes
- The degraded WMA C surface barrier fully covered with vegetation that has undergone reclaiming soil and ecological processes.

**7.2.2.1.3 Vadose Zone Beneath Waste Management Area C.** The vadose zone underlying WMA C consists of heterogeneous layers of sedimentary units that vary in thickness at different locations (see Section 3.1.9). The west-east and north-south geologic cross-sections used in WMA C RCA modeling are shown in Figures 7-2 and 7-3, respectively.

**Figure 7-17. Inferred Surface Conditions In and Around Waste Management Area C during the Post-Closure Period.**




WMA = Waste Management Area

Conceptually, and for the purpose of simplification, each heterogeneous sedimentary unit is defined as an equivalent homogeneous media (or EHM) having macroscopic flow properties as discussed in Appendix B. The porous media continuum assumption, an extended form of Darcy-Buckingham Law for vadose zone applications and the soil relative permeability/ saturation/capillary pressure relations provide the basis for vadose zone flow and transport modeling. In the model domain, the hydraulic properties describing flow and transport characteristics associated with each geologic layer are approximated by average up-scaled values. The upscaled hydraulic property values used in the flow and transport model for each EHM are derived from small- and micro-scale (sample) measurements (Appendix B). Each EHM unit thus possesses different flow and transport parameters (hydraulic conductivity, bulk density, and dispersivity). For each heterogeneous hydrostatigraphic unit having spatially variable hydraulic properties, moisture-dependent anisotropy represents the bulk behavior for the EHM ("Application of Stochastic Methods to Transient Flow and Transport in Heterogeneous Unsaturated Soils" [Polmann 1990]). The model thus describes the bulk (or mean) flow and contaminant transport behavior in the vadose zone that is applicable and appropriate to the evaluation and estimation of overall and eventual contaminant impacts to groundwater. Appendix B provides details on the approach for developing the effective (upscaled) flow and transport parameters for the vadose zone.

Features such as clastic dikes, sills, and tectonic structures can allow water and contaminants to bypass vadose zone continuum fate and transport processes. Clastic dikes (subvertical linear features composed of fine-textured sediments), discussed in Section 3.1.4.2.3, Clastic Dikes, do occur in the vadose zone, extend up to tens of meters in length, and crosscut the major layers. Within the Central Plateau, there is little evidence of enhanced transport in these preferential pathways in arid and semiarid climates with low-water flux in the vadose zone, particularly where soils are coarse-grained such as in Hanford formation sediments ("Influence of Clastic Dikes on Vertical Migration of Contaminants at the Hanford Site" [Murray et al. 2007]). While these features may form preferentially faster flow pathways under saturated conditions, under unsaturated flow conditions these features tend to act as barriers to transport. Precipitation at arid sites is usually too low (in relation to saturated hydraulic conductivity) to invoke preferential flow. Much of the water in the dry soils is simply retained on grain surfaces by capillary forces and does not move along preferential pathways (Murray et al. 2007; "Hydrologic Mechanisms Governing Fluid Flow in a Partially Saturated, Fractured, Porous Medium" [Wang and Narasimhan 1985]).

**7.2.2.1.4 Aquifer System Beneath Waste Management Area C.** The integrated, saturated-unsaturated, 3-D WMA C RCA model calculates concentrations of hazardous chemicals in groundwater downgradient of the WMA C fenceline. For these calculations, flow and transport parameters need to be estimated for the unconfined aquifer because, as recharge containing contaminants enters the aquifer, the leachate mixes with groundwater and becomes more dilute. The flow and transport parameters needed for unconfined aquifer calculations are saturated hydraulic conductivity, specific storage, effective porosity, hydraulic gradient, depth to water table, and dispersivity.

A fundamental difference exists as to how the large-scale macroscopic parameters are derived for saturated media versus unsaturated media. First, in a highly heterogeneous flow domain such

as WMA C exists a hierarchy of length scales that needs to be recognized (Appendix C, Figure C-1) and an increase in parameter estimates with an increase in flow domain is noticeable. The evolving heterogeneities at various length scales result in a scale dependence of effective parameters such as saturated hydraulic conductivity and dispersivity. For WMA C RCA saturated media modeling, the flow domain of interest is the "Field Scale," which is shown on the right of Figure C-1. The unconfined aquifer is treated as an EHM, and an equivalent saturated hydraulic conductivity is estimated for the undifferentiated Hanford gravels (Appendix C).

For the large-time, large-scale RCA modeling applications, the macro-scale parameterization for saturated media effective parameters depends on the configuration of the heterogeneous media, as well as the establishment and setup of the local boundary conditions. This is unlike the WMA C vadose zone parameterization wherein the effective parameters at the large and macro scale are derived from properties at the small and micro scale using upscaling methods. Instead, the effective parameterization for WMA C saturated media hydraulic conductivity, for example, is best achieved via a field-scale calibrated groundwater model, which accounts for appropriate local-scale boundary conditions, flow configuration, and history matching. Estimates of hydraulic properties are based on the groundwater flux in the aquifer around WMA C according to the Central Plateau groundwater model calibration reported in CP-47631, "Model Package Report: Central Plateau Groundwater Model Version 6.3.3." Flux is a rate measurement defined as the flow through a defined area. It is well suited for the RCA because the emphasis of its evaluation is the contaminant mass conveyed through the aquifer to a Point of Calculation (PoCal) aligned with the direction of groundwater flow. Thus, the hydraulic property values derived from the calibrated Central Plateau groundwater model fluxes are applied to the WMA C RCA flow model domain.

**7.2.2.1.5 Chemical Transport in the Environment.** The geochemical and sorption conceptual model primarily concerns the movement and retardation of contaminants in the vadose zone. For the RCA analysis, the empirical equilibrium sorption-based approach is assumed to approximate contaminant sorption during transport. The focus of the modeling is on far-field transport, away from WMA C, with the bulk of the residence time of contaminants likely to be in the thick vadose zone. Concentration-dependent sorption/desorption of chemicals, development of reaction fronts from dissolution and precipitation of mineral phases, and variable soil vapor pressures are possible at or very close to the tanks, vault, and pipelines. But away from these structures, due to mixing and continued buffering by mineral-water reactions, residual waste-derived water is expected to become similar to the ambient pore water within a short distance from the base of WMA C. The effluent concentrations from the base of the tank are likely to be so low that they cannot appreciably diminish the thick vadose zone's substantial capacity for sorption and buffering.

The use of the linear isotherm (constant $K_d$ model) is assumed to be generally applicable when: (1) contaminants are present at low concentrations, (2) the geochemical environment being modeled is not affected by large spatial or temporal changes, and (3) the possible sorption sites occupied by the contaminant remain much less than the sorption capacity over the scale of transport. $K_d$ values are chosen assuming low-salt, near-neutral waste chemistry. It is acknowledged that the $K_d$ values used in fate and transport models are effective $K_d$ values

representing the effective combinations of processes contributing to the overall contaminant retardation and/or release behavior. The advantage of the empirical linear adsorption model or $K_d$ approach is that it is easy to implement and generally deemed sufficient for modeling contaminant transport in the far-field through thick sediment column (DOE/RL-2011-50).

**7.2.2.1.6 Summary of Assumptions.** The integrated, saturated-unsaturated, 3-D WMA C RCA model calculates concentrations of chemicals in groundwater downgradient of the WMA C fenceline. For the conceptual model, the following simplifying assumptions were made for the base case:

- WMA C closure occurs in 2020
- Release of hazardous chemicals contained within the grouted residual waste is controlled by the process of diffusion, and remains diffusive with no advection occurring through the tank during the simulated time period of 10,000 years
- The impact of the varying size and shapes of waste material within the grouted tanks and ancillary equipment was ignored
- Moisture flow within the grouted tanks and ancillary equipment is negligible
- Episodic precipitation events and net infiltration through the thick, heterogeneous vadose zone in the 200 Areas can be approximated by an average annual recharge rate
- Impacts resulting from plausible climate change that may occur during the evaluation period do not adversely impact the performance of the surface or vadose zone as a barrier
- The modified RCRA Subtitle C barrier functions according to its design specifications for 500 years
- The impact of the closure barrier on moisture flow was approximated by an assumed recharge rate into the facility
- Flow in the vadose zone occurs in accordance with the porous media continuum assumption
- The hydrostratigraphy of the vadose zone is adequately represented by the delineation of equivalent homogeneous units for evaluating bulk (or mean) flow and contaminant transport
- Vadose zone hydraulic property values upscaled from small- and micro-scale (sample) measurements apply to the field scale for the equivalent homogeneous units
- The inclusion of moisture-dependent anisotropy functions allows the homogeneous hydrostratigraphic units [HSUs] to adequately approximate the effects of heterogeneity

- Features such as clastic dikes, sills, and tectonic structures that can allow water and contaminants to bypass vadose zone continuum fate and transport processes are not consequential to the analysis for estimating impacts due to contaminants left in the tank residuals

- Effective parameterization for WMA C saturated media is best achieved via a field-scale calibrated groundwater model (Appendix C).

### 7.2.3 Exposure Pathways and Scenarios

This section discusses the exposure scenarios that are developed to meet RCRA closure requirements.

To meet RCRA requirements, risk-based calculations are performed using the tap water (resident) scenario. This scenario is used to estimate exposure to both radionuclides and chemicals to a resident receptor who uses the contaminated water from the well located at the PoCal for domestic purposes. Exposure parameters and toxicity values that are used in the equations are obtained from EPA guidance. The receptor is assumed to be exposed to radionuclides and chemicals in groundwater from the following exposure routes:

- Ingestion of tap water

- Inhalation of volatiles (chemicals and radionuclides) while showering and other domestic purposes

- External exposure to immersion in tap water

- Dermal contact with skin while showering and using groundwater for other domestic purposes (such as washing dishes).

Excess lifetime cancer risks for carcinogens and non-cancer hazards for noncarcinogens are calculated. Estimation of intake is based on age-specific ingestion, inhalation and dermal contact rates for children and adults assuming 6-year exposure duration for children and 20-year exposure duration for the adults.

To evaluate protection of water resources, chemical concentrations in groundwater 100 m (328 ft) downgradient from WMA C fenceline are compared to 2007 MTCA risk-based concentrations. Risk-based concentrations are based on equations and exposure assumptions presented in 2007 MTCA WAC 173-340-720, “Groundwater Cleanup Standards” using a target risk level of $1 \times 10^{-6}$ for carcinogens or an HQ of 1 for noncarcinogens.

## 7.3 MATHEMATICAL MODELS

This section presents development and implementation of mathematical models that are used to evaluate flow and chemical transport and long-term human health impacts. Mathematical

models and their implementation into process-level or system-level models are described for the following components of the conceptual model of the closed WMA C facility including 1) source-term and engineered system (Section 7.3.1); 2) chemical transport (Section 7.3.2); and 3) exposure, cancer risk, and non-cancer hazard analysis (Section 7.3.3).

### 7.3.1 Source Term and Engineered Features

The processes associated with the release of contaminants into the pore waters of the material in the tank and ancillary equipment, and their migration from the residual waste matrix through the surrounding engineered barriers, are denoted as the source term in this RCA.

The experimental observation and conceptualizations related to each of these processes have been presented in Sections 6 and Section 7.2.1. The objective of this section is to present the mathematical description of the processes implemented for modeling the release of contaminants from the waste form (source) through the engineered features (tank) to the near-field just outside the tanks and ancillary equipment.

Both mineral phase solubility-limited and matrix degradation rate-limited processes are considered for the key analytes. These have been studied in detail in the laboratory, and the laboratory results have been incorporated in the source term analysis. In particular, the following release model is used, which is based on empirical evidence:

- dissolved concentration limits for chromium.

A matrix degradation rate based release of $^{99}$Tc and a solubility controlled release of uranium is evaluated in the WMA C PA (RPP-ENV-58782, Sections 6.3.1.1 Source Release Model for Technetium-99 and 6.3.1.2 Source Release Model for Uranium).

While the tank (and ancillary equipment) infill material remains intact, it is assumed that releases occur by a diffusion process through the base of the tank base mat, consisting of grout and concrete layers.

For volatiles released from the residual wastes, it is assumed that their transport through the tank infill grout material and the soil overburden is controlled by an upward diffusion process.

In the following subsection of this section, the empirical evidence for the release model for chromium is established. Multi-year leaching studies have been conducted on tank residual samples focused on leaching behavior of chromium. Based on evaluation of the results, models based on solubility control or matrix degradation are implemented in the RCA calculations for chromium, as discussed below. For all other analytes evaluated in this RCA, conservative source-term calculations are performed whereby all of the analytes are assumed to be instantly and completely available in solution within the residual waste volume, and available for an immediate diffusive release.

In the following subsection, the basis is presented for considering diffusive releases for the source term when the tank structure and infill grout material are intact.

**7.3.1.1 Source Release Model for Chromium.** Chromium concentrations in the SPFT leachates for all three leachates are presented in Figure 7-18 for the C-202 and C-203 tank residual waste samples (PNNL-20616, "Contaminant Release from Hanford Tank Residual Waste – Results of Single-Pass Flow-Through Tests"). Results for C-103 tank residuals are not presented because most of the measured concentrations were below the detection limit of 5 ppb. As discussed in Section 5, the chromium concentrations in the $Ca(OH)_2$ leachates are much higher than the DI water and $CaCO_3$ leachates. Cantrell et al. (2013) hypothesized that some chromate may have been co-precipitated with phosphate in $NaUO_2PO_4.xH_2O$. As residual waste is leached with $Ca(OH)_2$, and portions of $NaUO_2PO_4.xH_2O$ are converted to $CaUO_4$, both $PO_4$ and $CrO_4$ are slowly released. The high chromium concentrations observed in the C-202 and C-203 tank leachates are indicative of chromium being released in the form of highly soluble chromate ($CrO_4^{2-}$) or Cr(VI) oxidation state. This is not the case for tank C-103 residual waste. The low concentrations observed in these leachates could be due to chromium being present in the form of a $Cr(OH)_3$-$Fe(OH)_3$ solid solution (PNNL-20616).

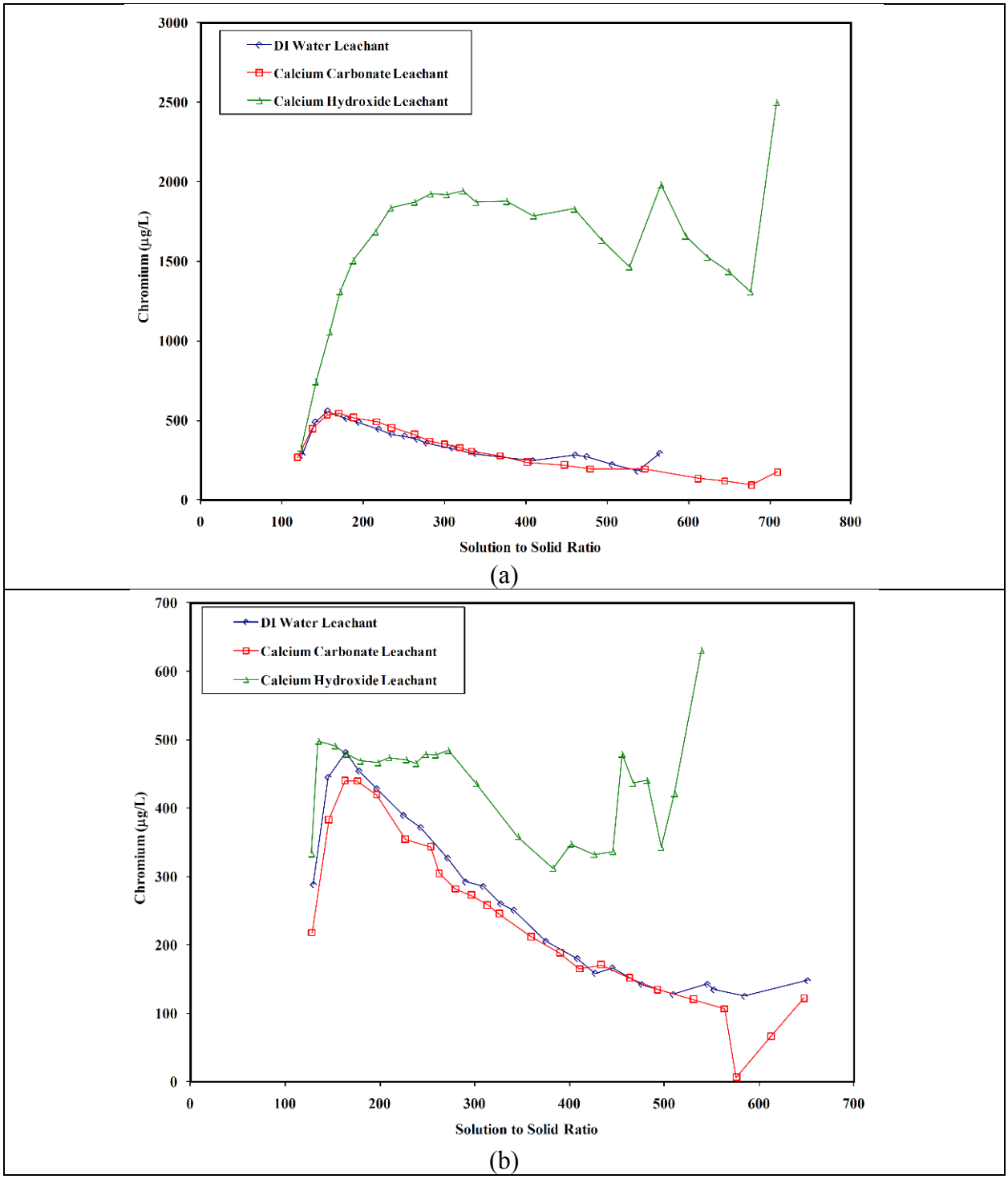
These results indicate large variations in the chromium release characteristics, and perhaps reflect the variability in the chromium present in trivalent and hexavalent oxidation states, along with association with iron oxides/hydroxides. For the purpose of the RCA calculations, a constant high dissolved concentration limit of 2,000 µg/L is imposed. This value is at the high end of observed values in tank C-202 leachate.

**7.3.1.2 Effective Diffusion Coefficient for Transport Through Tank Structure.** Observations of retrieved tanks show that the residual waste is primarily distributed on the tank bottoms (see Section 5.2 of RPP-RPT-42323). Consequently, the residual waste is represented as a uniform layer at the base of the tank. Under the likely scenario, where tank wall integrity is maintained and the infill grout is not physically degraded (Section 7.2.1.2), the primary contaminant transport process will be diffusive. The shortest diffusive pathway for release to the near-field environment is through the base of the tank as presented in Figure 7-19. The diffusive thickness being considered is the 20 cm (8 in.) combined thickness of concrete and grout layer located at the base of the tank (ignoring the steel plate). The aqueous phase diffusive transport will occur along the water phase within the pore spaces of the grout and concrete layer. The effective diffusion coefficient (which includes effects of tortuosity), concentration gradient, and sorption behavior within the grout and concrete layer control the diffusive mass flux.

The effective diffusion coefficient of mobile contaminants (such as $^{99}Tc$) through the combined grout and concrete base mat is considered a key parameter that controls the diffusive flux. Over the past decade, several experiments have been conducted to determine the effective diffusion coefficient through concrete for relatively mobile contaminants under unsaturated conditions. The results of various experiments are presented in PNNL-23841. Of particular interest are the sediment-concrete half-cell experiments conducted in Year 2008 (for a period of 351 days) with $^{99}Tc$ and stable iodine.

Laboratory-scale concrete mixtures were prepared by omitting coarse aggregates and using 40 to 60 mesh size sand instead. The concrete mix prepared consisted of mainly Type I/II sulfate resistant Portland cement (27%), Class F fly ash (4%), sand (51%), and steel fiber (4%). The water-to-cement ratio was 0.5.

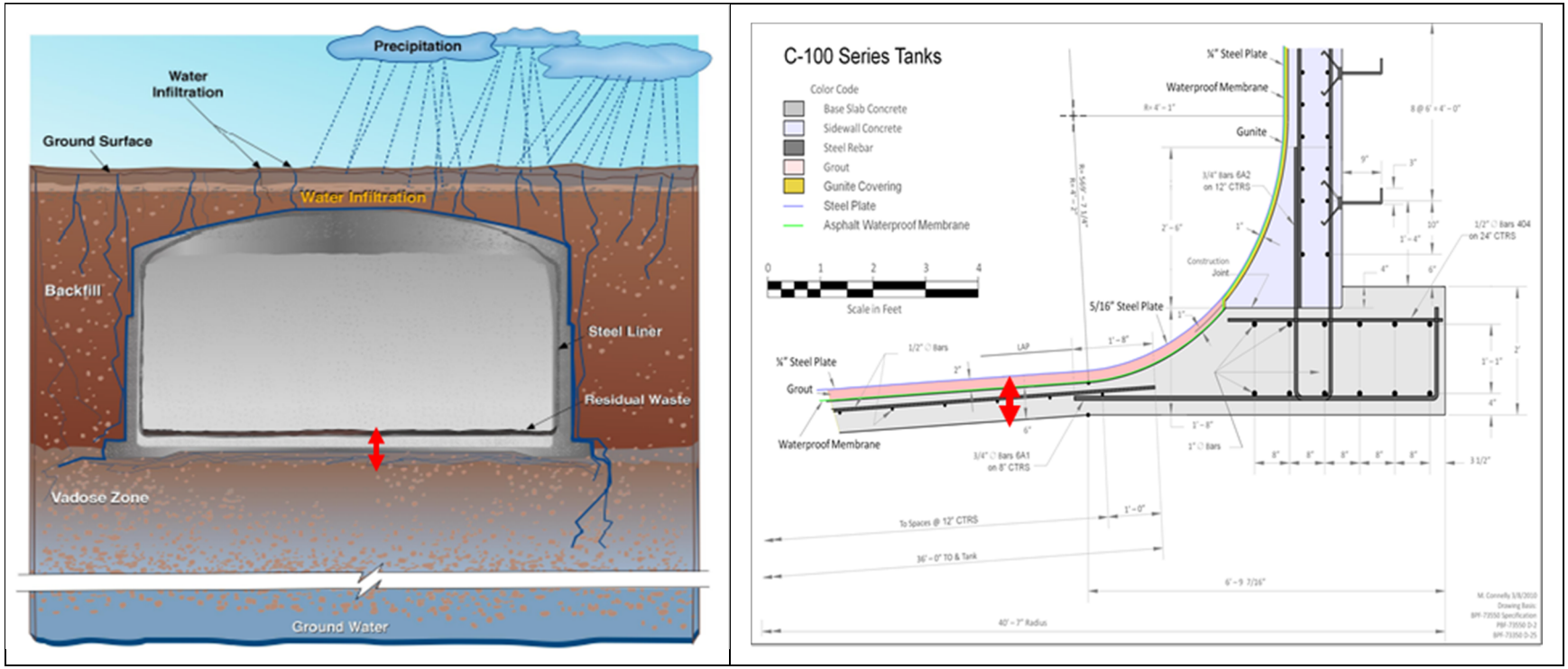
**Figure 7-18. Effluent Concentrations of Chromium (µg/L) from the Single-Pass Flow-Through Experiments Conducted on (a) Tank 241-C-202 and (b) Tank 241-C-203 Residual Waste.**




DI = deionized

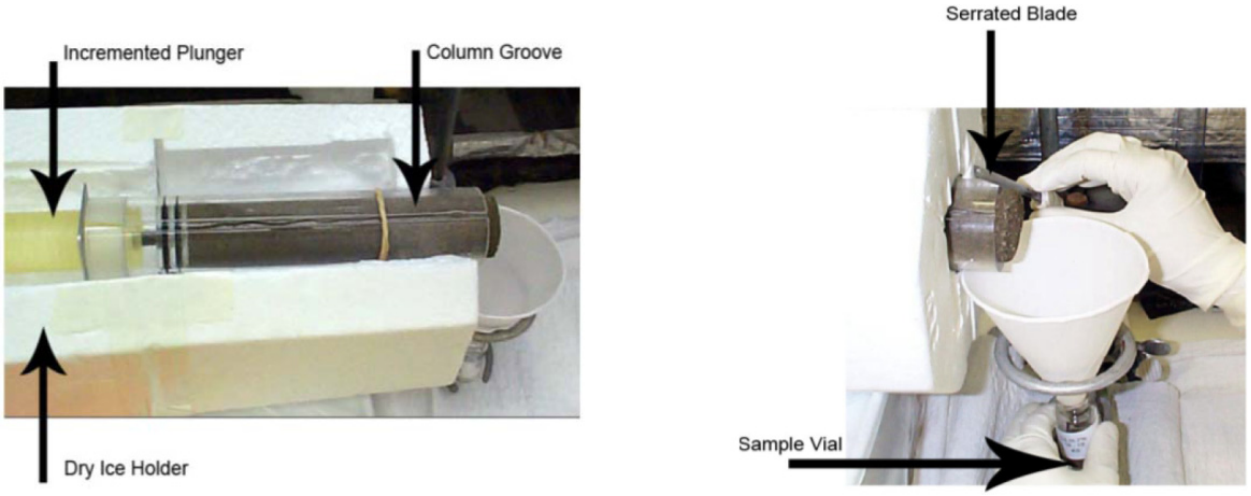
Source: PNNL-20616, "Contaminant Release from Hanford Tank Residual Waste – Results of Single-Pass Flow-Through Tests."

**Figure 7-19. Diffusive Pathway for Transport of Non-Volatile Contaminants to the Near-Field Environment.**



The experiments were conducted using cylindrical cells made of Schedule 40 PVC pipe (Figure 7-20). Caps were machined to fit into both ends of the PVC pipe and fitted with O-rings to minimize moisture loss during the test. For the sediment-concrete half-cells, the cell containing contaminant-spiked sediment was placed in contact with the non-spiked concrete monolith. The diffusion tests were run horizontally and undisturbed, with periodic rotation of the cell by 90 degrees. At the completion of the experiment, the concrete half-cells were sectioned parallel to the sediment-concrete interface. The concrete slices were then ground and two-to-one extracts (due to small sample size) by mass were performed on concrete fractions using the distilled deionized (DDI) water.

**Figure 7-20. Set-Up of the Diffusive Half-Cell Experiment Contacting Contaminant-Spiked Sediment (or Concrete) Sample with the Non-Spiked Sediment (or Concrete) Sample.**




The concentration profiles developed in the concrete are analyzed by fitting the analytical solution to Fick's second law, with the assumption of zero concentration downstream boundary condition, and deriving effective bulk diffusion coefficient for the media. This bulk diffusion coefficient implicitly incorporates the effects of porosity and tortuosity due to diffusion that primarily occurs along the water films in the concrete. For the purpose of modeling mass transport along the water (liquid) phase the effective diffusion coefficient in the water phase is needed (instead of bulk diffusion coefficient), which can be derived by multiplying bulk diffusion coefficient with the moisture content. Since the moisture content of the base mat concrete and grout material is not known and would likely change with time due to slow but steady physical and chemical degradation, the effective diffusion coefficient is chosen conservatively to be the same as the measured bulk diffusion coefficient for the purpose of source-term modeling. In other words, the reduction due to multiplying with moisture content is not applied for calculating the diffusive flux. Note that the effective diffusion coefficient incorporates the effects of tortuosity resulting from transport along water films in the porous media.

Sediment-concrete diffusion experiments were initiated to investigate the effect of sediment moisture, concrete iron content, and concrete carbonation on the diffusivity of $^{99}$Tc from

sediment into concrete (PNNL-23841, Section 4.2.2). Sediment half-cell specimens were spiked with $^{99}$Tc ($4.2 \times 10^{-4}$ mg $^{99}$Tc/g sediment) to achieve a measurable diffusion profile in the concrete part of the half-cell. Hanford fine sand was used for the sediment half-cell. In these experiments, iron content was varied in the concrete specimens from 0% to 12%, sediment moisture content was varied (4%, 7%, or 15%), and half of the concrete monoliths were carbonated prior to preparing the half-cells. Half-cell sampling was conducted at 351 days.

The calculated effective diffusion coefficients of $^{99}$Tc derived from the experimental results are presented in (RPP-ENV-58782, Figure 6-32 and Table 6-4). They range from $6.6 \times 10^{-9}$ cm$^2$/s to $1.6 \times 10^{-7}$ cm$^2$/s ($1.0 \times 10^{-7}$ in.$^2$/s to $2.5 \times 10^{-6}$ in.$^2$/s), with a median value of about $3 \times 10^{-8}$ cm$^2$/s ($4.7 \times 10^{-7}$ in.$^2$/s). Similar experiments using stable iodine (spiked with stable iodine at concentrations of ~7 mg of iodine per gram of sediment) (PNNL-23841, Section 4.1.2) resulted in effective diffusion coefficient that ranged from $1.4 \times 10^{-8}$ cm$^2$/s to $9.7 \times 10^{-8}$ cm$^2$/s ($2.17 \times 10^{-7}$ in.$^2$/s to $1.50 \times 10^{-6}$ in.$^2$/s) with a median value of $2.6 \times 10^{-8}$ cm$^2$/s ($4.03 \times 10^{-7}$ in.$^2$/s). The range of effective diffusion coefficient (and the median value) for iodine in concrete is very similar to that for $^{99}$Tc.

Experiments were also performed to assess the effect of fractures in the concrete on diffusion of $^{99}$Tc and iodine. The derived effective diffusion coefficient ranged from $1.9 \times 10^{-9}$ cm$^2$/s to $2.5 \times 10^{-8}$ cm$^2$/s ($2.94 \times 10^{-8}$ in.$^2$/s to $3.88 \times 10^{-7}$ in.$^2$/s). Similar experiments conducted using stable iodine (spiked at 7 mg per gram of sediment [246.9 oz/ton]) resulted in effective diffusion coefficient that ranged from $4.7 \times 10^{-9}$ cm$^2$/s to $8.4 \times 10^{-8}$ cm$^2$/s ($7.29 \times 10^{-8}$ in.$^2$/s to $1.30 \times 10^{-6}$ in.$^2$/s). These ranges are similar to the ranges calculated for diffusion in the unfractured concrete monolith.

For the purpose of the RCA base case calculations, the experimental median value of $3 \times 10^{-8}$ cm$^2$/s ($4.65 \times 10^{-7}$ in.$^2$/s) is chosen as the best estimate for the effective diffusion coefficient in concrete. This value is applied to all species diffusing through the concrete.

**7.3.1.3 Sorption of Contaminants to Grout and Concrete.** A linear sorption isotherm (using a $K_d$ approach) is considered for determining sorption within the grout and concrete layer for various contaminants as they undergo diffusive (and advective) transport through the tank. The $K_d$ values are presented in Table 7-4 in terms of best estimate and the uncertainty range that are derived from relevant published literature for chemical conditions that are likely to exist within the grout/concrete layer within the tanks.

Development of a sophisticated sorption model depends on the availability of complete sets of experimental data, including measurement of isotherm, and dependence on solid to liquid ratio under conditions that are applicable to the near-field environment. Presently the vast majority of sorption data on cementitious material are based on single-point measurements, and information on uptake mechanisms and uptake controlling phases in cement systems are lacking to a large extent (NAGRA NTB 02-20, "Cementitious Near-Field Sorption Data Base for Performance Assessment of an ILW Repository in Opalinus Clay"). Until studies are performed at the molecular level to discern uptake processes, sorption databases, in conjunction with scientific expertise, can be used to select site-specific sorption values.

**Table 7-4. $K_d$ Values (mL/g) for Grout/Concrete Used for Waste Management Area C RCRA Closure Analysis.**

| Element | Best | Minimum | Maximum | Reference |
|---|---|---|---|---|
| Ac | 1.00E+05 | 3.00E+03 | 3.30E+05 | NAGRA NTB 02-20 |
| Al | 0.00E+00 | 0.00E+00 | 0.00E+00 | No relevant information |
| Am | 1.00E+03 | 2.00E+02 | 5.00E+03 | SKB R-05-75 |
| B | 0.00E+00 | 0.00E+00 | 0.00E+00 | No relevant information |
| C | 2.00E+02 | 1.00E+02 | 4.00E+03 | SKB R-05-75 |
| Cd | 4.00E+01 | 2.00E+00 | 8.00E+02 | SKB R-05-75 |
| Cm | 1.00E+03 | 2.00E+02 | 5.00E+03 | SKB R-05-75 |
| CN | 0.00E+00 | 0.00E+00 | 0.00E+00 | No relevant information |
| Co | 4.00E+01 | 4.00E+00 | 4.00E+02 | SKB R-05-75 |
| Cr | 0.00E+00 | 0.00E+00 | 0.00E+00 | No relevant information |
| Cs | 1.00E+00 | 1.00E-01 | 1.00E+01 | SKB R-05-75 |
| Eu | 5.00E+03 | 1.00E+03 | 2.50E+04 | SKB R-05-75 |
| F | 0.00E+00 | 0.00E+00 | 0.00E+00 | No relevant information |
| Fe | 0.00E+00 | 0.00E+00 | 0.00E+00 | No relevant information |
| H | 1.00E-01 | 7.10E-02 | 1.40E-01 | NAGRA NTB 02-20 |
| Hg | 0.00E+00 | 0.00E+00 | 0.00E+00 | No relevant information |
| I | 3.00E+00 | 3.00E-01 | 3.00E+01 | SKB R-05-75 |
| Mn | 0.00E+00 | 0.00E+00 | 0.00E+00 | No relevant information |
| Nb | 5.00E+02 | 1.00E+02 | 2.50E+04 | SKB R-05-75 |
| Ni | 4.00E+01 | 8.00E+00 | 2.00E+02 | SKB R-05-75 |
| $NO_2$ | 0.00E+00 | 0.00E+00 | 0.00E+00 | No relevant information |
| $NO_3$ | 0.00E+00 | 0.00E+00 | 0.00E+00 | No relevant information |
| Np | 1.00E+02 | 7.10E+01 | 1.40E+02 | NAGRA NTB 02-20 |
| Pa | 1.00E+02 | 7.10E+01 | 1.40E+02 | NAGRA NTB 02-20 |
| Pb | 5.00E+02 | 3.60E+02 | 7.10E+02 | NAGRA NTB 02-20 |
| Pu | 1.00E+02 | 7.14E+01 | 1.40E+02 | NAGRA NTB 02-20 |
| Ra | 5.00E+01 | 5.00E+00 | 5.00E+02 | SKB R-05-75 |
| Rn | 0.00E+00 | 0.00E+00 | 0.00E+00 | No relevant information |
| Se | 6.00E+00 | 1.00E-01 | 4.00E+02 | SKB R-05-75 |
| Sm | 5.00E+03 | 1.00E+03 | 2.50E+04 | SKB R-05-75 |
| Sn | 5.00E+02 | 2.50E+01 | 1.00E+04 | SKB R-05-75 |
| Sr | 1.00E+00 | 5.00E-01 | 5.00E+01 | SKB R-05-75 |
| Tributyl phosphate | 0.00E+00 | 0.00E+00 | 0.00E+00 | No relevant information |
| Tc | 1.00E+00 | 7.10E-01 | 1.40E+00 | NAGRA NTB 02-20 |
| Th | 3.00E+04 | 1.00E+03 | 1.00E+06 | NIROND-TR 2008-23 E |
| U | 2.00E+03 | 1.40E+03 | 2.80E+03 | NAGRA NTB 02-20 |
| Zr | 1.00E+04 | 3.03E+03 | 3.30E+04 | NAGRA NTB 02-20 |

RCRA = Resource Conservation and Recovery Act of 1976

References:

NAGRA NTB 02-20, "Cementitious Near-Field Sorption Data Base for Performance Assessment of an ILW Repository in Opalinus Clay."
NIROND-TR 2008-23 E, "Review of sorption values for the cementitious near field of a near surface radioactive waste disposal facility, Project near surface disposal of category A waste at Dessel."
PSI Bericht Nr. 95-06, "Sorption Databases for the Cementitious Near-Field of a L/ILW Repository for Performance Assessment."
SKB Rapport R-05-75, "Assessment of uncertainty intervals for sorption coefficients SFR-1 uppföljning av SAFE."

As described below, selections for sorption values ($K_d$) have been made based on review of past reports that are focused on developing internally consistent cement sorption databases for cementitious near-field material (hardened cement paste) based on the composition of cement porewaters and stage of cement degradation.

- Conditions in the closed tank farm are expected to be moderately oxidizing, owing to the position of the waste in unsaturated conditions. Where data are available to differentiate between oxidizing and reducing conditions, $K_d$ values under oxidizing conditions are preferentially selected, as it leads to lower $K_d$ values relative to reducing conditions.

- Composition of the cementitious material (grout or concrete) may have different chemical compositions, and therefore differ in contaminant uptake mechanisms and cement phases. Due to lack of information, the differences in sorption between various types of cements and concrete are ignored.

- The selected $K_d$ values are based on assumption of $Ca(OH)_2$ saturated waters contacting the waste, and therefore represent the so-called stage II of the chemical degradation of cementitious material. In this stage, chemical composition of the alkali-depleted cement pore water is controlled by the solubility of portlandite. The impact on $K_d$ values during evolution of chemical conditions from stage I (higher alkali content and pH) to stage II is expected to be minor and incorporated within the uncertainty range.

- The reviews of SKB R-05-75, "Assessment of uncertainty intervals for sorption coefficients, SFR-1 uppföljning av SAFE" and NIROND-TR 2008-23 E, "Review of sorption values for the cementitious near field of a near surface radioactive waste disposal facility, Project near surface disposal of category A waste at Dessel" are more recent, and represent critical reviews and independent data from NAGRA NTB 02-20 and PSI Bericht Nr. 95-06, "Sorption Databases for the Cementitious Near-Field of a L/ILW Repository for Performance Assessment." Where appropriate values are available from these more recent references, they are preferred to the older ones.

- When literature values are absent from these references, a value of zero has been assigned to the analyte. At this stage of the RCA, no attempt has been made to draw chemical equivalences between similar analytes to justify nonzero $K_d$ values. As necessary, the chemical equivalences suggested by SKB R-05-75 may be used to update $K_d$ values.

- When there was significant disagreement between literature sources, the more conservative (lower) $K_d$ value has been chosen. This occurs, for instance, in a preference for NAGRA NTB 02-20 data for oxidizing conditions, compared to values from more recent references.

The $K_d$ values were compared to values used in Savannah River F and H tank farm PAs (WSRC-STI-2007-00369 and WSRC-STI-2007-00607). The values used for WMA C are generally consistent with or more conservative than comparable values used for the

facility-specific grout used at Savannah River. When WMA C values are more conservative, it has been for one of the following two reasons.

- The grout used at Savannah River produces reducing conditions. In the absence of a specific grout formulation for WMA C, it has been assumed that oxidizing conditions will exist in the grout, which leads to lower (more conservative) $K_d$ values for some radionuclides of interest.

- The disposal system at WMA C is very robust with respect to meeting performance objectives. As a result, when data were ambiguous or insufficient in any way, it was more efficient to make a conservative assumption about $K_d$ than to spend resources to resolve the value in greater detail. So, for instance, when data are lacking for a contaminant it is assigned a value of zero.

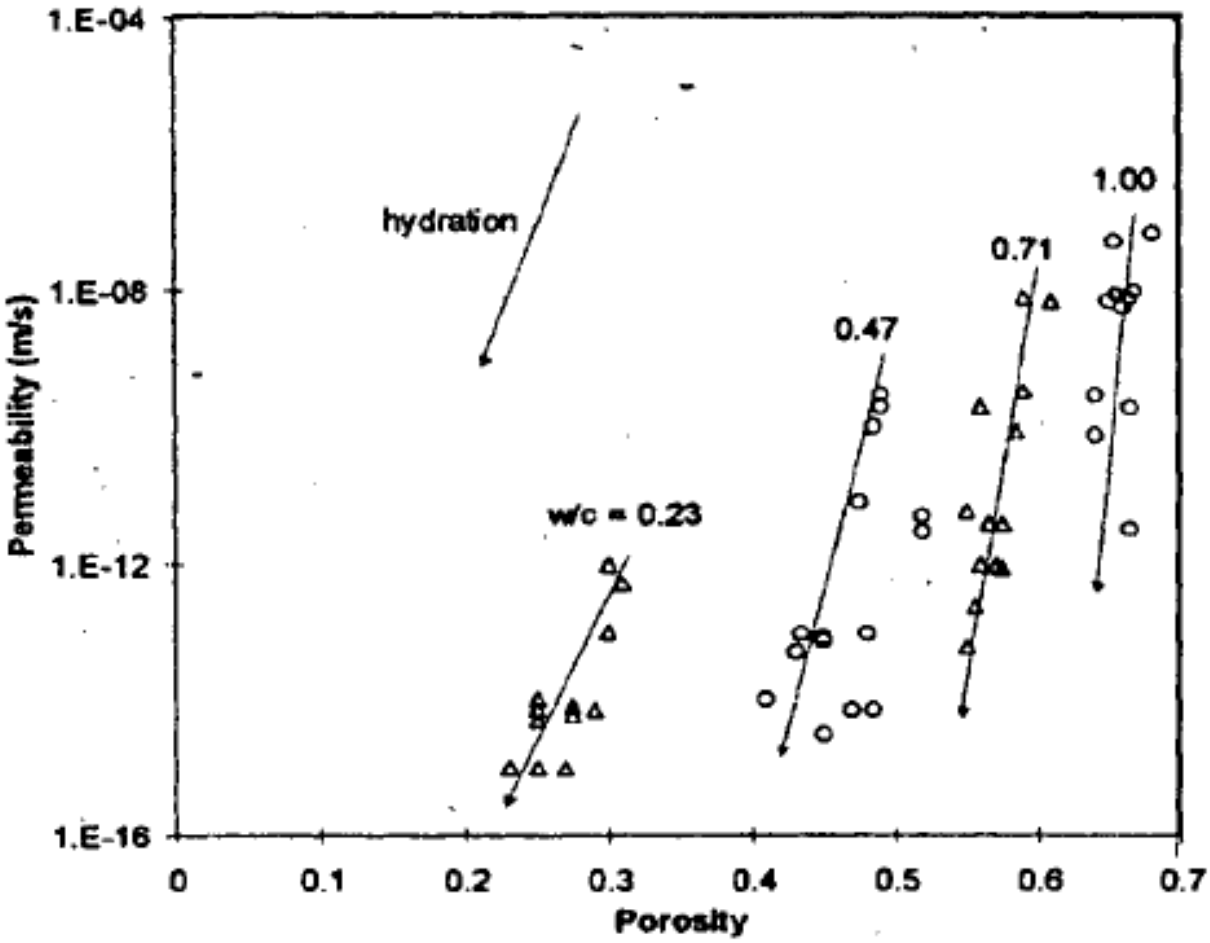
**7.3.1.4 Evaluation of Diffusive Release Assumption for Intact Tank Condition.** Based on the tank infill grout and concrete degradation mechanisms discussed in Section 6.2.1.2, it was determined that tanks are not likely to be fully degraded within the modeled time period of 10,000 years. Due to the unlikely development of continuous fracture pathways within the infill grout over the 10,000 years, advective flow is likely to be very slow, to the extent that it is negligible. Therefore, the primary contaminant transport process will be diffusion (in the aqueous phase), where concentration differences across the grout and concrete tank base mat provide a gradient leading to diffusion. The predominance of diffusion with negligible amount of advection, if any, is based on the following reasoning.

1. The backfill material surrounding the tank structure will provide a preferential pathway for any water infiltrating through the surface cover. Due to large contrast in relative permeability (several orders of magnitude) between gravel-dominated backfill material and grout monolith inside the tank under ambient conditions, most of the infiltrating water is going to flow around and bypass the tank structure.

2. The capillary forces within the grout micropores are much larger than surrounding backfill soil. Therefore, initially when the grout is emplaced in the tank, the grout will wick water from the surrounding material and hold it in place, much like a clay lens within a sand body. With increasing degree of hydration over time that leads to formation of calcium silicate hydrate (C-S-H) gel, the amount of interconnected pore space is known to reduce, and some capillary pores will become discontinuous. This is likely to further reduce the permeability appreciably ("Relationships between permeability and pore structure of hardened cement paste" [Nyame and Illston 1981]) as shown in Figure 7-21.

A numerical simulation of flow around the grouted tank surrounded by backfill material was undertaken to evaluate the relative importance of advective flow. For this analysis, the tank was simplified by assuming that the concrete wall behaved identically to grout in hydraulic properties. The hydraulic properties assigned to the grout were chosen from WSRC-STI-2007-00369 that represented strong grout material. The corresponding characteristic curves are presented in Figure 7-22.

**Figure 7-21. Porosity-Permeability Relationship as a Function of Hydration and Water to Cement Ratio.**

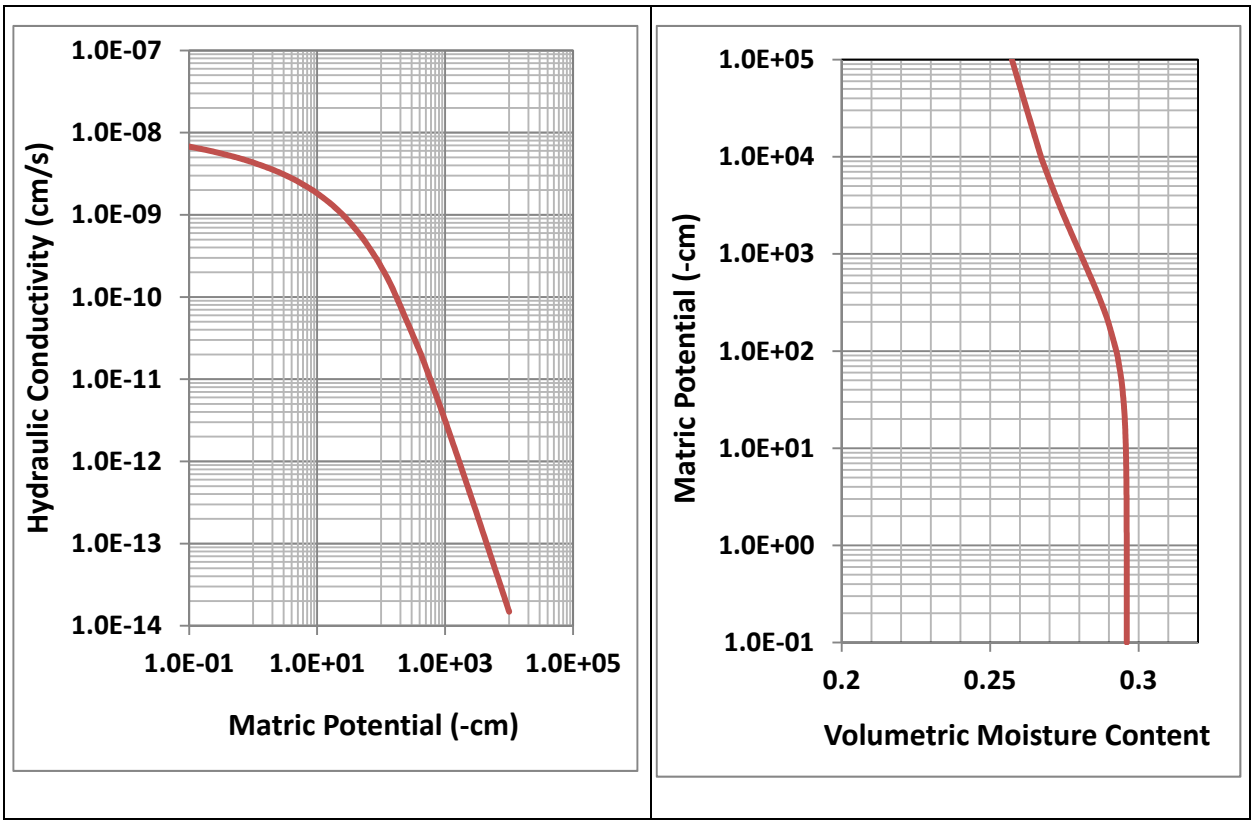



Reference: "Relationships between permeability and pore structure of hardened cement paste" (Nyame and Illston 1981).

The numerical calculations were performed in a two-dimensional (2-D) vertical cross-section for a row of tanks under a 3.5 mm/yr (0.14 in./yr) constant recharge rate (same as the long-term post-closure recharge rate). The transient calculations were performed by setting the initial matric potential for the tank nodes to be -2,000 cm, representing conditions that are between fully saturated and near residual saturations. The 2-D cross-section, along with the long-term near steady-state flow-field, is shown in Figure 7-23. The vertical Darcy flux in the backfill material is orders of magnitude higher than in the tank, consistent with the choice of parameters.

The transient conditions, showing the changing vertical Darcy flux and volumetric moisture content, are presented in Figure 7-24 for two selected nodes: one within the tank, and the other outside in the backfill. These results indicate that the vertical Darcy flux in the grout remains over three orders of magnitude lower than through the backfill. The Darcy flux in the grout is negligibly small for the first few thousand years, and gradually increases as the large capillary suction draws water in, eventually increasing the unsaturated hydraulic conductivity compared to the initial state.

**Figure 7-22. Soil-Moisture Characteristics Curves For the Grout Hydraulic Properties Evaluated.**




To compare the relative importance of advection and diffusion, the dimensionless Peclet number (ratio of advective transport to diffusive transport rate) was calculated for the simulated results at 10,000 years. The characteristic length chosen was 1.25 m (4.1 ft), which is the vertical grid discretization over which the Darcy flux calculations are computed. The Peclet number for transport in the tank is approximately 0.1 while in the backfill it is about 2, indicating that transport through the tank is predominantly diffusion-controlled while transport through the backfill has a higher advective component. During the first 1,000 years, the Peclet number for the tank is close to zero due to negligibly small Darcy flux as shown in Figure 7-24, and increases gradually. Therefore, during the 10,000-year period, it is clear that diffusion dominates transport within the grouted tank; whereas in the backfill, both advection and diffusion play a role in transport.

These analyses support the assumption of diffusion-dominated releases from an intact tank.

**Figure 7-23. Two-Dimensional Cross Section Model to Evaluate the Flow Through the Tanks along with the Flow-Field at Long Time Representing near Steady-State Conditions.**

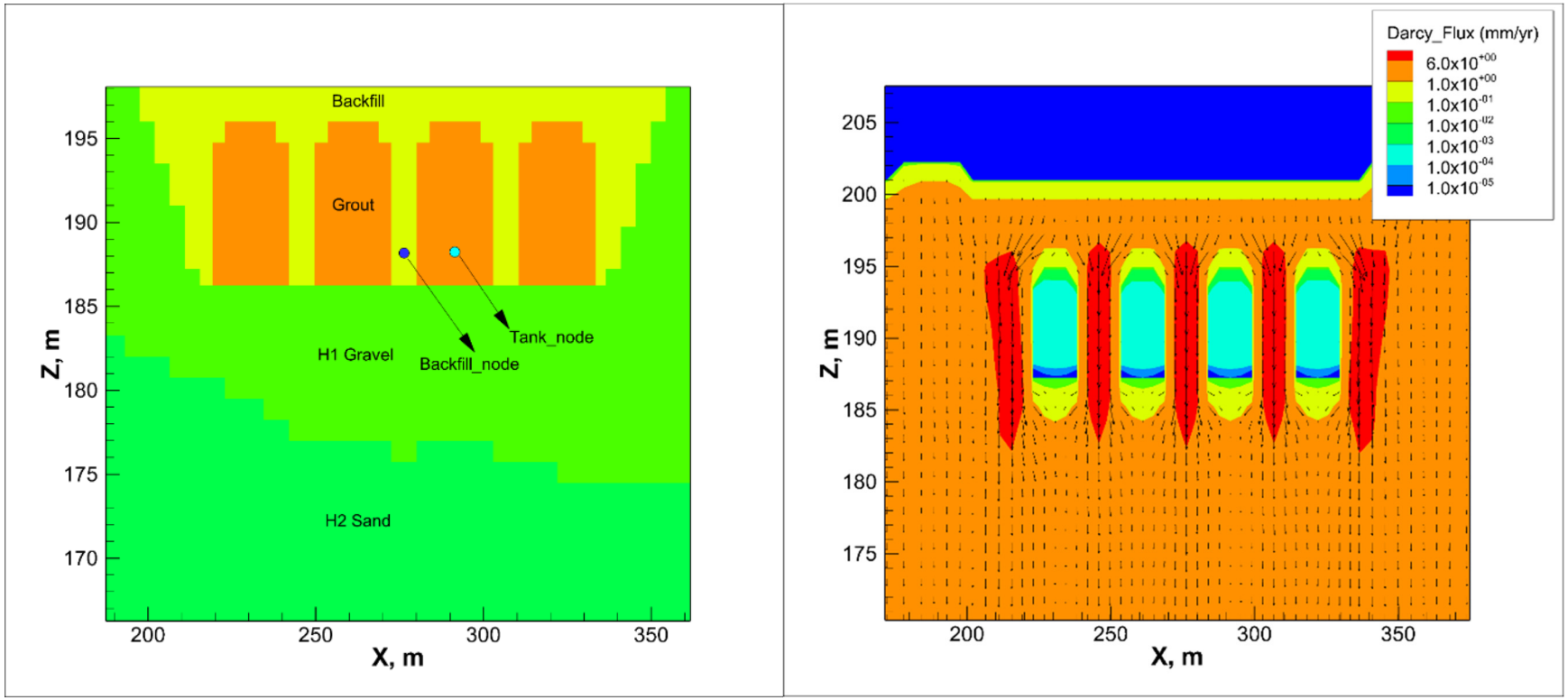
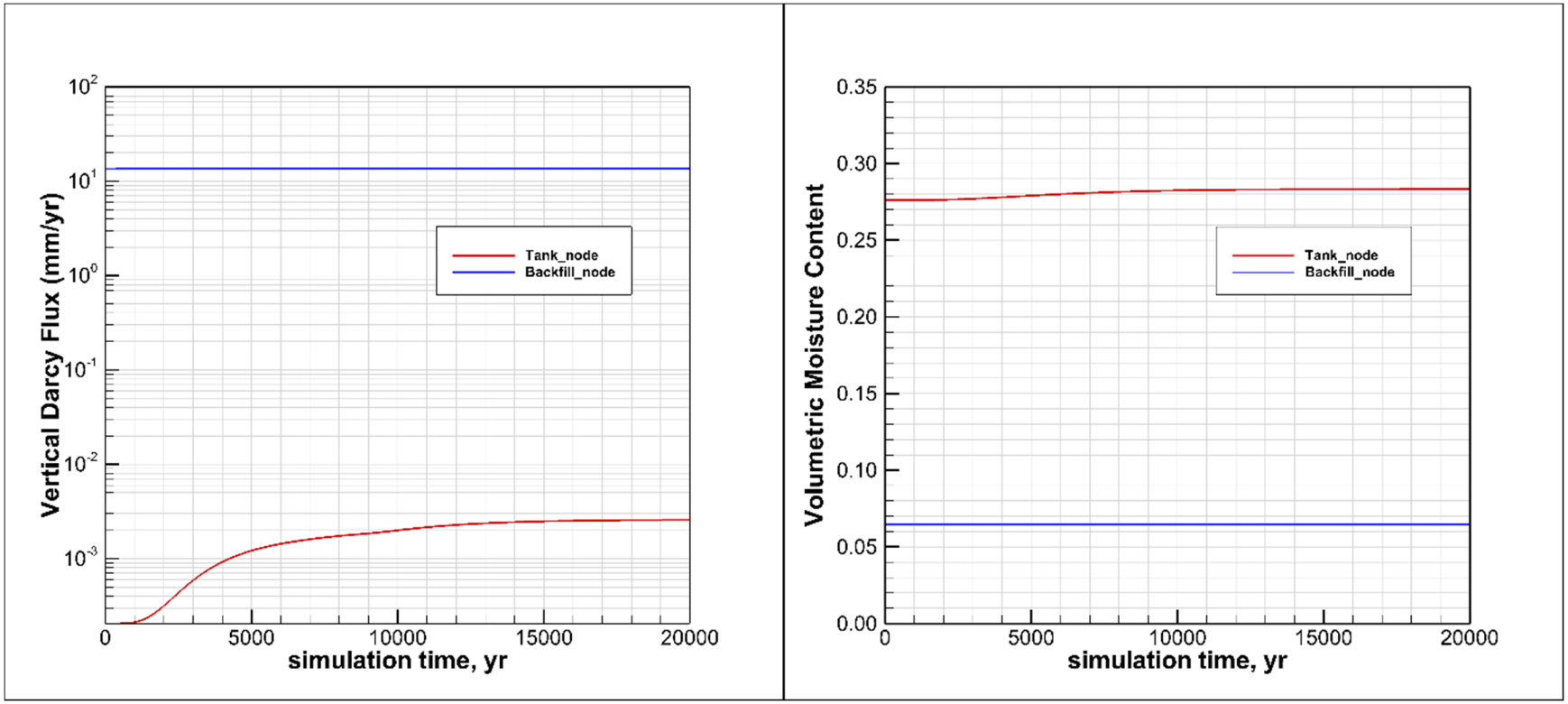


**Figure 7-24. Simulated Vertical Darcy Flux and Volumetric Moisture Content for the Tank Node and Backfill Node over a Large Time Scale.**



**7.3.1.5 Parameters Used in Source Term Calculations.** Following is the list of parameters used in developing source-term release calculations.

| Parameter | Value | Reference |
|---|---|---|
| Porosity of Residual Waste Layer | 0.4 | Assumed |
| Saturation of Residual Waste Layer | 1 | Assumed fully saturated to maximize diffusive release |
| Residual Waste Volume | Variable by source | Section 3.1 |
| Porosity of Concrete and Grout layer below the waste layer | 0.11 | SRNL-STI-2008-00421, Table 39 |
| Porosity of infill Grout within the tank (at closure) | 0.269 | WSRC-STI-2007-00369, Table 29; Strong grout assumed. |
| Saturation of Concrete and Grout layer below the waste layer | 1 | Assumed to maximize diffusive release |
| Bulk Density of Concrete and Grout layer below the waste layer | 2.41 g/cm$^3$ | RPP-RPT-50934, p. C-3 (C-107 dome core density of 2.41 g/cm$^3$ [151 lb/ft$^3$]) |
| Diffusive Length of Waste form layer | 0 m | Assumed to maximize diffusive release |
| Diffusive Length of Concrete and Grout layer below the waste layer | 0.203 m (8 in.) | Minimum diffusive thickness based on tank bottom geometry |
| Diffusive Area for source term release | 410.4 m$^2$ for 100-Series Tanks;<br>29.2 m$^2$ for 200-Series Tanks and C-301 catch tank;<br>162.4 m$^2$ for CR-Vaults;<br>22,500 m$^2$ for Pipelines | Base area for tanks based on circular geometry; area of CR-Vault is based on rectangular area with length of 92 ft and average width of 19 ft; area of Pipeline assumed to be 150 m × 150 m. |
| Effective Diffusion Coefficient through grout and concrete layer (incorporates effects of tortuosity) | $3 \times 10^{-8}$ cm$^2$/s | Section 7.3.1.2 |
| Chromium dissolved concentration limit | 2,000 µg/L dissolved concentration limit imposed | Section 7.3.1.1 |
| Contaminant $K_d$ values for transport through the grout and concrete layer | Variable; See Table 7-4 | Table 7-4 |

| Parameter | Value | Reference |
|---|---|---|
| Release Type | Diffusive release from the tanks and CR-Vaults under intact conditions;<br>Both advective and diffusive release for the Pipelines<br>Both advective and diffusive release for tanks and CR-Vaults under degraded conditions | |

References:
RPP-RPT-50934, "Inspection and Test Report for the Removed 241-C-107 Dome Concrete."
SRNL-STI-2008-00421, "Hydraulic and Physical Properties of Saltstone Grouts and Vault Concretes."
WSRC-STI-2007-00369, "Hydraulic and Physical Properties of Tank Grouts and Base Mat Surrogate Concrete for FTF Closure."

**7.3.1.6 Source-Term Mathematical Model.** The source-term model is implemented in GoldSim© using its Contaminant Transport Module. The Contaminant Transport Module allows the user to dynamically model mass transport using a compartment-based model of the system. The Contaminant Transport Module includes the following key features (GoldSimTechnology Group 2014a).

- Specialized elements in GoldSim© called Source and Cells are available to model key release mechanisms from source term that include waste form degradation rate and solubility control.

- Both advective and diffusive transport mechanisms can be explicitly represented using the "Cell" pathway element, by specifying the flow rates for advective transport and the diffusion coefficient and geometric factors for diffusive transport. Media properties through which advection and diffusion occur also need to be specified.

- When multiple Cells are linked together via advective and diffusive mechanisms, the behavior of the Cell network is mathematically described using a coupled system of ordinary differential equations in time. A network of Cells is mathematically equivalent to a finite difference network of nodes. GoldSim© numerically solves the coupled system of equations to compute the contaminant mass present in each Cell and the mass fluxes between Cells as a function of time. The solution technique uses backwards-difference (fully implicit) algorithm for each cell-net and each species decay-chain family.

The basic mass balance equation for Cell *i* is as follows:

$$m'_{is} = -m_{is}\lambda_s + \sum_{p=1}^{NP_s} m_{ip}\lambda_p f_{ps} R_{sp}\left(\frac{A_s}{A_p}\right) + \sum_{c=1}^{NF_i} f_{cs} + S_{is} \qquad (7\text{-}1)$$

Where:

$m'_{is}$ = rate of increase of mass of species s in Cell i (M/T)
$m_{is}$ = mass of species s in Cell i (M)
$\lambda_s$ = decay rate of species s ($T^{-1}$)

$NP_s$ = Number of direct parents for species s
$f_{ps}$ = fraction of parent p which decays into species s
$R_{sp}$ = stoichiometric ratio of moles of species s produced per mole of species p decayed
$A_s$ = molecular (or atomic) weight of species s (M/mol)
$A_p$ = molecular (or atomic) weight of species p (M/mol)
$NF_i$ = number of mass flux links from/to Cell i
$f_{cs}$ = influx rate of species s (into Cell i) through mass flux link c (M/T)
$S_{is}$ = rate of direct input of species s to Cell i from external source (M/T).

The first term on the right-hand side in Equation 7-1 represents decay (or chemical reaction), the second term represents ingrowth, the third term represents mass transfer in or out of the Cell via mass flux links, and the fourth term represents the rate of direct input to the Cell from other sources.

Equation 7-1 couples in two ways to other mass balance equations: 1) through the ingrowth terms, which couple all species in a decay chain; and 2) through the mass flux terms, which couple all Cells that are connected by mass flux links. Representation of the mass flux terms ($f_{cs}$) is the most complex part of the above equation, and is described in detail below in terms of advective mass flux and diffusive mass flux.

Advective mass flux from Cell i to Cell j for species s is computed as follows:

$$f_{s,i\rightarrow j} = c_{ims}\, q \tag{7-2}$$

Where:

$q$ = the rate of advection of water for the mass flux link i to j ($L^3/T$)
$c_{ims}$ = the total dissolved concentration of species s in medium m within Cell i ($M/L^3$).

Diffusive mass flux links are used to transport mass through a stagnant or slowly moving fluid via the process of molecular diffusion. Diffusive mass transport is proportional to a concentration difference, with mass diffusing from high concentration to low concentration. The constant of proportionality is referred to as the diffusive conductance:

Diffusive Mass Rate = (Diffusive Conductance) × (Concentration Difference)

In this equation, the Diffusive Mass Rate has dimensions of mass/time, the Diffusive Conductance has dimensions of volume/time, and the Concentration Difference has dimensions of mass/volume. Diffusive Conductance is a function of the properties of the species and fluids involved and the geometry of the diffusive process. For diffusion through a single fluid, the Diffusive Conductance for species s ($D_s$) is computed as:

$$D_s = \frac{(A\, d\, \tau\theta)}{L} \tag{7-3}$$

Where:

$A$ = mean cross-sectional area of the connection ($L^2$)
$d$ = free-water diffusivity of species s
$\tau$ = tortuosity of continuous liquid film in the porous medium
$\theta$ = moisture content (porosity times saturation)
$L$ = diffusive length.

The diffusive flux $f_s$ from pathway i to pathway j is computed as follows:

$$f_{s,i\rightarrow j} = D_s(C_{ims} - C_{jms}) \tag{7-4}$$

Where $C_{ims}$ and $C_{jms}$ are the dissolved concentrations of species s for medium m in Cell i and j.

The diffusion can occur in either direction, so the flux can be positive or negative. When media properties are changing for diffusive release calculation, such as when diffusion occurs between tank wall concrete layer and the surrounding soil, the diffusive conductance is calculated using a harmonic average of the physical properties of the two cell pathways as follows:

$$D_s = \frac{A}{\frac{L_i}{d_{msi}\theta_i\tau_{Pi}} + \frac{L_j}{d_{msj}\theta_j\tau_{Pj}}} \tag{7-5}$$

Where:

$A$ = the area of the diffusive mass flux link ($L^2$)
$L_i$ = diffusive length for the diffusive mass flux link in Cell i (L)
$L_j$ = diffusive length for the diffusive mass flux link in Cell j (L)
$d_{msi}$ = free-water diffusivity of species s for fluid m in Cell i ($L^2$/T)
$d_{msj}$ = free-water diffusivity of species s for fluid m in Cell j ($L^2$/T)
$\tau_{Pi}$ = tortuosity for the porous medium for Cell i
$\tau_{Pj}$ = tortuosity for the porous medium for Cell j
$\theta_i$ = moisture content of porous media in Cell i
$\theta_j$ = moisture content of porous media in Cell j.

When mass enters a Cell, it is instantaneously partitioned among the media present in the Cell. The partitioning is controlled by the partition coefficients defined for each species in each medium, and the quantity of each medium present. In the absence of solubility limits, the concentration of the species s in medium m in Cell i is computed by GoldSim© as follows:

$$C_{ims} = \left(\frac{K_{mrs}}{\sum_{g=1}^{NM_i} K_{grs}.VM_{ig}}\right) m_{is} \tag{7-6}$$

Where:

$C_{ims}$ = concentration of species s in medium m in Cell i ([M/L$^3$] for Fluids or [M/M] for solids)
$m_{is}$ = mass of species s in Cell i (M)
$K_{mrs}$ = partition coefficient between medium m and Reference Fluid r for species s (L$^3$/L$^3$) for Fluids or (L$^3$/M) for Solids
$K_{grs}$ = partition coefficient between medium g and Reference Fluid r for species s (L$^3$/L$^3$) for Fluids or (L$^3$/M) for Solids
$VM_{ig}$ = quantity (volume or mass) of medium g in Cell i (L$^3$ for Fluids or M for Solids)
$NM_i$ = the number of media in Cell i.

When a solubility constraint is applied for a species in a Cell, the Cell has a saturation capacity with respect to that species, which represents the maximum amount of species mass the Cell can contain before the species will start to precipitate out of solution. It is calculated as:

$$msat_{is} = sol_{sr} \sum_{g=1}^{NM_i} K_{grs}.VM_{ig} \tag{7-7}$$

Where:

$msat_{is}$ = saturation capacity for species s in Cell i (M)
$sol_{sr}$ = solubility of species s in the Reference Fluid r (M/L$^3$)
$K_{grs}$ = partition coefficient between medium g and Reference Fluid r for species s ([L$^3$/L$^3$] for Fluids or [L$^3$/M] for Solids)
$VM_{ig}$ = quantity (volume or mass) of medium g in Cell i (L$^3$ for Fluids or M for Solids)
$NM_i$ = the number of media in Cell i.

### 7.3.2 Chemical Transport

This section provides the detailed methods of analysis for the transport of chemicals for the hydrologic (groundwater) and biotic transport pathways.

**7.3.2.1 Process-Level Model Based on STOMP© Flow and Transport Simulator.** The WMA C RCA groundwater pathway modeling makes use of detailed process-level numerical models based on the STOMP© code, which was used to simulate 3-D flow and contaminant transport through the vadose zone and unconfined aquifer system. To calculate water flow, the STOMP©-based numerical model includes the assumption that the vadose zone and unconfined aquifer system can be represented and approximated by an equivalent porous continuum. The STOMP©-based numerical model solves a conservation of mass equation using a finite difference approximation to the matric potential form of the Richards' equation (Soil Physics, 6th edition [Jury and Horton 2004]) that calculates fluid flow entering, exiting, and accumulating within the finite numerical volumes as follows:

$$C(h)\frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left[K(h)\frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial y}\left[K(h)\frac{\partial h}{\partial y}\right] + \frac{\partial}{\partial z}\left[K(h)(\frac{\partial h}{\partial z} + 1)\right] \pm S \tag{7-8}$$

Where:

| | | |
|---|---|---|
| $h$ | = | matric potential $h = h(x,y,z,t)$, $t=time$ |
| $C(h) = d\theta/dh$ | = | specific moisture capacity, $C$ for a given $h$, and is equal to $d\theta/dh$, i.e., the inverse slope of the matric potential-moisture content, $\theta$, relation (cm) |
| $K(h)$ | = | the hydraulic conductivity (cm/s), which may be anisotropic and is dependent on matric potential |
| $S$ | = | the amount of water added (source) or subtracted (sink) per unit volume through time (1/s). |

Moisture content is a function of soil matric potential, and the soil matric potential-moisture retention relationship is described for each HSU using the following empirical relationship ("A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils" [van Genuchten 1980]; EPA/600/2-91/065, The RETC Code for Quantifying the Hydraulic Functions of Unsaturated Soils):

$$\theta(h) = \theta_r + (\theta_s - \theta_r)\{1 + [\alpha h]^n\}^{-m} \tag{7-9}$$

Where $\theta(h)$ is the moisture content, here expressed explicitly as a function of the soil matric potential, and the other terms are defined as follows:

| | | |
|---|---|---|
| $\theta_r$ | = | residual moisture content (dimensionless) |
| $\theta_s$ | = | saturated moisture content (dimensionless) |
| $\alpha$ | = | a fitting parameter ($cm^{-1}$) |
| $n$ | = | a fitting parameter (dimensionless) |
| $m$ | = | $1 - 1/n$. |

Combining the van Genuchten model with Mualem's (1976) model ("A New Model for Predicting the Hydraulic Conductivity of Unsaturated Porous Media") for unsaturated conductivity produces the following relationship for hydraulic conductivity and soil matric potential:

$$K(h) = \frac{K_s\{1-(\alpha h)^{mn}[1+(\alpha h)^n]^{-m}\}^2}{[1+(\alpha h)^n]^{ml}} \tag{7-10}$$

Where $K(h)$ is the hydraulic conductivity (cm/s), which is, as expressed, dependent on the soil matric potential; $K_s$ is the saturated hydraulic conductivity (cm/s); and $l$ is a pore-connectivity parameter (dimensionless) that Mualem (1976) estimates to be about 0.5 for many soils and is assumed to equal 0.5 in this analysis.

Within the STOMP© code, tension-dependent anisotropy provides a framework for upscaling small-scale measurements to the effective (upscaled) properties for the large-scale vadose zone (Section 7.4 and Appendix B). Each heterogeneous geologic unit is represented in the model by an EHM with macroscopic flow and transport properties. With each heterogeneous unit assigned its upscaled or effective hydraulic properties, the simulated flow fields predict the bulk or mean flow behavior at the field scale. Upscaling, in effect, accounts for the differences in scale between small, core-scale measurements and large, field-scale modeling. Tension-dependent

anisotropy provides a framework for upscaling small-scale measurements to the effective (upscaled) properties for the large-scale, macroscopic vadose zone. The stochastic model developed in Polmann (1990) is used to evaluate and apply tension-dependent anisotropy for the hydrostatrigraphic units at WMA C. Details about the development of the Polmann stochastic tension-dependent anisotropy model and its application to the hydrostatrigraphic units at WMA C are presented in Appendix B, Section B.3.2. Figures B-19 through B-21 in Appendix B illustrate the relationship between the matric potential and the resulting anisotropy.

Contaminant transport within the STOMP© code is described by the conventional advective-dispersive transport solution to the conservation of mass equation described in Jury and Horton (2004) and applied to finite difference volumes:

$$\frac{\partial}{\partial t} M_c = \frac{\partial}{\partial \mathrm{x}}\left(D_e \frac{\partial C_l}{\partial \mathrm{x}}\right) + \frac{\partial}{\partial \mathrm{y}}\left(D_e \frac{\partial C_l}{\partial \mathrm{y}}\right) + \frac{\partial}{\partial \mathrm{z}}\left(D_e \frac{\partial C_l}{\partial \mathrm{z}}\right) - \frac{\partial}{\partial \mathrm{x}}(J_x\, C_l) - \frac{\partial}{\partial \mathrm{y}}(J_y\, C_l) - \frac{\partial}{\partial z}(J_z\, C_l) \tag{7-11}$$

Where:

| | | |
|---|---|---|
| $\frac{\partial}{\partial t} M_c$ | = | the change in contaminant mass or activity present in the finite volume (g) through time and the mass or activity is calculated according to the equation ($\rho_b\, C_a + \theta\, C_l$) |
| $\rho_b$ | = | soil bulk density (g/cm$^3$) |
| $C_a$ | = | adsorbed solute concentration (g per g soil) |
| $\theta$ | = | moisture content (dimensionless), and as discussed previously, dependent on the soil matric potential |
| $C_l$ | = | dissolved solute concentration (g per cm$^3$ water) |
| $J_x, J_y, J_z$ | = | water or moisture flux (cm/s) along the x, y, and z directions, respectively |
| $D_e$ | = | effective dispersion/diffusion coefficient (cm$^2$/s); note that the entire terms represent the flux of solutes that crosses the planes normal to the x, y, and z directions, respectively, because of diffusion and dispersion |

In Equation 7-11, positive is used to indicate solute entering the finite volume, and negative is used to indicate what is exiting or lost to decay. The adsorbed and dissolved solute concentrations are related through an equilibrium linear sorption coefficient ($K_d$ mL water per g soil) formulation: $C_a = K_d\, C_l$. No temperature effects are considered for the vadose zone model (i.e., the model used is isothermal).

**7.3.2.2 STOMP©-Based Process Level Model Implementation of the Groundwater Pathway.** This section describes the details of the implementation of the STOMP©-based process level model used in the WMA C RCA for evaluation of the groundwater pathway. The descriptions presented in this section primarily address the development of the conceptual model components and base case parameters. The discussion includes the alternative geologic interpretations evaluated as part of the sensitivity analysis because those interpretations involve uncertainty in a conceptual model component. Parameter sensitivity is addressed in Section 9. DOE/RL-2011-50 contains the description of the generalized models, conditions, and parameters

applicable to the Hanford Site vadose zone, which were refined and augmented for the WMA C RCA evaluation.

The site-specific STOMP© model components for the WMA C RCA evaluation are:

- Model domain and boundary conditions
- Geologic setting
- Source term
- Recharge
- Vadose zone hydrogeology and fluid transport
- Groundwater domain and characteristics
- Geochemistry.

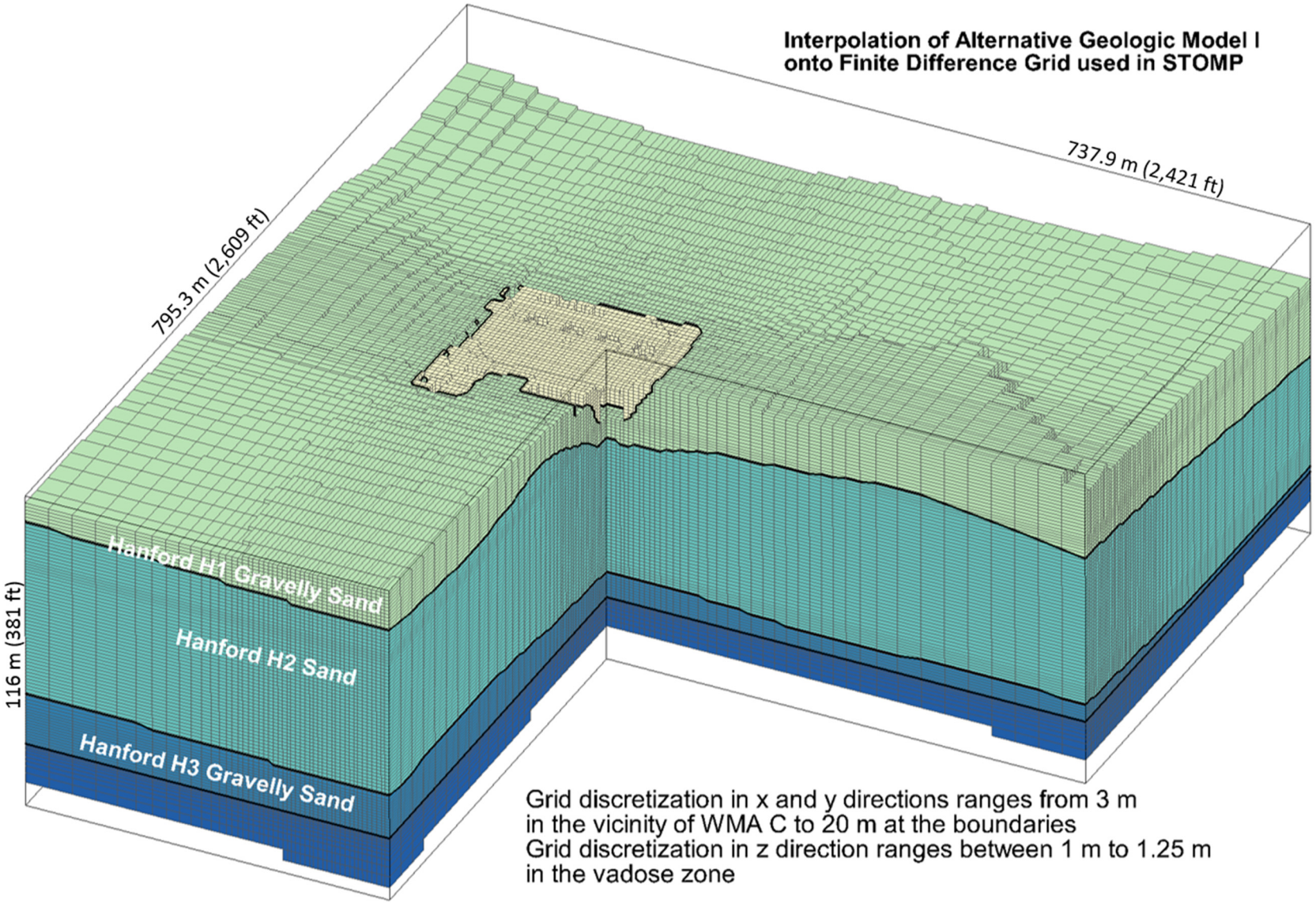
The model domain and boundary conditions are included in the list above to emphasize the fundamental nature of boundary conditions used in the modeling. The evaluation adopted modeling assumptions and parameter estimates for WMA C site-specific conditions to determine the impacts to groundwater resulting from post-retrieval residual waste remaining in tanks, ancillary equipment, and pipelines.

The following subsections for the individual conceptual model components provide the basis, rationale, and references for the base case values. These parameters represent the values selected for use in the model from the ranges of plausible parameter values. These values may differ from parameter estimates for other Hanford Site modeling performed for different purposes or areas of the Hanford Site, or at different scales.

**7.3.2.2.1 Model Domain and Boundary Conditions.** The model domain and boundary conditions establish both a framework and limiting conditions for the numerical model. The model domain for flow and transport in the vadose zone is represented numerically in 3-D space, with one of the horizontal axes aligned in the general direction of groundwater flow. Aligning an axis with the general direction of groundwater flow allows concentrations to be calculated more easily downgradient of the waste sites. The numerical model adapts the physical elements of the conceptual model to a Cartesian grid, and also assigns numerical values to the parameters used in algorithms to represent the physical and geochemical systems and processes.

The WMA C model domain is 737.9 m (2,421 ft) northwest to southeast by 795.3 m (2,609 ft) southwest to northeast by 116 m (381 ft), vertically, extending about 12 m (49 ft) below the water table (Figure 7-25). The southwestern and northwestern boundaries of the model are 574656.09 m, 136454.41 m, and 575218.45 m, 137016.78 m, respectively (Lambert Coordinate system easting, NOAA Manual NOS NGS 5, “State Plane Coordinate System of 1983”). The southeastern and northeastern boundaries are 575177.86 m, 135932.64 m, and 575740.22 m, 136495.00 m, respectively. The vertical base elevation of the model is nominally 95 m (312 ft) (North American Vertical Datum of 1988 [NAVD88]), although the bottom and top of the model domain vary spatially according to the top of basalt elevation and surface relief, respectively (RPP-RPT-56356).

**Figure 7-25. The Interpolated Numerical Three-Dimensional Post-Closure Alternative I Hydrogeologic Model.**




STOMP = Subsurface Transport Over Multiple Phases (computer code) WMA = Waste Management Area

The horizontal node spacing varies between 3.0 and 20 m (9.8 and 65.6 ft) to optimize the discretization in the areas attempting to approximate the slopes associated with construction of WMA C and the 100-series tanks without overwhelming the available computational resources. Figure 7-26 shows the plan view distribution of the calculation nodes. The vertical spacing in the vadose zone ranged between 1 and 1.25 m (3.28 and 4.10 ft) except around the water table, where the spacing decreased to 0.5 m to capture the impact of the capillary fringe above the water table. The total number of nodes in the modeled rectangular prism equals 736,653. During the pre-operational phase, the number of active nodes equals 640,565 with 96,088 inactive. Inactive nodes represent space where no flow occurs, e.g., above ground surface, within basalt, or within intact tanks. During the operational and post-closure phases, the number of active nodes equals 637,543 with 99,110 inactive, the increase in inactive nodes attributed to the inactivation of the tank and ancillary equipment nodes within the WMA C excavation.

A specified-flux boundary condition was applied at the surface to simulate recharge. Recharge rates varied spatially and temporally along the upper boundary, depending on surface conditions, the presence of WMA C and other facilities, and the time of WMA C operations and surface conditions simulated (RPP-RPT-44042). The bottom boundary of the unsaturated (vadose) zone is the water table, and the bottom of the model (aquifer) was defined as a no-flow boundary condition. Boundary conditions at the sides of the model domain were assumed to be no flow in the vadose zone and prescribed flux and prescribed head in the aquifer on the upgradient and downgradient boundaries, respectively.

The boundary condition in the aquifer on the upgradient boundary was assumed to be prescribed flux, calculated on the basis of the hydraulic conductivity and gradient, and independent of recharge. The prescribed flux boundary condition value includes a factor to account for the varying thickness of the unconfined aquifer and uneven surface of the underlying basalt. To account for the non-uniform aquifer thickness from the underlying basalt boundary, the nominal flux rate was calculated as the product of the hydraulic conductivity and gradient (base case values of 11,000 m/day [6.8 mi/day] and $2.0 \times 10^{-5}$ m/m [$6.6 \times 10^{-5}$ ft/m], respectively; see the upcoming "Groundwater Domain and Characteristics" discussion and Appendix C for the basis of these parameter estimates), and was proportioned according to the ratio of the average aquifer cross-sectional area throughout the model domain (9,440 $m^2$ [2.3 acres]) and the aquifer area along the southwest-northwest boundary (6,151 $m^2$) where the prescribed flux is applied. The aquifer cross-sectional area refers to the area perpendicular to the direction of groundwater flow. The aquifer cross-sectional area varies from the northwest to southeast boundaries because of the uneven top of the basalt.

**7.3.2.2.2 Hydrogeologic Model.** The hydrogeologic conceptual model developed for the WMA C RCA (RPP-RPT-46088 and RPP-RPT-56356) provides the information basis and data necessary to prepare the 3-D geologic inputs used in the 3-D numerical model. Each node in the numerical model represents a unique set of horizontal (x and y) coordinates and vertical (z) elevation. A node is assigned the hydrogeologic properties associated with the HSU identified in the RPP-RPT-56356 geologic models as existing in the space represented by the node coordinates and elevation.

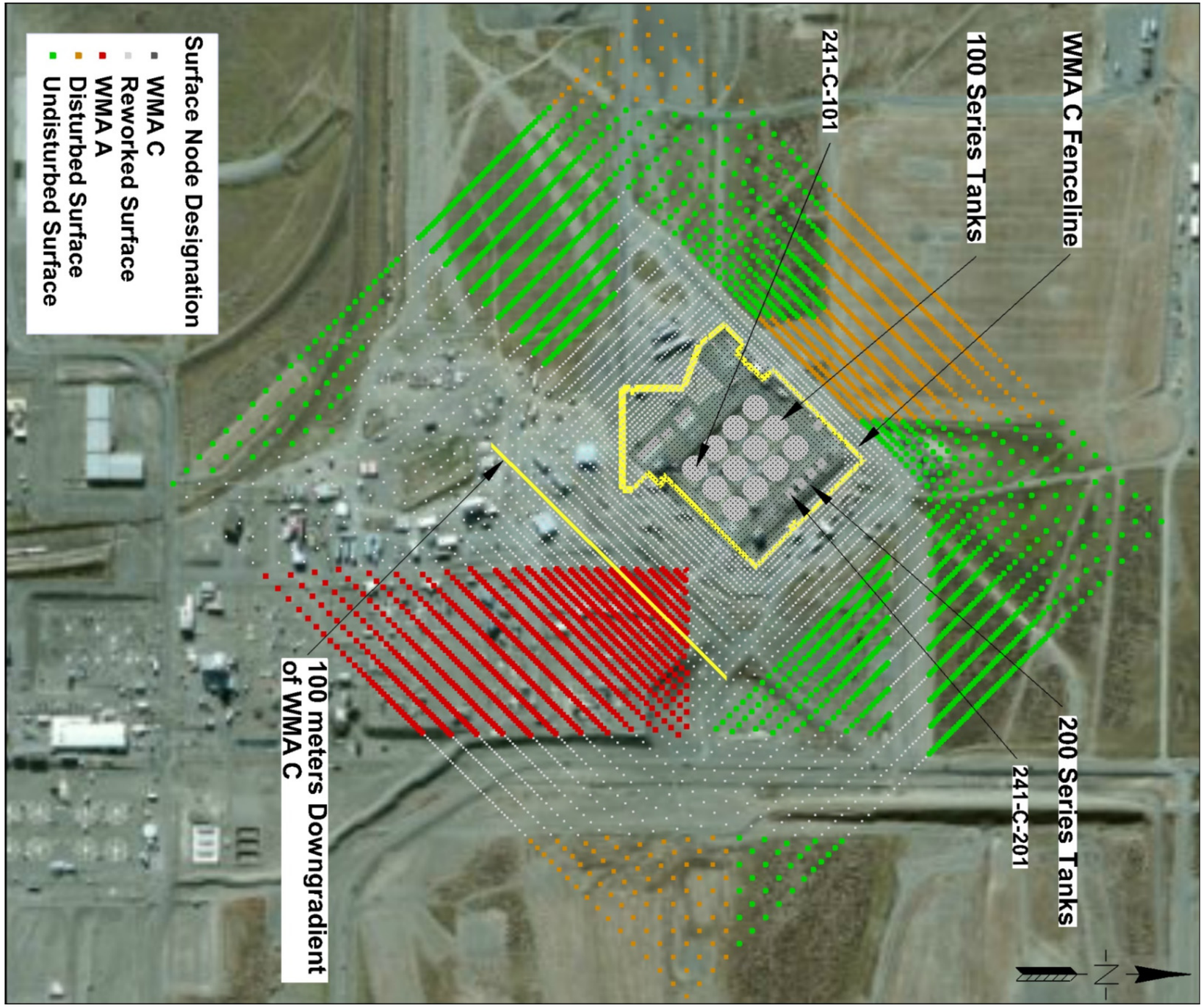



**Figure 7-26. Plan View of Waste Management Area C Performance Assessment Model Domain Showing the Horizontal Distribution and Surface Type of the Irregularly-Spaced Calculation Nodes.**
The resolution increases in the area of Waste Management Area C.

WMA = Waste Management Area

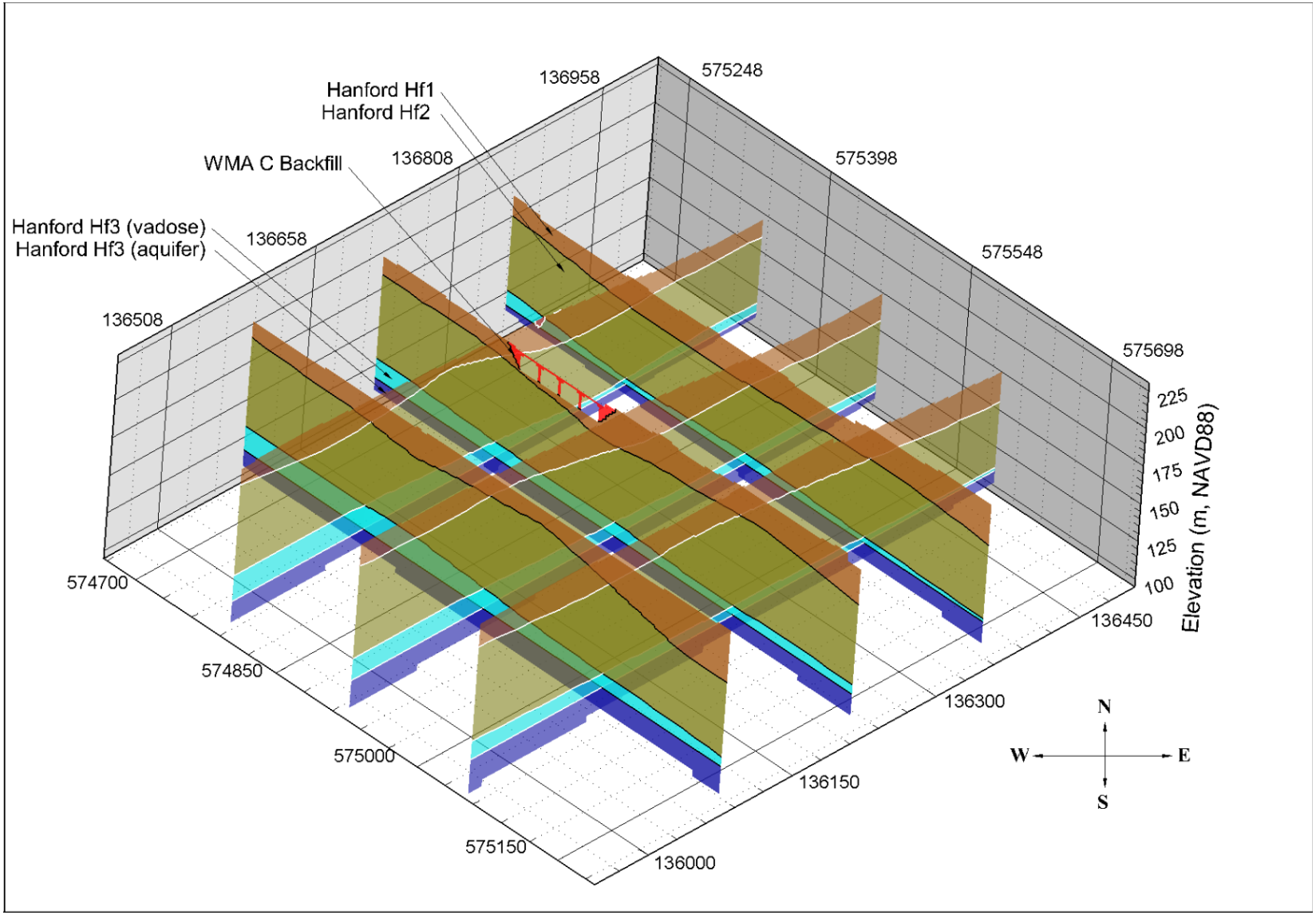
Figure 7-25 shows the geologic interpretation prepared by Washington River Protection Solutions, LLC (WRPS) staff and identified as Alternative Model I as interpolated onto the numerical grid used in the fate and transport model. Figure 7-27 shows some internal cross-sections of the geology to illustrate the shape and layering of the hydrogeologic units. Figures 7-28 and 7-29 show the geologic interpretation prepared with input from technical staff of the Nez Perce and identified as Alternative Model II. Alternative Model II includes the separation of the Hanford H2 sand unit into three distinct subunits: the Hanford H2 sand, the Hanford H2 gravelly sand, and the Hanford H2 fine or silty sand. Explanation of the basis and the development of the two geologic interpretations is presented in RPP-RPT-56356. The sensitivity analysis includes evaluation of a third alternative geologic model that is identical to Alternative Model I, except that a clastic dike is assumed to exist under tanks C-102, C-105, C-108, and C-111, and another is assumed to exist under tanks C-110, C-111, and C-112. These clastic dikes extend the length and width, respectively, of WMA C, and extend from the bottom of the WMA C excavation to the capillary fringe of the aquifer.

**Source Term.** The results from the source term release model implemented using GoldSim© provide the time varying release functions of residual waste inventory for all sources (tanks and ancillary equipment) as input to the STOMP©-based model. The nodes in the STOMP©-based model that define the base of tanks and ancillary equipment uniformly distribute the mass release provided by the GoldSim©-based source term for simulating the fate and transport through the vadose zone and saturated zone. The source term model calculations are described in Section 7.3.1 and use residual inventory information presented in Tables 3-13, 3-14, and 3-15, where the radionuclide inventory has been decayed to January 1, 2020.

**7.3.2.2.3 Recharge.** The magnitude of recharge for soils at the Hanford Site varies as a function of the soil type, condition of the vegetation cover, and soil integrity (e.g., disturbed versus undisturbed). The range of recharge values reported in RPP-RPT-44042 represents distinct populations of data based on lysimetry and isotopic measurements, and interpretation—and, in some instances, extrapolation—by Hanford Site subject matter experts. The natural background recharge rates represent a population for natural vegetated conditions. The range of values for operational conditions represents a population of recharge rates for vegetation-free disturbed soil.

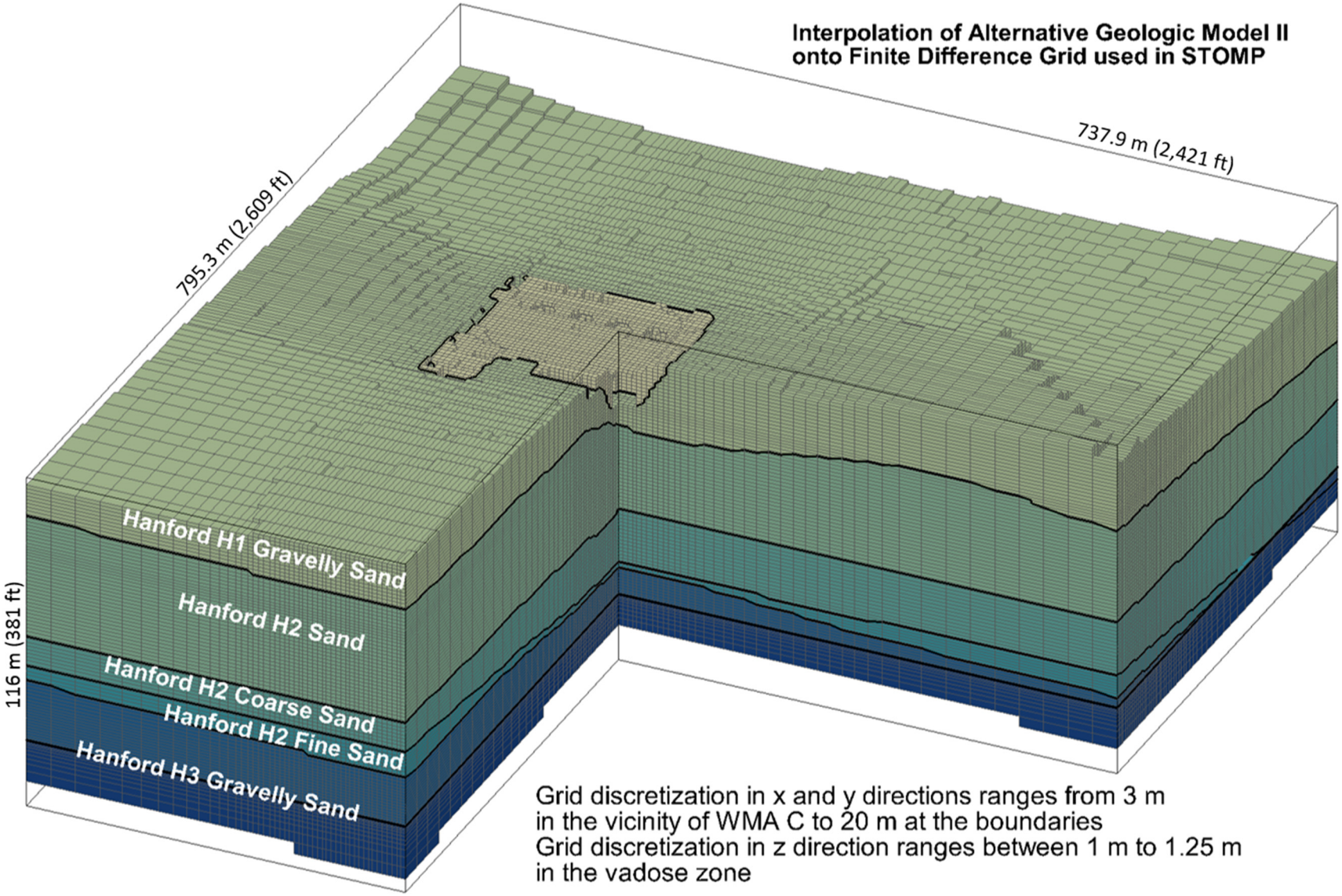
The final design for the surface barrier for WMA C at closure has not been developed. The surface barrier is expected to function comparably to a Modified RCRA Subtitle C Barrier (Section 3.2.1.2.2), which PNNL-16688 indicates should function similarly to the Prototype Hanford Barrier. Summary of data collected over 13 years at the Prototype Hanford Barrier (PNNL-17176, "200-BP-1 Prototype Hanford Barrier Annual Monitoring Report for Fiscal Years 2005 Through 2007"; DOE/RL-93-33) indicates that infiltration through the prototype is much less than 0.1 mm/yr (0.004 in./yr), and evaluations of the design using lysimeter data indicate that the barrier is capable of limiting recharge to this amount even with a complete lack of vegetation (Fayer and Gee 2006). However, for base case simulations involving WMA C RCA with a functioning surface barrier, a base case recharge rate of 0.5 mm/yr (0.02 in./yr) is assumed, which is consistent with the drainage design specification in DOE/RL-93-33.

**Figure 7-27. Diagram of the Interpolated Numerical Three-Dimensional Post-Closure Alternative I Hydrogeologic Model.**




NAVD88 = North American Vertical Datum of 1988, WMA = Waste Management Area, Hf = Hanford formation

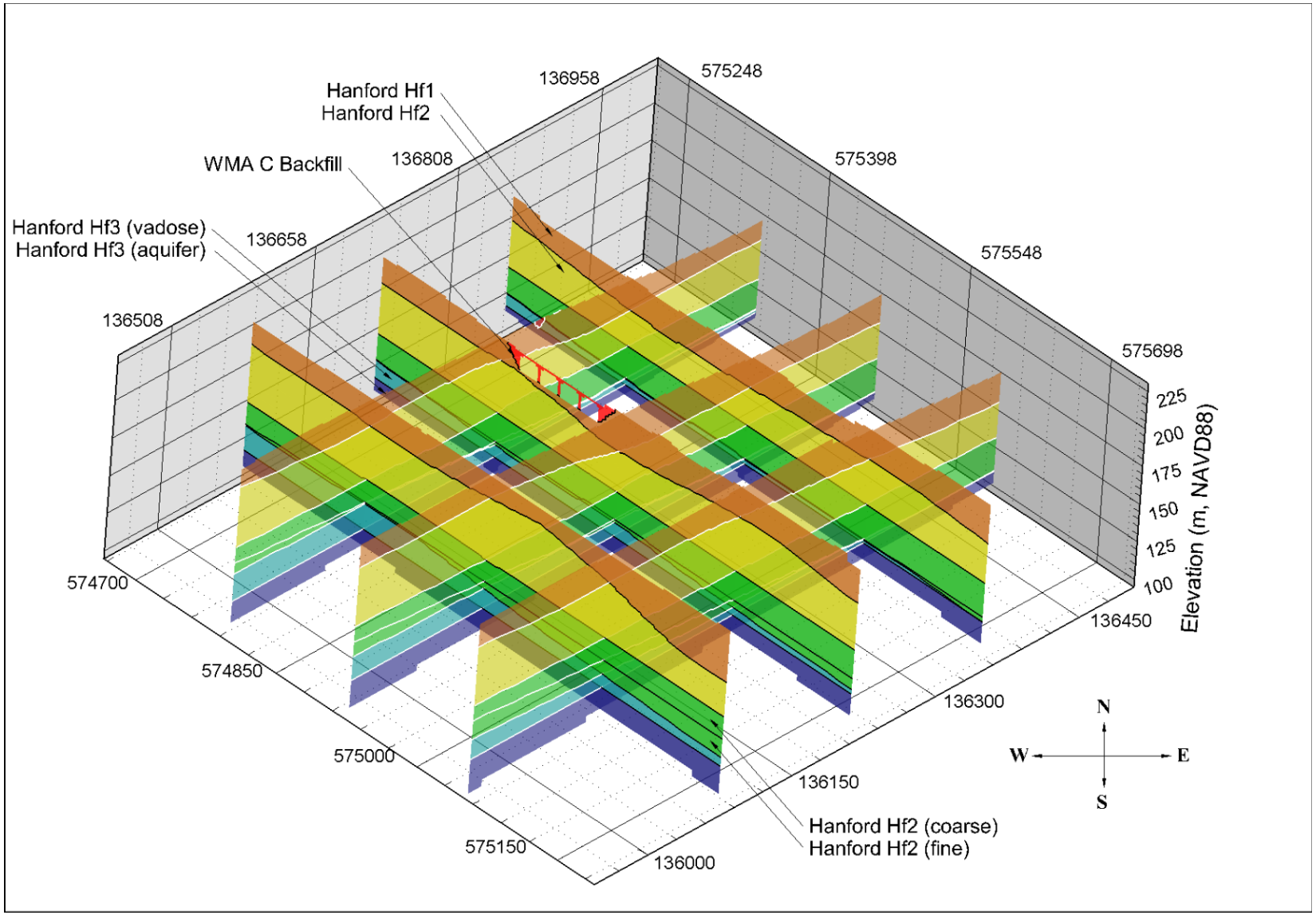
**Figure 7-28. The Interpolated Numerical Three-Dimensional Post-Closure Alternative II Hydrogeologic Model.**




STOMP = Subsurface Transport Over Multiple Phases (computer code)

WMA = Waste Management Area

**Figure 7-29. Diagram of the Interpolated Numerical Three-Dimensional Post-Closure Alternative II Hydrogeologic Model.**




NAVD88 = North American Vertical Datum of 1988, WMA = Waste Management Area, Hf = Hanford formation

At the end of 500 years, the surface barrier performance is assumed to degrade to permit an infiltration rate of 3.5 mm/yr (0.14 in./yr) and maintain that infiltration rate for the remainder of the simulation for the base case. No quantifying data are available for specifying the performance of the barrier top after its design life, but the performance of the surface barrier in limiting recharge is not expected to diminish appreciably (PNNL-16688). According to PNNL-13033, not even the erosion of the silt loam layer and deposition of dune sand on the barrier is likely to alter the barrier performance significantly. The value of 3.5 mm/yr (0.14 in./yr) corresponds to the recharge in an undisturbed area, which indicates that native vegetation is assumed to reclaim the land.

Although the side slopes and berm are likely to function and perform differently than the surface of the barrier, they are included as part of the barrier surface. The impact of the side slopes on the overall recharge rate is expected to be relatively negligible. The sandy gravel/gravelly sand barrier side slope and berm are assumed eventually to resemble a Burbank loamy sand, and if that assumption is valid, then PNNL-16688 indicates that the long-term recharge rate for that soil type is 1.9 mm/yr (0.07 in./yr), which is less than the 3.5 mm/yr (0.14 in./yr) used in the analysis for the degraded barrier surface. Table 7-5 presents a summary of the base case recharge rates applied to the different surface types present within the WMA C model domain.

**7.3.2.2.4 Vadose Zone Hydrogeology and Transport.** The vadose zone hydrogeology and transport information presented here is a brief summary of the information presented in Appendix B. Appendix B includes detailed discussion and description of the data available and the methods used to develop the base case parameters, and sensitivity distributions and percentile values.

The flow and transport pathway process used for the WMA C vadose zone modeling is porous media continuum flow. The porous media continuum assumption and the soil relative permeability/saturation/capillary pressure relations provide the basis for vadose zone flow and transport modeling (PNNL-11216, PNNL-12030). The vadose zone at the Hanford Site is composed of sediments ranging in particle size associated with gravels to silts or clays. In the model domain, the hydraulic properties describing fluid transport characteristics associated with each geologic layer (also referred to as HSUs) are approximated by average upscaled values, with each unit having different flow and transport parameter values (hydraulic conductivity, bulk density, and dispersivity). The model describes bulk (or mean) flow and chemical transport behavior in the vadose zone, limiting the evaluation to estimating overall and eventual contaminant impacts to groundwater. Porous media continuum transport in unsaturated media of this type is regarded as the fundamental process and feature for modeling contaminant fate and transport behavior in the vadose zone at the Hanford Site (DOE/RL-2011-50).

Table 7-6 lists the upscaled composite-fitted van Genuchten-Mualem (van Genuchten 1980, Mualem 1976, EPA/600/2-91/065) base case parameters for the various strata at the WMA C site. A stochastic model of variable moisture or tension-dependent anisotropy provides the framework for upscaling small-scale measurements to the effective (upscaled) properties for the large-scale vadose zone (Polmann 1990). The upscaling processes factor the inherent spatial variability that occurs on different scales in heterogeneous media into the field scale parameter estimates (“Stochastic analysis of moisture plume dynamics of a field injection experiment”

[Ye et al. 2005], "Estimation of effective unsaturated hydraulic conductivity tensor using spatial moments of observed moisture plume" [Yeh et al. 2005]). Specific upscaled flow parameters include moisture retention, and saturated and unsaturated hydraulic conductivity. Upscaled transport parameters include bulk density, diffusivity, sorption coefficients, and macrodispersivity. Detailed discussion of the Polmann (1990) model and the derivation of the upscaled parameters are presented in Appendix B.

**Table 7-5. Base Case Recharge Rate (Net Infiltration) Estimates for Surface Conditions during the Pre-Construction, Operational, and Post-Closure Periods.**

| Period | Waste Management Area (WMA) C Region and Surface Condition | Base Case Value of Recharge Rate (mm/yr) |
|---|---|---|
| Pre-construction (before 1944) | Undisturbed region (Rupert sand with vegetation) | 3.5 |
| Operational period (1945 to 2020) | Undisturbed region (Rupert sand with vegetation) | 3.5 |
| | WMA C Surface region (Gravel without vegetation) | 100 |
| | WMA A Surface region (Gravel without vegetation) | 100 |
| | Disturbed revegetated region (Rupert sand with vegetation) | 22 |
| | Disturbed unrevegetated region (Rupert sand with no vegetation) | 63 |
| Early post-closure (2020 to 2520) | Undisturbed region (Rupert sand with vegetation) | 3.5 |
| | WMA C Surface region (Surface barrier with vegetation) | 0.5 |
| | WMA A Surface region (Surface barrier with vegetation beginning in 2050) | 0.5 |
| | Disturbed revegetated region (Rupert sand with vegetation beginning in 2050 with vegetation recovery completed in 2080) | 3.5 |
| | Disturbed unrevegetated region (Rupert sand with no vegetation until vegetation recovery begins in 2050 and completes in 2080) | 3.5 |
| Late post-closure (2520 to 3020 and beyond) | Undisturbed region (Rupert sand with vegetation) | 3.5 |
| | WMA C Surface region (Surface barrier with vegetation) | 3.5 |
| | WMA A Surface region (Degraded surface barrier with vegetation begins in 2550) | 3.5 |
| | Disturbed revegetated region (Rupert sand with vegetation recovery completed in 2080) | 3.5 |
| | Disturbed unrevegetated region (Rupert sand with vegetation recovery completed in 2080) | 3.5 |

Estimated unsaturated conductivities, based on saturated conductivity and the van Genuchten retention model, can differ by up to several orders of magnitude with measured conductivities at the dry end (e.g., Khaleel et al. 1995). Therefore, unlike the conventional approach, the unsaturated conductivities are not based on predictions using the measured retention curve and

the measured saturated conductivity. Rather, the soil hydraulic properties are based on a simultaneous fit of moisture retention and unsaturated conductivity data, and all five unknown parameters θr, θs, α, n, and $K_s$, with m=1-1/n (van Genuchten 1980) were fitted to the data via a code named RETention Curve (RETC) (EPA/600/2-91/065). Thus, in order to obtain a better agreement with experimental data for the region of interest (i.e., relatively dry moisture regime), $K_s$ is treated as a fitted parameter during the curve fitting process. This is considered appropriate because the WMA C RCA predictions are needed for the relatively dry moisture regime observed in the field, rather than for the saturated or near-saturated regime. The pore size distribution factor, ℓ, was kept fixed at 0.5 during the simultaneous fitting.

**Table 7-6. Composite van Genuchten-Mualem Parameters for Various Strata at the Waste Management Area C Site Used in the Base Case Evaluations of Alternative Geologic Models I and II.**

| Strata | Number of Samples | $\theta_s$ | $\theta_r$ | α (1/cm) | *n* | $\ell^c$ | Fitted $K_s$ (cm/s) |
|---|---|---|---|---|---|---|---|
| Backfill (Gravelly) | 10 | 0.138 | 0.010 | 0.021 | 1.374 | 0.5 | 5.60E-04 |
| Hanford H1/H3 (Gravel-dominated) | 15 | 0.171 | 0.011 | 0.036 | 1.491 | 0.5 | 7.70E-04 |
| Hanford H2 (Sand-dominated) | 44 | 0.315 | 0.039 | 0.063 | 2.047 | 0.5 | 4.15E-03 |
| Hanford H2 –Gravel/coarse sand subunit* | not applicable | 0.265 | 0.002 | 0.108 | 1.724 | 0.5 | 1.68E-02 |
| Hanford H2 – Silty-sand subunit* | not applicable | 0.354 | 0.029 | 0.040 | 1.633 | 0.5 | 1.79E-03 |

*Hydraulic properties of these units are only used in numerical model simulation of Alternative Geologic Model II. As an initial estimate of these properties, the hydraulic properties associated with the 5th and 95th percentile realizations of unsaturated hydraulic conductivity curves developed in the Uncertainty and Sensitivity Analysis for the Hanford H2 sand unit (see RPP-ENV-58782, Section 8.1.3.4 Uncertainties in Vadose Zone Hydraulic Properties.) were considered to be representative of the Hanford H2 silty sand and the Hanford H2 gravel/coarse sand subunits, respectively.

For the Alternative Geologic Model II evaluation, the Hanford H2 gravel/coarse sand subunit was assumed to be more transmissive, and the Hanford H2 silty sand less transmissive, than the Hanford H2 sand. Therefore, as an initial estimate of these properties, the hydraulic properties associated with the $5^{th}$ and $95^{th}$ percentile realizations of unsaturated hydraulic conductivity curves developed for the Hanford H2 sand unit were considered representative of the Hanford H2 gravel/coarse sand and the Hanford H2 silty sand subunits, respectively.

The effective transport parameter (i.e., macrodispersivity, bulk density, and diffusivity) estimates used in the base case and sensitivity cases are presented. Because of natural variability, the transport parameters are all spatially variable. The purpose is similar to the upscaled flow parameters, to evaluate the effect of such variability on the large-scale transport process. Effective bulk density ($\rho_b$) estimates are needed to calculate retardation factors for different species. The average $\rho_b$, E[$\rho_b$] estimates for various strata at WMA C are presented in Table 7-7.

These estimates are derived from bulk density sample values listed in Appendix B. Appendix B also provides a summary of the numerical simulation, stochastic theory, and 200 Areas experimental data that provide the basis for the base case estimates of macrodispersivity (Table B-11). The estimated values of macrodispersivity applicable to the scale of the WMA C RCA model for the base case evaluation are shown in Table 7-8.

**Table 7-7. Effective Bulk Density ($E[\rho_b]$, g/cm$^3$) Estimates for Various Strata at Waste Management Area C Used in the Base Case Evaluations of Alternative Geologic Models I and II.**

| Strata | $E[\rho_b]$ |
|---|---|
| Backfill (Gravelly)[1] | 2.13 |
| Hanford H1/H3 (Gravel-dominated)[1] | 2.05 |
| Hanford H2 (Sand-dominated)[2] | 1.71 |
| Hanford H2 – Gravel/coarse sand subunit[3] | 1.83 |
| Hanford H2 – Silty-sand subunit[3] | 1.61 |

[1]See Appendix B.

[2]From Table 7 of RPP-20621, "Far-Field Hydrology Data Package for the Integrated Disposal Facility Performance Assessment," by taking the average of soil samples 7A through 35A.

[3]Effective bulk densities of these units are only used in numerical model simulation of Alternative Geologic Model II. The values are calculated based on particle density of 2.49 g/cm$^3$ and porosity equal to saturated moisture content presented in Table 7-6. The particle density of 2.49 g/cm$^3$ is derived from the bulk density of 1.71 g/cm$^3$ for Hanford H2 sand with porosity of 0.315 (Table 7-6).

**Table 7-8. Macrodispersivity Estimates for Various Strata at Waste Management Area C Used in the Base Case Evaluations of Alternative Geologic Models I and II.**

| Strata | $A_L$ (cm) | $A_T$ (cm) |
|---|---|---|
| Backfill (Gravelly) | ~20 | 2.0 |
| Hanford H1/H3 (Gravel-dominated) | ~20 | 2.0 |
| Hanford H2 (Sand-dominated) | ~25 | 2.5 |
| Hanford H2 –Gravel/coarse sand subunit* | ~25 | 2.5 |
| Hanford H2 – Silty-sand subunit* | ~25 | 2.5 |

*Macrodispersivities of these units are only used in numerical model simulation of Alternative Geologic Model II.

See Appendix B.

It is assumed that the effective, large-scale diffusion coefficients for all strata in the vadose zone at the WMA C site are a function of volumetric moisture content, θ, and can be expressed using

the Millington-Quirk ("Permeability of Porous Solids" [Millington and Quirk 1961]) empirical relation:

$$D_e(\theta) = D_0 \frac{\theta^{10/3}}{\theta_s^2} \tag{7-12}$$

Where:

$D_e(\theta)$ = the effective diffusion coefficient of an ionic species
$D_0$ = the effective diffusion coefficient for the same species in free water
$\theta$ = the localized volumetric moisture content
$\theta_s$ = the localized volumetric moisture content at saturation.

The tortuosity formulation in the Millington-Quirk model is based on theoretical considerations absent from other empirical models, and accounts for the ranges of moisture contents present in the vadose zone around WMA C. The molecular diffusion coefficient for all species in pore water is assumed to be $2.5 \times 10^{-5}$ cm$^2$/sec ($6.98 \times 10^{-4}$ in.$^2$/sec) (WHC-SD-WM-EE-004), which is consistent with, and representative of, values used in other Hanford PAs (WHC-EP-0645, BHI-00169, WHC-SD-WM-TI-730, WHC-SD-WM-EE-004, and DOE/ORP-2000-24).

**7.3.2.2.5 Groundwater Domain and Characteristics.** The groundwater in the aquifer system in the vicinity of WMA C has been studied extensively as part of the site characterization that is discussed in RPP-RPT-46088. The groundwater conceptual model for WMA C includes the uppermost unconfined aquifer system that exists within a channel eroded by the cataclysmic floods of the Pleistocene. The base of the aquifer is the underlying basalt surface. The undifferentiated lower sands and gravels associated with the Hanford formation, CCU, and the Ringold Formation (Unit A) that comprise the aquifer sediments are simply categorized as saturated Hanford H3 sediments in the model. The thickness of the uppermost aquifer beneath WMA C is ~12 m (39 ft). The model results provided represent concentrations in the upper 5 m (16.4 ft) of the aquifer. The 5 m (16.4 ft) vertical interval corresponds to the well screen length of a conceptual groundwater monitoring well, and the basis for that delimiter to the groundwater concentrations calculation is presented in upcoming discussion regarding "Point of Calculation, Protectiveness Metric, and Time Frame Considerations."

Groundwater flow beneath WMA C has been historically difficult to measure because the hydraulic gradient is very small and the hydraulic conductivity is very large in this region of the Hanford Site. In addition, the water table continues to recover from the operational liquid discharges at 216-B-3 Pond system and other large discharge sites in 200 East Area. The projected equilibrium state is expected to be similar to its pre-Hanford behavior (see Section 3 and Appendix C). As a result, the post-closure position of the water table and associated hydraulic gradient can only be evaluated through modeling. Consequently, the groundwater flux in the aquifer beneath WMA C is calculated on the basis of the aquifer hydraulic properties, and the hydraulic gradient projected to exist in the future.

The hydraulic heads around WMA C are expected to continue declining slowly until they stabilize around 119.5 m (392 ft) within 100 years into the future (CP-47631). The gradient is

generally expected to slope from northwest to southeast with a value of about 0.00002 m/m, which is close to the one observed prior to start of Hanford operations (Figure 7-30). Appreciable changes in hydraulic gradient are not expected in the future once the hydraulic heads stabilize. Thus, the hydraulic gradient is assumed to remain stable for the base case analysis.

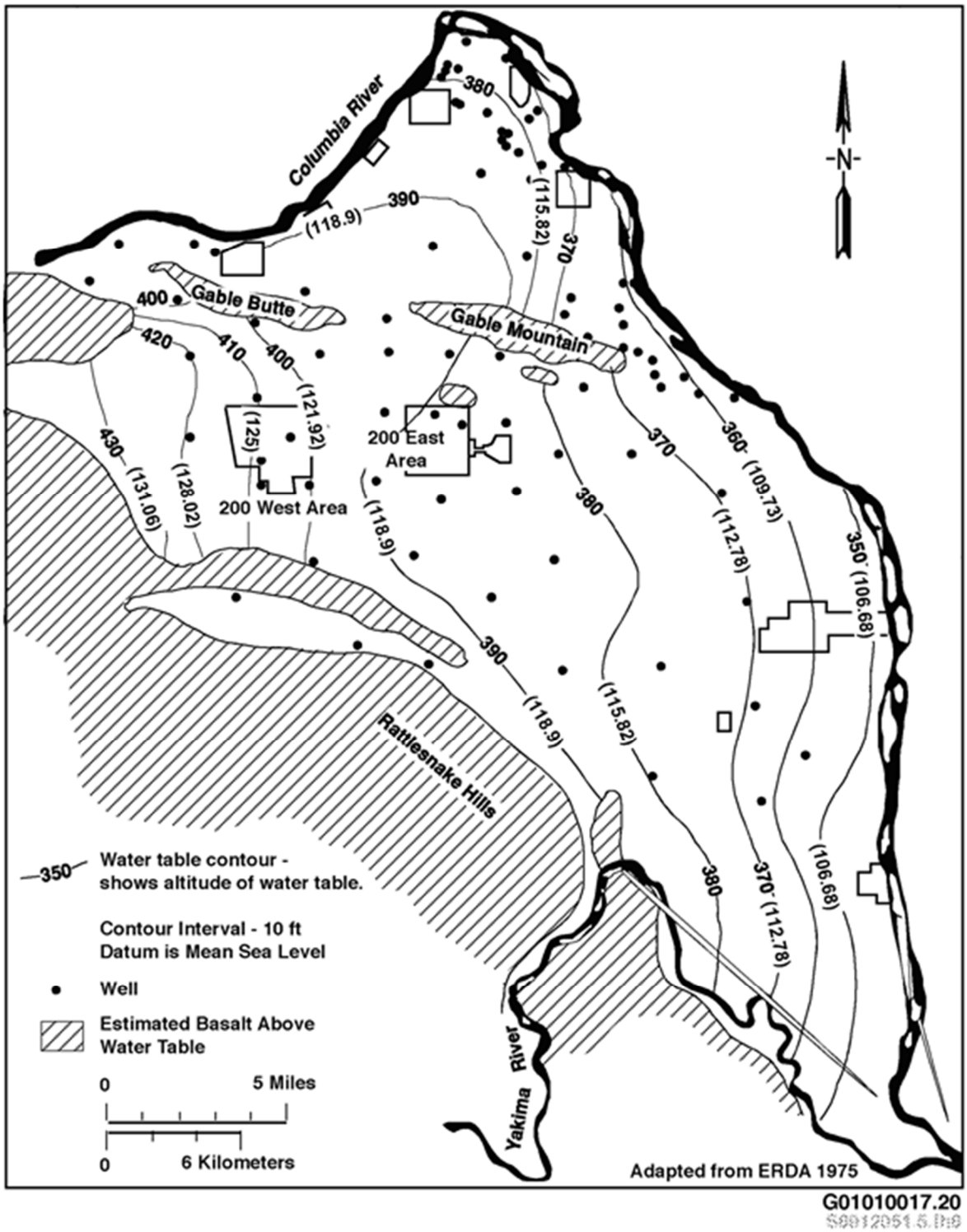
Appendix C discusses the scale dependence of aquifer properties and indicates that field-scale calibrated groundwater models are the most appropriate approach for parameterization of the WMA C saturated media hydraulic conductivity. To date, the Central Plateau Groundwater Model (CPGWM, CP-47631) appears to be the most appropriate and applicable calibrated model to provide that parameterization. The CPGWM provides calibrated hydraulic conductivity estimates for the model layers and HSUs present within the aquifer in the vicinity of WMA C. Within the WMA C flow domain, the weighted average of hydraulic conductivity derived from the CPGWM is approximately 11,000 m/day (33,000 ft/day). Thus, the base case horizontal saturated hydraulic conductivity for the aquifer is estimated to be 11,000 m/day (33,000 ft/day). The CPGWM estimate of vertical anisotropy ratio of 0.1 is also incorporated in the WMA C base case. Table 7-9 presents a summary of the aquifer base case hydraulic parameters for the Hanford H3 – aquifer. The aquifer, identified as Hanford H3 – aquifer, is separated from that portion of the Hanford H3 above the water table, reflecting the distinctly different saturation conditions.

**7.3.2.2.6 Sorption Characteristics.** Linear $K_d$ isotherm is a reasonable representation for modeling sorption of contaminants on the sediments when released from tank residuals and ancillary equipment. The rationale for the use of a $K_d$-based approach for vadose zone units is presented in Section 7.2.2.1.5 and discussed in detail in DOE/RL-2011-50. The $K_d$ values are chosen assuming low-salt, near-neutral waste chemistry in the vadose and saturated zone (PNNL-13895).

The basis for the $K_d$ values used to approximate the transport of the contaminants are presented in Table 7-10, including the values lowered to account for the gravel content per the procedure described in PNNL-17154, "Geochemical Characterization Data Package for the Vadose Zone in the Single-Shell Tank Waste Management Areas at the Hanford Site." PNNL-17154 indicates that $K_d$ values are typically lower for materials that contain significant amounts of gravel (notably Backfill, Hanford H1, and Hanford H3) than those determined with <2 mm (0.08-in.) size material. The gravel corrected values are not included in the table for the contaminants that the 3-D screening evaluation indicated would not arrive at the water table within 10,000 years.

**7.3.2.2.7 Point of Calculation, Protectiveness Metric, and Time Frame Considerations.** In accordance with long-term assessment guidelines (NUREG-1854), the determination of soil contamination impacts to groundwater also requires the definition and rationale for (1) the PoCal, i.e., the place and points in the groundwater domain where modeled groundwater concentrations are to be assessed for potential impacts and protectiveness; (2) the protectiveness metric, i.e., the groundwater metric(s) to be used in the assessment of protectiveness at the PoCal, and; (3) the time frame considered applicable for the calculation of impacts to groundwater.

**Figure 7-30. Hindcast Water Table Map of the Hanford Site, January 1944.**




ERDA 1975 = ERDA-1538, "Final Environmental Statement, Waste Management Operations, Hanford Reservation, Richland, Washington."

Source: WHC-SD-ER-TI-003, "Geology and Hydrology of the Hanford Site: A Standardized Text for Use in Westinghouse Hanford Company Documents and Reports."

**Table 7-9. Base Case Soil Hydraulic Properties for Aquifer Soil Type Used for Base Case at Waste Management Area C.**

| Aquifer Soil Type | Total Porosity | Saturated Moisture Content | Horizontal Saturated Hydraulic Conductivity[a] (m/day) | Longitudinal Dispersivity[b] (m) | Aquifer Hydraulic Gradient (m/m) | Average Aquifer Water Flux ($m^3/day/m^2$) |
|---|---|---|---|---|---|---|
| Hanford H3 (aquifer) | 0.20 | 0.20 | 11,000 | 10.5 | 0.00002 | 0.22 |

[a] Vertical Saturated Hydraulic Conductivity assumed equal to 1/10 of the Horizontal Saturated Hydraulic Conductivity.
[b] Transverse dispersivity assumed to be equal to 1/10 of the longitudinal dispersivity.

See Appendix C.

**Table 7-10. Distribution Coefficients ($K_d$) Values Used to Approximate the Transport of the Hazardous Chemicals in the Base Case. (2 sheets)**

| Element or Contaminant | Base Case $K_d$ (mL/g) | | | | |
|---|---|---|---|---|---|
| | < 2 mm Material | Backfill | Hanford H1/H3 | Hanford H2 | Reference |
| Ac | 350 | NM | NM | NM | PNNL-16663 |
| Al | 1,500 | NM | NM | NM | RPP-RPT-46088 |
| Am | 600 | NM | NM | NM | PNNL-17154 |
| B | 3 | NM | NM | NM | RPP-RPT-46088 |
| C | 1 | 0.46 | 0.58 | 0.8 | PNNL-17154 |
| Cm | 350 | NM | NM | NM | PNNL-16663 |
| CN | 0 | NM | NM | NM | RPP-RPT-46088 |
| Co | 0 | 0 | 0 | 0 | PNNL-17154 |
| Cr | 0 | 0 | 0 | 0 | PNNL-17154 |
| Cs | 100 | NM | NM | NM | PNNL-17154 |
| Eu | 10 | NM | NM | NM | PNNL-17154 |
| F | 0 | 0 | 0 | 0 | PNNL-17154 |
| Fe | 25 | NM | NM | NM | RPP-RPT-46088 |
| H | 0 | 0 | 0 | 0 | PNNL-17154 |
| Hg | 52 | NM | NM | NM | RPP-RPT-46088 |
| I | 0.2 | 0.09 | 0.12 | 0.16 | PNNL-17154 |
| Mn | 65 | NM | NM | NM | RPP-RPT-46088 |

**Table 7-10. Distribution Coefficients ($K_d$) Values Used to Approximate the Transport of the Hazardous Chemicals in the Base Case. (2 sheets)**

| Element or Contaminant | Base Case $K_d$ (mL/g) | | | | |
|---|---|---|---|---|---|
| | < 2 mm Material | Backfill | Hanford H1/H3 | Hanford H2 | Reference |
| Nb | 0 | 0 | 0 | 0 | PNNL-16663 |
| Ni | 3 | 1.4 | 1.7 | 2.4 | PNNL-17154 |
| $NO_2$ | 0 | 0 | 0 | 0 | PNNL-17154 |
| $NO_3$ | 0 | 0 | 0 | 0 | PNNL-17154 |
| Np | 10 | NM | NM | NM | PNNL-17154 |
| Pa | 300 | NM | NM | NM | PNNL-17154 |
| Pb | 10 | NM | NM | NM | PNNL-17154 |
| Pu | 600 | NM | NM | NM | PNNL-17154 |
| Ra | 10 | NM | NM | NM | PNNL-17154 |
| Rn | 0 | 0 | 0 | 0 | No relevant information available |
| Se | 0.1 | 0.05 | 0.06 | 0.08 | PNNL-17154 |
| Sm | 10 | NM | NM | NM | PNNL-17154 |
| Sn | 0.5 | 0.23 | 0.29 | 0.4 | PNNL-17154 |
| Sr | 10 | NM | NM | NM | PNNL-17154 |
| TBP | 1.89 | NM | NM | NM | RPP-RPT-46088 |
| Tc | 0 | 0 | 0 | 0 | PNNL-16663 |
| Th | 300 | NM | NM | NM | PNNL-16663 |
| U | 0.6 | 0.28 | 0.35 | 0.48 | RPP-RPT-46088 |
| Zr | 300 | NM | NM | NM | PNNL-16663 |

NM = not included in the three-dimensional modeling because the results of screening indicated the element or contaminant does not arrive at the water table within 10,000 years.

References:
PNNL-16663, "Geochemical Processes Data Package for the Vadose Zone in the Single-Shell Tank Waste Management Areas at the Hanford Site."
PNNL-17154, "Geochemical Characterization Data Package for the Vadose Zone in the Single-Shell Tank Waste Management Areas at the Hanford Site.
RPP-RPT-46088, "Flow and Transport in the Natural System at Waste Management Area C."

The PoCal evaluated in this RCA was selected to be consistent with the analysis being evaluated in the WMA C PA. The PoCal for the groundwater impact analysis is 100 m downgradient from the WMA C fenceline. The PoCal is intended to effectively serve as the point where exposure point groundwater concentrations are evaluated in the model for the purpose of evaluating the achievement of the groundwater protection performance measures. This is also consistent with

the NUREG-1854 (Section 4.1.1.4 Receptor Characteristics) description of the buffer zone for evaluation.

The aquifer mixing zone extends into the upper 5 m (16.4 ft) of the aquifer for the purpose of the evaluations. The Washington Administrative Code does specify a 5-m (16.4-ft) mixing zone in groundwater that is consistent with a 5-m (16.4-ft) vertical interval corresponding to a conceptual groundwater monitoring well with the 4.6-m (15-ft) well screen length (and mixing zone dimension) associated with State monitoring well descriptions (e.g., see Equation 747-4 in WAC 173-340-747).

The period of analysis evaluated in this RCA was selected to be consistent with the time frames of analysis being examined in the WMA C PA, and is defined as 1,000 years following closure of the facility (DOE M 435.1-1; DOE G 435.1-1, Implementation Guide for Use with DOE M 435.1-1, Radioactive Waste Management Manual, Chapter 4). The sensitivity analysis along with NRC guidance (NUREG-1854, Section 4.1.1.1 Period of Performance and Institutional Controls) extends the evaluation to 10,000 years, which is sufficient to evaluate the peak concentrations from all of the chemicals that the screening analysis indicates may not impact groundwater within the period of analysis. The sensitivity analysis time frame includes calculation of the maximum concentration for contaminants that are adsorbed, but whose concentrations are rising at the end of 10,000 years regardless of the time at which the maximum occurs, as a means of increasing confidence in the outcome of the modeling and increasing the understanding of the models used. However, EPA-SAB-RAC-ADV-99-006, An SAB Advisory: Modeling of Radionuclide Releases from Disposal of Low Activity Mixed Waste warns that extending the modeling time frame beyond 10,000 years could make the results irrelevant and hinder public acceptance of the results because of the inherent scientific and social uncertainties associated with such an extended time frame.

Defining the protection of groundwater in the context of vadose zone fate and transport requires consideration of the soil and groundwater media as a hybrid or coupled pathway. This pathway involves the determination of future concentrations in the groundwater medium that result from the transport of the contaminant inventory existing in the WMA C tank residuals. Per this working definition, protection of groundwater pathway is considered achieved if contaminant risks and hazards do not exceed risk thresholds. Table 7-11 provides a summary of key site-specific model elements and parameters used for the model components.

**7.3.2.3 Groundwater Pathway Screening Analysis Methodology.** The screening phase streamlines the RCA modeling effort and computation time by distinguishing those contaminants that may impact groundwater during the period of analysis time frames from those that are not. The screening phase uses the 3-D model to determine the maximum $K_d$ value of contaminants contained within the WMA C tank residuals that reach the water table within 1,000 and 10,000 years. For consistency with the DOE O 435.1 WMA C PA (RPP-ENV-58782, Section 2.3 Assessment Period), performance measures are evaluated for 1,000 years, and a 10,000-year post-closure period to clarify long-term impacts. The $K_d$ screening evaluation includes the use of vadose zone hydraulic and recharge parameter values that minimize travel time to groundwater to prevent the occurrence of a false negative, i.e., that a chemical could impact groundwater within the 1,000- or 10,000-year simulation time frames is screened from the 3-D fate and transport model evaluations when it should not be.

**Table 7-11. Summary of Key Elements and Base Case Parameters Associated with Site-Specific Model Components for Waste Management Area C (The basis for the elements and parameter selection provided in the individual model components sections). (2 sheets)**

| | |
|---|---|
| **Model Domain and Boundary Conditions** | Rectangular Prism: 737.9 m (2,421 ft) × 795.3 m (2,609 ft) × 116 m (381 ft)<br><br>Prescribed flux across the top (Recharge); no-flow along vertical side boundaries in the vadose zone; prescribed flux and head along the upgradient and downgradient vertical side boundaries in the aquifer, respectively; no-flow along the bottom of the model (aquifer). The prescribed volumetric water flux boundary condition is calculated to maintain mass conservation in the aquifer independent of recharge. |
| **Geologic Setting** | The Waste Management Area (WMA) C cross-section includes the following anthropogenic or natural units that occur from surface to groundwater (RPP-RPT-56356, "Development of Alternative Digital Geologic Models of Waste Management Area C"):<br>• WMA C Backfill<br>• Hanford H1 (gravel-dominated, generally identified as gravel or very coarse sand)<br>• Hanford H2 Sand (sand-dominated facies generally identified as fining upward sequences of gravel, sandy/gravel to sand to very fine sand)<br>• Hanford H3 (coarse-grained open framework gravel to sandy gravel; in the vicinity of WMA C is variously referred to in different references as undifferentiated H3 gravels, Cold Creek, or Ringold)<br>• In Alternative Geologic Model II, the Hanford H2 Sand includes the following two additional subunits<br>  o Hanford H2 Coarse (gravel/coarse-grained facies that underlies the H2 fines)<br>  o Hanford H2 Silty Sand – (a silty sand unit that is only observed in deep groundwater wells and a mappable unit may not be readily identified) |
| **Groundwater Domain and Characteristics** | WMA C post-closure water table elevation ~119.5 m NAVD88 and average hydraulic gradient ~0.00002 m/m<br>Aquifer area along northwest cross-section boundary = 6,151 $m^2$<br>Aquifer area along southeast cross-section boundary = 13,998 $m^2$<br>Average aquifer area along all aquifer cross-sections = 9,440 $m^2$<br>Prescribed flux along northwest cross-section boundary (saturated K = 11,000 m/d); 11,000 m/d × 0.2000E-04 × 365.25 d/yr = 8.04E+01 m/yr; 8.04E+01 m/yr × 9,440 $m^2$ / 6,151 $m^2$ = 1.23E+02 m/yr<br>Prescribed head along southeast cross-section boundary = 119.49 m<br>Groundwater thickness is ~12 m (39 ft) in the aquifer; Groundwater concentrations evaluated for upper 5 m (16 ft) of the aquifer (rationale for aquifer depth presented in Section 7.3.2.2.7 Point of Calculation, Protectiveness Metric, and Time Frame Considerations)<br><br>Aquifer Hydraulic Conductivity Horizontal to Vertical Anisotropy = **10:1**<br>Aquifer Dispersivity Longitudinal to Transverse Anisotropy = **10:1**<br><br>Appendix C identifies and describes the methods used to derive the aquifer properties and parameter values. |

**Table 7-11. Summary of Key Elements and Base Case Parameters Associated with Site-Specific Model Components for Waste Management Area C (The basis for the elements and parameter selection provided in the individual model components sections). (2 sheets)**

| | |
|---|---|
| **Source Term/ Inventory** | Table 3-13 "241-C Tank Farm Residual Inventory Estimates for Retrieved Tanks with Post-Retrieval Sampling," Table 3-14 "241-C Tank Farm Residual Inventory Estimates for Tanks Undergoing Retrieval," and Table 3-15 "241-C Tank Farm Residual Inventory Estimates for Ancillary Equipment" include tank, ancillary equipment, and pipeline-specific WMA C Base Case inventory estimates for the contaminants evaluated in this RCA.<br><br>Diffusion controlled release occurs from the grouted tanks, and advection-controlled release occurs from the pipelines along with equilibrium sorption-desorption processes (i.e., $K_d$ control). |
| **Vadose Zone Hydrogeology and Fluid Transport** | Table 7-6 "Composite van Genuchten-Mualem Parameters for Various Strata at the Waste Management Area C Site Used in the Base Case Evaluations of Alternative Geologic Models I and II" includes the hydrogeologic property estimates for WMA C RCA models.<br><br>Vadose Zone Hydraulic Conductivity Anisotropy allowed to vary as a function of the moisture content in accordance with the Polmann model ("Application of Stochastic Methods to Transient Flow and Transport in Heterogeneous Unsaturated Soils" [Polmann 1990]).<br><br>Vadose Zone Dispersivity Longitudinal to Transverse Anisotropy = **10:1**<br><br>Appendix B and Appendix D identify and describe the methods used to derive the properties and parameter values. |
| **Recharge** | Recharge varies spatially and temporally on the basis of surface conditions.<br><br>Table 7-5 "Base Case Recharge Rate (Net Infiltration) Estimates for Surface Conditions during the Pre-Construction, Operational, and Post-Closure Periods" includes the base case recharge estimates applicable to the different surface conditions and periods evaluated in this RCA. |
| **Sorption Characteristics** | $K_d$-control for chemical transport<br><br>Table 7-10 "Distribution Coefficients ($K_d$) Values Used to Approximate the Transport of the Hazardous Chemicals in the Base Case" includes the base case distribution coefficient estimates applicable to the different chemicals evaluated in this RCA. |

*Applies to all subfacies of this unit.

NAVD88 = North American Vertical Datum of 1988, National Geodetic Survey, U.S. Department of Commerce.
NP = Not present

The $K_d$ screening threshold values are based on any non-zero chemical impact to groundwater. This threshold represents the first indication of a groundwater impact, i.e., leading edge of a groundwater plume arriving at the water table, rather than peak concentration, which arrives later than the leading edge. The groundwater arrival time screening criteria are only focused on whether there was any non-zero impact to groundwater within the time frames considered and are applied regardless of subsequent peak concentrations. The screening analysis includes vadose zone hydraulic property values and recharge rates, which are discussed in Appendix B.

In particular, the screening analysis applies the maximum recharge rates associated with each period for each surface type, assigns the vadose zone hydraulic properties that produce the fastest pore water velocity for each HSU (as determined for the uncertainty analysis identified in the WMA C PA; see RPP-ENV-58782, Section 8.1.4 Development of Vadose Zone Flow Fields and Propagation of Uncertainty), and executes an advection release function for the chemical.

As part of the uncertainty evaluation (RPP-ENV-58782, Section 8.1.3.1 Uncertainty in Recharge Rates), parametric distributions of recharge estimates were developed that identified maximum values for the different surface types and simulation periods. The maximum net infiltration rate present during the different simulation periods for each surface type (Table 7-12) is used for the screening evaluation. The maximum net infiltration rate during the operations time frame is assumed to be sufficient to account for any anthropogenic water sources and hypothetical leaks occurring during retrieval. Interim measures enacted during fiscal year 2002 included constructing surface water controls to reduce surface water run-on from major meteorological events and from breaks in waterlines by 1) isolating, cutting, and capping unnecessary waterlines, and 2) testing operating waterlines and replacing any lines found to be leaking (DOE/ORP-2008-01, Appendix K). This provides almost 20 years of drainage before the surface barrier is emplaced, and contaminant releases from tank residuals are assumed not to occur. Long-term recharge after barrier failure is the only source of water expected to result in any significant transport of contaminant from the facility to groundwater. WMA C tank residuals are not expected to contain appreciable quantities of liquid, and the retrieval operations are conducted in a manner to minimize uncontrolled retrieval leachate from escaping the tanks.

**Table7-12. Maximum Net Infiltration (Recharge) Estimates for Pre-Construction Period, Operational Period, and Post-Closure of Waste Management Area C.**

| Surface Status | Pre-Construction (mm/yr) | Operational Period (mm/yr) | Post Closure | |
|---|---|---|---|---|
| | | | Until End of Barrier Design Life (500 yr after closure) (mm/yr) | After End of Barrier Design Life (mm/yr) |
| Waste Management Area C | 5.2 | 140 | 1.0 | 5.2 |
| Undisturbed | 5.2 | 5.2 | 5.2 | 5.2 |
| Disturbed | 5.2 | 22 | 5.2 | 5.2 |
| Reworked | 5.2 | 63 | 5.2 | 5.2 |
| Waste Management Area A | 5.2 | 140 | 1.0 | 5.2 |

The WMA C PA (see RPP-ENV-58782, Section 8.1.3.4 Uncertainties in Vadose Zone Hydraulic Properties) evaluated the uncertainty in the vadose zone hydraulic properties by randomly producing 200 combinations of van Genuchten-Mualem hydraulic parameter values for each HSU from the parameter distributions identified in RPP-ENV-58782 (Section 8.1.4 Development of Vadose Zone Flow Fields and Propagation of Uncertainty). From these realizations, an empirical cumulative distribution function is calculated for the pore water velocity estimates, and

the hydraulic parameter set corresponding to the maximum pore water velocity occurring with a steady flux of 3.5 mm/yr (0.14 in./yr) is selected for the screening evaluation (Table 7-13).

**Table 7-13. van Genuchten-Mualem Parameters Associated with the Maximum Pore Water Velocity Based on the Cumulative Distribution Functions in Appendix B.**

| Strata | $\theta_s$ | $\theta_r$ | α (1/cm) | n | Fitted $K_s$ (cm/s) |
|---|---|---|---|---|---|
| Hanford H1 (gravelly sand) | 0.100 | 0.0006 | 0.0190 | 1.789 | 5.07E-04 |
| Hanford H2 (sand-dominated) | 0.239 | 0.0006 | 0.0743 | 2.042 | 8.84E-03 |
| Hanford H3 (gravelly sand) | 0.100 | 0.0006 | 0.0190 | 1.789 | 5.07E-04 |
| Aquifer | 0.20 | 0.0006 | 0.0190 | 1.789 | 1.27* |
| Backfill | 0.100 | 0.0003 | 0.0116 | 1.464 | 9.42E-05 |
| *Value listed is 1/10 of the aquifer horizontal hydraulic conductivity. | | | | | |

For the purpose of the screening evaluation, the screening-phase model considers only the advective release of contaminants from the sediments. All of the contamination in the source area is available for advective transport, and the release occurs during a one-year span at closure and according to the equilibrium $K_d$. Results from the groundwater pathway screening analysis are presented in Section 8.2.1 Result of Screening Analysis for Groundwater Pathway of this document.

**7.3.2.4 Abstraction Approach for System-Level Modeling.** The system model is implemented to reduce the computational time needed to carry out sensitivity analyses. The flow field for the vadose zone is derived from the 3-D STOMP©-based model calculations, abstracted to provide a close approximation to the full STOMP©-based solution. The objective of the system model is to evaluate the interaction of various submodels within the overall system. This is carried out by conducting transport analyses in one dimension (1-D) within the vadose zone and saturated zone for each source type (tank, ancillary equipment, and pipeline). This flow-field abstraction methodology was considered reasonable because of the EHM approach and upscaled flow parameters adopted in the STOMP©-based models. The reasonableness of the abstraction approach was demonstrated by comparing the results of the transport analysis conducted using the 1-D abstracted model to the full 3-D STOMP©-based model.

The flow field generated from the STOMP©-based model was evaluated by considering the following aspects of the flow field abstraction:

1. Variable HSU thickness within the model domain and its impact on flow velocity

2. Spatial and temporal variability in imposed recharge rates

3. Spatial and temporal variability in flow underneath the tank

4. Variable distances of tanks from the compliance location boundary.

The GoldSim©-based system model relies on the user to provide the moisture content, saturation, and Darcy flux as inputs; these flow-field related parameters were extracted from the STOMP©-based model. Figure 7-31 shows the STOMP©-based model node locations along with the extent of WMA C. For the abstraction of the flow field, the primary regions of interest were the ones underneath the various source locations within WMA C.

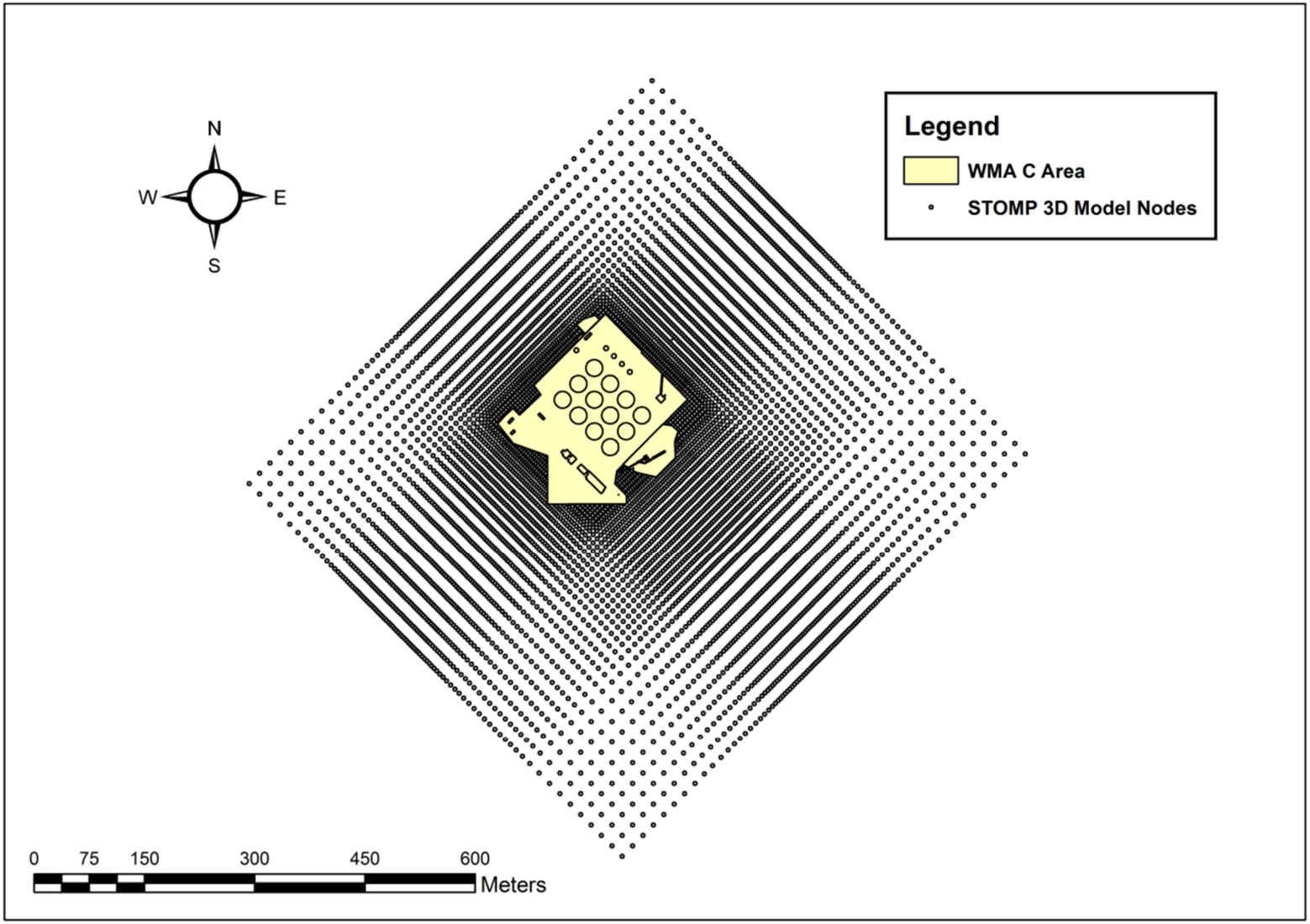
First, the approximate thicknesses of the HSUs were extracted from the STOMP©-based model under each of the twelve 100-series tank and four 200-series tank locations. Figure 7-32 shows the location of the nodes, along with the cross-section lines used in extracting the HSU thickness. Figure 7-33 shows the northwest-southeast trending geologic cross-sections through the tank farm area, while Table 7-14 summarizes the thicknesses of the HSUs directly underneath the tanks, along with the median values of the HSU thicknesses. The median value of the 100-series tanks is very similar to the HSU thickness below tank C-105. Similarly, median value for 200-series tanks is close to the thickness below tank C-203. Therefore, tanks C-105 and C-203 were selected as representative columns for the flow-field abstraction for the 100-series tanks and 200-series tanks, respectively.

The flow-field abstractions were performed separately for the 100-series and 200-series tanks because (a) 100-series tanks are 22.9 m (75) ft in diameter compared to 6.1 m (20 ft) in diameter for the 200-series tanks, which leads to different flow paths, and (b) the thickness of HSU below the 100-series tanks differs from the 200-series tanks.

Due to varying recharge conditions at the top boundary (see Section 7.3.2.2 Recharge subsection for details), the moisture content and Darcy flux profiles within the soil column vary with depth and respond differently at different times as shown in Figures 7-34 and 7-35, respectively. While the surface barrier is effective (between years 2020 and 2520), moisture content and Darcy fluxes decrease with time as they respond to the change in the recharge rate from 100 mm/yr to 0.50 mm/yr (3.94 in./yr to 0.02 in./yr). After the barrier design period (year 2520 onwards), moisture content and Darcy fluxes equilibrate quickly to the change in recharge rate from 0.50 mm/yr to 3.5 mm/yr (0.02 in./yr to 0.14 in./yr). The flow-field abstraction process was implemented to capture these trends.

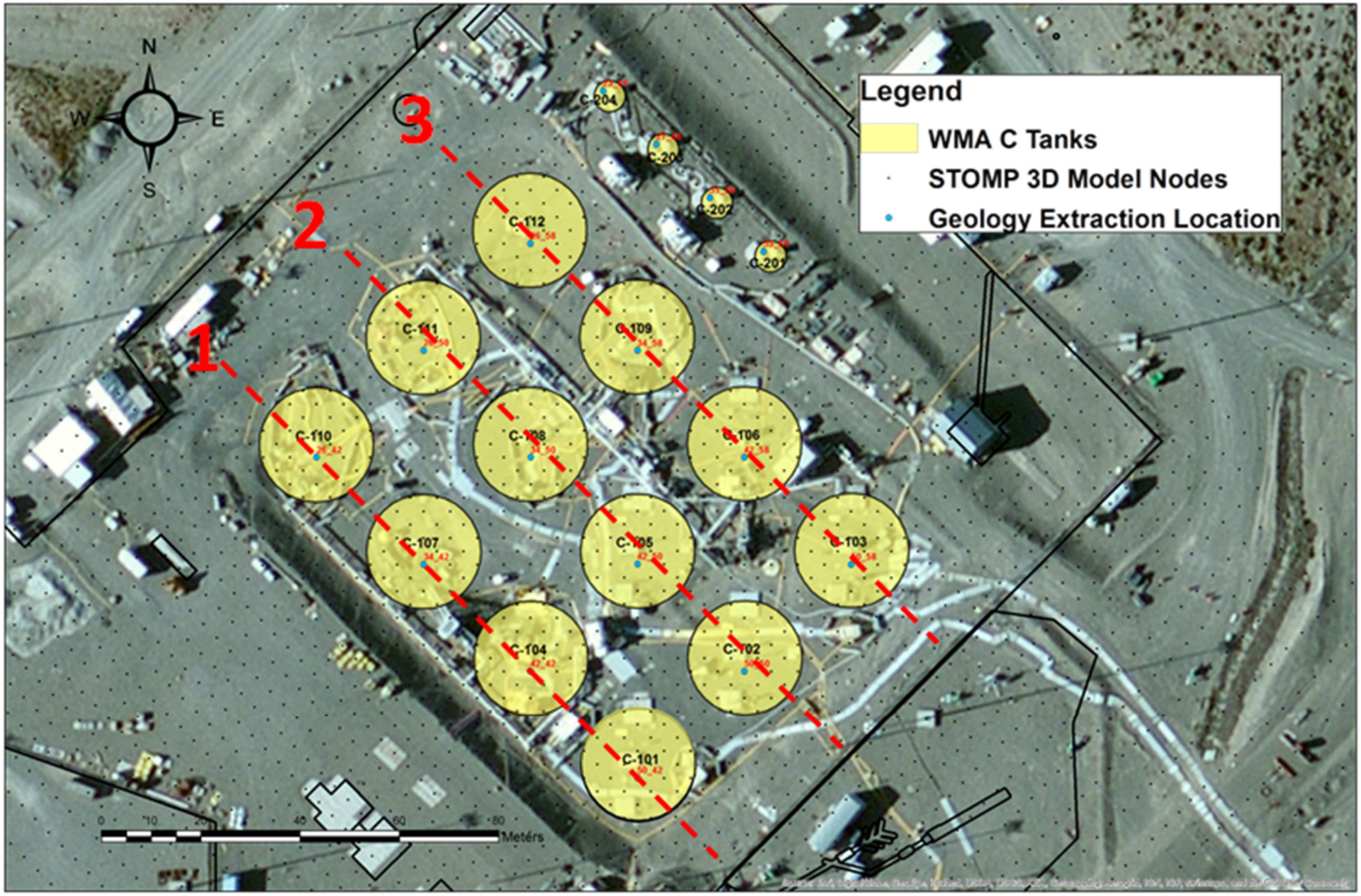
The representative hydrostratigraphic columns for the 100-series tanks and 200-series tanks are compared against the vertical discretization chosen for the system-level model in Figure 7-36. Also presented is the vertical discretization implemented in the STOMP©-based model. For the system-level model, finer discretization was chosen at shallow depths with increasingly coarser discretization at deeper depths. However, near the HSU contacts, finer discretization was used to capture the flow field at the interface. Coarser discretization was allowable in the deeper portion of the vadose zone (e.g., H3 gravelly sand) because the flow field did not change appreciably with depth.

**Figure 7-31. Waste Management Area C Subsurface Transport Over Multiple Phases Three-Dimensional Model Subsurface Transport Over Multiple Phases (STOMP©)-Based Model Node Locations.**




STOMP© 3D = Subsurface Transport Over Multiple Phases (code) three-dimensional WMA = Waste Management Area

**Figure 7-32. Three-Dimensional Subsurface Transport Over Multiple Phases (STOMP©)-Based Model Node Locations for Waste Management Area C along with Location of Cross-section Lines.**




STOMP© 3D = Subsurface Transport Over Multiple Phases (code) three-dimensional WMA = Waste Management Area

**Figure 7-33. Northwest-Southeast Trending Geologic Cross-sections Through the Tank Farm Using Information from Three-Dimensional Subsurface Transport Over Multiple Phases (STOMP©)-Based Model.**

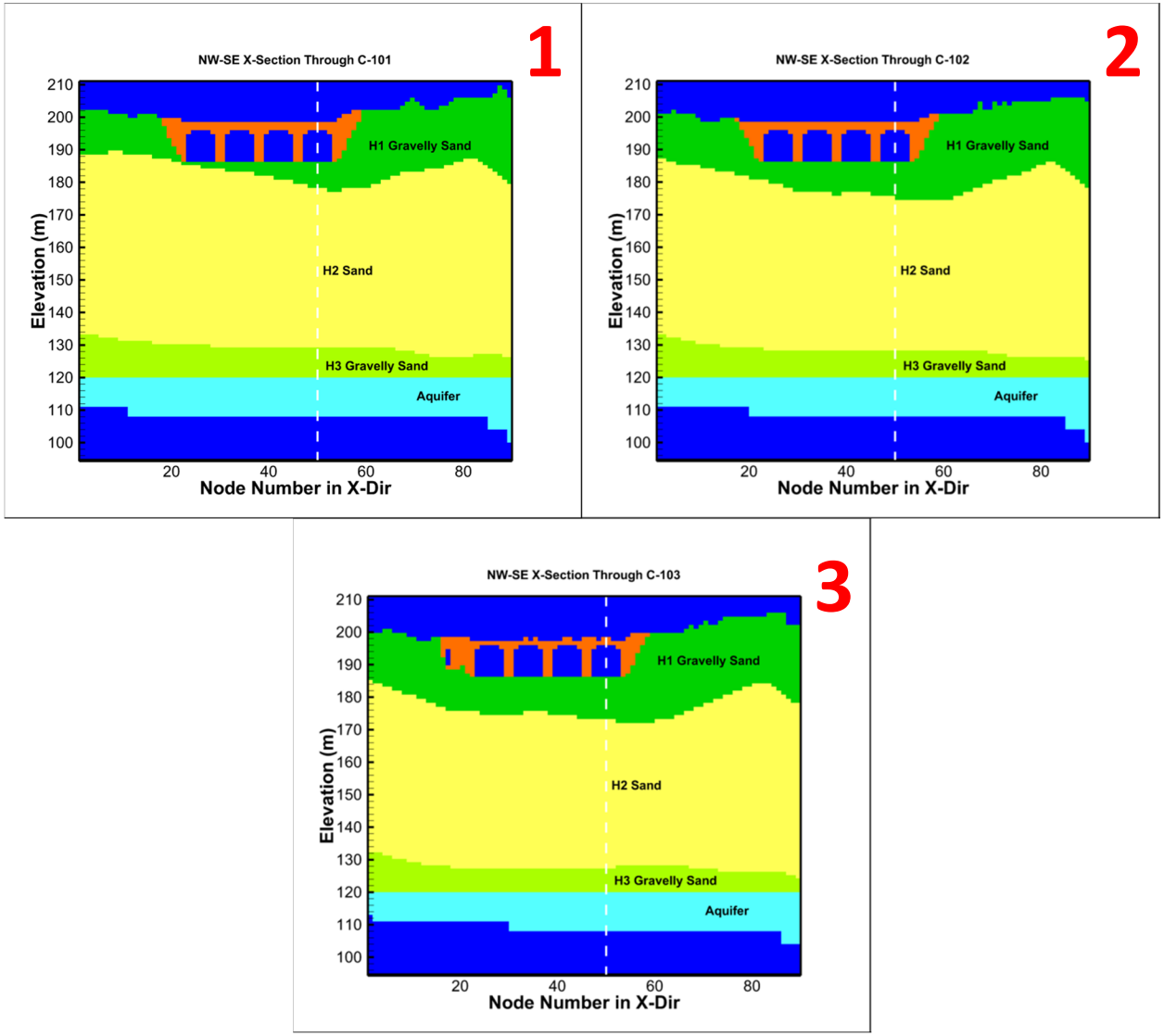


**Table 7-14. Hydrostratigraphic Unit Thickness Under the Tanks Taken From the Three-Dimensional Subsurface Transport Over Multiple Phases (STOMP©)-Based Model.**

| Tank | STOMP_NODE (I_J) | H1 Gravelly Sand (m) | H2 Sand (m) | H3 Gravelly Sand (m) | Aquifer (m) |
|---|---|---|---|---|---|
| **241-C-101** | 50_42 | 8.00 | 49.00 | 9.25 | 12.00 |
| **241-C-102** | 50_50 | 11.75 | 46.25 | 8.25 | 12.00 |
| **241-C-103** | 50_58 | 13.00 | 46.00 | 7.25 | 12.00 |
| **241-C-104** | 42_42 | 5.50 | 51.50 | 9.25 | 12.00 |
| **241-C-105** | 42_50 | 9.25 | 48.75 | 8.25 | 12.00 |
| **241-C-106** | 42_58 | 11.75 | 47.25 | 7.25 | 12.00 |
| **241-C-107** | 34_42 | 3.00 | 54.00 | 9.25 | 12.00 |
| **241-C-108** | 34_50 | 9.25 | 48.75 | 8.25 | 12.00 |
| **241-C-109** | 34_58 | 10.50 | 48.50 | 7.25 | 12.00 |
| **241-C-110** | 26_42 | 2.00 | 54.00 | 10.25 | 12.00 |
| **241-C-111** | 26_50 | 6.75 | 51.25 | 8.25 | 12.00 |
| **241-C-112** | 26_58 | 11.75 | 47.25 | 7.25 | 9.00 |
| **241-C-201** | 35_66 | 13.00 | 47.00 | 6.25 | 9.00 |
| **241-C-202** | 31_66 | 13.00 | 48.00 | 5.25 | 9.00 |
| **241-C-203** | 27_66 | 14.25 | 46.75 | 5.25 | 9.00 |
| **241-C-204** | 23_66 | 14.25 | 46.75 | 5.25 | 9.00 |
| **Median** | 100-Series Tank | 9.2 | 48.7 | 8.2 | 12.0 |
| **Median** | 200-Series Tank | 13.6 | 47.1 | 5.5 | 9.0 |

Subsurface Transport Over Multiple Phases (STOMP)© is copyrighted by Battelle Memorial Institute, 1996.

The STOMP©-based model nodes that were used to represent the moisture content and Darcy flux for the grid cells in the system model are highlighted in brown color in Figure 7-36. For example, the H1 Gravelly Sand unit in the representative column for the 100-series tank has a total thickness of 9.25 m (30.3 ft) and is divided into three grid cells of 2 m, 3.5 m and 3.75 m (6.6 ft, 11.5 ft and 12.3 ft) thickness. The flow field (moisture content and Darcy flux) extracted from STOMP© model node 69 is applied in the first cell of this unit in the system-level abstraction model. Similarly, the flow field from STOMP© model node 66 and node 63 is applied to the second and third cell of this unit in the system model. The H2 Sand unit is the thickest HSU in the vertical profile. It is discretized into a 3.75-m (12.3-ft) grid cell at the top and 5-m (16.4-ft) grid cell at the bottom. The middle 40 m (131 ft) is discretized into 80 grid cells, each being 0.5 m (1.6 ft) in length to match the 0.25-m (0.82-ft) longitudinal dispersivity applied within the H2 Sand unit (the numerical dispersivity in GoldSim© cell is calculated to be equal to half the cell length). The top and bottom grid cells for the H2 Sand unit are assigned the

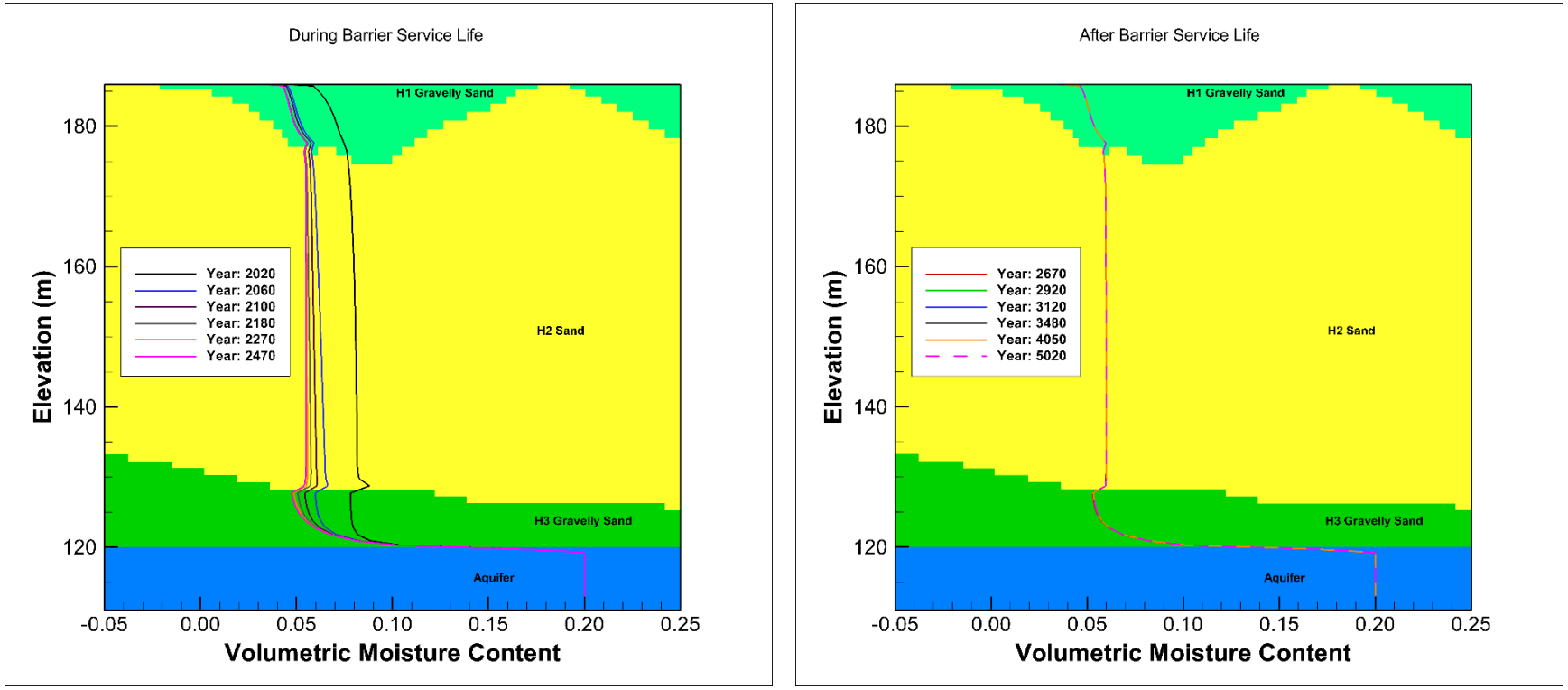
flow field extracted from STOMP© nodes 61 and 24, respectively, while the middle 40-m (131-ft) length (consisting of 20 grid cells) is represented by the flow field from STOMP© node 47. A single flow field over the 40-m (131-ft) length is used, since the flow field varies little for the corresponding STOMP© nodes at depth. A similar discretization scheme is adopted for the 200-series tanks as shown in Figure 7-36. The details of the grid discretization are presented in Table 7-15.

Figure 7-37 provides an overview of how the moisture content and Darcy flux vary over time for the selected STOMP© nodes in relation to the location in the vertical direction in the system model under an intact 100-series tank. This flow field is applied to model the transport underneath the 100-series tank. The representative flow field underneath an intact 200-series tank is presented in Figure 7-38. In the early time period, the moisture content and Darcy flux decreases due to the decrease in recharge rate from 100 mm/yr to 0.50 mm/yr (3.94 in./yr to 0.02 in./yr) associated with the emplacement of the surface barrier. As the surface barrier is assumed to be degraded 500 years after closure, the recharge rate transitions from a barrier rate of 0.5 mm/yr (0.02 in./yr) to a natural background rate of 3.5 mm/yr (0.14 in./yr), and reaches steady state by year 3000. The STOMP© node 14 used to set the flow field for the grid cell at the base of the H3 Gravelly Sand unit shows high moisture content because it is located in the capillary fringe just above the water table.

The above results are for the situation when the grout is structurally stable and provides a hydraulic barrier. However, a number of the sensitivity cases evaluate conditions where the effectiveness of grout as a hydraulic barrier is assumed to degrade at different times. Under degraded grout conditions, the grout is assumed to be highly fractured, and the infill material in the tank is assumed to behave like a porous material with hydraulic properties same as the H2 Sand unit. The STOMP©-based model is run with the H2-sand hydraulic properties for the tank, and the flow field is calculated and abstracted in a manner similar to that described earlier for the intact tank. The flow field is calculated separately for the degraded tank conditions for the 100-series and 200-series tanks, as shown in Figure 7-39. One additional STOMP© node result (node 73) is extracted and added to the system model to represent the flow conditions inside the tank. In the sensitivity cases, when the tank degradation occurs, the flow field is switched from the intact tank flow field to the degraded tank flow field. As a result, the contaminants are released via advection at the time when the tank is degraded in addition to the ongoing diffusive release mechanism.

The flow field applied to pipeline releases is calculated separately. Vertical Darcy fluxes and volumetric moisture contents from the STOMP© nodes that fall within the pipeline source area (150 m by 150 m [492 ft by 492 ft]) but outside the tank footprint are averaged to calculate the pipeline flow field. The representative hydrostratigraphic column for the 100-series tanks is applied to the pipeline source area. Advective flow occurs through the pipelines for all time periods. The hydraulic effect of the presence of buried pipelines in the vadose zone are not modeled explicitly, and the areas occupied by the pipelines are modeled with hydraulic properties of soil backfill material.

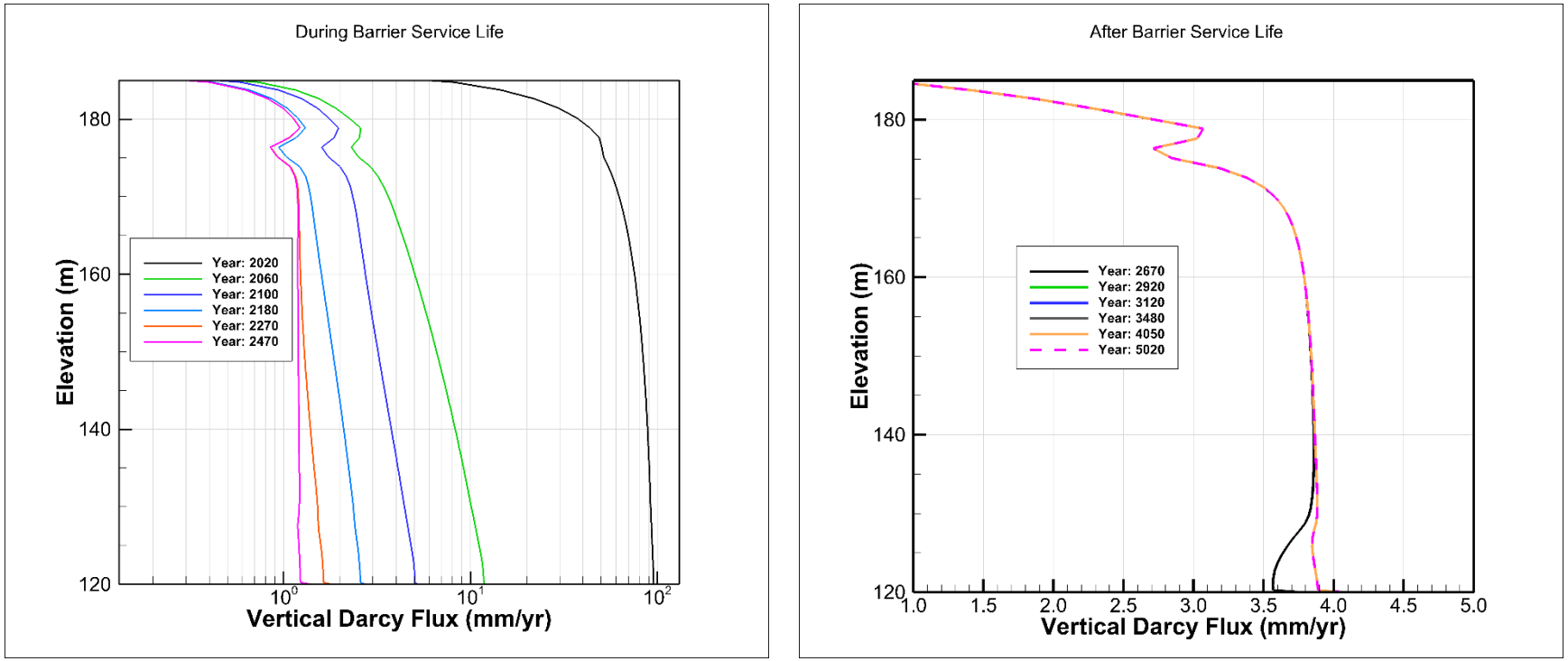
**Figure 7-34. Moisture Content Distribution below Tank 241-C-105 at Various Times during (a) Surface Barrier Design Time Period of 500 years Following Closure and (b) Post-Surface Barrier Design Time Period.**




(a) (b)

Note: Barrier Service Life assumes intact surface cover leading to reduced net infiltration while Post-Barrier Service Life assumes degraded surface cover.

**Figure 7-35. Vertical Darcy Flux Distribution below Tank 241-C-105 at Various Times.**




(a) (b)

**Figure 7-36. Representative Hydrostratigraphic Column for (a) 100-Series and (b) 200-Series Tanks.**

| Hydrostratigraphy Below C-105 | STOMP Node Elevation (m) | STOMP Node Numbers | STOMP Vertical Discretization (m) | GoldSim Vertical Discretization (m) |
|---|---|---|---|---|
| H1 Gravelly Sand | 185.75 | 69 | 1.00 | 2 m |
| | 184.75 | 68 | 1.00 | |
| | 183.75 | 67 | 1.00 | 3.5 m |
| | 182.625 | 66 | 1.25 | |
| | 181.375 | 65 | 1.25 | |
| | 180.125 | 64 | 1.25 | 3.75 m |
| | 178.875 | 63 | 1.25 | |
| | 177.625 | 62 | 1.25 | |
| H2 Sand | 176.375 | 61 | 1.25 | 3.75 m |
| | 175.125 | 60 | 1.25 | |
| | 173.875 | 59 | 1.25 | |
| | 172.625 | 58 | 1.25 | 2 m (over 40 m thickness) |
| | 171.375 | 57 | 1.25 | |
| | 170.125 | 56 | 1.25 | |
| | 168.875 | 55 | 1.25 | |
| | 167.625 | 54 | 1.25 | |
| | 166.375 | 53 | 1.25 | |
| | 165.125 | 52 | 1.25 | |
| | 163.875 | 51 | 1.25 | |
| | 162.625 | 50 | 1.25 | |
| | 161.375 | 49 | 1.25 | |
| | 160.125 | 48 | 1.25 | |
| | 158.875 | 47 | 1.25 | |
| | 157.625 | 46 | 1.25 | |
| | 156.375 | 45 | 1.25 | |
| | 155.125 | 44 | 1.25 | |
| | 153.875 | 43 | 1.25 | |
| | 152.625 | 42 | 1.25 | |
| | 151.375 | 41 | 1.25 | |
| | 150.125 | 40 | 1.25 | |
| | 148.875 | 39 | 1.25 | |
| | 147.625 | 38 | 1.25 | |
| | 146.375 | 37 | 1.25 | |
| | 145.125 | 36 | 1.25 | |
| | 143.875 | 35 | 1.25 | |
| | 142.625 | 34 | 1.25 | |
| | 141.375 | 33 | 1.25 | |
| | 140.125 | 32 | 1.25 | |
| | 138.875 | 31 | 1.25 | |
| | 137.625 | 30 | 1.25 | |
| | 136.375 | 29 | 1.25 | |
| | 135.125 | 28 | 1.25 | |
| | 133.875 | 27 | 1.25 | |
| | 132.75 | 26 | 1.00 | 5 m |
| | 131.75 | 25 | 1.00 | |
| | 130.75 | 24 | 1.00 | |
| | 129.75 | 23 | 1.00 | |
| | 128.75 | 22 | 1.00 | |
| H3 Gravelly Sand | 127.75 | 21 | 1.00 | 7 m |
| | 126.75 | 20 | 1.00 | |
| | 125.75 | 19 | 1.00 | |
| | 124.75 | 18 | 1.00 | |
| | 123.75 | 17 | 1.00 | |
| | 122.75 | 16 | 1.00 | |
| | 121.75 | 15 | 1.00 | |
| | 120.875 | 14 | 0.75 | 1.25 m |
| | 120.25 | 13 | 0.50 | |
| Aquifer | 119.75 | 12 | 0.50 | 12 m |
| | 119.25 | 11 | 0.50 | |
| | 118.625 | 10 | 0.75 | |
| | 117.75 | 9 | 1.00 | |
| | 116.625 | 8 | 1.25 | |
| | 115.25 | 7 | 1.50 | |
| | 113.75 | 6 | 1.50 | |
| | 112 | 5 | 2.00 | |
| | 109.5 | 4 | 3.00 | |
| Inactive | 106 | 3 | 4.00 | |
| | 102 | 2 | 4.00 | |
| | 97.5 | 1 | 5.00 | |

Node used in Flow-Field abstraction

(a)

| Hydrostratigraphy Below C-203 | STOMP Node Elevation (m) | STOMP Node Numbers | STOMP Vertical Discretization (m) | GoldSim Vertical Discretization (m) |
|---|---|---|---|---|
| H1 Gravelly Sand | 185.75 | 69 | 1.00 | 2 m |
| | 184.75 | 68 | 1.00 | |
| | 183.75 | 67 | 1.00 | 3.5 m |
| | 182.625 | 66 | 1.25 | |
| | 181.375 | 65 | 1.25 | |
| | 180.125 | 64 | 1.25 | 8.75 m |
| | 178.875 | 63 | 1.25 | |
| | 177.625 | 62 | 1.25 | |
| | 176.375 | 61 | 1.25 | |
| | 175.125 | 60 | 1.25 | |
| | 173.875 | 59 | 1.25 | |
| | 172.625 | 58 | 1.25 | |
| H2 Sand | 171.375 | 57 | 1.25 | 3.75 m |
| | 170.125 | 56 | 1.25 | |
| | 168.875 | 55 | 1.25 | |
| | 167.625 | 54 | 1.25 | 2 m (over 40 m thickness) |
| | 166.375 | 53 | 1.25 | |
| | 165.125 | 52 | 1.25 | |
| | 163.875 | 51 | 1.25 | |
| | 162.625 | 50 | 1.25 | |
| | 161.375 | 49 | 1.25 | |
| | 160.125 | 48 | 1.25 | |
| | 158.875 | 47 | 1.25 | |
| | 157.625 | 46 | 1.25 | |
| | 156.375 | 45 | 1.25 | |
| | 155.125 | 44 | 1.25 | |
| | 153.875 | 43 | 1.25 | |
| | 152.625 | 42 | 1.25 | |
| | 151.375 | 41 | 1.25 | |
| | 150.125 | 40 | 1.25 | |
| | 148.875 | 39 | 1.25 | |
| | 147.625 | 38 | 1.25 | |
| | 146.375 | 37 | 1.25 | |
| | 145.125 | 36 | 1.25 | |
| | 143.875 | 35 | 1.25 | |
| | 142.625 | 34 | 1.25 | |
| | 141.375 | 33 | 1.25 | |
| | 140.125 | 32 | 1.25 | |
| | 138.875 | 31 | 1.25 | |
| | 137.625 | 30 | 1.25 | |
| | 136.375 | 29 | 1.25 | |
| | 135.125 | 28 | 1.25 | |
| | 133.875 | 27 | 1.25 | |
| | 132.75 | 26 | 1.00 | |
| | 131.75 | 25 | 1.00 | |
| | 130.75 | 24 | 1.00 | |
| | 129.75 | 23 | 1.00 | |
| | 128.75 | 22 | 1.00 | |
| | 127.75 | 21 | 1.00 | 3 |
| | 126.75 | 20 | 1.00 | |
| | 125.75 | 19 | 1.00 | |
| H3 Gravelly Sand | 124.75 | 18 | 1.00 | 4 |
| | 123.75 | 17 | 1.00 | |
| | 122.75 | 16 | 1.00 | |
| | 121.75 | 15 | 1.00 | |
| | 120.875 | 14 | 0.75 | 1.25 |
| | 120.25 | 13 | 0.50 | |
| Aquifer | 119.75 | 12 | 0.50 | 9 |
| | 119.25 | 11 | 0.50 | |
| | 118.625 | 10 | 0.75 | |
| | 117.75 | 9 | 1.00 | |
| | 116.625 | 8 | 1.25 | |
| | 115.25 | 7 | 1.50 | |
| | 113.75 | 6 | 1.50 | |
| | 112 | 5 | 2.00 | |
| Inactive | 109.5 | 4 | 3.00 | |
| | 106 | 3 | 4.00 | |
| | 102 | 2 | 4.00 | |
| | 97.5 | 1 | 5.00 | |

Node used in Flow-Field abstraction

(b)

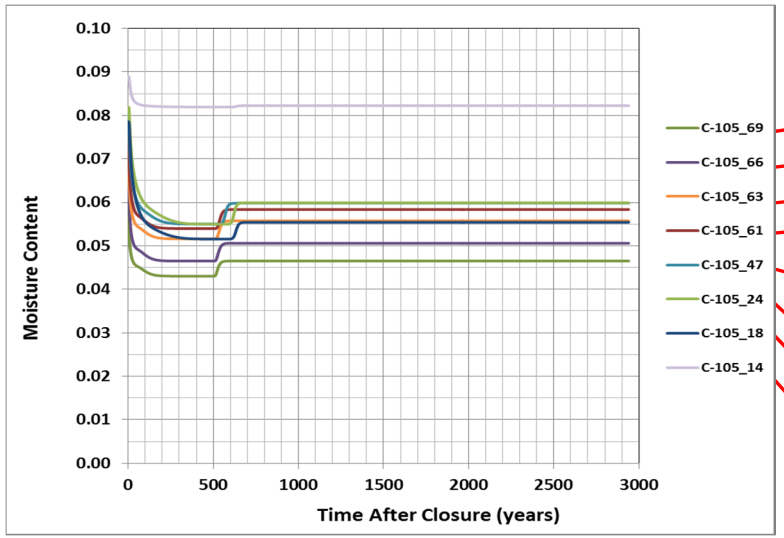
The saturated zone is modeled as a 1-D aquifer, oriented along the primary flow direction using the aquifer pathway capability in GoldSim©. The volumetric flow rate through the aquifer is calculated based on the hydraulic gradient under steady-state conditions and saturated hydraulic conductivity consistent with the values used in the STOMP©-based model. The saturated zone thickness for the 100-series tanks is chosen to be 12 m (39.4 ft), while that for the 200-series tanks is chosen to be 9 m (29.5 ft) (Table 7-15).

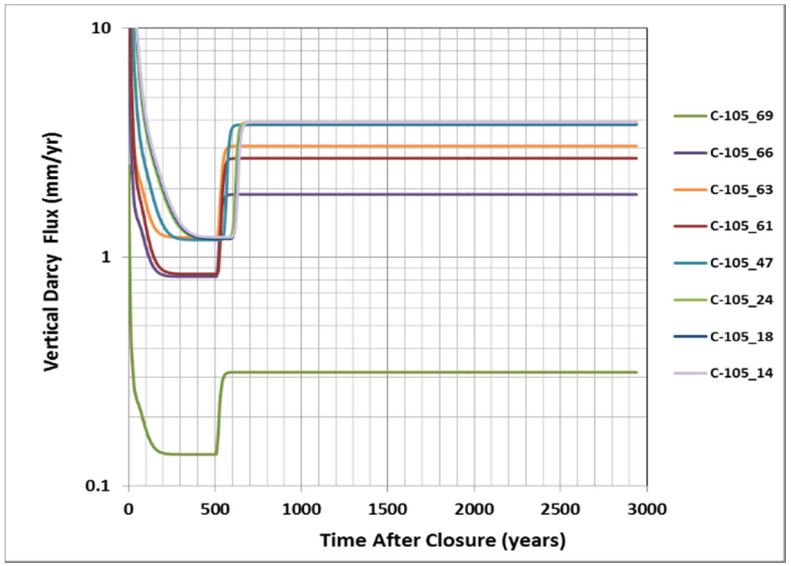
**Table 7-15. Vertical Grid Discretization and Flow Field for the System-Level Model.**

| | Unit | Thickness (m) | Number of Grid Block Cells | Grid Discretization | Flow Field Discretization (Moisture Content and Vertical Darcy Flux) |
|---|---|---|---|---|---|
| **100-Series Tanks** | H1 Gravelly Sand | 9.25 | 3 | 1 at 2 m,<br>1 at 3.5 m,<br>1 at 3.75 m | One flow field for each cell |
| | H2 Sand | 48.75 | 22 | 1 at 3.75 m,<br>20 cells of 2 m thickness each for a total of 40 m<br>1 at 5 m | One flow field for the first cell. One flow field for the next 20 cells and One flow field for the remaining one cell |
| | H3 Gravelly Sand | 8.25 | 2 | 1 at 7 m,<br>1 at 1.25 m. | One flow field for each cell |
| | Saturated Zone | 12.00 | | Aquifer pathway | One flow field |
| **200-Series Tanks** | H1 Gravelly Sand | 14.25 | 3 | 1 at 2 m,<br>1 at 3.5 m,<br>1 at 8.75 m | One flow field for each cell |
| | H2 Sand | 46.75 | 22 | 1 at 3.75 m,<br>20 cells of 2 m thickness each for a total of 40 m<br>1 at 3 m | One flow field for the first cell. One flow field for the next 20 cells and One flow field for the remaining one cell |
| | H3 Gravelly Sand | 5.50 | 2 | 1 at 4 m,<br>1 at 1.25 m. | One flow field per cell |
| | Saturated Zone | 9.00 | | Aquifer pathway | One flow field |

The mass flux from the vadose zone for each source term (each of the 100- and 200-series tanks, the C-301 catch tank, the 244-CR vault, and pipelines) is calculated separately. Each source term is then transported to the aquifer, assuming that vertical mass transport in the vadose zone stays within the footprint of the source area, ignoring any lateral dispersion as shown in Figure 7-40. The aquifer pathway from each source area starts under its associated source in WMA C and extends to the PoCal, 100 m (328 ft) downgradient from the WMA C fenceline along the groundwater flow direction. The width of the aquifer pathway is taken to be the width of the source area. The length of the aquifer pathway varies depending on the location of the source area being modeled (tanks and ancillary equipment), relative to the PoCal 100 m (328 ft) downgradient from the WMA C fenceline along the groundwater flow path. As an example, the total length of the aquifer pathway from tank C-102 is ~144 m (472 ft), compared with ~174 m (571 ft) for tank C-105, and ~235 m (771 ft) for tank C-111. For the pipeline source, the aquifer pathway is assumed to begin at the center of the WMA C area leading to a total length of 175 m (574 ft). This length represents an average distance from all of the pipeline sources to the PoCal.

**Figure 7-37. Representative Flow Field Applied Under 100-Series Tank for the Base Case (Intact Tank Condition).**




| Hydrostratigraphy Below C-105 | STOMP Node Elevation (m) | STOMP Node Numbers | STOMP Vertical Discretization (m) | GoldSim Vertical Discretization (m) |
|---|---|---|---|---|
| H1 Gravelly Sand | 185.75 | 69 | 1.00 | 2 m |
| | 184.75 | 68 | 1.00 | |
| | 183.75 | 67 | 1.00 | 3.5 m |
| | 182.625 | 66 | 1.25 | |
| | 181.375 | 65 | 1.25 | |
| | 180.125 | 64 | 1.25 | 3.75 m |
| | 178.875 | 63 | 1.25 | |
| | 177.625 | 62 | 1.25 | |
| H2 Sand | 176.375 | 61 | 1.25 | 3.75 m |
| | 175.125 | 60 | 1.25 | |
| | 173.875 | 59 | 1.25 | |
| | 172.625 | 58 | 1.25 | 2 m (over 40 m thickness) |
| | 171.375 | 57 | 1.25 | |
| | 170.125 | 56 | 1.25 | |
| | 168.875 | 55 | 1.25 | |
| | 167.625 | 54 | 1.25 | |
| | 166.375 | 53 | 1.25 | |
| | 165.125 | 52 | 1.25 | |
| | 163.875 | 51 | 1.25 | |
| | 162.625 | 50 | 1.25 | |
| | 161.375 | 49 | 1.25 | |
| | 160.125 | 48 | 1.25 | |
| | 158.875 | 47 | 1.25 | |
| | 157.625 | 46 | 1.25 | |
| | 156.375 | 45 | 1.25 | |
| | 155.125 | 44 | 1.25 | |
| | 153.875 | 43 | 1.25 | |
| | 152.625 | 42 | 1.25 | |
| | 151.375 | 41 | 1.25 | |
| | 150.125 | 40 | 1.25 | |
| | 148.875 | 39 | 1.25 | |
| | 147.625 | 38 | 1.25 | |
| | 146.375 | 37 | 1.25 | |
| | 145.125 | 36 | 1.25 | |
| | 143.875 | 35 | 1.25 | |
| | 142.625 | 34 | 1.25 | |
| | 141.375 | 33 | 1.25 | |
| | 140.125 | 32 | 1.25 | |
| | 138.875 | 31 | 1.25 | |
| | 137.625 | 30 | 1.25 | |
| | 136.375 | 29 | 1.25 | |
| | 135.125 | 28 | 1.25 | |
| | 133.875 | 27 | 1.25 | |
| | 132.75 | 26 | 1.00 | 5 m |
| | 131.75 | 25 | 1.00 | |
| | 130.75 | 24 | 1.00 | |
| | 129.75 | 23 | 1.00 | |
| | 128.75 | 22 | 1.00 | |
| H3 Gravelly Sand | 127.75 | 21 | 1.00 | 7 m |
| | 126.75 | 20 | 1.00 | |
| | 125.75 | 19 | 1.00 | |
| | 124.75 | 18 | 1.00 | |
| | 123.75 | 17 | 1.00 | |
| | 122.75 | 16 | 1.00 | |
| | 121.75 | 15 | 1.00 | |
| | 120.875 | 14 | 0.75 | 1.25 m |
| | 120.25 | 13 | 0.50 | |
| Aquifer | 119.75 | 12 | 0.50 | 12 m |
| | 119.25 | 11 | 0.50 | |
| | 118.625 | 10 | 0.75 | |
| | 117.75 | 9 | 1.00 | |
| | 116.625 | 8 | 1.25 | |
| | 115.25 | 7 | 1.50 | |
| | 113.75 | 6 | 1.50 | |
| | 112 | 5 | 2.00 | |
| | 109.5 | 4 | 3.00 | |
| Inactive | 106 | 3 | 4.00 | |
| | 102 | 2 | 4.00 | |
| | 97.5 | 1 | 5.00 | |

Node used in Flow-Field abstraction

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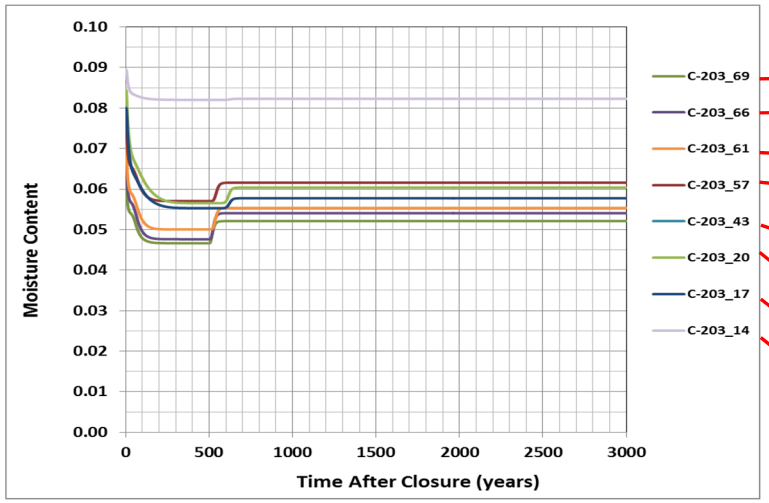
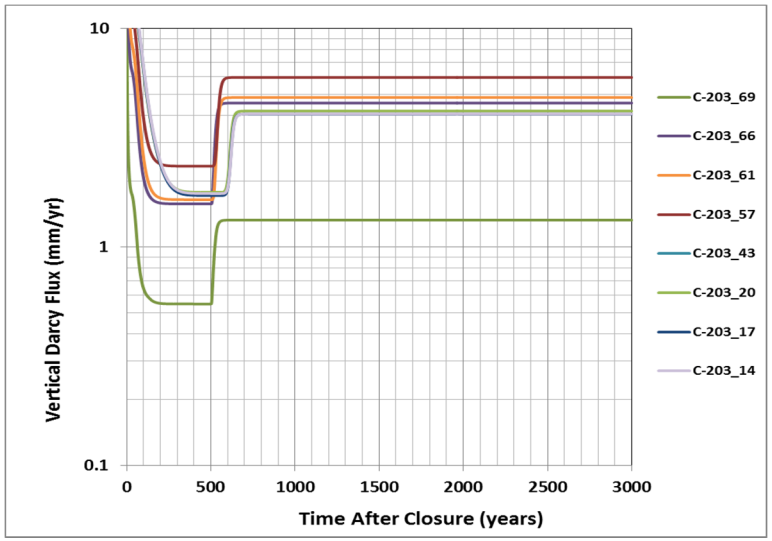
GoldSim© simulation software is copyrighted by GoldSim Technology Group LLC of Issaquah, Washington (see http://www.goldsim.com).

**Figure 7-38. Representative Flow Field Applied Under 200-Series Tank for the Base Case (Intact Tank Condition).**




| Hydrostratigraphy Below C-203 | STOMP Node Elevation (m) | STOMP Node Numbers | STOMP Vertical Discretization (m) | GoldSim Vertical Discretization (m) |
|---|---|---|---|---|
| H1 Gravelly Sand | 185.75 | 69 | 1.00 | 2 |
| | 184.75 | 68 | 1.00 | |
| | 183.75 | 67 | 1.00 | 3.5 |
| | 182.625 | 66 | 1.25 | |
| | 181.375 | 65 | 1.25 | |
| | 180.125 | 64 | 1.25 | 8.75 |
| | 178.875 | 63 | 1.25 | |
| | 177.625 | 62 | 1.25 | |
| | 176.375 | 61 | 1.25 | |
| | 175.125 | 60 | 1.25 | |
| | 173.875 | 59 | 1.25 | |
| | 172.625 | 58 | 1.25 | |
| H2 Sand | 171.375 | 57 | 1.25 | 3.75 |
| | 170.125 | 56 | 1.25 | |
| | 168.875 | 55 | 1.25 | |
| | 167.625 | 54 | 1.25 | 2 m (over 40 m thickness) |
| | 166.375 | 53 | 1.25 | |
| | 165.125 | 52 | 1.25 | |
| | 163.875 | 51 | 1.25 | |
| | 162.625 | 50 | 1.25 | |
| | 161.375 | 49 | 1.25 | |
| | 160.125 | 48 | 1.25 | |
| | 158.875 | 47 | 1.25 | |
| | 157.625 | 46 | 1.25 | |
| | 156.375 | 45 | 1.25 | |
| | 155.125 | 44 | 1.25 | |
| | 153.875 | 43 | 1.25 | |
| | 152.625 | 42 | 1.25 | |
| | 151.375 | 41 | 1.25 | |
| | 150.125 | 40 | 1.25 | |
| | 148.875 | 39 | 1.25 | |
| | 147.625 | 38 | 1.25 | |
| | 146.375 | 37 | 1.25 | |
| | 145.125 | 36 | 1.25 | |
| | 143.875 | 35 | 1.25 | |
| | 142.625 | 34 | 1.25 | |
| | 141.375 | 33 | 1.25 | |
| | 140.125 | 32 | 1.25 | |
| | 138.875 | 31 | 1.25 | |
| | 137.625 | 30 | 1.25 | |
| | 136.375 | 29 | 1.25 | |
| | 135.125 | 28 | 1.25 | |
| | 133.875 | 27 | 1.25 | |
| | 132.75 | 26 | 1.00 | |
| | 131.75 | 25 | 1.00 | |
| | 130.75 | 24 | 1.00 | |
| | 129.75 | 23 | 1.00 | |
| | 128.75 | 22 | 1.00 | |
| | 127.75 | 21 | 1.00 | |
| | 126.75 | 20 | 1.00 | |
| | 125.75 | 19 | 1.00 | |
| H3 Gravelly Sand | 124.75 | 18 | 1.00 | 4 |
| | 123.75 | 17 | 1.00 | |
| | 122.75 | 16 | 1.00 | |
| | 121.75 | 15 | 1.00 | |
| | 120.875 | 14 | 0.75 | 1.25 |
| | 120.25 | 13 | 0.50 | |
| Aquifer | 119.75 | 12 | 0.50 | 9 |
| | 119.25 | 11 | 0.50 | |
| | 118.625 | 10 | 0.75 | |
| | 117.75 | 9 | 1.00 | |
| | 116.625 | 8 | 1.25 | |
| | 115.25 | 7 | 1.50 | |
| | 113.75 | 6 | 1.50 | |
| | 112 | 5 | 2.00 | |
| Inactive | 109.5 | 4 | 3.00 | |
| | 106 | 3 | 4.00 | |
| | 102 | 2 | 4.00 | |
| | 97.5 | 1 | 5.00 | |

Node used in Flow-Field abstraction

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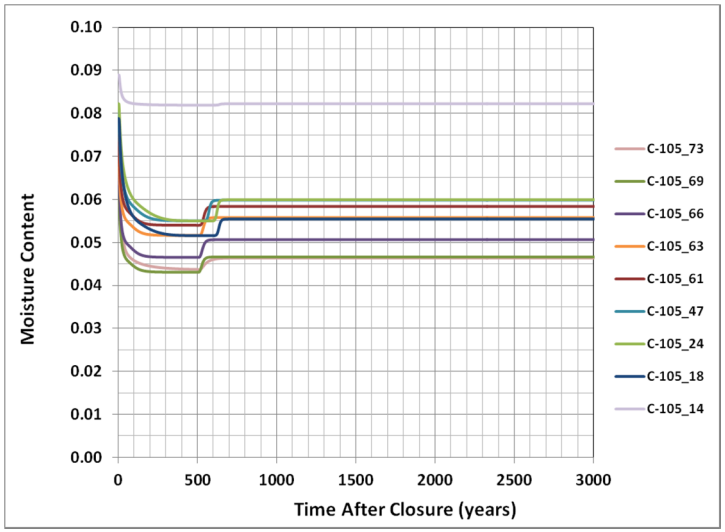
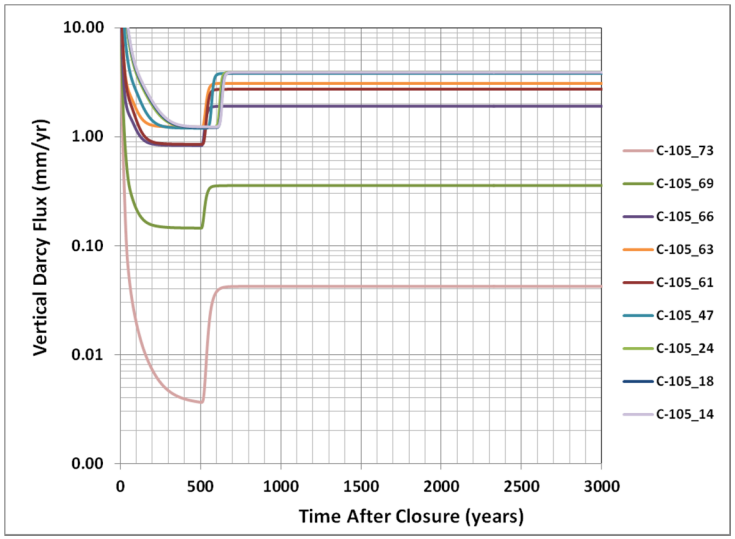
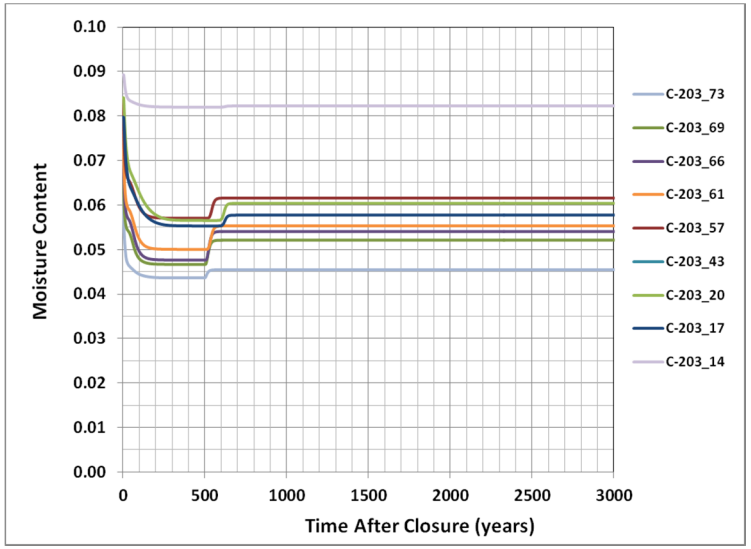
Subsurface Transport Over Multiple Phases (STOMP)© is copyrighted by Battelle Memorial Institute, 1996.

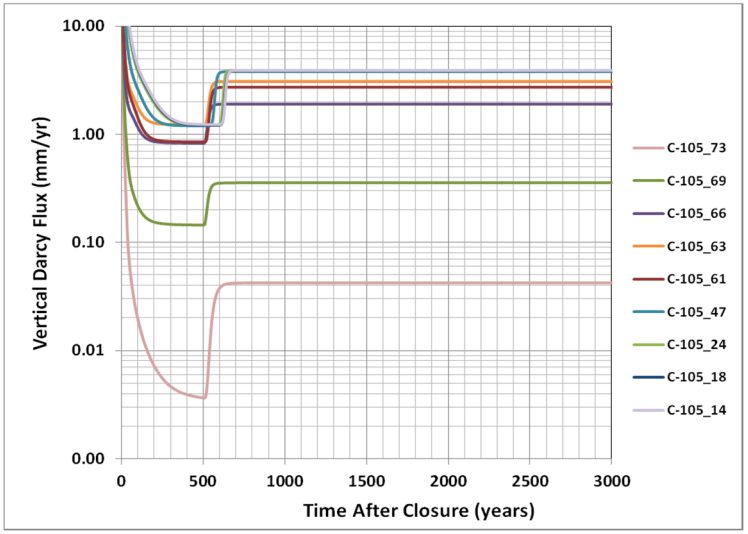
**Figure 7-39. Representative Flow Field Applied For Degraded Tank Conditions for (a) 100-Series Tank and (b) 200-Series Tank.**



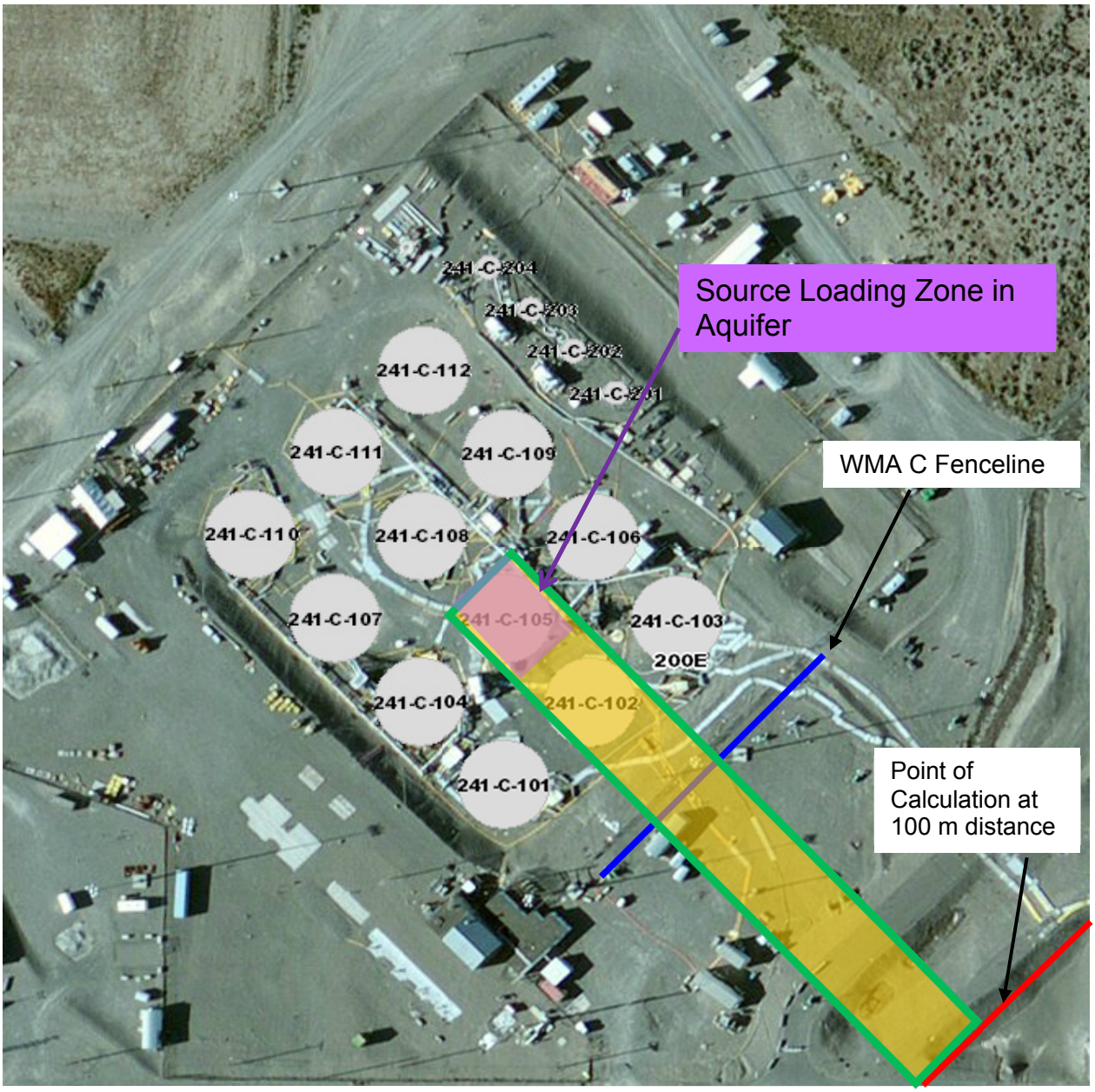

(a)




(b)

**Figure 7-40. Implementation of Aquifer Pathway for a Given Source Area Along with Points of Evaluation of Concentrations.**




WMA = Waste Management Area

The mass loading on the aquifer pathway from the vadose zone occurs over the length of the source parallel to the flow path. For the tank sources, this is equivalent to the diameter of the tank. For the pipeline source, the source loading from the vadose zone to the aquifer is conservatively assumed to occur over the 75 m (246 ft) that represents the half-length of the pipeline source area along the flow path.

The average aquifer pathway concentrations at the 100 m (328 ft) downgradient boundary are calculated for each source separately, by assuming that the mass within the defined 1-D aquifer

stream tube configuration does not laterally disperse. This 1-D approach tends to maximize the concentrations for a given source term, but it does not take account of overlapping plumes from lateral dispersion from other sources that are on parallel flow paths (Figure 7-40). To determine the maximum concentration, a separate calculation is performed. Since the highest concentrations were expected to occur along the centerline of the WMA C width, extended to the 100 m boundary due to location of highest residual inventory tanks along the centerline, the calculated concentrations for the C-102, C-105, C-108 and C-111 tank sources at the 100 m (328 ft) boundary were combined. These four tanks fall along a single flow path (stream tube), since the flow direction is aligned with the orientation of these tanks. The amount of additional contaminant mass from lateral dispersion along adjacent flow paths is included by using an analytical solution (*Plume function* within GoldSim©) that calculates the concentration away from the centerline of the plume. Using this approach, the concentration from surrounding aquifer pathways are calculated and added to the combined concentration for the aquifer pathway that includes C-102, C-105, C-108, and C-111 tank sources. The two laterally adjacent and parallel aquifer pathways are (a) along the orientation of tanks C-101, C-104, C-107, and C-110, and (b) along the orientation of tanks C-103, C-106, C-109, and C-112. The primary groundwater flow path on which the 200-series tanks occur is deemed too far to influence the concentrations along the centerline, and therefore is not considered based on evaluation of STOMP© 3-D model results.

A spatial-variability study was undertaken to evaluate the adequacy of using one representative flow field for all of the 100-series tanks. For this purpose, the vertical Darcy fluxes from STOMP©-based model nodes located underneath intact tanks were compared. The vertical Darcy flux underneath tank C-105 (located near the center of the tank farm) was compared to that of tank C-112 (located at the northern edge of the tank farm). The vertical Darcy flux under a 200-series tank (C-201) located near tank C-112 was also compared. The comparison results are presented in Figure 7-41 for two nodes. Node 69 is located ~0.5 m (1.6 ft) below the base of the tank, while node 63 is located ~3 m (9.8 ft) below node 69. The results indicate that for node 69 the vertical Darcy flux for tank C-105 matches closely with tank C-112, and is quite different from that of tank C-201. For node 63, which is deeper, the differences among the three tanks are minor. The large difference observed for node 63 is attributed to its location near the base of the tank, where the amount of flow diversion around the tank is influenced by its diameter. The smaller diameter of tank C-201 (6.1 m [20 ft]) exhibits small flow diversion, and the Darcy flux under the tank is relatively high compared to the larger flow diversion observed for the larger-diameter (23 m [75 ft]) C-105 and C-112 tanks. These observations support the use of one representative flow field for all 100-series tanks and another for all 200-series tanks.

Confirmation of the abstraction modeling approach for evaluating system performance was undertaken by comparing the contaminant transport results to the STOMP©-based model results for the base case (RPP-ENV-58782, Section 6.3.2.4 Abstraction Approach for System Level Modeling). Due to coarser vertical discretization employed in the 1-D abstraction model, the results from those nodes that are closest to the STOMP©-based model grid nodes are compared. The time-varying diffusive mass flux of $^{99}$Tc calculated using the source term parameters for tank C-105 was applied as boundary conditions to both models. A comparison between the dissolved concentration of $^{99}$Tc in the vadose zone using a STOMP© 3-D model and a GoldSim© 1-D model are presented for selected locations in the vadose zone (Figure 7-42 and Figure 7-43).

There is a good match between the 3-D process model and 1-D abstraction model throughout the full thickness of the vadose zone under the tank (~66 m [217 ft]).

For the saturated zone, the groundwater concentration predicted by the STOMP©-based model (at the highest concentration PoCal) is compared to the GoldSim©-based abstraction model results at 100 m (328 ft) downgradient of the WMA C fenceline along the tank C-105 aquifer pathway (Figure 7-44). The first breakthrough times match well, but the 1-D model produces slightly higher concentrations following the peak. This result is expected, as the 1-D aquifer pathway does not allow lateral dispersion of the mass and assumes constant flow rate through the steam tube. Given these differences in the conceptual model used in the two analyses, the agreement is very reasonable.

The results given in Figures 7-42, 7-43, and 7-44 indicate that the abstraction model is appropriate and sufficiently accurate for its intended use in evaluating system performance. The abstracted model was used to evaluate a range of sensitivity cases (Section 9 of this document).

**7.3.2.5 Biotic Pathway.** In this section, an evaluation is presented of the potential for burrowing animals or deep-rooting plants to penetrate deeply enough to contact the residual waste left in tanks and ancillary equipment in its final closed configuration.

At closure, a modified RCRA Subtitle C engineered cover will be placed over the waste. The upper layer of this cover is intended to mimic natural surface conditions to the extent possible. That is, natural vegetation will be planted on a soil layer intended to support growth of a stable ecology system that is the same as the surrounding conditions. The ambient ecological system is not totally pristine because colonization and agricultural practices have introduced additional nonnative species that will likely remain at the Hanford Site. Ecological conditions at the Hanford Site have been studied extensively since the start of Hanford Site operations, and numerous documents that describe and quantify local conditions have been completed. The most recent compilation (DOE/RL-2007-50, Central Plateau Ecological Risk Assessment Data Package Report) describes recent information and includes copies of significant previous summaries (e.g., DOE/RL-2001-54). The descriptions provided below are taken from these and other documents.

The Hanford Site is a shrub-steppe ecosystem that is dominated by a shrub overstory with a grass understory. Because the climate is semi-arid, the dominant large shrub is big sagebrush (*Artemisia tridentate*) and the main grasses are Sandberg's bluegrass (*Poa Sandbergii*) and bluebunch wheatgrass (*Pseudoregneria spicata*). A ubiquitous nonnative species at the Hanford Site is cheatgrass, which often makes up a large fraction of the grasses. Less abundant plant species on the Central Plateau include threetip sagebrush, bitterbrush, gray rabbitbrush, spiny Hopsage, Indian ricegrass, and prairie June grass. Altogether, over 100 species of plants have been observed in the 200 Area on the Central Plateau. A survey of the 200 Area made prior to its construction showed the presence of big sagebrush and an understory of which approximately 90% was a mix of cheatgrass and Sandberg's bluegrass (PNNL-14233). The remaining 10% of the understory was a mix of cheatgrass and needle-and-thread grass.

**Figure 7-41. Vertical Darcy Flux Extracted from Three-Dimensional Subsurface Transport Over Multiple Phases (STOMP©)-Based Model Nodes Located below Tanks 241-C-105, 241-C-112, and 241-C-201 along with Their Location in Waste Management Area C. Node 69 is located 0.5 m below the tank bottom while node 63 is located about 3 m below node 69.**

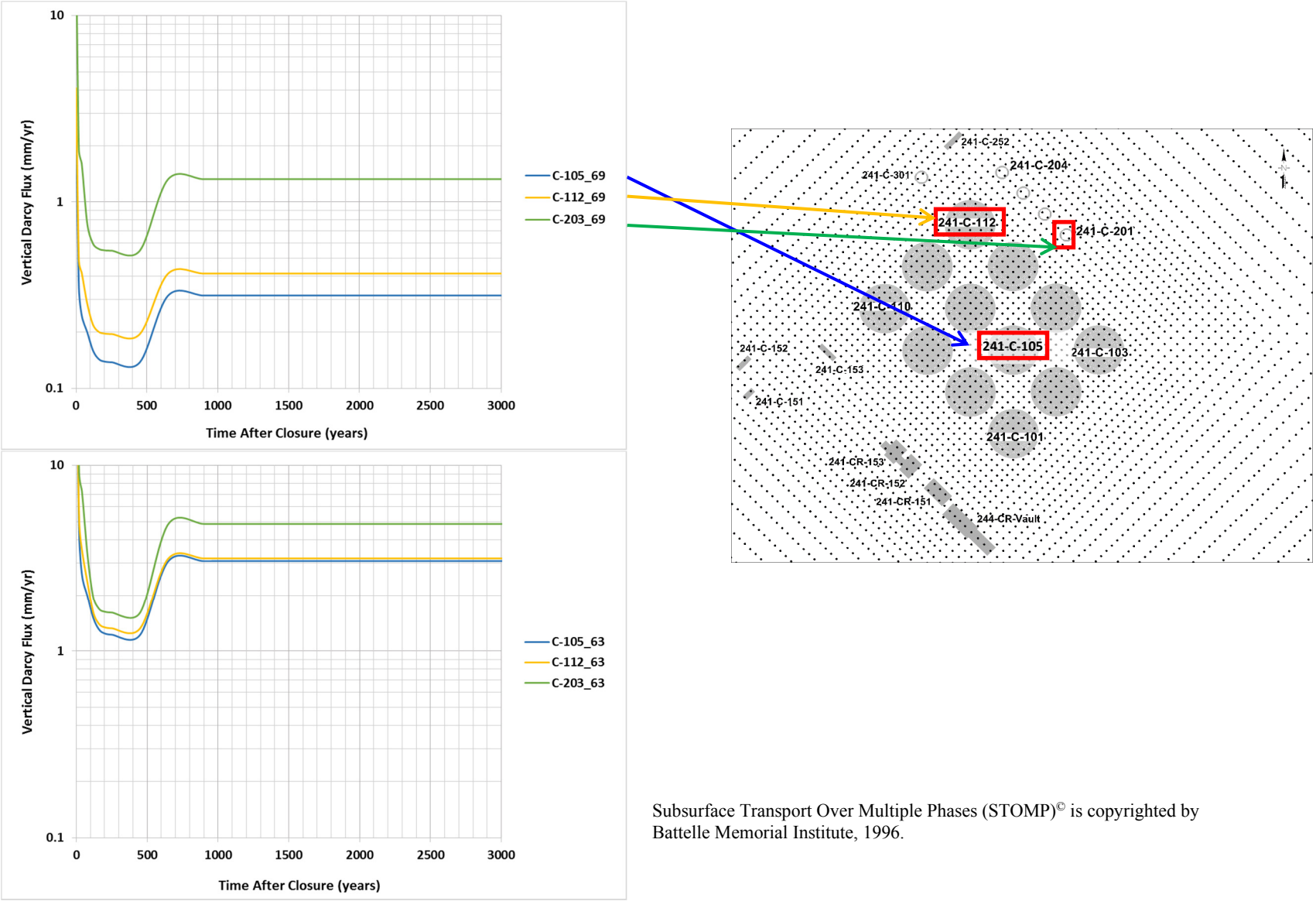



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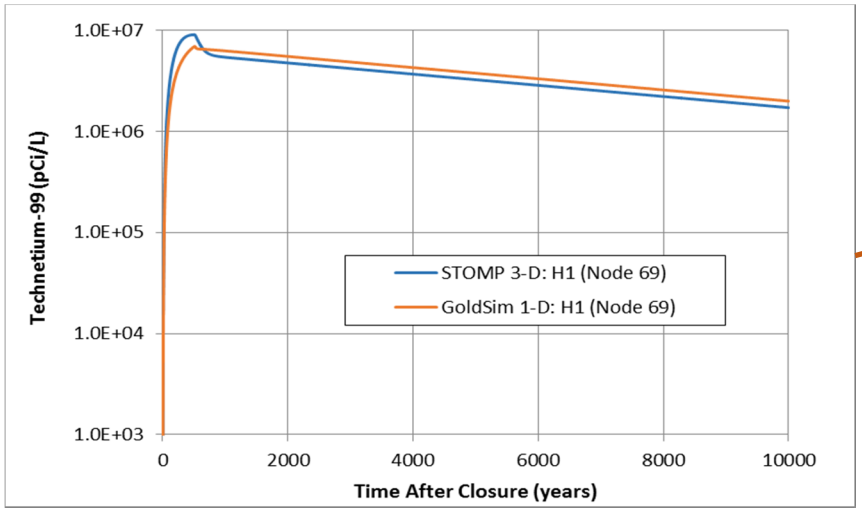
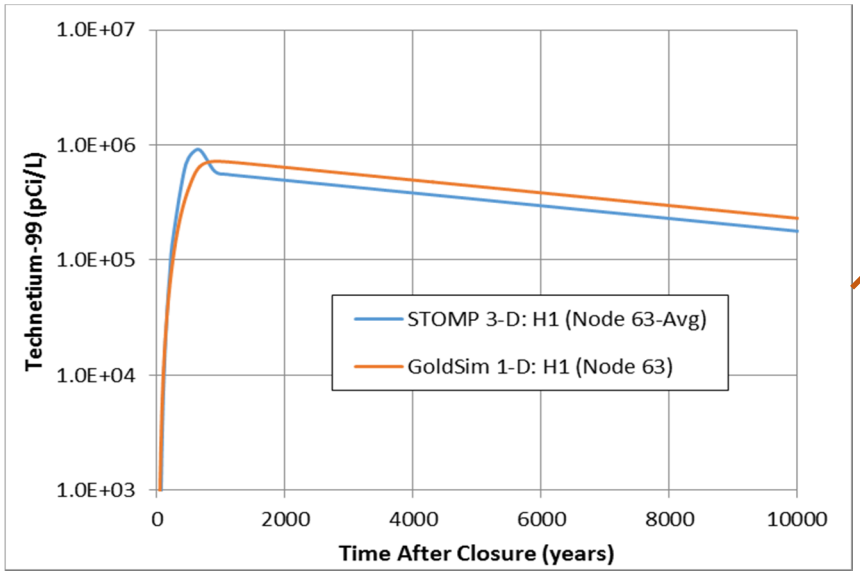
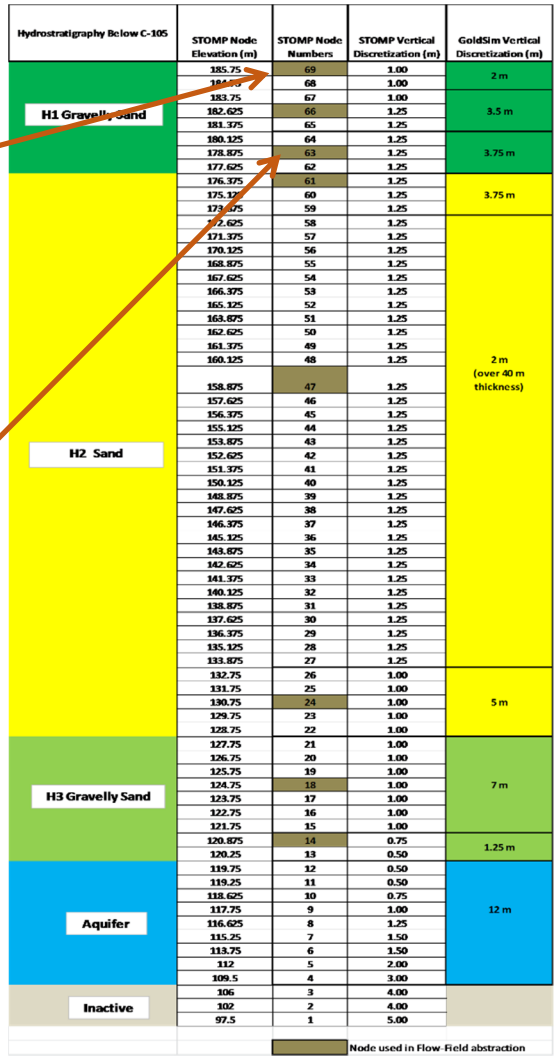
**Figure 7-42. Comparison between Three-Dimensional Subsurface Transport Over Multiple Phases (STOMP©)-Based Model Prediction and GoldSim©-Based One-Dimensional Abstraction Model Prediction for Nodes Located in H1 Gravelly Sand Unit.**



| Hydrostratigraphy Below C-105 | STOMP Node Elevation (m) | STOMP Node Numbers | STOMP Vertical Discretization (m) | GoldSim Vertical Discretization (m) |
|---|---|---|---|---|
| H1 Gravelly Sand | 185.75 | 69 | 1.00 | 2 m |
| | 184.75 | 68 | 1.00 | |
| | 183.75 | 67 | 1.00 | 3.5 m |
| | 182.625 | 66 | 1.25 | |
| | 181.375 | 65 | 1.25 | |
| | 180.125 | 64 | 1.25 | 3.75 m |
| | 178.875 | 63 | 1.25 | |
| | 177.625 | 62 | 1.25 | |
| H2 Sand | 176.375 | 61 | 1.25 | 3.75 m |
| | 175.125 | 60 | 1.25 | |
| | 173.875 | 59 | 1.25 | |
| | 172.625 | 58 | 1.25 | 2 m (over 40 m thickness) |
| | 171.375 | 57 | 1.25 | |
| | 170.125 | 56 | 1.25 | |
| | 168.875 | 55 | 1.25 | |
| | 167.625 | 54 | 1.25 | |
| | 166.375 | 53 | 1.25 | |
| | 165.125 | 52 | 1.25 | |
| | 163.875 | 51 | 1.25 | |
| | 162.625 | 50 | 1.25 | |
| | 161.375 | 49 | 1.25 | |
| | 160.125 | 48 | 1.25 | |
| | 158.875 | 47 | 1.25 | |
| | 157.625 | 46 | 1.25 | |
| | 156.375 | 45 | 1.25 | |
| | 155.125 | 44 | 1.25 | |
| | 153.875 | 43 | 1.25 | |
| | 152.625 | 42 | 1.25 | |
| | 151.375 | 41 | 1.25 | |
| | 150.125 | 40 | 1.25 | |
| | 148.875 | 39 | 1.25 | |
| | 147.625 | 38 | 1.25 | |
| | 146.375 | 37 | 1.25 | |
| | 145.125 | 36 | 1.25 | |
| | 143.875 | 35 | 1.25 | |
| | 142.625 | 34 | 1.25 | |
| | 141.375 | 33 | 1.25 | |
| | 140.125 | 32 | 1.25 | |
| | 138.875 | 31 | 1.25 | |
| | 137.625 | 30 | 1.25 | |
| | 136.375 | 29 | 1.25 | |
| | 135.125 | 28 | 1.25 | |
| | 133.875 | 27 | 1.25 | |
| | 132.75 | 26 | 1.00 | 5 m |
| | 131.75 | 25 | 1.00 | |
| | 130.75 | 24 | 1.00 | |
| | 129.75 | 23 | 1.00 | |
| | 128.75 | 22 | 1.00 | |
| H3 Gravelly Sand | 127.75 | 21 | 1.00 | 7 m |
| | 126.75 | 20 | 1.00 | |
| | 125.75 | 19 | 1.00 | |
| | 124.75 | 18 | 1.00 | |
| | 123.75 | 17 | 1.00 | |
| | 122.75 | 16 | 1.00 | |
| | 121.75 | 15 | 1.00 | |
| | 120.875 | 14 | 0.75 | 1.25 m |
| | 120.25 | 13 | 0.50 | |
| Aquifer | 119.75 | 12 | 0.50 | 12 m |
| | 119.25 | 11 | 0.50 | |
| | 118.625 | 10 | 0.75 | |
| | 117.75 | 9 | 1.00 | |
| | 116.625 | 8 | 1.25 | |
| | 115.25 | 7 | 1.50 | |
| | 113.75 | 6 | 1.50 | |
| | 112 | 5 | 2.00 | |
| | 109.5 | 4 | 3.00 | |
| Inactive | 106 | 3 | 4.00 | |
| | 102 | 2 | 4.00 | |
| | 97.5 | 1 | 5.00 | |

Node used in Flow-Field abstraction

Source: RPP-ENV-58782, "Performance Assessment of Waste Management Area C, Hanford Site, Washington," Figure 6-53.

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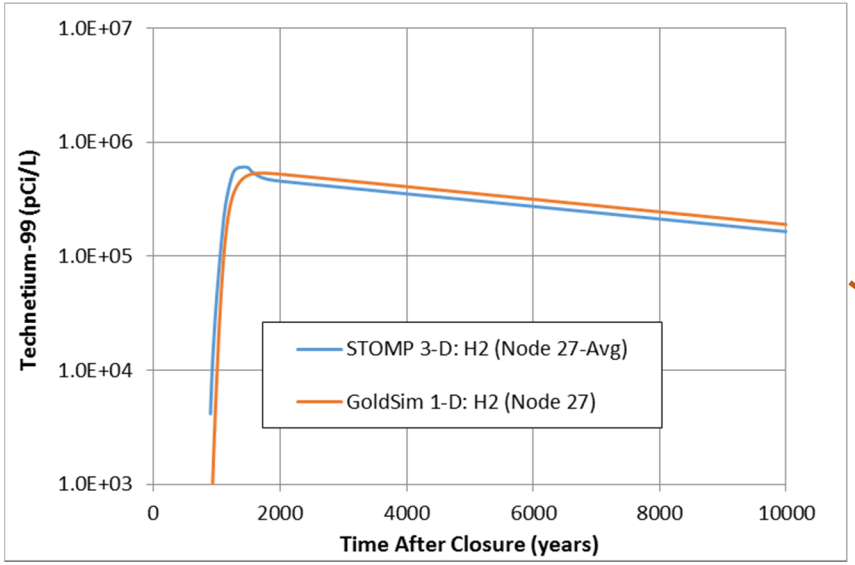
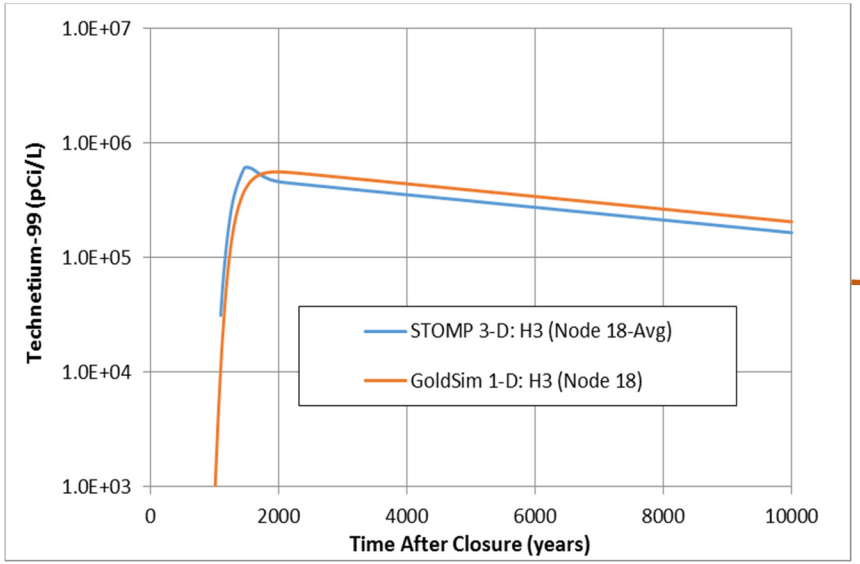
**Figure 7-43. Comparison between Three-Dimensional Subsurface Transport Over Multiple Phases (STOMP©)-Based Model Prediction and GoldSim©-Based One-Dimensional Abstraction Model Prediction for Nodes Located in H2 Sand Unit and H3 Gravelly Sand Unit.**




Source: RPP-ENV-58782, "Performance Assessment of Waste Management Area C, Hanford Site, Washington," Figure 6-54.

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Subsurface Transport Over Multiple Phases (STOMP)© is copyrighted by Battelle Memorial Institute, 1996.

| Hydrostratigraphy Below C-105 | STOMP Node Elevation (m) | STOMP Node Numbers | STOMP Vertical Discretization (m) | GoldSim Vertical Discretization (m) |
|---|---|---|---|---|
| H1 Gravelly Sand | 185.75 | 69 | 1.00 | 2 m |
| | 184.75 | 68 | 1.00 | |
| | 183.75 | 67 | 1.00 | 3.5 m |
| | 182.625 | 66 | 1.25 | |
| | 181.375 | 65 | 1.25 | |
| | 180.125 | 64 | 1.25 | 3.75 m |
| | 178.875 | 63 | 1.25 | |
| | 177.625 | 62 | 1.25 | |
| H2 Sand | 176.375 | 61 | 1.25 | 3.75 m |
| | 175.125 | 60 | 1.25 | |
| | 173.875 | 59 | 1.25 | |
| | 172.625 | 58 | 1.25 | 2 m (over 40 m thickness) |
| | 171.375 | 57 | 1.25 | |
| | 170.125 | 56 | 1.25 | |
| | 168.875 | 55 | 1.25 | |
| | 167.625 | 54 | 1.25 | |
| | 166.375 | 53 | 1.25 | |
| | 165.125 | 52 | 1.25 | |
| | 163.875 | 51 | 1.25 | |
| | 162.625 | 50 | 1.25 | |
| | 161.375 | 49 | 1.25 | |
| | 160.125 | 48 | 1.25 | |
| | 158.875 | 47 | 1.25 | |
| | 157.625 | 46 | 1.25 | |
| | 156.375 | 45 | 1.25 | |
| | 155.125 | 44 | 1.25 | |
| | 153.875 | 43 | 1.25 | |
| | 152.625 | 42 | 1.25 | |
| | 151.375 | 41 | 1.25 | |
| | 150.125 | 40 | 1.25 | |
| | 148.875 | 39 | 1.25 | |
| | 147.625 | 38 | 1.25 | |
| | 146.375 | 37 | 1.25 | |
| | 145.125 | 36 | 1.25 | |
| | 143.875 | 35 | 1.25 | |
| | 142.625 | 34 | 1.25 | |
| | 141.375 | 33 | 1.25 | |
| | 140.125 | 32 | 1.25 | |
| | 138.875 | 31 | 1.25 | |
| | 137.625 | 30 | 1.25 | |
| | 136.375 | 29 | 1.25 | |
| | 135.125 | 28 | 1.25 | |
| | 133.875 | 27 | 1.25 | |
| | 132.75 | 26 | 1.00 | 5 m |
| | 131.75 | 25 | 1.00 | |
| | 130.75 | 24 | 1.00 | |
| | 129.75 | 23 | 1.00 | |
| | 128.75 | 22 | 1.00 | |
| H3 Gravelly Sand | 127.75 | 21 | 1.00 | 7 m |
| | 126.75 | 20 | 1.00 | |
| | 125.75 | 19 | 1.00 | |
| | 124.75 | 18 | 1.00 | |
| | 123.75 | 17 | 1.00 | |
| | 122.75 | 16 | 1.00 | |
| | 121.75 | 15 | 1.00 | |
| | 120.875 | 14 | 0.75 | 1.25 m |
| | 120.25 | 13 | 0.50 | |
| Aquifer | 119.75 | 12 | 0.50 | 12 m |
| | 119.25 | 11 | 0.50 | |
| | 118.625 | 10 | 0.75 | |
| | 117.75 | 9 | 1.00 | |
| | 116.625 | 8 | 1.25 | |
| | 115.25 | 7 | 1.50 | |
| | 113.75 | 6 | 1.50 | |
| | 112 | 5 | 2.00 | |
| | 109.5 | 4 | 3.00 | |
| Inactive | 106 | 3 | 4.00 | |
| | 102 | 2 | 4.00 | |
| | 97.5 | 1 | 5.00 | |

Node used in Flow-Field abstraction

Range fires can be expected to occur every few years. Observation has shown that regrowth vegetation is initially dominated by nonnative species, particularly cheatgrass and, to a lesser extent, Russian thistle. Native grasses and shrubs take longer to reestablish, particularly the big sagebrush, which must regenerate from seed. However, repopulation with sagebrush and other smaller shrubs such as gray rabbitbrush, which reestablishes itself more easily than big sagebrush, eventually happens because these species are abundant in undisturbed areas that have been burned many times.

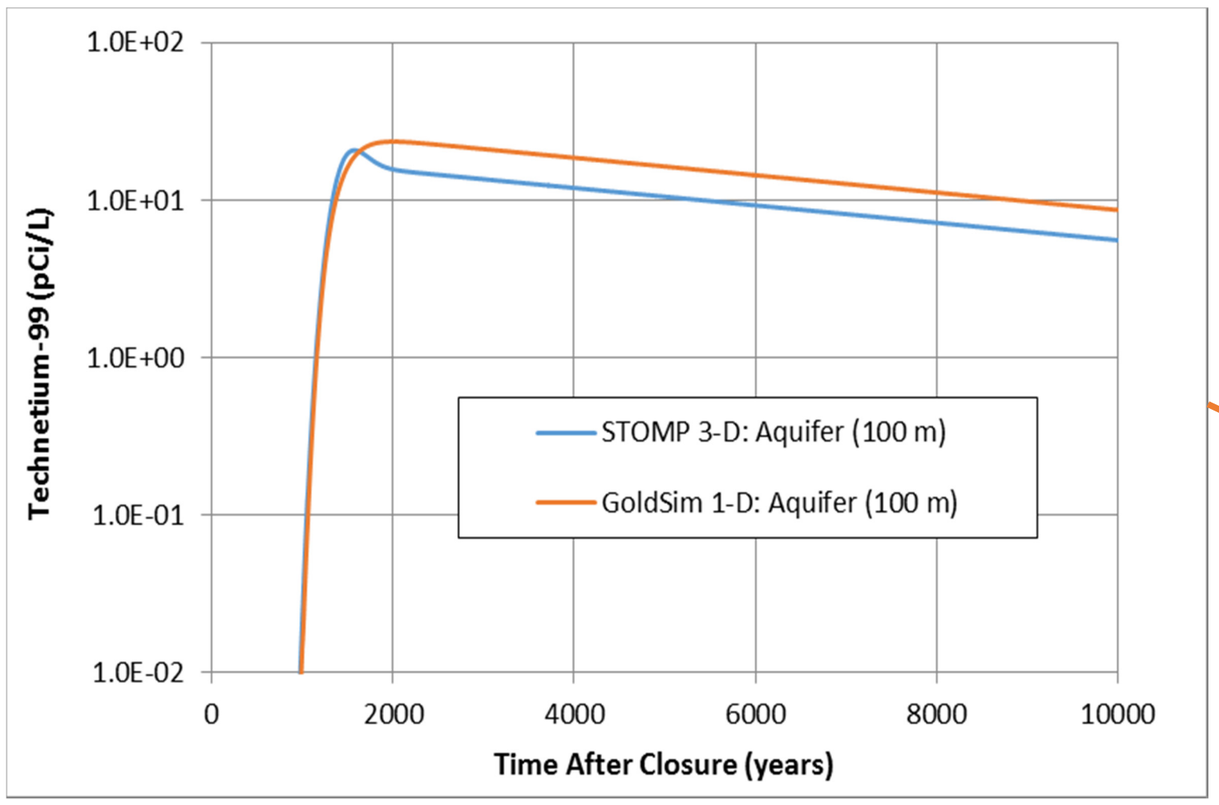
A wide variety of mammals (about 40 species), birds (about 100 species), reptiles (about 10 species), and insects (hundreds) have been observed on the Central Plateau. Large mammals include elk (*Cervus elaphus*) and mule deer (*Odocoileus hemionus*). Smaller species include badgers (*Taxidea taxus*), coyotes (*Canis latrans*), blacktail jackrabbits (*Lepus californicus*), Townsend ground squirrels (*Spermophilus townsendii*), pocket mice (*Perognathus parvus*), and deer mice (*Peromyscus maniculatus*). Of these, the Great Basin pocket mice are the most abundant. The mammal most likely to burrow in the soil is the badger, which can dig several feet down in search of food (e.g., mice and squirrels).

Birds commonly found on the Central Plateau include passerine varieties, raptors, game birds, and nesting birds. Common passerine birds are starlings (*Sturnus vulgaris*), meadowlarks (*Sturnella neglecta*), black-billed magpies (*Pica pica*), and ravens (*Corvus corax*). Common raptors are the American kestrels (*Falco sparvarius*) and redtailed hawks (*Buteo jamaicensis*). Game birds include the mourning dove (*Zenaida macroura*), California quail (*Callipepla californica*), and Chukar partridge (*Alectoris chukar*). Nesting birds include burrowing owls (*Athene cunicularia*), sage sparrows (*Amphispiza belli*), loggerhead shrikes (*Lanius ludovicianus*), and long-billed curlews (*Numenius americanus*).

Abundant reptiles include gopher snakes (*Pituophis melanoleucus*) and sideblotched lizards (*Uta stansburiana*). Other less abundant species include sagebrush lizards (*Sceloporus graciosus*), horned toads (*Phryosoma douglassii*), western spadefoot toads (*Scaphiopus intermontana*), yellow-bellied racers (*Coluber constrictor*), Pacific rattlesnakes (*Crotalus viridis*), and striped whipsnakes (*Masticophis taeniatus*). Amphibians are not expected at the WMA C location. Common groups of insects include several species of darkling beetles, grasshoppers, butterflies, bees, and ants. Of these, the harvester ants, darkling beetles, solitary bees, and pocket gophers burrow below ground surface (WMP-20570, “Central Plateau Terrestrial Ecological Risk Assessment Data Quality Objectives Summary Report - Phase I”).

The most likely means of plant and animal contact with buried waste is root penetration and burrowing habits. A summary of site-specific and generic data quantifying penetration depths for biota at the Hanford Site and similar semi-arid conditions is provided in WMP-20570. Most studies of biota at the Hanford Site catalog biota populations, record surface expression of biota, and measure contaminant uptake. However, a few studies have been completed to quantify penetration depths [PNL-5247, “Rooting Depth and Distributions of Deep-Rooted Plants in the 200 Area Control Zone of the Hanford Site”; RHO-SA-211, “Invasion of radioactive waste burial sites by the Great Basin Pocket Mouse (*Perognathus parvus*)”; DOE/RL-2001-54]. Measured maximum penetration depths at the Hanford Site are summarized in Table 7-16.

**Figure 7-44. Comparison Between Three-Dimensional Subsurface Transport Over Multiple Phases (STOMP©)-Based Model Prediction and GoldSim©-Based One-Dimensional Abstraction Model Prediction in the Saturated Zone at 100 m Distance from the Waste Management Area C Fenceline.**



Source: RPP-ENV-58782, "Performance Assessment of Waste Management Area C, Hanford Site, Washington," Figure 6-55.

1-D = one-dimensional 3-D = three-dimensional

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**Table 7-16. Maximum Penetration Depths for Biota at the Hanford Site.**

| Species | Maximum Depth | | Reference |
|---|---|---|---|
| | (cm) | (ft) | |
| **Plants** | | | |
| Antelope bitterbrush | 300 | 9.8 | PNL-5247, "Rooting Depth and Distributions of Deep-Rooted Plants in the 200 Area Control Zone of the Hanford Site" |
| Big sagebrush | 200 | 6.6 | PNL-5247 |
| Spiny hopsage | 195 | 6.5 | PNL-5247 |
| Russian thistle | 172 | 5.6 | PNL-5247 |
| **Mammals** | | | |
| Great Basin pocket mouse | 200 | 6.6 | RHO-SA-211, "Invasion of radioactive waste burial sites by the Great Basin Pocket Mouse (*Perognathus parvus*)" |
| **Soil Biota** | | | |
| Harvester ants | 270 | 8.8 | PNL-2774, "Characterization of the Hanford 300 Area Burial Grounds Task IV - Biological Transport" |

Source: WMP-20570, "Central Plateau Terrestrial Ecological Risk Assessment Data Quality Objectives Summary Report - Phase I," Table 2-1.

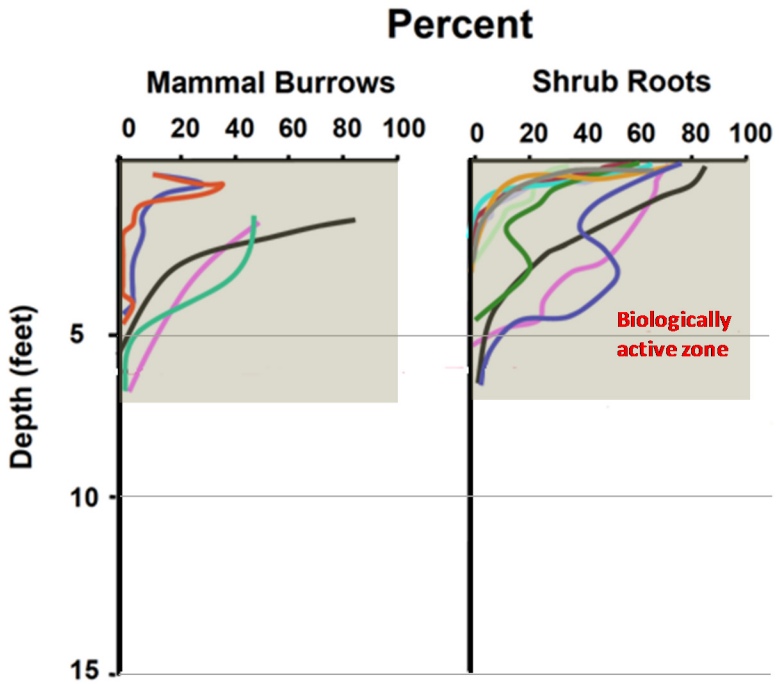
Two primary observations were made. First, the maximum likely depth is about 3 m (10 ft) bgs for both plant and animal behavior. Second, the frequency of roots and burrow depths are heavily skewed towards the surface (<1.5 m [5 ft] bgs), with only a few percent of penetration events reaching maximum depth. Soil sampling across Gable Mountain Pond and B Pond, two dried high-volume liquid discharge sites (DOE/RL-2001-54), yielded a large assortment of invertebrates that constructed burrows within a foot of the surface (several feet and 0.6 to 0.9 cm [2 to 3 ft], respectively). Deeper burrowing depths were associated with the harvester ants and solitary bees. Among mammals, badger burrows have been observed on a few occasions. One burrow in particular was found 1.2 m (4 ft) below a soil barrier (WHC-SA-1252-S, "Mammal Occurrence and Exclusion at the Hanford Site"). Offsite, badger burrows as deep as 3 m (10 ft) have been reported (The Mammals of North America [Hall 1981]).

Given the limited number of data collected at the Hanford Site, it is useful to compare these data with data collected at other semi-arid sites in the western United States. A collection of other site data is provided in INEEL/EXT-01-00273, "Biological Data to Support Operable Unit 7-13/14 Modeling of Plant and Animal Intrusion at Buried Waste Sites," and WMP-20570 (Appendix F). Badgers, squirrels, and mice are found at several sites with burrow penetration depths similar to the Hanford Site (Figure 7-45). Plant data from other northern desert sites in Idaho and Wyoming include a common set of species (e.g., sagebrush and various grasses) with similar penetration depth profiles (Figure 7-45).

A modified RCRA-compliant closure cover will be placed above WMA C that would be about 4.5 m (14.8 ft) in thickness (Figure 3-51). This cover will be placed above the interim

compacted soil cover of ~0.6 m (2 ft). Thus, the minimum depth of intrusion needed to access the waste will be more than 5 m, which is below the observations of the biologically active zone, described above. The upper 0.9 m (3.0 ft) of the soil cover system is composed of an admixture of silt and gravels. This layer is intended to both reduce infiltration through the cover and enhance the resistance of the cover to burrowing animals and long-term wind erosion. In addition, a geocomposite drainage layer (with a high-density polyethylene [HDPE] geomembrane liner) and 0.6 m (2 ft) of compacted clay admix will be present at a depth of ~4 m (13 ft), which will further enhance resistance to burrowing animals and plants. Given the features of the surface barrier above WMA C, the likelihood of a biotic pathway to access the hazardous chemicals from the waste is extremely small. As a result, the cancer risk and non-cancer hazard from this pathway is not considered in further analyses.

**Figure 7-45. Burrow and Root Density with Depth in Various Northwestern Semiarid Sites.**




Adapted from Figure 2-3 of WMP-20570, "Central Plateau Terrestrial Ecological Risk Assessment Data Quality Objectives Summary Report – Phase I."

### 7.3.3 Exposure, Cancer Risk, and Non-Cancer Hazard Analysis

The method for estimating cancer risks for radionuclides and chemicals and the method for estimating non-cancer hazards for chemicals is described below. The equations and exposure parameters for calculating cancer risks from exposure to radionuclides are presented first. Followed by equations and exposure parameters for calculating cancer risks and non-cancer hazards from exposure to hazardous substances. Additional details about the tap water (residential) scenario are presented in the supporting data package, RPP-ENV-58813.

**7.3.3.1 Tap Water (Residential) Scenario.** The tap water (residential) scenario considers exposure of adults and children who reside on or near WMA C. This assumes that a well is drilled 100 m downgradient of WMA C and water from this well is used for domestic purposes. The exposure assumptions used in this scenario reflect reasonable maximum exposure (RME).

For this exposure scenario, exposure pathways for radionuclides in water downgradient from WMA C include the following:

- Ingestion of tap water
- Inhalation of volatiles
- External exposure from immersion in tap water.

The exposure pathways included in this scenario for hazardous chemicals in water downgradient from WMA C include the following:

- Ingestion of tap water
- Inhalation of volatiles
- Dermal contact with skin while showering and using groundwater for other domestic purposes (such as washing dishes).

Equations and calculation methodologies for each exposure pathway are given below. The scenario-dependent exposure parameters for the tap water (residential) scenario are summarized in Table 7-17 for radionuclides and Table 7-18 for hazardous chemicals. The cancer slope factors on a radionuclide basis are provided in Table 7-19 and the toxicity factors for hazardous chemicals are provided in Table 7-20. Additionally, chemical-specific values used to calculate the dermal absorbed dose are provided in Table 7-20. For additional details on the tap water scenario, see RPP-ENV-58813.

**7.3.3.2 Cancer Risks from Exposure to Radionuclides.** The following sections provide the equations used to calculate cancer risks from exposure to radionuclides through tap water ingestion, inhalation of volatiles such as $^{14}C$, tritium, $^{226}Ra$, and $^{226}Ra$ plus daughters, and external exposure from immersion in tap water.

**7.3.3.2.1 Equations to Calculate Cancer Risk from Tap Water Ingestion.** The following equations (Equations 7-13 and 7-14) were derived by rearranging the equations from Section 4.1.4 Resident Tapwater in "PRG User's Guide" (Preliminary Remediation Goals for Radionuclides (PRG)/PRG Equations, Queried 06/19/2015, [United States Environmental Protection Agency Waste and Cleanup Risk Assessment, PRG User's Guide], https://epa-prgs.ornl.gov/radionuclides/PRG_UsersGuide.pdf) and is used to calculate cancer risks from ingestion of tap water:

$$Risk = C_w \times EF_r \times IFW_{r-adj} \times SF_w \tag{7-13}$$

Where:

$$IFW_{r-adj} = (ED_{res-c} \times IRW_{res-c}) + (ED_{res-a} \times IRW_{res-a}) \quad (7\text{-}14)$$

Where:

$C_w$ = water concentration (pCi/L)
$SF_w$ = ingestion slope factor—water (risk/pCi)
$EF_r$ = exposure frequency—resident (days/year)
$IFW_{r\text{-}adj}$ = drinking water ingestion rate—age-adjusted resident (L-yr/day)
$ED_{r\text{-}c}$ = exposure duration—child resident (years)
$IRW_{r\text{-}c}$ = drinking water ingestion rate—child resident (L/day)
$ED_{r\text{-}a}$ = exposure duration—adult resident (years)
$IRW_{r\text{-}a}$ = drinking water ingestion rate—adult resident (L/day).

**Table 7-17. Radiological Exposure Assumptions for Tap Water (Residential) Scenario. (2 sheets)**

| Parameter | Units | Symbol | Assigned Value | Source |
|---|---|---|---|---|
| **Exposure Frequency, Exposure Duration, and Exposure Time Variables** | | | | |
| Exposure frequency – resident | days/year | $EF_r$ | 350 | OSWER Directive 9285.6-03 (Page 15) |
| Exposure duration – resident | year | $ED_r$ | 26 | EPA/600/R-090/052F, Table 16-108; 90th percentile for current resident time |
| Exposure duration – adult resident | year | $ED_{r\text{-}a}$ | 20 | $ED_r$ (26 years)-$ED_{r\text{-}c}$ (6 years) OSWER Directive 9285.6-03 (Page 15) |
| Exposure duration – child resident | year | $ED_{r\text{-}c}$ | 6 | OSWER Directive 9285.6-03 (Pages 6 and 15) |
| Immersion event frequency | events/day | $EV_r$ | 1 | PRG User's Guide |
| Resident exposure time | hrs/day | $ET_r$ | 24 | 24 hours per day |
| **Inhalation and Ingestion Rates** | | | | |
| Inhalation rate – age-adjusted resident | $m^3$-yr/day | $IFA_{r\text{-}adj}$ | 460 | Calculated value |
| Inhalation rate – adult resident | $m^3$/day | $IRA_{r\text{-}a}$ | 20 | OSWER Directive 9285.6-03 (Page 15) |
| Inhalation rate – child resident | $m^3$/day | $IRA_{r\text{-}c}$ | 10 | EPA/600/P-95/002Fa (Page 5-11) |
| Drinking water ingestion rate – age-adjusted resident | L-yr/day | $IFW_{r\text{-}adj}$ | 54.68 | Calculated value |
| Drinking water ingestion rate – adult resident | L/day | $IRW_{r\text{-}a}$ | 2.5 | EPA/600/R-090/052F, Table 3-33; 90th percentile |

**Table 7-17. Radiological Exposure Assumptions for Tap Water (Residential) Scenario. (2 sheets)**

| Parameter | Units | Symbol | Assigned Value | Source |
|---|---|---|---|---|
| | | | | consumer-only ingestion of drinking water (≥ 21 years) |
| Drinking water ingestion rate – child resident | L/day | $IRW_{r\text{-}c}$ | 0.78 | EPA/600/R-090/052F, Tables 3-15 and 3-33; weighted average of 90th percentile consumer-only ingestion of drinking water (birth to <6 years) |
| Water immersion rate – age-adjusted resident | hr-yr/day | $DFA_{r\text{-}adj}$ | 17.44 | Calculated value |
| Immersion event time – adult resident | hours/event | $t_{r\text{-}a\text{-}event}$ | 0.71 | EPA/600/R-090/052F, Tables 16-30 and 16-36; weighted average of adult (21 to 78) 90th percentile of time spent bathing/showering in a day, divided by mean number of bath/showers taken in a day. |
| Immersion event time – child resident | hours/event | $t_{r\text{-}c\text{-}event}$ | 0.54 | EPA/R-090/052F, Table 16-29; weighted average of 90th percentile of time spent bathing (birth to <6 years). |
| **Inhalation Pathway** | | | | |
| Andelman Volatilization Factor | $L/m^3$ | K | 0.5 | EPA/540/R-92/003 (Page 20) |
| **Risk and MiscellaneousVariables** | | | | |
| Excess lifetime cancer risk | unitless | Risk | Calculated Value | Calculated value |
| Groundwater concentration | pCi/L | $C_w$ | Isotope-specific | Calculated value |
| **Conversion Factors** | | | | |
| Conversion Factor 1 | day/hr | $CF_1$ | 0.042 | 1 day = 24 hours |
| Conversion Factor 2 | yr/hour | $CF_2$ | 1.142E-4 | 1 year = 8,760 hours |

References:

EPA/540/R-92/003, Risk Assessment Guidance for Superfund: Volume I - Human Health Evaluation Manual (Part B, Development of Risk-based Preliminary Remediation Goals) Interim, Publication 9285.7-01 B.

EPA/600/R-090/052F, Exposure Factors Handbook: 2011 Edition.

EPA/600/P-95/002Fa, Exposure Factors Handbook Volume 1: General Factors.

Preliminary Remediation Goals for Radionuclides (PRG)/PRG Equations, Queried 06/19/2015, [United States Environmental Protection Agency Waste and Cleanup Risk Assessment, PRG User's Guide], https://epa-prgs.ornl.gov/radionuclides/PRG_UsersGuide.pdf.

OSWER Directive 9285.6-03, Risk Assessment Guidance for Superfund, Volume I: Human Health Evaluation Manual, Supplemental Guidance "Standard Default Exposure Factors" Interim Final.

**Table 7-18. Hazardous Chemical Exposure Assumptions for Tap Water (Residential) Scenario. (3 sheets)**

| Parameter | Units | Symbol | Assigned Value | Source |
|---|---|---|---|---|
| **Exposure Frequency, Exposure Duration, and Exposure Time Variables** | | | | |
| Exposure frequency – resident | day/year | $EF_r$ | 350 | OSWER Directive 9285.6-03 (Page 15) |
| Exposure duration - resident | year | $ED_r$ | 26 | EPA/600/R-090/052F, Table 16-108; 90th percentile for current residence time |
| Exposure duration – adult resident | year | $ED_{r-a}$ | 20 | $ED_r$ (26 years)-$ED_{r-c}$ (6 years) OSWER Directive 9285.6-03 (Page 15) |
| Exposure duration – child resident | year | $ED_{r-c}$ | 6 | OSWER Directive 9285.6-03 (Pages 6 and 15) |
| Resident exposure time | hrs/day | $ET_r$ | 24 | 24 hours per day |
| Carcinogenic averaging time – resident | days | $AT_c$ | 25,550 | Exhibit 6-11 of EPA/540/1-89/002 (70 years × 365 days/year) |
| Noncarcinogenic averaging time – resident | days | $AT_{nc}$ | 2,190 | Exhibit 6-11 of EPA/540/1-89/002 (6 years × 365 days/year) |
| **Water Ingestion Rates** | | | | |
| Drinking water ingestion rate – age-adjusted resident | L-yr/kg-day | $IFW_{r-adj}$ | 0.937 | Calculated value |
| Drinking water ingestion rate – adult resident | L/day | $IRW_{r-a}$ | 2.5 | EPA/600/R-090/052F, Table 3-33; 90th percentile of consumer-only ingestion of drinking water (≥ 21 years) |
| Drinking water ingestion rate – child resident | L/day | $IRW_{r-c}$ | 0.78 | EPA/600/R-090/052F, Tables 3-15 and 3-33; weighted average of 90th percentile consumer-only ingestion of drinking water (< 6 years) |
| **Skin Surface Area and Dermal Absorbed Dose Variables** | | | | |
| Skin surface area – age-adjusted resident | $cm^2$-yr-event/ kg-day | $SA_{r-adj}$ | 7,776 | Calculated value |
| Skin surface area – adult resident | $cm^2$ | $SA_{r-a}$ | 20,900 | EPA/600/R-090/052F, Table 7-10; weighted average of mean values for adults, male and female 21+. |

**Table 7-18. Hazardous Chemical Exposure Assumptions for Tap Water (Residential) Scenario. (3 sheets)**

| Parameter | Units | Symbol | Assigned Value | Source |
|---|---|---|---|---|
| Skin surface area – child resident | $cm^2$ | $SA_{r-c}$ | 6,378 | EPA/600/R-090/052F, Table 7-10; weighted average of mean values for children < 6 years. |
| Absorbed dose per event | $mg/cm^2$-event | $DA_{event}$ | Chemical-specific | Calculated value |
| Event frequency – resident | events/day | $EV_r$ | 1 | US EPA 06/19/2015 |
| Event duration - age-adjusted resident | hours/event | $T_{event-adj-r}$ | 0.671 | Calculated value |
| Event duration – adult resident | hours/event | $T_{event-r-a}$ | 0.71 | EPA/600/R-090/052F, Tables 16-30 and 16-36; weighted average of adult (21 to 78) 90th percentile of time spent bathing/showering in a day, divided by mean number of baths/showers taken in a day. |
| Event duration – child resident | hours/event | $T_{event-r-c}$ | 0.54 | EPA/600/R-090/052F, Table 16-29; weighted average of 90th percentile time spent bathing (birth to <6 years). |
| Body weight – adult | kg | $BW_a$ | 80 | EPA/600/R-090/052F, Table 8-3; weighted mean values for adults 21-78 |
| Body weight – child | kg | $BW_c$ | 15 | EPA/600/R-090/052F, Table 8-1; weighted average of mean body weights (birth to <6 years) |
| **Inhalation Pathway** | | | | |
| Andelman Volatilization Factor | $L/m^3$ | K | 0.5 | EPA/540/R-92/003 (Page 20) |
| **Risk and Hazard Quotient Variables** | | | | |
| Excess lifetime cancer risk | unitless | Risk | Calculated Value | Calculated value |
| Hazard quotient | unitless | HQ | Calculated Value | Calculated value |
| **Miscellaneous Variables** | | | | |
| Water concentration | µg/L | Cw | Chemical-specific | Calculated value |

**Table 7-18. Hazardous Chemical Exposure Assumptions for Tap Water (Residential) Scenario. (3 sheets)**

| Parameter | Units | Symbol | Assigned Value | Source |
|---|---|---|---|---|
| **Conversion Factors** | | | | |
| Conversion Factor 1 | mg/µg | $CF_1$ | 0.001 | 1 mg = 1,000 µg |
| Conversion Factor 2 | L/cm$^3$ | $CF_2$ | 0.001 | 1 liter = 1,000 cm$^3$ |
| Conversion Factor 3 | day/hr | $CF_3$ | 0.042 | 24 hours = 1 day |

References:
EPA/540/1-89/002, Risk Assessment Guidance for Superfund Volume I Human Health Evaluation Manual (Part A) Interim Final.
EPA/540/R-92/003, Risk Assessment Guidance for Superfund: Volume I - Human Health Evaluation Manual (Part B, Development of Risk-based Preliminary Remediation Goals) Interim, Publication 9285.7-01 B.
EPA/600/R-090/052F, Exposure Factors Handbook: 2011 Edition.
OSWER Directive 9285.6-03, Risk Assessment Guidance for Superfund, Volume I: Human Health Evaluation Manual, Supplemental Guidance "Standard Default Exposure Factors" Interim Final.
United States Environmental Protection Agency, Queried 06/19/2015, [Regional Screening Table | Mid-Atlantic Risk Assessment | US EPA], http://www.epa.gov/reg3hwmd/risk/human/rb-concentration_table/.

#### 7.3.3.2.2 Equations to Calculate Cancer Risk from Inhalation of Volatiles in Tap Water.

The following equations (Equations 7-15 and 7-16) were derived by rearranging the equations from Section 4.1.4 Resident Tapwater in "PRG User's Guide" (Preliminary Remediation Goals for Radionuclides (PRG)/PRG Equations, Queried 06/19/2015, [United States Environmental Protection Agency Waste and Cleanup Risk Assessment, PRG User's Guide], https://epa-prgs.ornl.gov/radionuclides/PRG_UsersGuide.pdf) and is used to calculate cancer risks from inhalation of volatiles in tap water:

$$Risk = C_w \times EF_r \times IFA_{r-adj} \times ET_r \times CF_1 \times K \times SF_i \quad (7\text{-}15)$$

Where:

$$IFA_{r-adj} = (ED_{r-c} \times IRA_{r-c}) + (ED_{r-a} \times IRA_{r-a}) \quad (7\text{-}16)$$

Where:

$C_w$ = water concentration (pCi/L)
$EF_r$ = exposure frequency—resident (days/year)
$ET_r$ = exposure time (hr/day)
$IFA_{r\text{-}adj}$ = inhalation rate—age-adjusted resident (m$^3$-yr/day)
K = Andelman volatilization factor (L/m$^3$)
$CF_1$ = conversion factor (day/hr)
$ED_{r\text{-}c}$ = exposure duration—child resident (years)
$IRA_{r\text{-}c}$ = inhalation rate—child resident (m$^3$/day)
$ED_{r\text{-}a}$ = exposure duration—adult resident (years)
$IRA_{r\text{-}a}$ = inhalation rate—adult resident (m$^3$/day)
$SF_i$ = slope factor—inhalation (risk/pCi).

**Table 7-19. Slope Factors for Radiological Contaminants in Water at Waste Management Area C. (2 sheets)**

| Isotope | Radionuclide Name | Water Ingestion Slope Factor* (risk/pCi) | Inhalation Slope Factor* (risk/pCi) | Immersion Slope Factor* (risk/yr per pCi/L) |
|---|---|---|---|---|
| Ac-227 | Actinium-227 | 2.01E-10 | — | 7.10E-16 |
| Am-241 | Americium-241 | 1.04E-10 | — | 1.32E-13 |
| Am-243+D | Americium-243 | 1.09E-10 | — | 1.86E-12 |
| Ba-137m | Barium-137 | — | — | 5.46E-12 |
| C-14 | Carbon-14 | 1.55E-12 | 1.7E-11 | 5.80E-17 |
| Cd-113m | Cadmium-113 | 2.90E-11 | — | 2.58E-15 |
| Cm-242 | Curium-242 | 3.85E-11 | — | 6.84E-16 |
| Cm-243 | Curium-243 | 9.51E-11 | — | 1.07E-12 |
| Cm-244 | Curium-244 | 8.36E-11 | — | 7.23E-16 |
| Co-60 | Cobalt-60 | 1.58E-11 | — | 2.44E-11 |
| Cs-134 | Cesium-134 | 4.22E-11 | — | 1.44E-11 |
| Cs-137+D | Cesium-137 | 3.05E-11 | — | 5.16E-12 |
| Eu-152 | Europium-152 | 5.85E-12 | — | 1.10E-11 |
| Eu-154 | Europium-154 | 9.84E-12 | — | 1.18E-11 |
| Eu-155 | Europium-155 | 1.94E-12 | — | 4.33E-13 |
| H-3 | Hydrogen-3 | 5.07E-14 | 8.50E-13 | — |
| I-129 | Iodine-129 | 1.51E-10 | — | 5.13E-14 |
| Nb-93m | Niobium-93 | 8.33E-13 | — | 5.25E-16 |
| Ni-59 | Nickel-59 | 2.72E-13 | — | 1.40E-16 |
| Ni-63 | Nickel-63 | 6.81E-13 | — | — |
| Np-237+D | Neptunium-237 | 6.85E-11 | — | 2.04E-12 |
| Pa-231 | Protactinium-231 | 1.72E-10 | — | 2.93E-13 |
| Pu-238 | Plutonium-238 | 1.31E-10 | — | 5.95E-16 |
| Pu-239+D | Plutonium-239 | 1.35E-10 | — | 7.25E-16 |
| Pu-240 | Plutonium-240 | 1.35E-10 | — | 5.86E-16 |
| Pu-241 | Plutonium-241 | 1.76E-12 | — | 1.24E-17 |
| Pu-242 | Plutonium-242 | 1.28E-10 | — | 1.24E-15 |
| Ra-226+D | Radium-226 | 3.85E-10 | 2.80E-08 | 1.68E-11 |
| Ra-228+D | Radium-228 | 1.04E-09 | — | 8.15E-12 |
| Ru-106 | Ruthenium-106 | 4.22E-11 | — | — |

**Table 7-19. Slope Factors for Radiological Contaminants in Water at Waste Management Area C. (2 sheets)**

| Isotope | Radionuclide Name | Water Ingestion Slope Factor* (risk/pCi) | Inhalation Slope Factor* (risk/pCi) | Immersion Slope Factor* (risk/yr per pCi/L) |
|---|---|---|---|---|
| Sb-125 | Antimony-125 | 4.44E-12 | — | 3.85E-12 |
| Se-79 | Selenium-79 | 6.92E-12 | — | 6.74E-17 |
| Sm-151 | Samarium-151 | 5.59E-13 | — | 4.46E-18 |
| Sn-126+D | Tin-126 | 2.76E-11 | — | 1.81E-11 |
| Sr-90+D | Strontium-90 | 7.40E-11 | — | 3.97E-14 |
| Tc-99 | Technetium-99 | 2.75E-12 | — | 5.62E-16 |
| Th-229+D | Thorium-229 | 3.38E-10 | — | 7.10E-13 |
| Th-232+D | Thorium-232 | 1.14E-09 | — | 8.15E-12 |
| U-232 | Uranium-232 | 2.90E-10 | — | 2.09E-15 |
| U-233 | Uranium-233 | 7.18E-11 | — | 2.09E-15 |
| U-234 | Uranium-234 | 7.07E-11 | — | 1.17E-15 |
| U-235+D | Uranium-235 | 7.18E-11 | — | 1.48E-12 |
| U-236 | Uranium-236 | 6.66E-11 | — | 7.01E-16 |
| U-238+D | Uranium-238 | 8.70E-11 | — | 2.69E-13 |
| Y-90 | Yttrium-90 | 1.80E-11 | — | 3.75E-14 |
| Zr-93 | Zirconium-93 | 1.08E-12 | — | 7.86E-21 |

*United States Environmental Protection Agency, Queried 06/18/2015, [Preliminary Remediation Goals for Radionuclides], http://epa-prgs.ornl.gov/radionuclides/.

**7.3.3.2.3 Equations to Calculate Cancer Risk from Immersion in Tap Water.** The following equations (Equations 7-17 and 7-18) were derived by rearranging the equations from Section 4.1.4 Resident Tapwater in "PRG User's Guide" (Preliminary Remediation Goals for Radionuclides (PRG)/PRG Equations, Queried 06/19/2015, [United States Environmental Protection Agency Waste and Cleanup Risk Assessment, PRG User's Guide], https://epa-prgs.ornl.gov/radionuclides/PRG_UsersGuide.pdf) and is used to calculate cancer risks from external exposure by immersion in tap water:

$$Risk = C_w \times EF_r \times EV_r \times DFA_{r-adj} \times CF_2 \times SF_{imm} \quad (7\text{-}17)$$

Where:

$$DFA_{r-adj} = (ED_{r-c} \times t_{r-c-event}) + (ED_{r-a} \times t_{r-a-event}) \quad (7\text{-}18)$$

Where:

$C_w$ = water concentration (pCi/L)
$EF_r$ = exposure frequency—resident (days/year)
$EV_r$ = immersion event frequency (events/day)
$CF_2$ = conversion factor (yr/hr)
$DFA_{r\text{-}adj}$ = water immersion factor—age-adjusted resident (hr-yr/day)
$ED_{r\text{-}c}$ = exposure duration—child resident (years)
$t_{r\text{-}c\text{-}event}$ = immersion event time—child resident (hr/event)
$ED_{r\text{-}a}$ = exposure duration—adult resident (years)
$t_{r\text{-}a\text{-}event}$ = immersion event time—adult resident (hr/event)
$SF_{imm}$ = slope factor—immersion (risk/yr per pCi/L).

**7.3.3.3 Cancer Risks and Non-Cancer Hazards from Exposure to Hazardous Chemicals.** The following sections provide the equations used to calculate cancer risks and non-cancer hazards from exposure to hazardous chemicals through ingestion of water, dermal contact with water, and inhalation of volatiles.

**7.3.3.3.1 Cancer Risk and Non-Cancer Hazards from Tap Water Ingestion.** The following equations (Equations 7-19 and 7-20) were derived by rearranging the equations from EPA/540/1-89/002, Risk Assessment Guidance for Superfund Volume I Human Health Evaluation Manual (Part A) Interim Final (Exhibit 6-11) and the EPA Regional Screening Levels for Chemicals website (United States Environmental Protection Agency, Queried 06/19/2015, [Regional Screening Table | Mid-Atlantic Risk Assessment | US EPA], http://www.epa.gov/reg3hscd/risk/human/rb-concentration_table/) and are used to calculate cancer risks from ingestion of tap water:

$$Risk = \frac{C_w \times EF_r \times IFW_{r-adj} \times CF_1 \times CSF_o}{AT_c} \tag{7-19}$$

Where:

$$IFW_{r-adj} = \frac{ED_{r-c} \times IRW_{r-c}}{BW_c} + \frac{ED_{r-a} \times IRW_{r-a}}{BW_a} \tag{7-20}$$

The following equation (Equation 6-21) was derived by rearranging the equations from EPA/540/1-89/002 (Exhibit 6-11) and the EPA Regional Screening Levels for Chemicals website (US EPA 06/19/2015) and is used to calculate the non-cancer HQ from ingestion of tap water:

$$HQ = \frac{C_w \times CF_1 \times IRW_{r-c} \times EF_r \times ED_{r-c}}{BW_c \times AT_{nc} \times RfD_o} \tag{7-21}$$

Where:

$C_w$ = water concentration (µg/L)
$EF_r$ = exposure frequency—resident (days/year)
$IFW_{r\text{-}adj}$ = water ingestion rate—age-adjusted resident (L-yr/kg-day)

$CF_1$ = conversion factor (mg/µg)
$AT_c$ = carcinogenic averaging time —resident (days)
$ED_{r-c}$ = exposure duration—child resident (years)
$IRW_{r-c}$ = water ingestion rate—child resident (L/day)
$BW_c$ = body weight—child (kg)
$ED_{r-a}$ = exposure duration—adult resident (years)
$IRW_{r-a}$ = water ingestion rate—adult resident (L/day)
$BW_a$ = body weight—adult (kg)
$AT_{nc}$ = noncarcinogenic averaging time —resident (days)
$CSF_o$ = slope factor—oral (mg/kg-day) $^{-1}$
$RfD_o$ = chronic oral reference dose (mg/kg-day).

**7.3.3.3.2 Cancer Risk and Non-Cancer Hazards from Dermal Contact with Tap Water.** The following equations (Equations 7-22 and 7-23) were derived by rearranging the equations from EPA/540/R/99/005, Risk Assessment Guidance for Superfund Volume I: Human Health Evaluation Manual (Part E, Supplemental Guidance for Dermal Risk Assessment) Final (Equation 3.1) and the EPA Regional Screening Levels for Chemicals website (US EPA 06/19/2015) and are used to calculate cancer risk from dermal contact with tap water:

$$Risk = \frac{DA_{event} \times EF_r \times EV_r \times SA_{r-adj} \times \frac{CSF_o}{GIABS}}{AT_c} \quad (7\text{-}22)$$

Where:

$$SA_{r-adj} = \frac{ED_{r-c} \times SA_{r-c}}{BW_c} + \frac{ED_{r-a} \times SA_{r-a}}{BW_a} \quad (7\text{-}23)$$

The following equation (Equation 7-24) was derived by rearranging the equations from EPA/540/R/99/005 (Equation 3.1) and the EPA Regional Screening Levels for Chemicals website (US EPA 06/19/2015) and is used to calculate the non-cancer HQ's from dermal contact with tap water:

$$HQ = \frac{DA_{event} \times EF_r \times EV_r \times SA_{r-c} \times ED_{r-c}}{AT_{nc} \times BW_c \times RfD_o \times GIABS} \quad (7\text{-}24)$$

Where:

$DA_{event}$ = absorbed dose per event (mg/cm$^2$-event)
$EF_r$ = exposure frequency—resident (days/year)
$EV_r$ = event frequency—resident (events/day)
$SA_{r-adj}$ = skin surface area—age-adjusted resident (cm$^2$-yr-event/kg-day)
$AT_c$ = carcinogenic averaging time—resident (days)
$ED_{r-c}$ = exposure duration—child resident (years)
$SA_{r-c}$ = skin surface area—child resident (cm$^2$)
$BW_c$ = body weight—child (kg)
$ED_{r-a}$ = exposure duration—adult resident (years)
$SA_{r-a}$ = skin surface area—adult resident (cm$^2$)

$BW_a$ = body weight—adult (kg)
$AT_{nc}$ = noncarcinogenic averaging time—resident (days)
$CSF_o$ = slope factor— oral $(mg/kg\text{-}day)^{-1}$
$RfD_o$ = chronic oral reference dose (mg/kg-day)
GIABS = fraction of contaminant absorbed in gastrointestinal tract (unitless).

**7.3.3.3.3 Dermal-Absorbed Dose.** For organics, the following equations (Equations 7-25 through 7-29) from EPA/540/R/99/005 (Equations 3.2 through 3.4) are used to calculate the dermally absorbed dose per event ($DA_{event}$), using the child event time for noncarcinogenic effects and the age-adjusted event time for carcinogenic effects.

If $T_{event} \leq t^*$, then the following nonsteady-state equation is used:

$$DA_{event} = 2FA \times K_p \times C_w \times CF_1 \times CF_2 \sqrt{\frac{6\tau \times T_{event}}{\pi}} \quad (7\text{-}25)$$

If $T_{event} > t^*$, then the following pseudosteady-state equation is used:

$$DA_{event} = FA \times K_p \times C_w \times CF_1 \times CF_2 \left[\frac{T_{event}}{1+B} + 2\tau\left(\frac{1+3B+3B^2}{(1+B)^2}\right)\right] \quad (7\text{-}26)$$

Where:

$$T_{event} = T_{event-r-c} \text{ (noncarcinogens)} \quad (7\text{-}27)$$

$$T_{event} = T_{event-r-adj} = \frac{T_{event-r-c} \times ED_{r-c} + T_{event-r-a} \times ED_{r-a}}{ED_r} \text{ (carcinogens)} \quad (7\text{-}28)$$

For inorganics, the following steady-state equation is used to estimate $DA_{event}$:

$$DA_{event} = K_p \times C_w \times T_{event} \times CF_1 \times CF_2 \quad (7\text{-}29)$$

Where:

$T_{event}$ = event duration (hours/event)
$t^*$ = time to reach steady state (hr)
$DA_{event}$ = absorbed dose per event ($mg/cm^2$-event)
FA = fraction of absorbed water (unitless)
$K_p$ = dermal permeability coefficient (cm/hour)
$C_w$ = water concentration (µg/L)
$CF_1$ = conversion factor (mg/µg)
$CF_2$ = conversion factor ($L/cm^3$)
$\tau$ = lag time (hours/event)
B = partitioning constant derived from Bunge Model (unitless)
$T_{event-r-c}$ = event duration—child resident (hours/event)
$T_{event-r-adj}$ = event duration—age-adjusted resident (hours/event)
$ED_r$ = exposure duration—resident (years).

**7.3.3.3.4 Cancer Risk and Non-Cancer Hazards from Inhalation of Volatiles in Tap Water.** The following equations (Equations 7-30 and 7-31) were derived by rearranging equations from EPA-540-R-070-002, Risk Assessment Guidance for Superfund Volume I: Human Health Evaluation Manual (Part F, Supplemental Guidance for Inhalation Risk Assessment) Final (Equations 6, 11, and 12) and the EPA Regional Screening Levels for Chemicals website (US EPA 06/19/2015) and are used to calculate the cancer risks and non-cancer HQ's for the inhalation pathway:

$$Risk = \frac{C_W \times EF_r \times ED_r \times ET_r \times CF_3 \times K \times IUR}{AT_c} \quad (7\text{-}30)$$

And:

$$HQ = \frac{C_W \times CF_1 \times EF_r \times ED_{r-c} \times ET_r \times CF_3 \times K}{AT_{nc} \times RfC} \quad (7\text{-}31)$$

Where:

$C_w$ = water concentration (µg/L)
$EF_r$ = exposure frequency—resident (days/year)
$ED_r$ = exposure duration—resident (years)
$ET_r$ = exposure time—resident (hours/day)
$CF_1$ = conversion factor (mg/µg)
$CF_3$ = conversion factor (day/hour)
K = Andelman volatilization factor (L/m$^3$)
$AT_c$ = carcinogenic averaging time (days)
$ED_{r-c}$ = exposure duration—resident child (years)
$ED_{r-a}$ = exposure duration—resident adult (years)
$AT_{nc}$ = noncarcinogenic averaging time (days)
IUR = inhalation unit risk (µg/m$^3$)$^{-1}$
RfC = chronic inhalation reference concentration (mg/m$^3$).

**7.3.3.3.5 Cumulative Cancer Risk and Non-Cancer Hazard Index.** The following sections provide the equations (Equations 7-32 and 7-33) used to calculate cumulative cancer risk and the non-cancer HI.

**7.3.3.3.6 Cumulative Cancer Risk.** For estimating the cancer risks from exposure to multiple carcinogens from a single exposure route, the following equation is used. The basis for the equation is provided in EPA/540/1-89/002.

$$Risk_T = \sum_1^N Risk_i \quad (7\text{-}32)$$

Where:

$Risk_T$ = total cancer risk from route of exposure
$Risk_i$ = cancer risk for the i$^{th}$ chemical
N = number of chemicals.

**7.3.3.3.7 Non-Cancer Hazard Index.** The HI is calculated using the following equation. The basis for the equation is provided in EPA/540/1-89/002.

$$HI = \sum_{1}^{N} {CDI_i}/{RfD_i} \tag{7-33}$$

Where:

HI = hazard index
$CDI_i$ = chronic daily intake of the $i^{th}$ chemical (mg/kg-day)
$RfD_i$ = reference dose of the $i^{th}$ chemical (mg/kg-day)
N = number of chemicals.

## 7.4 MODEL VALIDATION[2]

A substantial body of literature exists indicating the manner in which scientific validation of models is pursued (e.g., "Ground-Water Models: Validate or Invalidate" [Bredehoeft and Konikow 1993], "Validation of safety assessment models as a process of scientific and public confidence building" [Neuman 1992], "The Modeling Process and Model Validation" [Tsang 1991]). Because RCA and PA models cannot be tested over the spatial scales of interest and the long time periods for which the models make predictions, the customary definition of model validation (i.e., comparison of model estimates with actual data at the space-time scales of interest) is precluded (NUREG-1573, A Performance Assessment Methodology for Low-Level Radioactive Waste Disposal Facilities: Recommendations of NRC's Performance Assessment Working Group; NUREG-1636, Regulatory Perspectives on Model Validation in High-Level Radioactive Waste Management Programs: A Joint NRC/SKI White Paper). We therefore view validation efforts as a documented evidence of building or enhancement of confidence in the model's theoretical or scientific basis to an extent that the model's results can support in RCA decision-making. We present below a variety of topical areas which serve as the basis of confidence building and confidence enhancement for WMA C RCA models and results.

### 7.4.1 Basis for Recharge Estimates Used for Land Surface Boundary Condition

Recharge rates have been estimated from studies conducted at the Hanford Site over the last 30 years. Recharge rates are available for natural and disturbed soils, for soils with and without vegetation, and for various plant communities. In addition, recharge has been estimated for surface covers with varying plant communities. These estimates are based on lysimeter records, tracer tests (chloride mass balance), and computer simulations to match field data. PNNL-16688 and PNNL-14702 provide primary sources of information on recharge estimates for the Hanford Site that are relevant to tank farms. The estimates used in the RCA consider estimates of recharge made for the 200 Areas and for conditions at WMA C inferred from measurements made at the Field Lysimeter Test Facility (Section 3.1.5.2.2).

[2] In this section and in the context of WMA C RCA modeling, the terms "confidence," "confidence building," "confidence enhancement," "validation," and "validation process" are used interchangeably.

An extensive set of data exists for estimates of recharge for engineered barriers. For example, almost two decades of field-scale recharge studies have been conducted on an engineered Prototype Hanford Barrier (PHB) (a 5-m [16.4-ft] thick multilayered capillary barrier with 2 m [6.6 ft] of silt loam) that was constructed in the 200 East Area (north of WMA C) in August 1994. The barrier performance was monitored almost continuously for 15 years to document structural stability, erosion, and components of the water balance including precipitation, surface runoff, water storage, percolation out of the root zone, and evapotranspiration. The barrier recharge estimates used in the PA are supported by the PHB data (PNNL-18845).

Additional details related to developing the uncertainty distributions for the recharge estimates is given in Section 8.1.3.1 Uncertainty in Recharge Rates of RPP-ENV-58782.

### 7.4.2 Basis for Source-Term Model Development and Implementation

The basis for the source-term model development and implementation is rooted in results of laboratory studies conducted of the tank waste residuals collected in a number of tanks following cessation of retrieval. As part of the waste characterization efforts, analytical methods are used to measure the chemical and radiological constituents in the waste sludge and to understand their composition, solid-phase characteristics, and the leachability of primary contaminants of interest. Several detailed characterization reports are available for various tank residuals (see Section 6).

Both mineral phase solubility-limited and matrix degradation rate-limited processes are considered for release of contaminant from the waste. These conceptual models are based on observations made through multi-year leaching tests and identification of mineral phases as presented in Section 6. Results from the flow-through and batch leach tests were used to develop both thermodynamic equilibrium and reaction progress models. Both empirical and process model-based information were used to develop the waste form release models for the RCA (Section 7.2.1 provides additional details).

The effective diffusion coefficient of mobile contaminants (such as $^{99}$Tc and $^{129}$I) through the combined grout and concrete base mat is considered a key parameter that controls the diffusive flux. Over the past decade, several experiments have been conducted to determine the effective diffusion coefficient through concrete for relatively mobile contaminants under unsaturated conditions. The results of various experiments are presented in PNNL-23841 and summarized in Section 7.3.1.4. Of particular interest are the sediment-concrete half-cell experiments conducted in Year 2008 (for a period of 351 days) with $^{99}$Tc and stable iodine. Sediment half-cell specimens were spiked with $^{99}$Tc (or stable iodine) to achieve a measurable diffusion profile in the concrete part of the half-cell. In these experiments, iron content was varied in the concrete specimens from 0% to 12%, sediment moisture content was varied (4%, 7%, or 15%), and half of the concrete monoliths were carbonated prior to preparing the half-cells. Half-cell sampling was conducted at 351 days. The effective diffusion coefficient through grout and concrete is based on evaluation of such experiments.

**Table 7-20. Toxicity Values for Hazardous Chemicals in Groundwater at Waste Management Area C.**

| Chemical Name | Oral Reference Dose[a] (mg/kg-day) | Source | Oral Cancer Slope Factor[a] $(mg/kg\text{-}day)^{-1}$ | Source | Inhalation Reference Concentration[a] $(mg/m^3)$ | Source | Inhalation Unit Risk[a] $(\mu g/m^3)^{-1}$ | Source | Volatile?[a] | GIABS[a] (unitless) | Kp[b] (cm/hr) | B[b] (unitless) | τ [b] (hours/event) | t*[b] (hours) | FA[b] (unitless) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Aluminum | 1 | P | — | — | — | — | — | — | — | 1 | 0.001 | — | — | — | 1 |
| Boron | 0.2 | I | — | — | — | — | — | — | — | 1 | 0.001 | — | — | — | 1 |
| Chromium | 1.5 | I | — | — | — | — | — | — | — | 0.013 | 0.001 | — | — | — | 1 |
| Cobalt | 0.0003 | P | — | — | — | — | — | — | — | 1 | 0.0004 | — | — | — | 1 |
| Cyanide | 0.0006 | I | — | — | 0.0008 | S | — | — | Yes | 1 | 0.001 | — | — | — | 1 |
| Fluoride | 0.06 | I | — | — | — | — | — | — | — | 1 | 0.001 | — | — | — | 1 |
| Iron | 0.7 | P | — | — | — | — | — | — | — | 1 | 0.001 | — | — | — | 1 |
| Lead | — | — | — | — | — | — | — | — | — | 1 | 0.0001 | — | — | — | — |
| Manganese | 0.024 | S | — | — | — | — | — | — | — | 0.04 | 0.001 | — | — | — | 1 |
| Mercury | 0.0003 | I | — | — | — | — | — | — | — | 0.07 | 0.001 | — | — | — | — |
| Nickel | 0.02 | I | — | — | — | — | — | — | — | 0.04 | 0.0002 | — | — | — | 1 |
| Nitrate | 7.1 | I | — | — | — | — | — | — | — | 1 | 0.001 | — | — | — | 1 |
| Nitrite | 0.3 | I | — | — | — | — | — | — | — | 1 | 0.001 | — | — | — | 1 |
| Selenium | 0.005 | I | — | — | — | — | — | — | — | 1 | 0.001 | — | — | — | 1 |
| Strontium | 0.6 | I | — | — | — | — | — | — | — | 1 | 0.001 | — | — | — | 1 |
| Tin | 0.6 | H | — | — | — | — | — | — | — | 1 | 0.001 | — | — | — | 1 |
| Tributyl phosphate | 0.01 | P | 0.009 | P | — | — | — | — | — | 1 | 0.0228[c] | — | — | — | 0.9 |
| Uranium | 0.003 | I | — | — | — | — | — | — | — | 1 | 0.001 | — | — | — | 1 |

[a]U.S. Environmental Protection Agency web site (United States Environmental Protection Agency, Queried 06/19/2015, [Regional Screening Table | Mid-Atlantic Risk Assessment | US EPA], http://www.epa.gov/reg3hwmd/risk/human/rb-concentration_table/.).
Reference key:
- A = The Agency for Toxic Substances and Disease Registry
- C = The California Environmental Protection Agency
- E = Environmental Criteria and Assessment Office
- H = Health Effects Assessment Summary Tables
- I = U.S. Environmental Protection Agency's Integrated Risk Information System
- P = Provisional Peer Reviewed Toxicity Values
- S = Special Case chemical; basis for value discussed in Section 6 on EPA Regional Screening Levels website (EPA, Nov 2015)

[b]EPA/540/R/99/005, Risk Assessment Guidance for Superfund Volume I: Human Health Evaluation Manual (Part E, Supplemental Guidance for Dermal Risk Assessment) Final.
- GIABS = gastrointestinal absorption factor
- H = Health Effects Assessment Summary Tables
- I = U.S. Environmental Protection Agency's Integrated Risk Information System
- B = Partitioning constant derived from Bungee model
- $K_p$ = dermal permeability constant
- t* = time to reach steady-state
- τ = lag time

[c]Kp value for tributyl phosphate taken from Oak Ridge National Laboratory Risk Assessment Information System database available online at http://ornl.gov.

A linear sorption isotherm (using a $K_d$ approach) is considered for determining sorption within the grout and concrete layer for various contaminants as they undergo diffusive (and advective) transport through the tank. The $K_d$ values are presented in Table 7-6 in terms of best estimate and the uncertainty range that are derived from relevant published literature for chemical conditions that are likely to exist within the grout/concrete layer within the tanks.

### 7.4.3 Basis for Vadose Zone Model Development

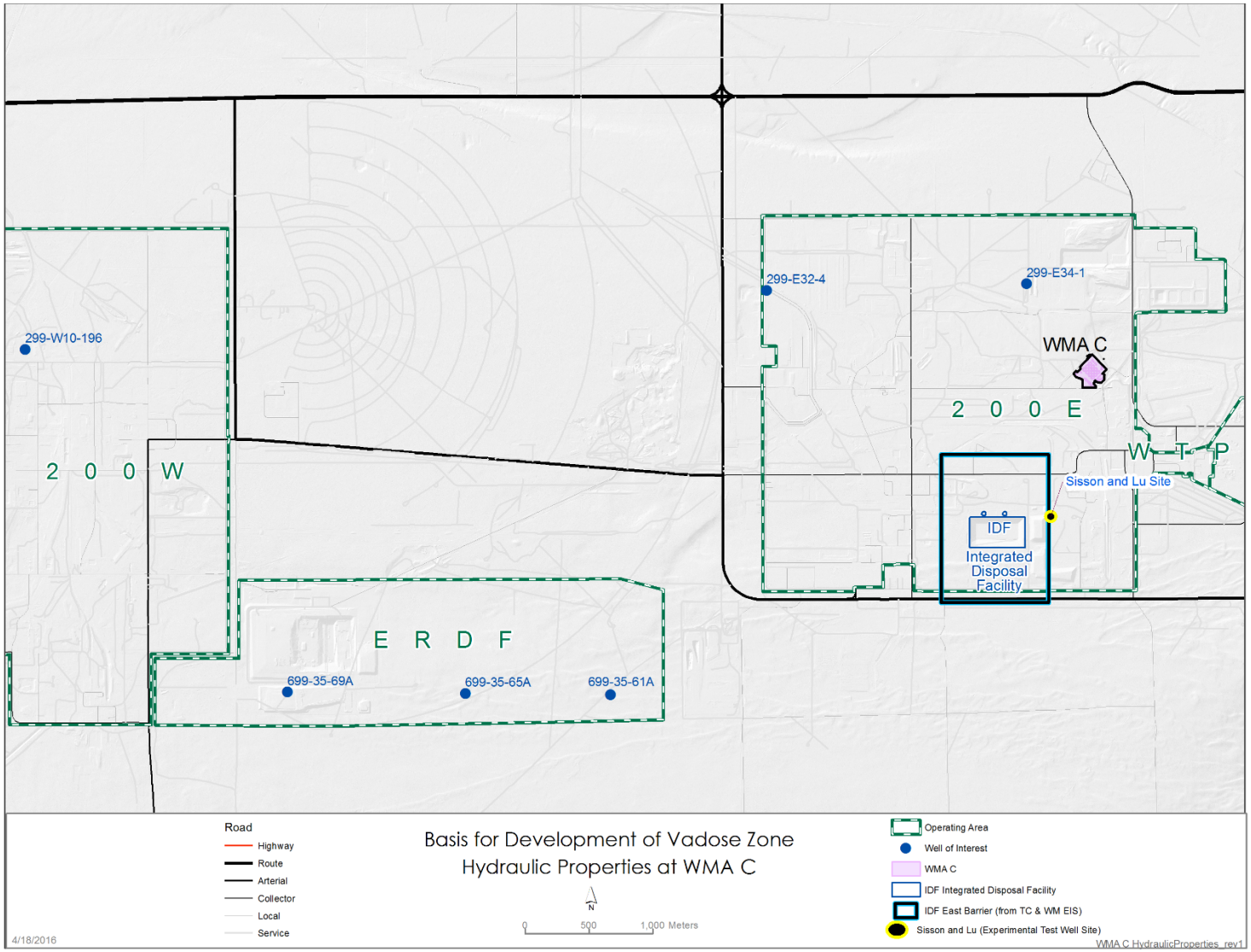
The spatial extent of various HSUs within the WMA C model domain are based on an extensive borehole dataset discussed in Section 3.2.1. The geologic framework model for WMA C is derived from the information provided in RPP-RPT-56356 (Section 3.2.1). It should be noted that at the Hanford Site more than 3,000 boreholes have been logged (PNNL-13653, "A Catalog of Geologic Data for the Hanford Site") and primary HSU designations and extents are well established.

The vadose zone hydraulic properties for WMA C are derived from a set of laboratory (core-scale) experiments conducted on samples representative of Hanford H1, H2, and H3 units and backfill material. The methodology is discussed in detail in Appendix B (Section B.2). For WMA C vadose zone modeling, each heterogeneous geologic unit is replaced by an EHM with macroscopic flow properties. With each heterogeneous unit assigned its upscaled or effective hydraulic properties, the simulated flow fields predict the bulk or mean flow behavior at the field scale. The method of upscaling is discussed in Appendix B (Section B.3).

An independent evaluation of the vadose zone conceptual model and the EHM approximation was performed using the 200 East Area Sisson and Lu injection test site (Figure 7-46) moisture content database. The database at the nearby Sisson and Lu site therefore serves as a proxy for WMA C, and is an important resource in understanding large-scale moisture movement in imperfectly stratified heterogeneous media and a relatively dry moisture regime such as those existing at WMA C. Details of the Sisson and Lu site, field injections and the spatio-temporal distribution of observed moisture plume are described in Appendix B.

Two variations of EHM model for the heterogeneous Hanford sediments were explored based on the Sisson and Lu experiments. In the first method, the small-scale core measurements for hydraulic properties were used to predict the large-scale flow behavior at the Sisson and Lu site ("Simulating field-scale moisture flow using a combined power-averaging and tensorial connectivity-tortuosity approach" [Zhang and Khaleel 2010]). The second method is based on an inverse approach which inverts the large-scale unsaturated properties using the temporal evolution of the moisture content distribution (Yeh et al. 2005). For both approaches, a moment analysis (Ye at al. 2005) was used to quantify the center of mass and the spread of the injected water for the observed and simulated moisture plumes. The first moments represent the mass center of the moisture plume in different directions at a given time. The second moments measure the spread of the plume about its mass centers. For the forward as well as the inverse EHM-based methods, spatial moments (first and second) of the simulated plume based on the effective hydraulic conductivities were in good agreement with those for the observed plume (Zhang and Khaleel 2010; Yeh et al. 2005).

**Figure 7-46. Location of Sisson and Lu Field Injection Site in 200 East Area.**




ERDF = Environmental Restoration Disposal Facility
TC&WM EIS = Tank Closure and Waste Management Environmental Impact Statement
WMA = Waste Management Area
WTP = Waste Treatment Plant

The Sisson and Lu site database also provided a framework for testing two heterogeneous modeling approaches based on combining soft (initial moisture content, bulk density and particle-size distribution) and hard (soil hydraulic properties) data ("Simulation of field injection experiments in heterogeneous unsaturated media using cokriging and artificial neural network" [Ye et al. 2007]; "A Markov chain model for characterizing medium heterogeneity and sediment layering structure" [Ye and Khaleel 2008]). The heterogeneous models do not invoke the EHM approximation. The use of both soft and hard data was valuable in reproducing the detailed moisture plume for the two heterogeneous models (i.e., the splitting of the moisture plume sandwiched within the coarse media between two fine layers at the Sisson and Lu site). However, the observed and simulated spatial moments (first and second) were not significantly different from those using the EHM-based models. Hence, models using both hard and soft data, in addition to honoring the observed first and second moments, were able to reproduce the splitting of the observed plume. On the other hand, the EHM-based modeling does not capture the detailed plume behavior, but honors the first and second moments of the observed moisture plume. With the WMA C RCA simulations being conducted over a large flow domain and over a long time frame, the fact that the calculated moments for both the EHM and heterogeneous models are of similar magnitude is an important finding, and provides justification for use of EHM approximation for vadose zone modeling.

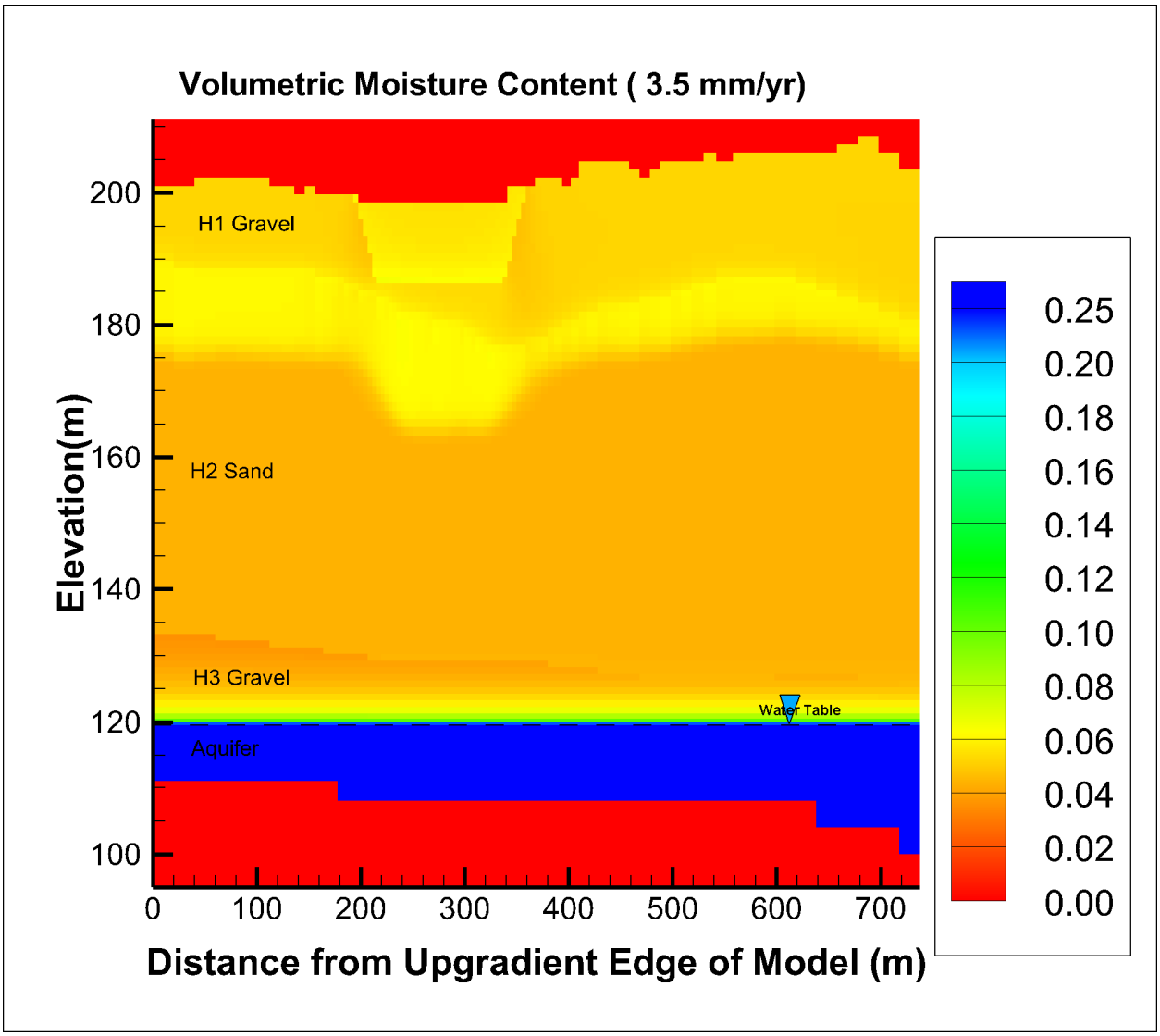
### 7.4.4 Comparison of Vadose Zone Modeling Results with Measured Data in Vicinity of Waste Management Area C

As part of WMA C site characterization, an extensive database of moisture content information is available for various HSUs. The moisture content database was developed as part of a direct push campaign conducted at WMA C in 2008, and understood as being long after the occurrence of past leaks and discharges at the farm. Figure 7-47 shows the simulated steady-state moisture profile for different stratigraphic units for the base case under long-term recharge conditions (3.5 mm/yr [0.14 in./yr]). The simulated volumetric moisture contents for different units vary within a narrow range of 4% and 7%. These values compare well with an extensive dataset of field observations where the average volumetric moisture content for the various HSUs vary from 5.1% to 6.2% (Appendix B, Table B-1). With moisture being the key driver for contaminant transport, the fact that the intermediate calculations for the simulated average moisture for different units is in overall agreement with field data enhances confidence in the PA modeling approach and calculations.

Figure 7-48 provides a comparison, for Hanford H2 unit, of the measured moisture profile (circles) for borehole C4297 that is located within WMA C and the simulated steady-state moisture profile (blue) from the base case. As indicated, for an expected long-term recharge estimate of 3.5 mm/yr (0.14 in./yr), the simulated H2 moisture profile, on the average, compares well with the measurements. As expected, the field-measured moisture contents are significantly impacted by small-scale heterogeneities and exhibit considerable variability (Figure 7-48). To the contrary, the PA simulations are based on upscaled or effective hydraulic properties; each heterogeneous formation is replaced by its homogeneous equivalent, and the upscaled or effective flow parameters are used to represent the EHM. This effectively results in a smoothing of the model estimates (Figure 7-3). Therefore, the variability of field-measured moisture contents, induced by media heterogeneities, is inherently larger in comparison to that based on

PA simulations using homogenized upscaled properties, and the ensemble average, embedded in EHM approximation, cannot capture the field-scale variability.

**Figure 7-47. Simulated Average Moisture Contents for H2 and Other Units for the Base Case (Equivalent Homogeneous Medium) Model.**

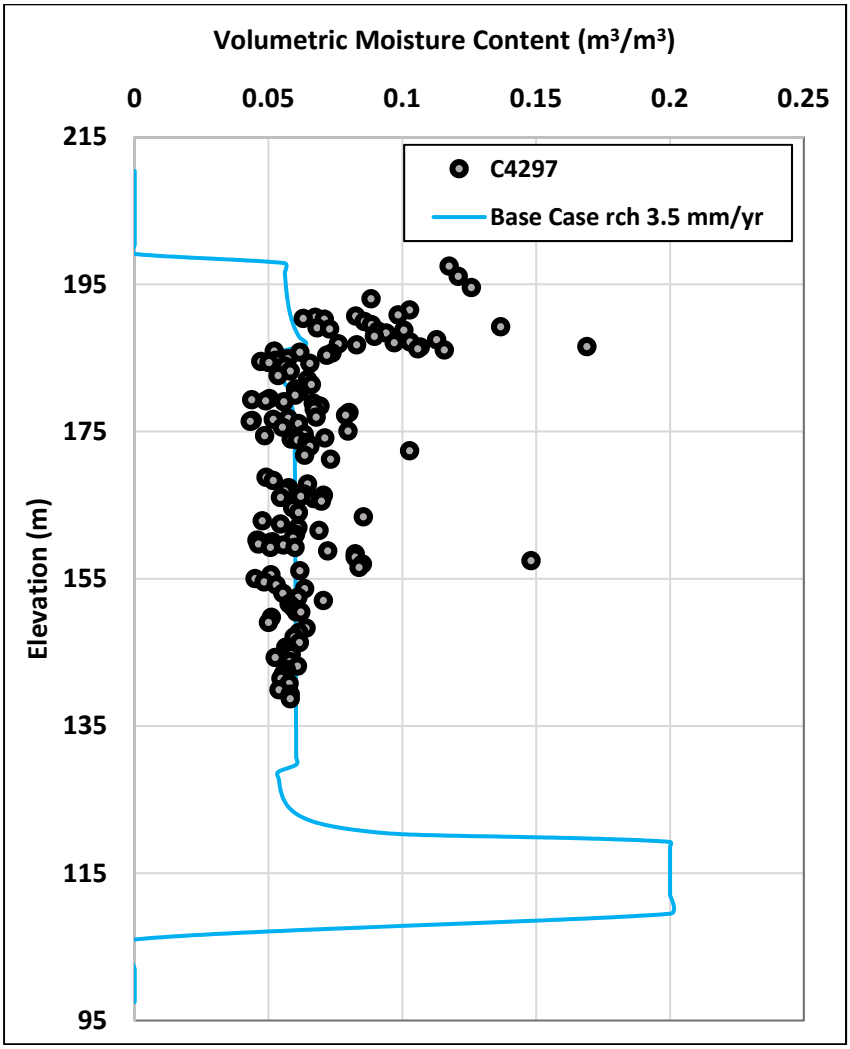



### 7.4.5 Comparison of Vadose Zone Model with Tank Closure and Waste Management Environmental Impact Statement Model for Alternative 2B

A comparison was performed to evaluate the vadose zone model developed for the WMA C PA against the TC&WM EIS model (DOE/EIS-0391) developed for WMA C. Due to varying inputs related to the residual waste inventory and waste release processes, direct comparison of results is not possible. Therefore, the residual waste inventory, waste release functions, and recharge rates were made consistent with the TC&WM EIS model by changing the inputs within the WMA C PA model (see Appendix G). The flux at the base of the vadose zone was compared

between the two models for $^{129}I$. The time series releases of $^{129}I$ to the groundwater calculated in both models include two relative maxima and negligible difference between the two peak values are observed. The results of the comparison, provided in Appendix G, show that the two models are capable of producing consistent results indicating that the hydraulic properties used in the two models produce similar results.

**Figure 7-48. Comparison of Simulated (Blue) and Observed (Circle) Moisture Content for Hanford H2 Sand-Dominated Unit.**




### 7.4.6 Basis for Saturated Zone Model Development

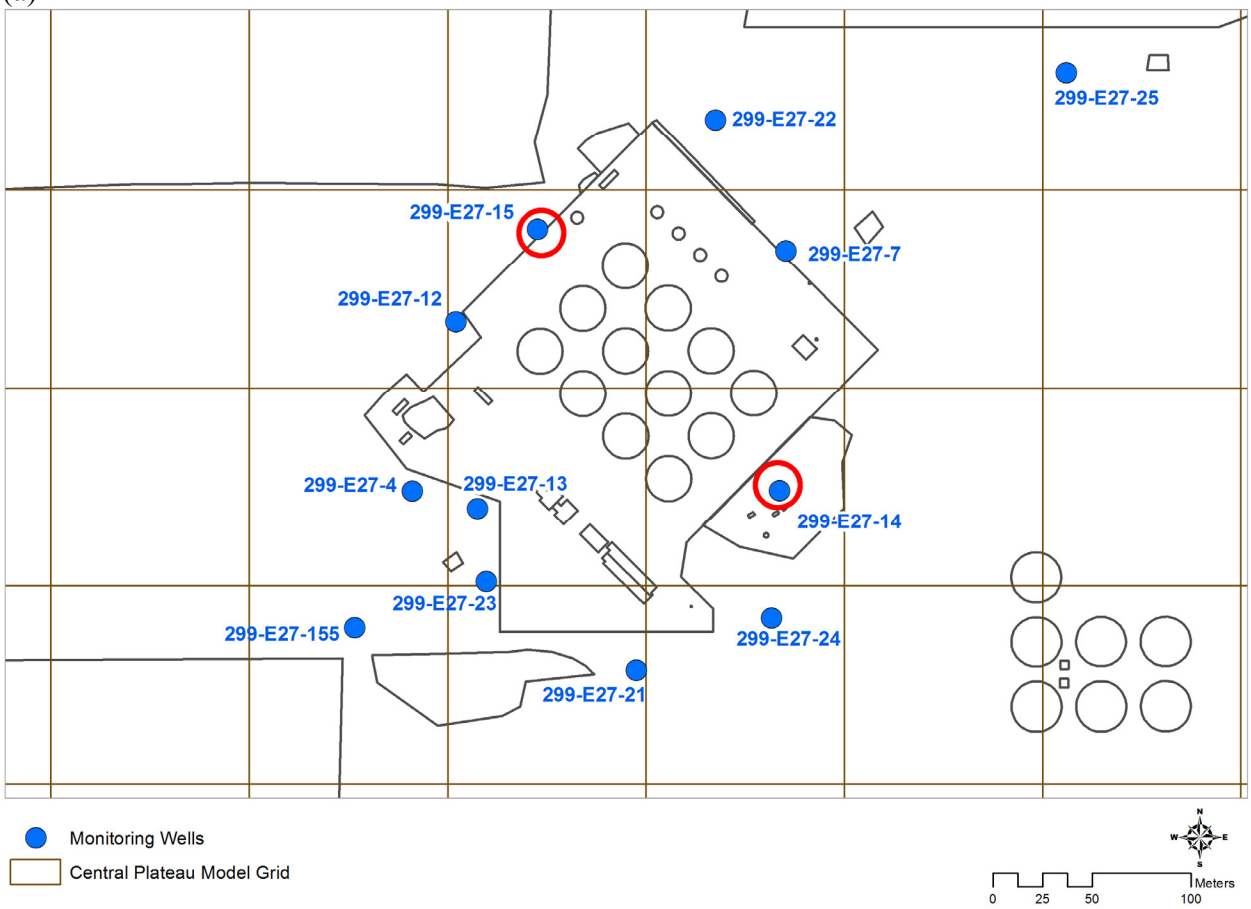
For the WMA C PA modeling, the unconfined aquifer is treated as an EHM, where effective parameters and appropriate boundary conditions derived from a regional scale groundwater flow model are used. The development of the model parameters is discussed in Appendix C. A calibrated CPGWM (CP-47631, Revision 2) serves as the basis for developing macro-scale parameters for the unconfined aquifer at WMA C. The development of CPGWM incorporates over 30 years of experience on development and application of groundwater models for the

Central Plateau [PNL-10886, "Development of a Three-Dimensional Ground-Water Model of the Hanford Site Unconfined Aquifer System: FY 1995 Status Report"; PNNL-13641; PNNL-14398, "Transient Inverse Calibration of the Site-Wide Groundwater Flow Model (ACM-2): FY 2003 Progress Report"; PNNL-14753, "Groundwater Data Package for Hanford Assessments"; PNNL-12261].

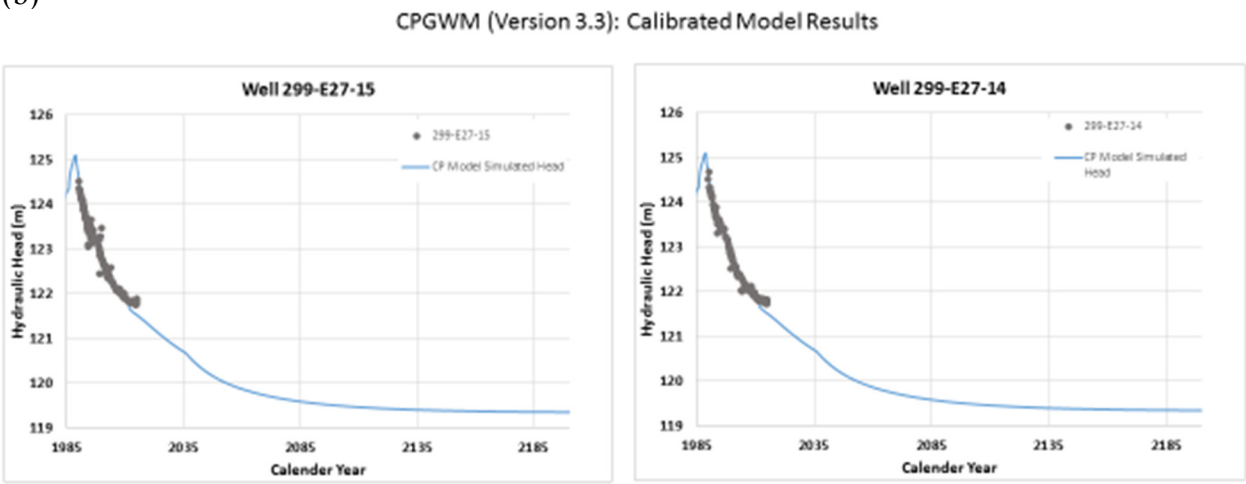
The CPGWM incorporates the large-scale geologic and hydrogeologic features and provides estimates of water levels, hydraulic gradients, and groundwater flows throughout the 200 West and 200 East Areas, for current and expected future groundwater conditions. Simulated water levels are compared to observed values for wells located upgradient (well 299-E27-15) and downgradient (well 299-E27-14) of WMA C (Figure 7-49). The observed heads and CPGWM-simulated heads, representing a time span of over 20 years, compare well, providing confidence in the predictive capabilities of the CPGWM as well as how the WMA C saturated media properties are parameterized and groundwater fluxes apportioned in the PA.

**Figure 7-49. (a) Waste Management Area C Well Locations, and (b) Central Plateau Groundwater Model Calibration Results (after CP-47631).**

(a)




(b)




CPGWM = Central Plateau Groundwater Model

Reference: CP-47631, "Model Package Report: Central Plateau Groundwater Model Version 6.3.3."

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# 8.0 RESULTS OF ANALYSIS

This Section presents the results of modeling at the PoCal in terms of contaminant concentration, non-cancer hazard and cancer risk at the PoCal. No comparisons are made against the performance objectives; see Section 10 for comparison against the performance objectives at the PoCal. This section presents the results of the analyses described in Section 7, and discusses the release of COPCs from the source term (Section 8.1) and the environmental transport of COPCs via the groundwater pathway (Section 8.2). The results of the analyses conducted for each part of the modeling effort are summarized independently, leading to the discussion of the groundwater cancer risk and non-cancer hazards presented in Section 8.3. Intermediate results are presented to illustrate the influence of each analysis step on the overall result. Results are provided for two time periods: the 0- to 1,000-year period (2020 to 3020) and 1,000- to 10,000-year period post-closure. Results are provided for the receptor located 100 m (328 ft) downgradient from the WMA C fenceline. Intermediate results and hazards are projected out 10,000 years to identify peaks for some COPCs that migrate slowly through the environment.

## 8.1 SOURCE TERM

The source term is defined as the rate of release from the facility as a function of time (NCRP Report 152, “Performance Assessment of Near-Surface Facilities for Disposal of Low-Level Radioactive Waste”). Since it is defined as a release from the facility, it includes a number of processes associated with mobilization of contaminants from the waste form, and migration of the contaminants to the boundary of the facility. The boundary of the facility for WMA C source term is considered the outer boundary of the engineered features (i.e., the bottom of the tank base mat, or the outer surface of catch tanks, pipelines, and other ancillary equipment).

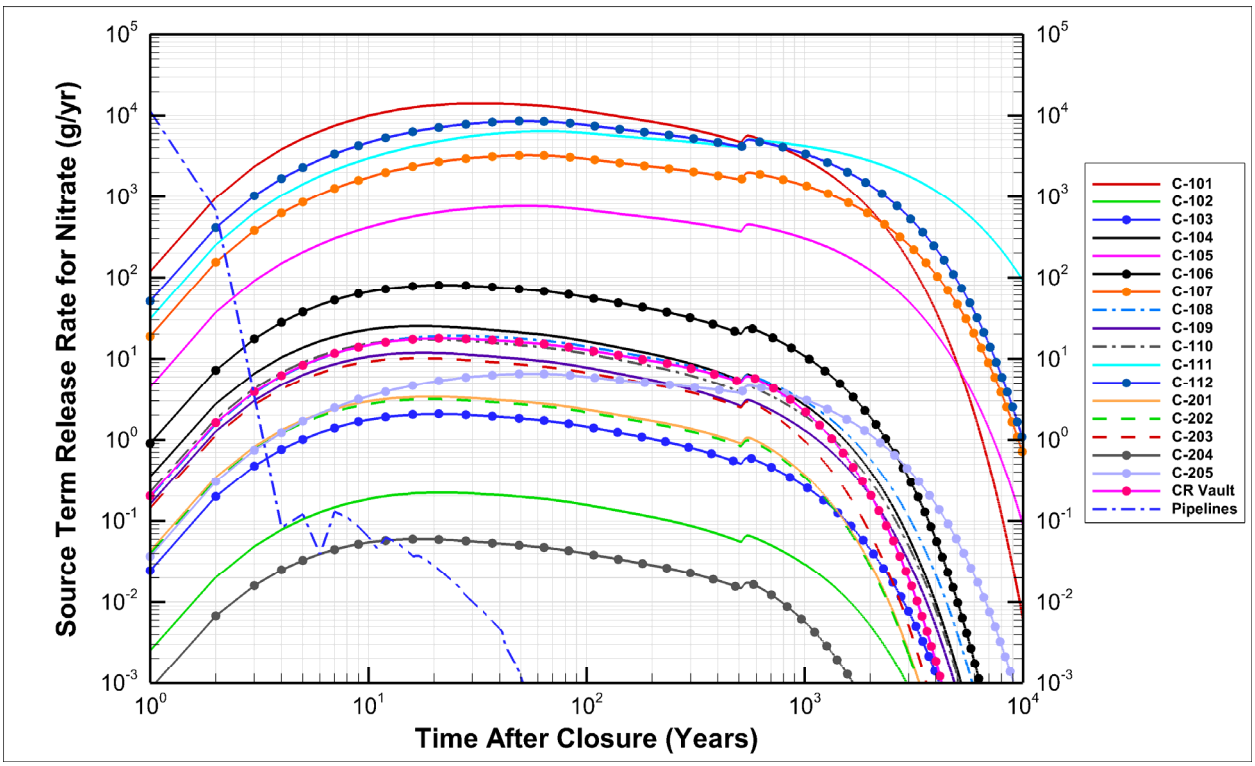
A total of 19 different sources for releases to groundwater are evaluated in the RCA, which contribute to the overall source term. These sources consist of the twelve 100-series tanks, four 200-series tanks, C-301 catch tank, 244-CR vaults, and pipelines. The residual inventory and waste volume associated with each source are treated separately, resulting in an analysis of transport through groundwater for each source. Sources are added together to calculate the total impact as part of the groundwater analysis, when the plumes from different sources overlap in the groundwater analysis.

For the situation when the tank concrete and infill grout are intact, the conceptual model is as follows. The intact concrete and grout cause any water in contact with residual wastes to be stagnant. As a result, the only driving force for migration of contaminants in residual wastes to the boundary of the engineered barriers is the chemical potential gradient between the waste and the tank surroundings. Therefore, mass release calculations are controlled by diffusion through the engineered structures (for tanks, the base mat) for all the sources except for the pipelines, which are considered advection-dominated because it is uncertain how much reliance can be placed on the grout being intact. It is noteworthy that the conditions that produce a diffusion-dominated transport condition are not primarily based on, and indeed are not reliant on, an assumption that the base mat is intact. Instead, the diffusional release is caused mainly by the

infill grout, which limits water flow rates through the base mat. As discussed in Section 7.2.1.2 (Evaluation of Tank Stability), the infill grout is expected to be stable for long periods of time. As a result, this intact tank configuration with diffusional releases is the primary situation modeled in this RCA, and is included in the base case analysis. Other conceptual models have been implemented in several of the sensitivity cases (see Section 9).

The base case release rate for nitrate from each of the sources in the source term is presented in Figure 8-1. An initial large release rate occurs for the pipeline source, and is attributable to the assumption that releases from the pipelines are dominated by advection. The sharp decline in the pipeline release rate is a reflection of source inventory depletion, and to a lesser extent a reflection of declining flow rate as the system responds to the placement of the cover. At closure (during emplacement of surface cover), the recharge rate changes from the Operations time period of 100 mm/yr (3.9 in./yr) to the early Post-Closure recharge rate of 0.5 mm/yr (0.02 in./yr) (over the 500 years). As a result, the vertical flow rate through the vadose zone adjusts slowly to the imposed boundary conditions. Nearly all of the nitrate inventory associated with the pipeline source term is released by about 50 years after closure. In contrast, the release rate from grouted tanks increases gradually. This is attributable to the slower diffusive transport through the tank base mat.

**Figure 8-1. Release Rate of Nitrate (g/yr) from Each Source.**

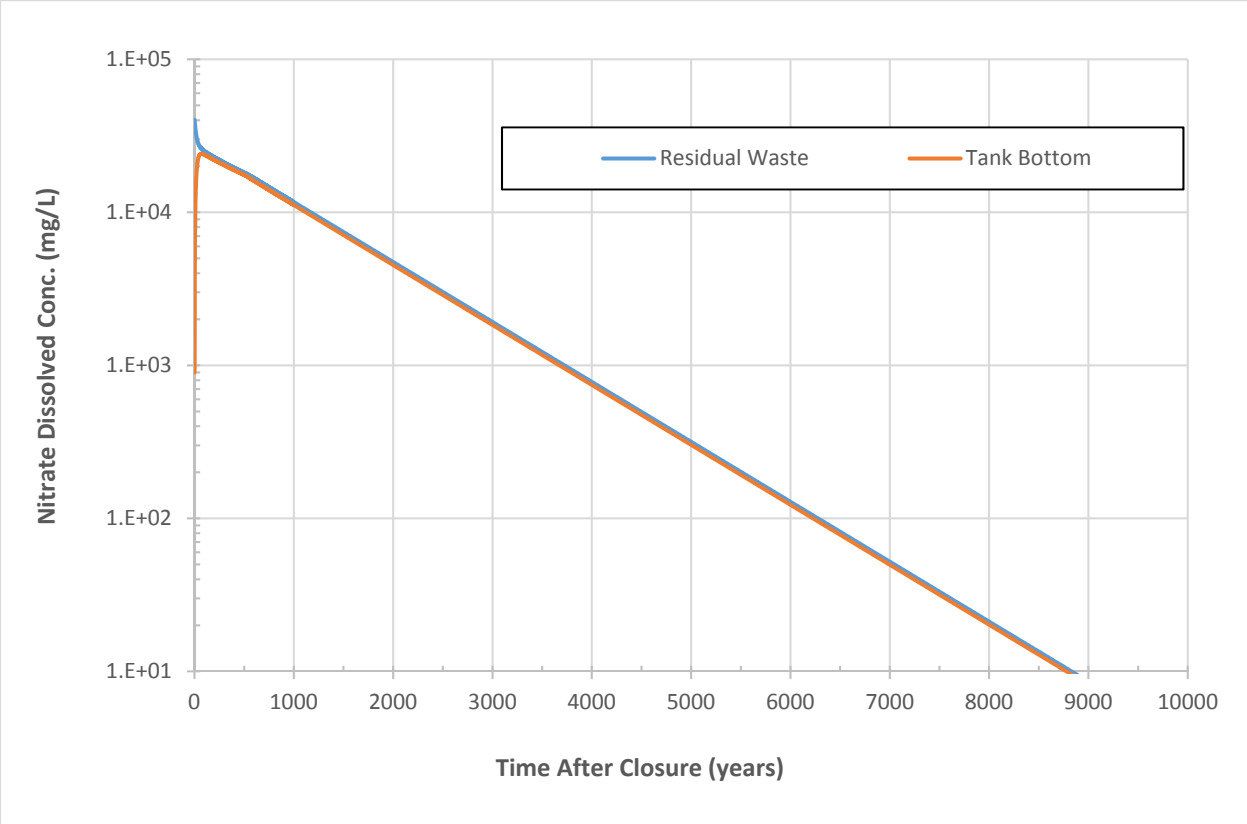



The magnitude of diffusive release rates for nitrate from each source are proportional to the residual concentration of nitrate (residual inventory per unit residual water volume) within each source. The release rate from tank C-101 remains the highest in the first 700 years due to the highest initial residual concentration. However, the release rate from tank C-111 becomes

highest after 700 years as the release rate from tank C-101 declines. This is primarily due to larger residual nitrate inventory in tank C-111 (14,700 kg) compared to tank C-101 (8,200 kg). Note that the initial residual waste volume of tank C-111 is larger (132,000 L) than that of tank C-101 (18,900 L) and therefore, even though the inventory is larger in tank C-111, it leads to a smaller initial concentration compared to tank C-101. The small rise in release rate noticeable at about 500 years is due to an increase in Darcy flux, when the surface barrier is assumed to transition to its degraded state and the recharge rate changes from 0.5 mm/yr to 3.5 mm/yr.

Figure 8-2 compares the concentration resulting from release of nitrate from the waste layer to the tank base mat for a representative tank (C-105). There is a sharp initial spike in concentration in the tank base mat as mass moves from the residual waste layer and concentration gradient is established. The concentrations gradually decline as mass is depleted due to continuous diffusive release. Release from other tanks are similar; however, the magnitudes are different due to differences in starting inventory.

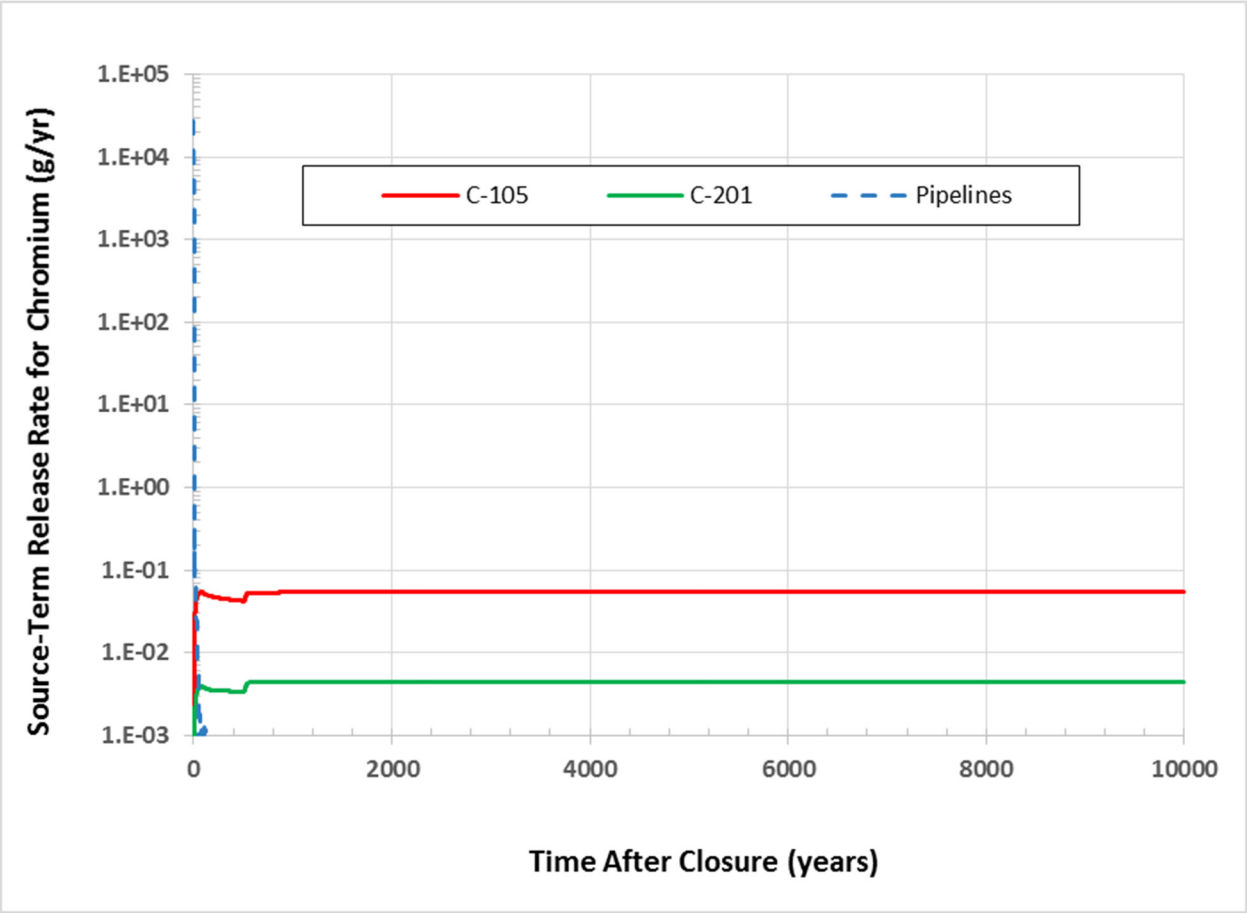
**Figure 8-2. Comparison of Dissolved Concentration of Nitrate (g/L) in the Residual Waste and Tank Bottom for Tank 241-C-105.**




The release rate for chromium from selected sources is presented in Figure 8-3; these sources are representative of the behavior of the other sources. Chromium has a dissolved concentration (solubility) limit of 2,000 µg/L in all sources except the pipeline. As a result, a sharp decline in the release is observed for the pipeline as the inventory is depleted at early times when the

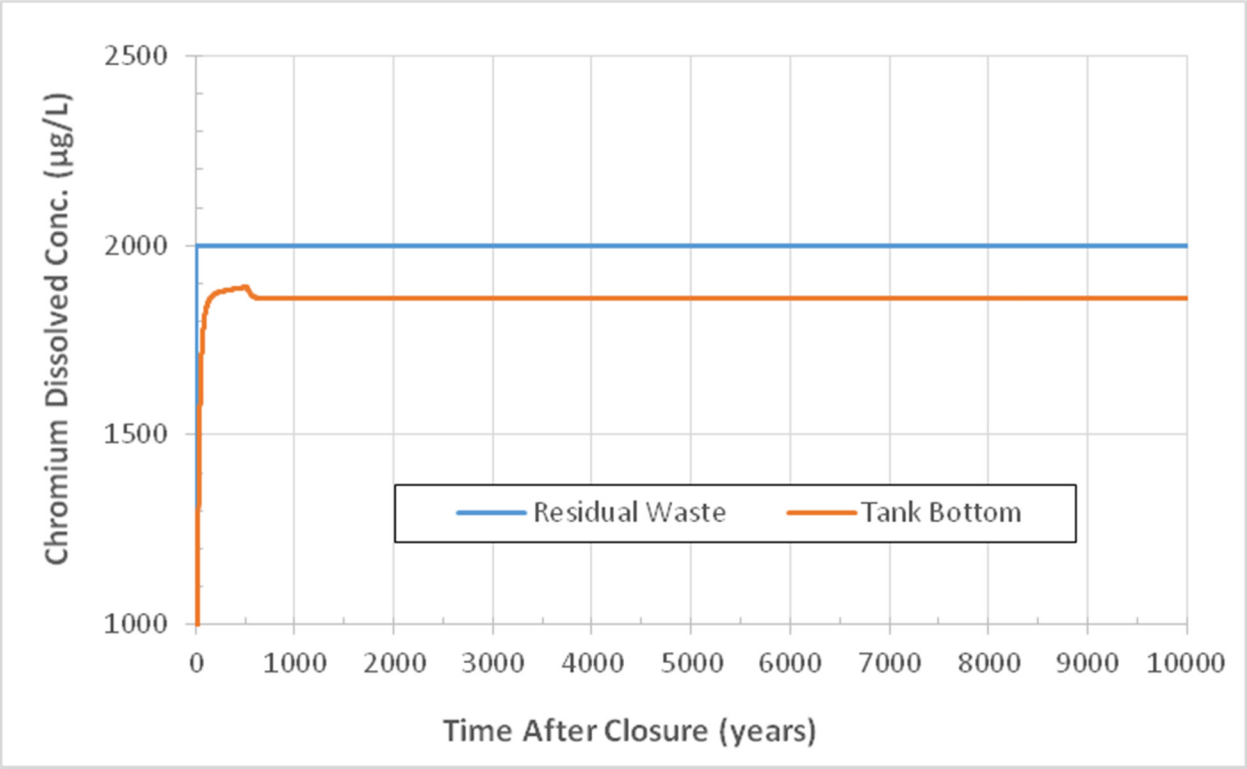
vertical Darcy flux is relatively high. In contrast, the release rate from tanks C-105 and C-201 is controlled by the dissolved solubility limit under diffusive release conditions. The dissolved concentration for chromium for tank C-105 is shown in Figure 8-4 exiting the residual waste and the tank bottom. The concentration in the residual waste remains at the solubility limit, indicating that inventory remains in the tank at the end of the simulation. The dissolved chromium concentration in the tank base mat remains slightly lower than the residual waste, reflecting diffusion gradient to the outside of the tank.

**Figure 8-3. Release Rate of Chromium (g/yr) from Representative Sources.**




For all other analytes modeled, the releases are simpler, as no solubility limits or waste form degradation mechanisms are considered. For pipelines, the release is primarily advective and similar in behavior to the release shown for nitrate. For the remaining sources, where intact grouted tank conditions are assumed, the release mechanism is diffusion through the tank base mat. Differences in diffusive behavior are the result of different grout partition coefficients ($K_d$) in the base mat and concentration differences due to varying inventories of each analyte. The effective diffusion coefficient for all the analytes through the concrete and grout layer is $3 \times 10^{-8}$ cm$^2$/s ($4.7 \times 10^{-8}$ in.$^2$/s) (based on the half-cell diffusion experiments conducted on $^{99}$Tc).

**Figure 8-4. Comparison of Dissolved Concentration of Chromium (µg/L) in the Residual Waste and Tank Bottom for Tank 241-C-105 Sources.**




## 8.2 ENVIRONMENTAL TRANSPORT OF CHEMICALS OF POTENTIAL CONCERN

This section presents the results of the environmental transport of COPCs for the groundwater. Included in this section are the results of the screening analysis used to determine which analytes are likely to reach the unconfined aquifer within 10,000 years (Section 8.2.1), flow and travel time analysis through the vadose zone (Section 8.2.2), and the groundwater transport of hazardous chemicals (Section 8.2.3) for the base case for two time periods: 1) from closure to 1,000 years and 2) from 1,000 years to 10,000 years. Tabular and graphical presentations of the summaries of the various transport calculations are presented.

### 8.2.1 Result of Screening Analysis for Groundwater Pathway

A version of the STOMP© 3-D groundwater flow and transport model was used to perform a screening analysis to identify those contaminants that are not sufficiently mobile to impact groundwater during the 0- to 1,000-year and 1,000- to 10,000-year analysis time frames. This screening step helps to streamline the RCA, and to focus attention on the contaminants that affect performance.

The criterion chosen for screening is the first-arrival time of the contaminant. By selecting this as the criterion, and by using conservatively chosen input parameters, there is assurance that

none of the screened contaminants can have a significant effect on RCA results. That is, the screening $K_d$ value thresholds are based on any non-zero impact to groundwater, obtained by using vadose zone properties associated with the maximum transport rates for each geologic unit and the maximum net infiltration rate present during each simulation period. The application of conservative parameter values in this manner is an approach accepted and applicable for the screening analysis, per the EPA guidance to use simple methods and conservative or simplified assumptions to facilitate screening (EPA/540/F-95/041, Soil Screening Guidance: Fact Sheet). By using such conservative input parameters, the number of contaminants screened out is minimized, so that important contributors to performance are not inadvertently omitted. As a result, some contaminants may only arrive at the water table for particular sensitivity evaluations (i.e., evaluations that minimize the time of transport through the vadose zone). For many of the sensitivity cases, a number of the contaminants may have no impact on the RCA results.

The first-arrival times for each of the representative $K_d$ values used in the screening calculations using STOMP© are summarized in Table 8-1. The results show that the time of first arrival is a strong linear function of the $K_d$ value. According to the screening model results, the $K_d$ cutoff value for the 1,000-year time frame is approximately 0.15 mL/g (without any gravel correction), and the $K_d$ cutoff value for the 10,000-year time frame is approximately 1.5 mL/g (without any gravel correction).

**Table 8-1. First-Arrival Time (in Calendar Year) of Constituents of Potential Concern for Various $K_d$ Values Based on Screening Analysis Using Subsurface Transport Over Multiple Phases (STOMP)©.**

| Contaminant $K_d$ (material < 2 mm) (mL/g) | Calendar Year of First Arrival at Water Table | Time of Arrival, Post-Closure (Closure occurring in 2020) Years |
|---|---|---|
| 0.10 | 2517.5 | 497.5 |
| 0.15 | 3022.5 | 1,002.5 |
| 0.20 | 3505 | 1,485 |
| 0.25 | 3900 | 1,880 |
| 0.30 | 4210 | 2,190 |
| 0.40 | 4840 | 2,820 |
| 0.60 | 6110 | 4,090 |
| 0.80 | 7390 | 5,370 |
| 1.0 | 8680 | 6,660 |
| 1.5 | 11900 | 9,880 |
| 2.0 | >12020 | >10,000 |
| 2.5 | >12020 | >10,000 |

Subsurface Transport Over Multiple Phases (STOMP)© is copyrighted by Battelle Memorial Institute, 1996.

The results of the screening analysis indicate that, even when using parameter estimates biased to produce the greatest pore water velocity in the vadose zone: (1) contaminants with a $K_d > 0.15$ mL/g do not reach groundwater within the 1,000-year time frame, and (2) radionuclides with a $K_d \geq 2.0$ mL/g do not reach groundwater within the 10,000-year period (Table 8-1). While it is likely the actual $K_d$ cutoff is only slightly greater than 1.5 mL/g, the screening evaluation did not include a representative contaminant with a $K_d$ value between 1.5 mL/g and 2 mL/g, because the list of COPCs include only one contaminant (TBP) with a $K_d$ value in this range (Table 7-10). The screening evaluation helps in reducing the number of radionuclides to be evaluated using 3-D modeling analysis.

Of the list of chemicals in the WMA C residuals inventory, and on the basis of the results of the screening phase, only nine (Table 8-2) are sufficiently mobile to arrive at groundwater in the 1,000-year period, and three others are sufficiently mobile to arrive at groundwater in the 1,000- to 10,000-year time frame. The other contaminants in the WMA C residual inventory are not included in further groundwater impact analysis because they do not reach the water table within the evaluation time frames.

**Table 8-2. Constituents of Potential Concern that Arrive at the Water Table within the 1,000-Year and 10,000-Year Time Frame Based on the Screening Analysis Conducted Using Subsurface Transport Over Multiple Phases (STOMP)©.**

| Contaminant | $K_d$ (material < 2 mm) (mL/g) | $K_d$ (Backfill) (mL/g) | $K_d$ (Hanford H1 and H3) (mL/g) | $K_d$ (Hanford H2) (mL/g) |
|---|---|---|---|---|
| **Contaminants that may arrive at the water table within 1,000 years** | | | | |
| CN | 0 | 0 | 0 | 0 |
| Co | 0 | 0 | 0 | 0 |
| Cr | 0 | 0 | 0 | 0 |
| F | 0 | 0 | 0 | 0 |
| H | 0 | 0 | 0 | 0 |
| Nb | 0 | 0 | 0 | 0 |
| $NO_2$ | 0 | 0 | 0 | 0 |
| $NO_3$ | 0 | 0 | 0 | 0 |
| Se | 0.1 | 0.05 | 0.06 | 0.08 |
| **Contaminants may arrive at the water table within 10,000 years** | | | | |
| Sn | 0.5 | 0.23 | 0.29 | 0.4 |
| U | 0.6 | 0.28 | 0.35 | 0.48 |
| C | 1 | 0.46 | 0.58 | 0.8 |
| Tributyl phosphate | 1.89 | 0.87 | 1.1 | 1.5 |

Subsurface Transport Over Multiple Phases (STOMP)© is copyrighted by Battelle Memorial Institute, 1996.

### 8.2.2 Base Case Flow Analysis in the Vadose Zone

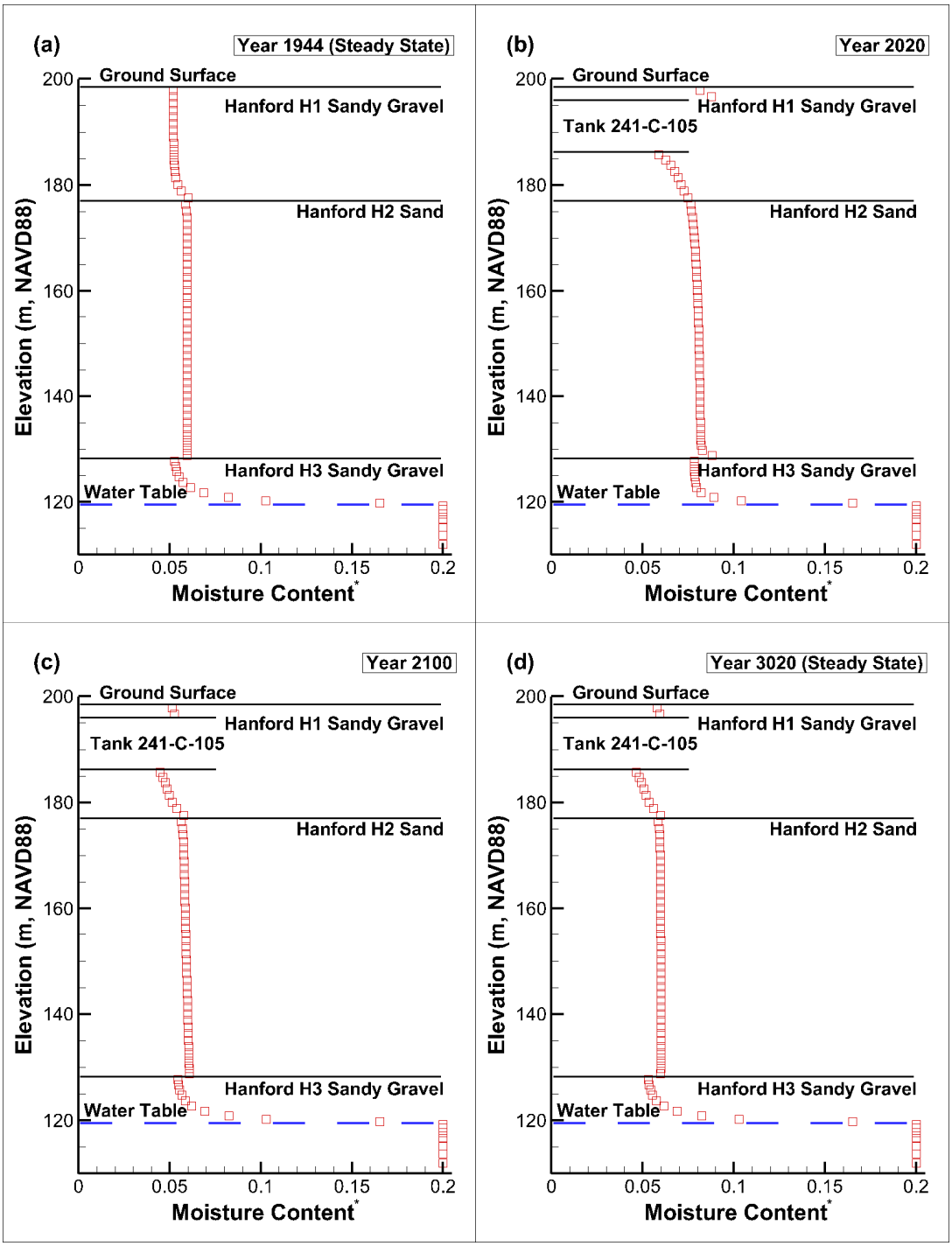
The moisture content in the vadose zone underneath WMA C changes in response to: (1) changes in the recharge regime imposed by the surface conditions; and (2) the inclusion of the tank farm structures, including an increase in moisture content that occurs during the operations period, and an eventual decrease in moisture content caused by the performance of the surface barrier (Figure 8-5). The moisture content underneath the tanks decreases slightly from the time of closure in year 2020, when the surface barrier is constructed, until steady-state conditions are reestablished approximately 1,000 years later [year 3020; compare Figure 8-5(b) and (d)]. Overall, the changes in the moisture content throughout the profile are relatively small in magnitude compared to the changes in net infiltration at the surface.

The changes in the vertical Darcy flux (the bulk flow rate of moisture in the vadose zone) are more apparent than the changes in moisture content (Figure 8-6). The function of the WMA C surface barrier is visible in Figure 8-6(a), where the trend approaches zero directly beneath the tanks but is approximately equal to the pre-WMA C undisturbed surface condition recharge rate throughout the remainder of the vadose zone. By the time the barrier performance is assumed to degrade in 2520, the Darcy flux appears to have been impacted throughout the Hanford H2 sand [Figure 8-6(b)], although the flux appears to remain unchanged in the units below the sand. By 1,000 years post-closure, the moisture profile reaches a condition of nearly uniform downward flow, particularly in the Hanford H2 Sand, reflective of the 3.5 mm/yr recharge imposed in the modeling domain [Figure 8-6(c) and (d)].

### 8.2.3 Transport Analysis

The WMA C RCA includes calculations of the highest calculated groundwater concentration at the 100–m (328-ft) buffer zone surrounding WMA C (Section 2.3 Point of Assessment and Timing Assumptions). To determine the highest groundwater concentration, a flux plane (used to determine the concentration in the aquifer) is located 100 m (328 ft) from the southeast edge of WMA C (Figure 8-7). This flux plane was further divided into nine segments such that the center lines of the plumes in the groundwater resulting from the residuals released from a single line of 100-series tanks parallel to the direction of groundwater flow (e.g., the center line of the plumes resulting from the tank residuals in C-102, C-105, C-108, and C-111) intersect the perpendicular flux plane within the same segment. Each of these segments is approximately 30 m (100 ft) wide and each one is considered a PoCal. EPA/540/R-95/128, Soil Screening Guidance: Technical Background Document and WAC 173-340-747 imply that the cross section width ought to equal the width of contamination entering the aquifer. The width of the PoCal segments is sufficient to intercept the centerline of the plumes resulting from the tank residuals from a single line of 100-series tanks, which appears consistent with the intent of EPA/540/R-95/128 and WAC 173-340-747. The concentration at each of these flux plane segments is calculated by dividing the flux of contaminant (kg/time/$m^2$) by the water flux (L/time/$m^2$). The aquifer mixing zone extends into the upper 5 m (16.4 ft) of the aquifer on the basis of the 4.5-m (15-ft) well screen length (and mixing zone dimension) associated with State monitoring well descriptions (e.g., see Equation 747-4 in WAC 173-340-747).

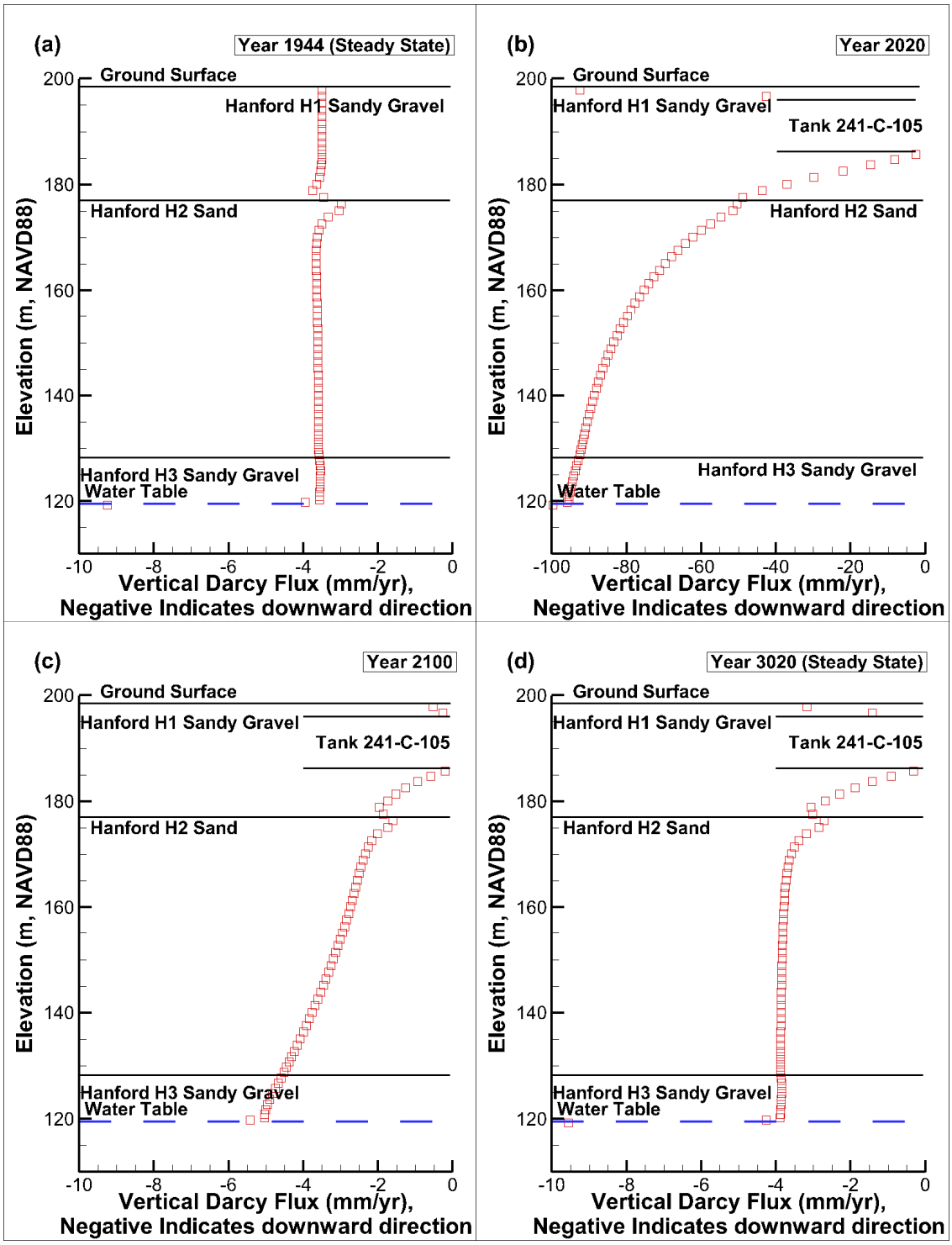
**Figure 8-5. Moisture Content in the Vadose Zone at Tank 241-C-105 in Waste Management Area C for Four Times of Interest: (a) Pre-Hanford Steady State, (b) Waste Management Area C Closure at Year 2020, (c) Approximately 100 Years after Closure, and (d) End of 0- to 1,000-Year Post-Closure Period and Approximate Reestablishment of Steady-State Flow Field.**




*The moisture content below the water table is equal to the porosity.

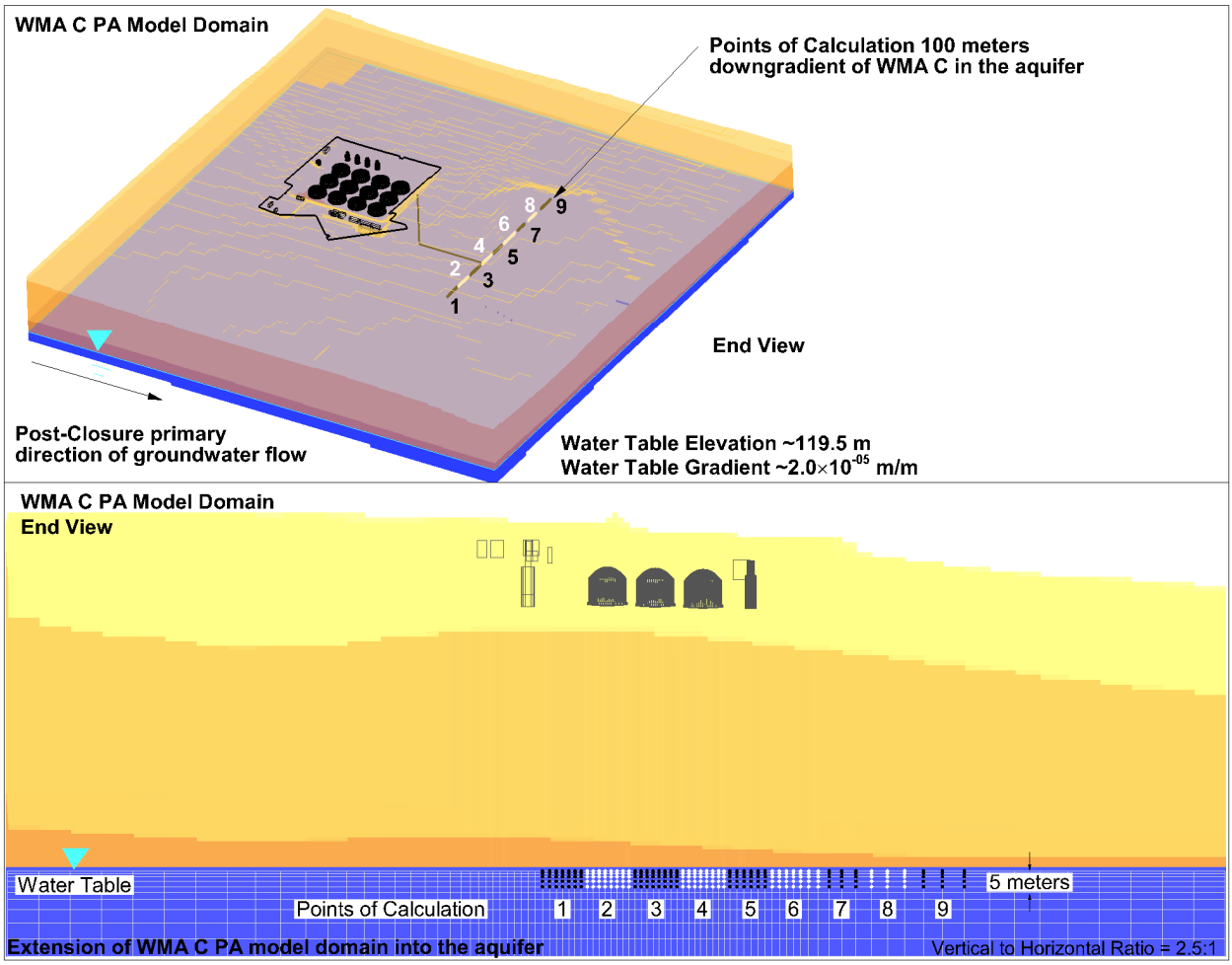
NAVD88 = North American Vertical Datum of 1988

**Figure 8-6. Darcy Flux in the Vadose Zone at Tank 241-C-105 in Waste Management Area C for Four Times of Interest: (a) Pre-Hanford Steady State, (b) Waste Management Area C Closure at Year 2020, (c) Approximately 100 Years after Closure, and (d) End of 0- to 1,000-Year Post-Closure Period and Approximate Reestablishment of Steady-State Flow Field.**




NAVD88 = North American Vertical Datum of 1988

**Figure 8-7. Points of Calculation 100 Meters Downgradient of Waste Management Area C.**




PA = performance assessment WMA = Waste Management Area

**8.2.3.1 Base Case Evaluation of Contaminant Transport for Groundwater Pathway During 0- to 1,000-Year Post-Closure Period.** The results of the base case modeling indicate that only chemical constituents with $K_d$ values equal to zero from the grouted WMA C tank residuals identified in the inventory reach groundwater within the 0- to 1,000-year post-closure period (1,000 years) (Table 8-3). The list includes cyanide, cobalt, chromium (assumed to be hexavalent chromium), fluoride, nitrate, nitrite, selenium, tin, and uranium. The earliest first arrival (numerically non-zero concentration calculation) of any contaminant to a PoCal on the line 100 m downgradient of WMA C is year 2055, which is 35 years after closure. However, the peak concentration of any of these COPCs does not occur until approximately 1,375 years after closure.

Only chromium impacts groundwater to within one one-thousandth of its MCL during the 1- to 1,000-year post-closure period. Note that this is only the case if all chromium is assumed to remain hexavalent chromium in the environment. No other COPCs impact groundwater to within one ten-thousandth of their MCL during the 0- to 1,000-year post-closure period.

**Table 8-3. Maximum Groundwater Concentration for Selected Chemicals at 100 meters Downgradient from Waste Management Area C Over the 0- to 1,000-Year and 1,000- to 10,000-Year Post-Closure Time Frames.**

| Chemical Constituents | Nominal $K_d$ Value (mL/g) | Concentration Units | Maximum Concentration during 0- to 1,000-year Post-Closure Time Frame | Point of Calculation | Years after Closure of Maximum Concentration | Maximum Concentration during the 1,000- to 10,000-year Post-Closure Time Frame | Point of Calculation |
|---|---|---|---|---|---|---|---|
| Cyanide | 0 | µg/L | 0.00008 | PoCal 5 | 1,500 | 0.01 | PoCal 5 |
| Cobalt | 0 | mg/L | 6E-10 | PoCal 6 | 1,535 | 5E-08 | PoCal 5 |
| Chromium | 0 | µg/L | 0.05 | PoCal 1 | 1,330 | 0.5 | PoCal 5 |
| Fluoride | 0 | mg/L | 0.0004 | PoCal 5 | 1,435 | 0.02 | PoCal 5 |
| Nitrite | 0 | mg/L | 0.0009 | PoCal 3 | 1,445 | 0.07 | PoCal 4 |
| Nitrate | 0 | mg/L | 0.009 | PoCal 3 | 1,375 | 0.3 | PoCal 3 |
| Selenium | 0.1 | mg/L | 0 | | 4,710 | 2E-06 | PoCal 5 |
| Tin | 0.5 | mg/L | 0 | | 1,0000 | 1E-09 | PoCal 6 |
| Uranium | 0.6 | µg/L | 0 | | 1,0000 | 0.049 | PoCal 3 |

The extent of transport in the vadose zone at the end of the 0- to 1,000-year post-closure period of the most mobile existing chemical constituents (e.g., chromium, fluoride, nitrate, and nitrite $K_d$ = 0 mL/g) appears as indicated with the depiction of transport for nitrate shown in Figure 8-8. Releases from the pipelines, vault, and tank residuals have reached the water table, but the center of the nitrate mass remains about halfway through the vadose zone above the water table. Immediately below WMA C, concentrations in groundwater only appear to be as high as 4.5 mg/L. The extent of transport of the less mobile COPCs (e.g., selenium [$K_d$ for < 2 mm size material = 0.1 mL/g], tin [$K_d$ for < 2 mm size material = 0.5 mL/g], and total uranium [$K_d$ for < 2 mm size material = 0.6 mL/g], respectively) during the 0- to 1,000-year post-closure period appears contained within the Hanford H1 sandy gravel unit, approximately 60 m above the water table (Figure 8-9, Figure 8-10, and Figure 8-11). None of these contaminants have reached the water table by the end of the 1,000-year post-closure period.

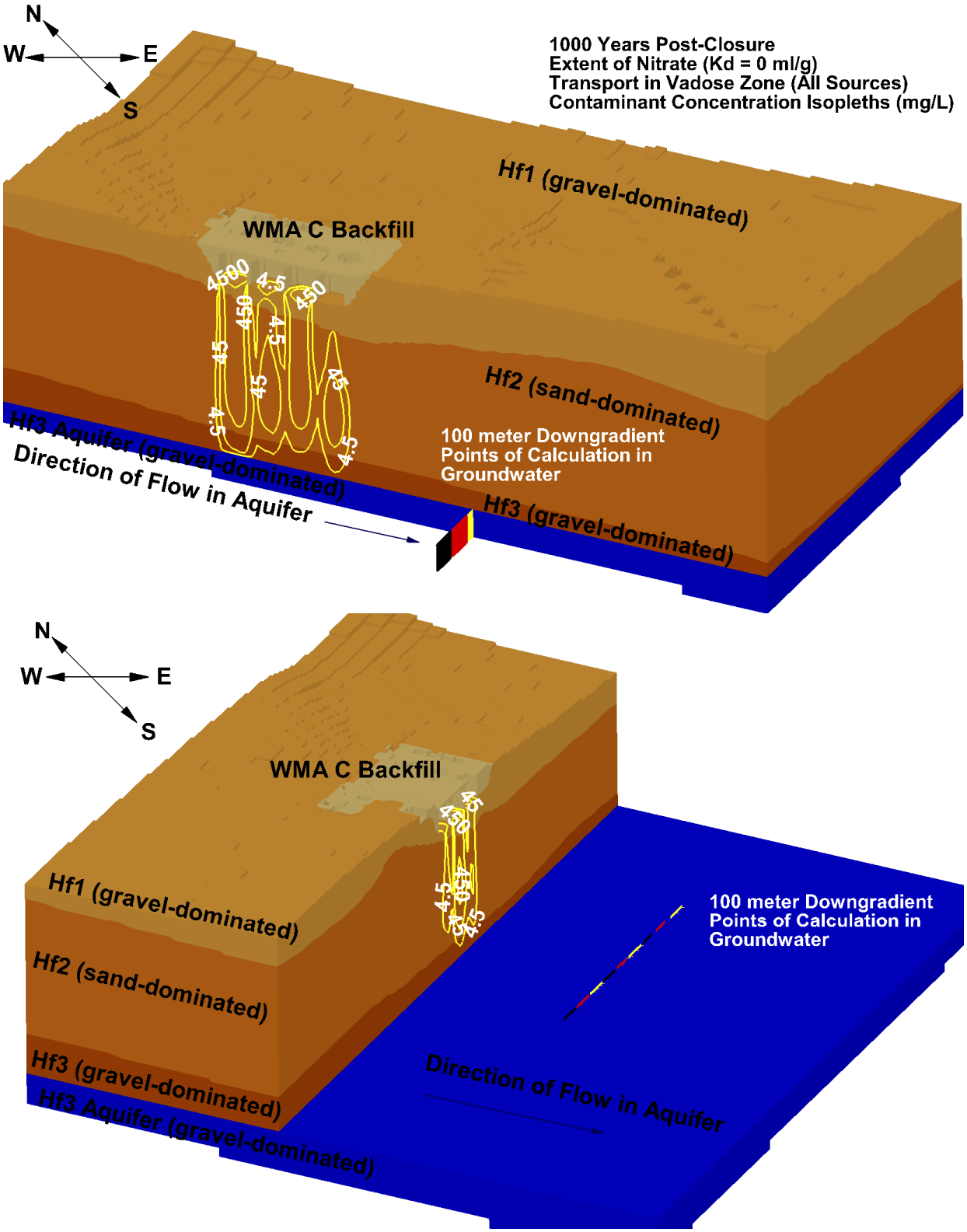
**8.2.3.2 Base Case Evaluation of Contaminant Transport for Groundwater Pathway During 1,000- to 10,000-Year Post-Closure Period.** During the 1,000- to 10,000-year post-closure period, the chemical constituents cyanide, cobalt, chromium, fluoride, nitrate, nitrite, selenium, and tin break through at the 100-m PoCal. Figure 8-12 shows breakthrough curves for the chemical constituents that have $K_d$ values equal to 0 mL/g. Note that only chromium (assumed to be hexavalent chromium) impacts groundwater to within one one-hundredth of its MCL during the 10,000-year post-closure time frame. The maximum concentration of chromium in groundwater is 0.5 µg/L, which occurs approximately 1,330 years after closure within PoCal 5 (Figure 8-12). All of the other chemical constituents evaluated do not impact groundwater to a degree more than a factor of 150 below their MCLs during this time frame.

Figure 8-13 through Figure 8-20 show detailed breakthrough curves for nitrate, selenium, tin, and uranium, respectively, as examples of transport results for constituents with varying transport mobility. The curves show the evaluations for each constituent at all PoCals 100 m downgradient of WMA C, and a breakdown of each source's contribution to the overall concentration at the PoCal where the maximum concentration occurs.

Nitrate, with a $K_d$ = 0 mL/g, migrates the furthest of the three constituents and has the largest peak concentration at 0.3 mg/L. The maximum concentration occurs at PoCal 3, with the residual waste from tank C-101 responsible for providing the largest contribution to the overall concentration.

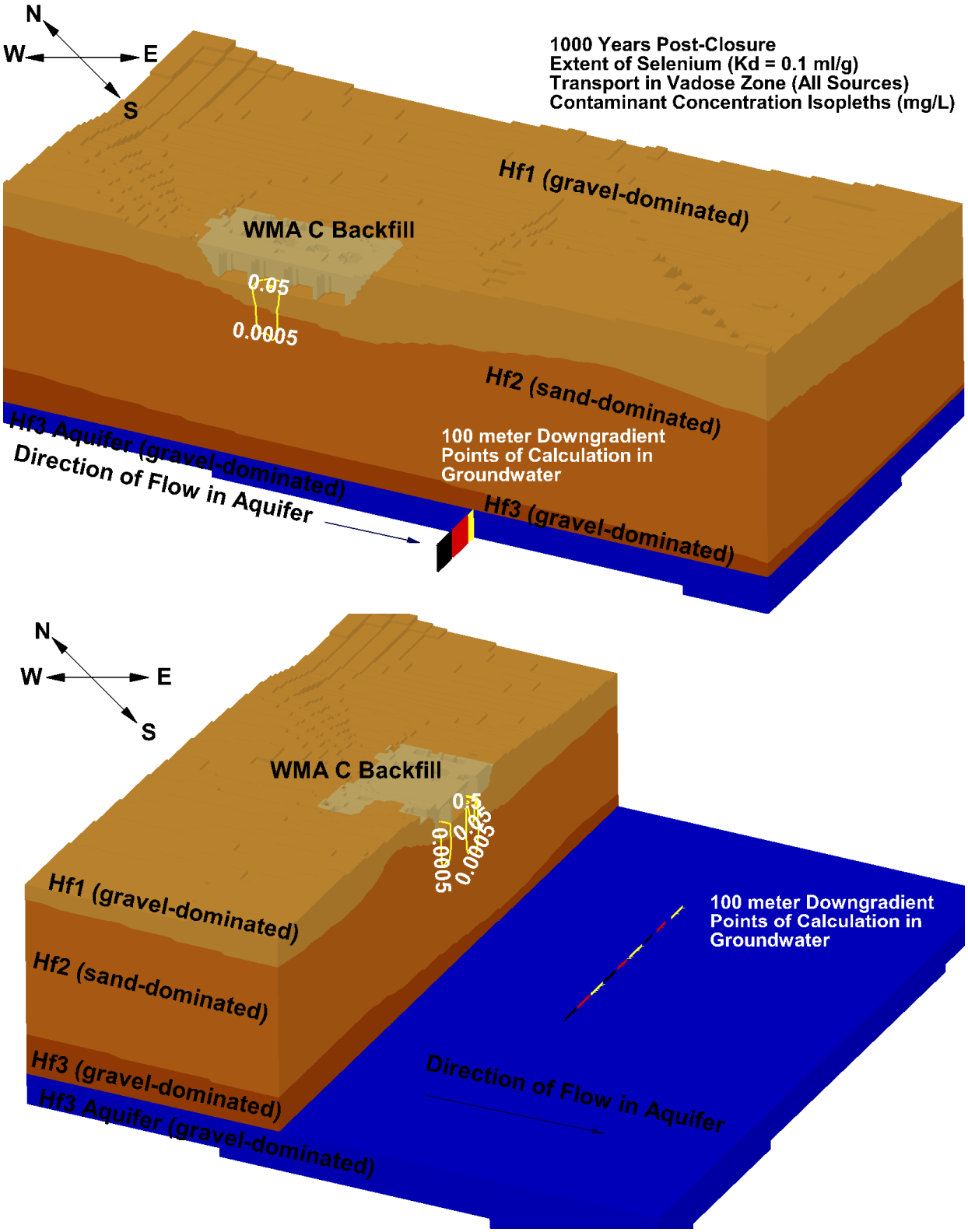
The breakthrough curves for selenium, with a $K_d$ of 0.1 mL/g (for < 2 mm size material), show the effect of slight retardation on contaminant transport through the vadose zone. First arrival does not occur until after 1,300 years after closure, and the peak concentration ($2 \times 10^{-6}$ µg/L) occurs approximately 4,700 years after closure. The maximum concentration occurs at PoCal 5, with the residual waste from tank C-106 responsible for providing the largest contribution to the overall concentration.

**Figure 8-8. Extent of Transport of Nitrate ($K_d$ = 0 mL/g) in the Vadose Zone at the End of the 1,000-Year Post-Closure Period.**



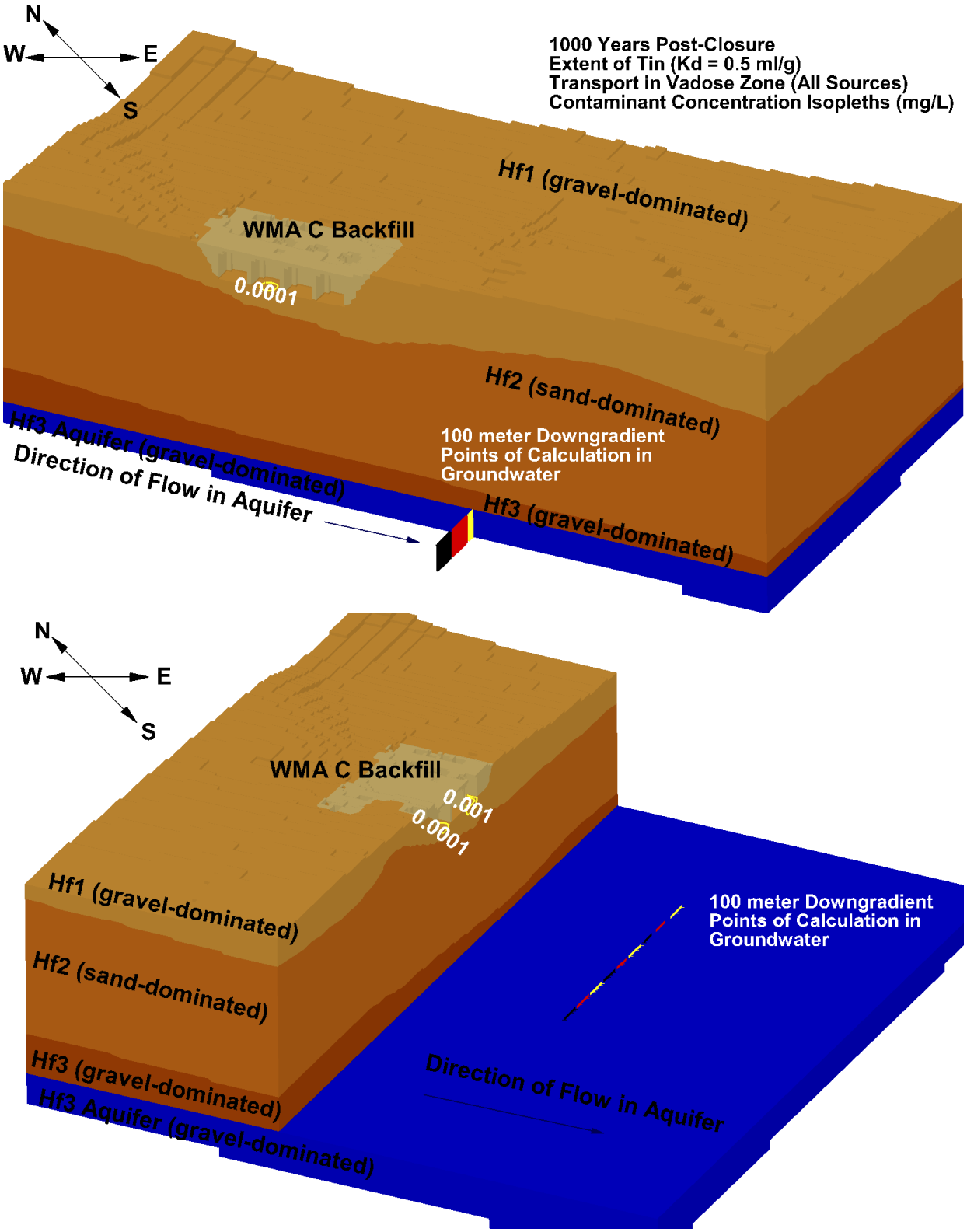

Hf = Hanford formation WMA = Waste Management Area

**Figure 8-9. Extent of Transport of Selenium ($K_d$ = 0.2 mL/g for Sand-Dominated Units) in the Vadose Zone at the End of the 1,000-Year Post-Closure Period.**



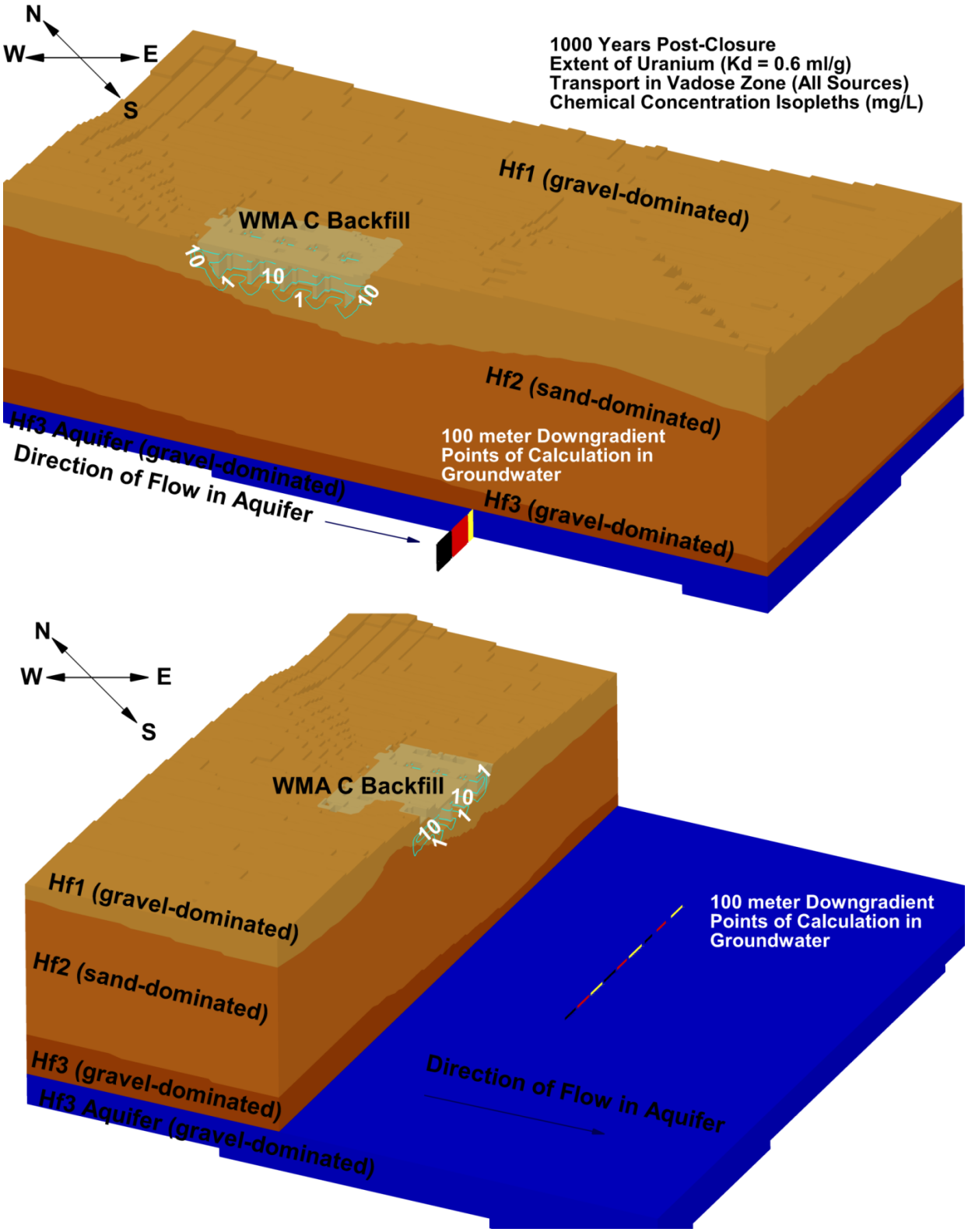

Hf = Hanford formation WMA = Waste Management Area

**Figure 8-10. Extent of Transport of Tin ($K_d$ = 0.5 mL/g for Sand-Dominated Units) in the Vadose Zone at the End of the 1,000-Year Post-Closure Period.**



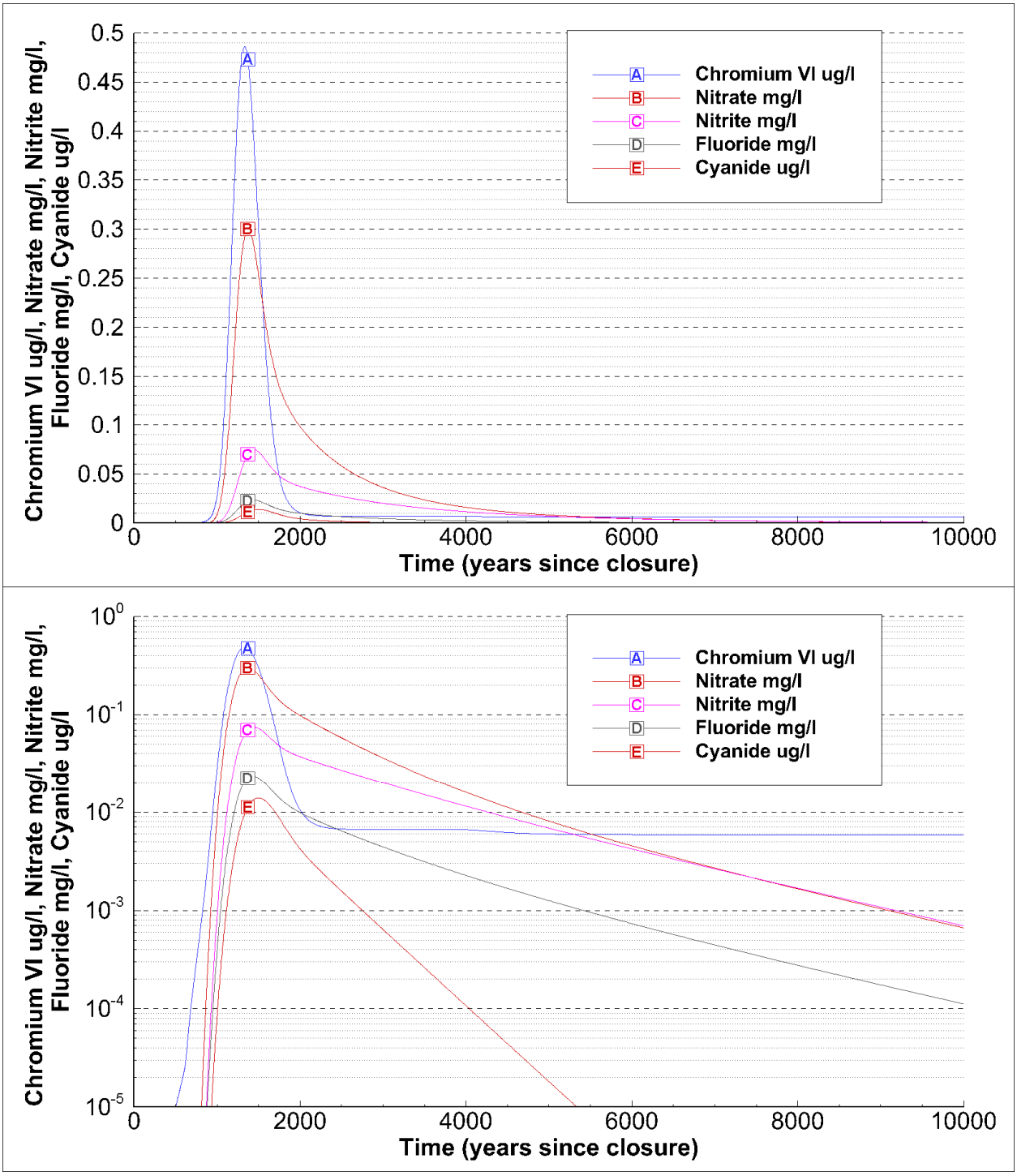

Hf = Hanford formation WMA = Waste Management Area

**Figure 8-11. Extent of Transport of Uranium ($K_d$ = 0.6 mL/g for Sand-Dominated Units) in the Vadose Zone at the End of the 1,000-Year Post-Closure Period.**




Hf = Hanford formation WMA = Waste Management Area

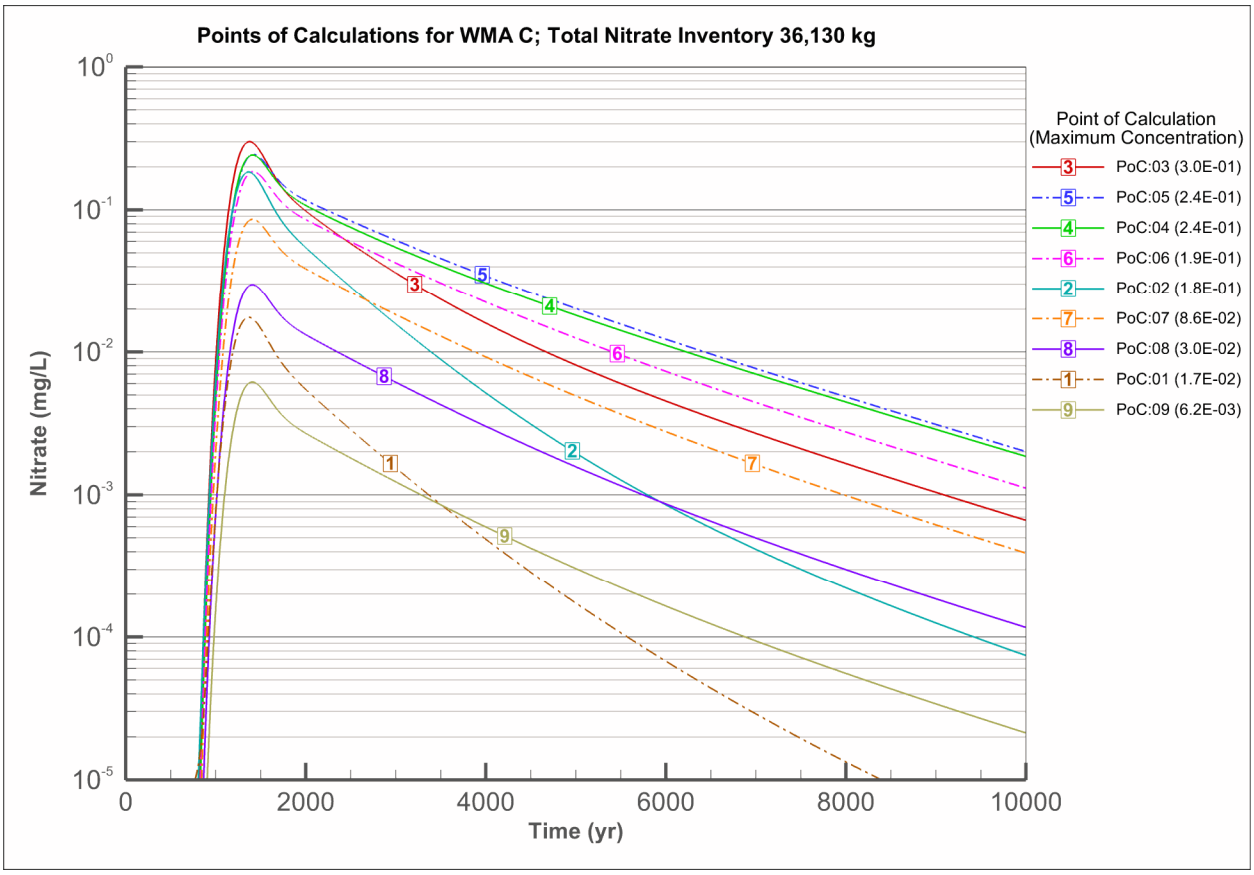
**Figure 8-12. Maximum Predicted Groundwater Concentration at 100 meters Downgradient from Waste Management Area C Through the End of the Post-Closure Period.**




The breakthrough curves for tin, which has a $K_d$ of 0.5 mL/g (for < 2 mm size material), show the effect of moderate retardation on contaminant transport through the vadose zone. First

arrival does not occur until after 5,600 years after closure, and the maximum concentration ($1 \times 10^{-9}$ µg/L) occurs at the end of the 10,000-year post-closure time frame, before the concentration reaches a peak. The maximum concentration occurs at PoCal 6. The residual wastes from tanks C-106 and C-202 provide the largest contributions to the overall concentration, although the contributions from the wastes in tank C-103 and the other 200-series tanks are comparable.

**Figure 8-13. Maximum Predicted Groundwater Concentration of Nitrate ($K_d$ = 0 mL/g) at all Points of Calculation 100 meters Downgradient from Waste Management Area C. See Figure 8-7 for point of calculation locations.**



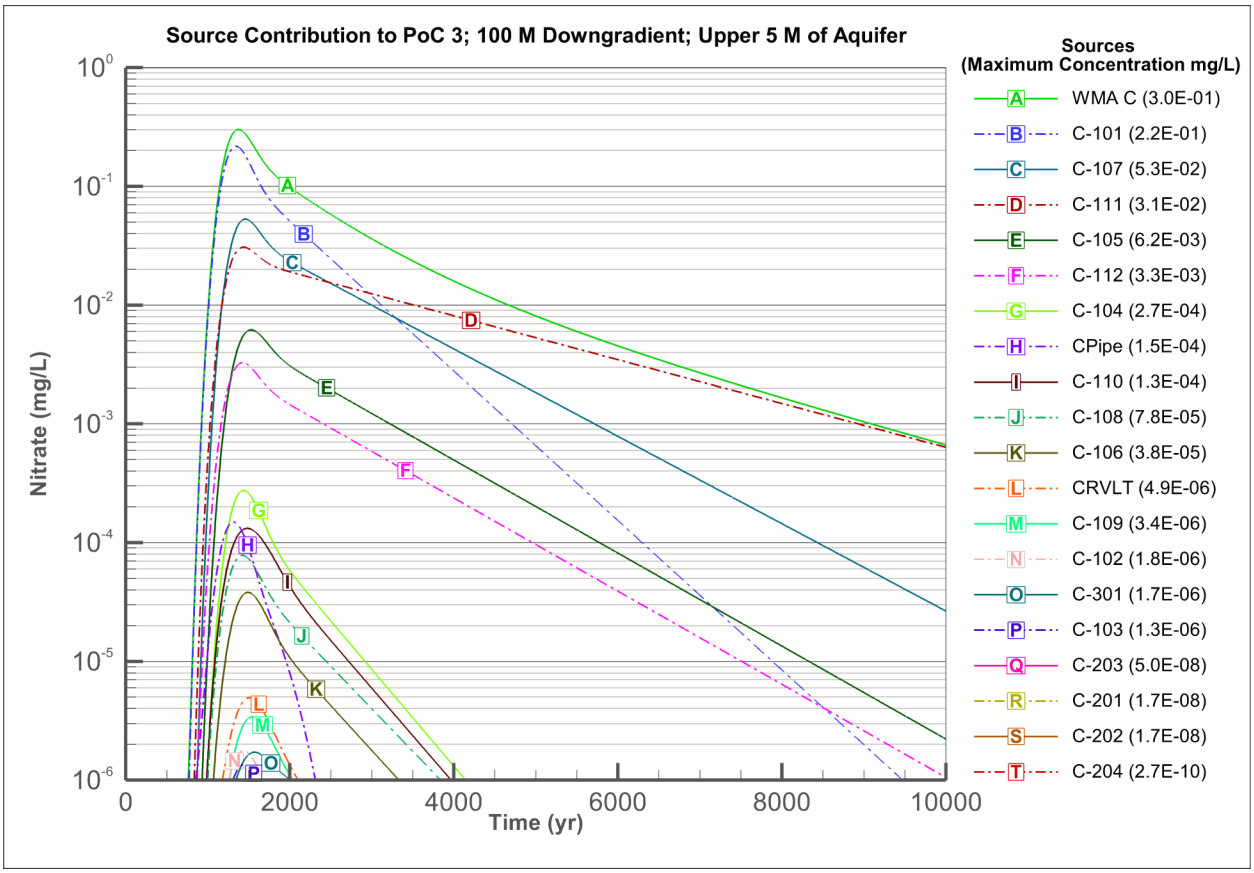

WMA = Waste Management Area

The breakthrough curves for uranium, which has a $K_d$ of 0.6 mL/g (for < 2 mm size material), show that the first arrival for uranium is approximately 6,000 years after closure with a concentration of $1 \times 10^{-7}$ µg/L. It reaches a maximum concentration (0.049 µg/L) at PoCal 3 by the end of the simulation. The WMA C source responsible for the highest concentration at all PoCals is the pipelines, which is not surprising because it has an advection-dominated release with a uranium inventory of approximately 1,080 kg.

Of the chemical constituents included in this analysis, the metal constituents selenium, tin and uranium reach the maximum, but not necessarily peak, values during the 1,000- to 10,000-year post-closure period, although these constituents each have $K_d$ values greater than zero. The

breakthrough curves for tin have just begun to rise and are increasing at the end of the 1,000- to 10,000-year post-closure period, whereas the concentration of the other chemical constituents with a $K_d$ of 0 mL/g reach peak values during, and are decreasing at the end of, the post-closure analysis period. The concentrations of cobalt, selenium, and tin are so small that they are considered to be negligible. The concentration of uranium at the end of the simulation is 0.049 µg/L (principally from the pipeline source) and is not considered negligible. Although the screening analysis did not remove TBP from the list of chemical constituents to be evaluated in the model, TBP did not reach the water table during the 10,000-year post-closure time frame under the base case conditions.

**Figure 8-14. Groundwater Concentration of Nitrate ($K_d$ = 0 mL/g) According to Each Source at Point of Calculation 3 Where the Maximum Concentration Occurs 100 meters Downgradient from Waste Management Area C. See Figure 8-7 for point of calculation locations.**

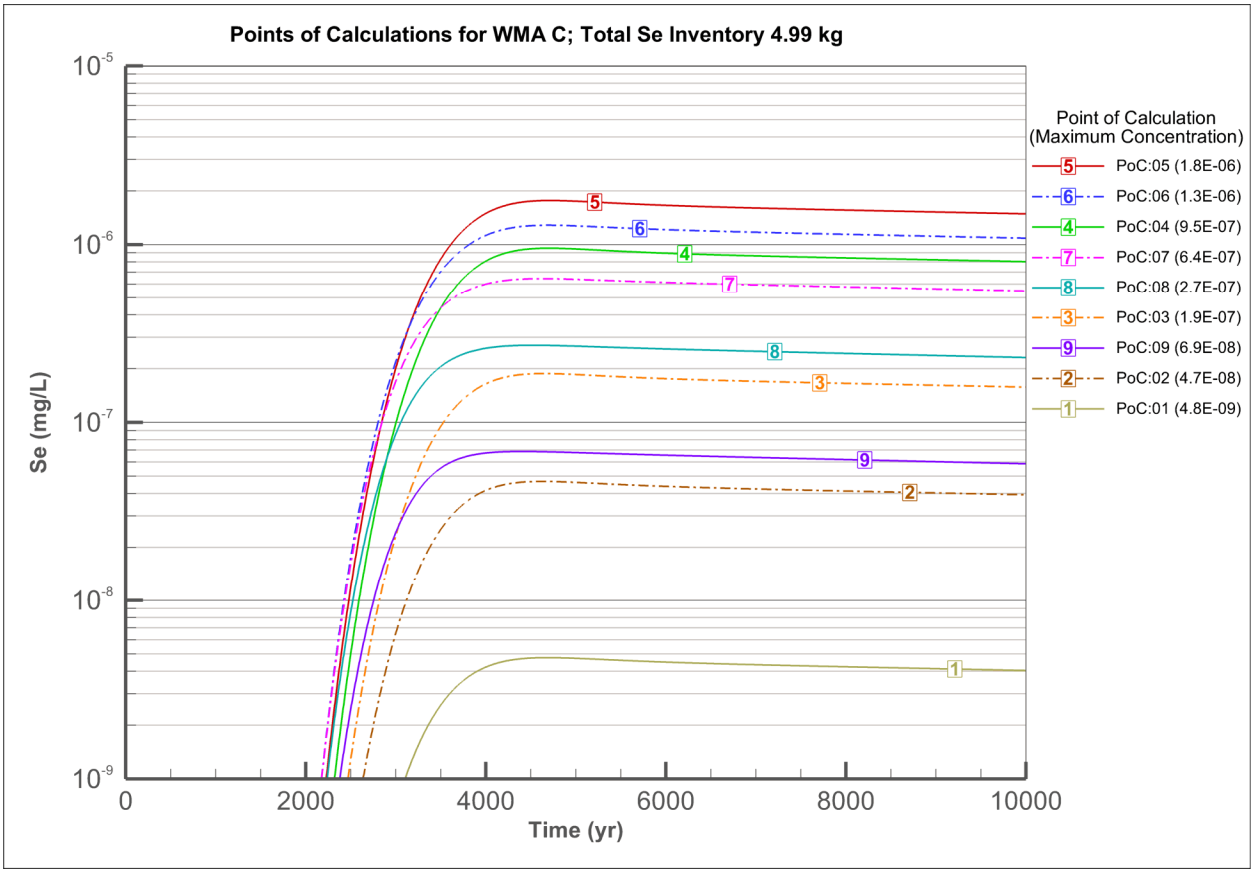



PoC = Point of Calculation WMA = Waste Management Area

Figures 8-21 through 8-23 show the progress of mobile constituent nitrate in the groundwater at 500, 1,000, and 1,570 years post-closure. These times correspond to the surface barrier design life and early arrival of nitrate at the downgradient PoCal, the extent of the 0- to 1,000-year post-closure time frame, and the approximate time of the peak concentration. At 500 years after closure, the first arrival approximately occurs near the south corner of the facility, in the vicinity of the 244-CR vault. Nitrate from residuals in both the vault and the pipelines has reached the

water table in this area. Although increasing in size from 500 to 1,000 years into the future, the magnitude of the maximum concentration in groundwater still remains less than 1 mg/L. At the time of the maximum concentration at the PoCal, the evolution of the plume becomes dominated by the sources from tanks C-101, C-111, and C-112.

**Figure 8-15. Maximum Predicted Groundwater Concentration of Selenium ($K_d$ = 0.1 mL/g) at All Points of Calculation 100 meters Downgradient from Waste Management Area C.**



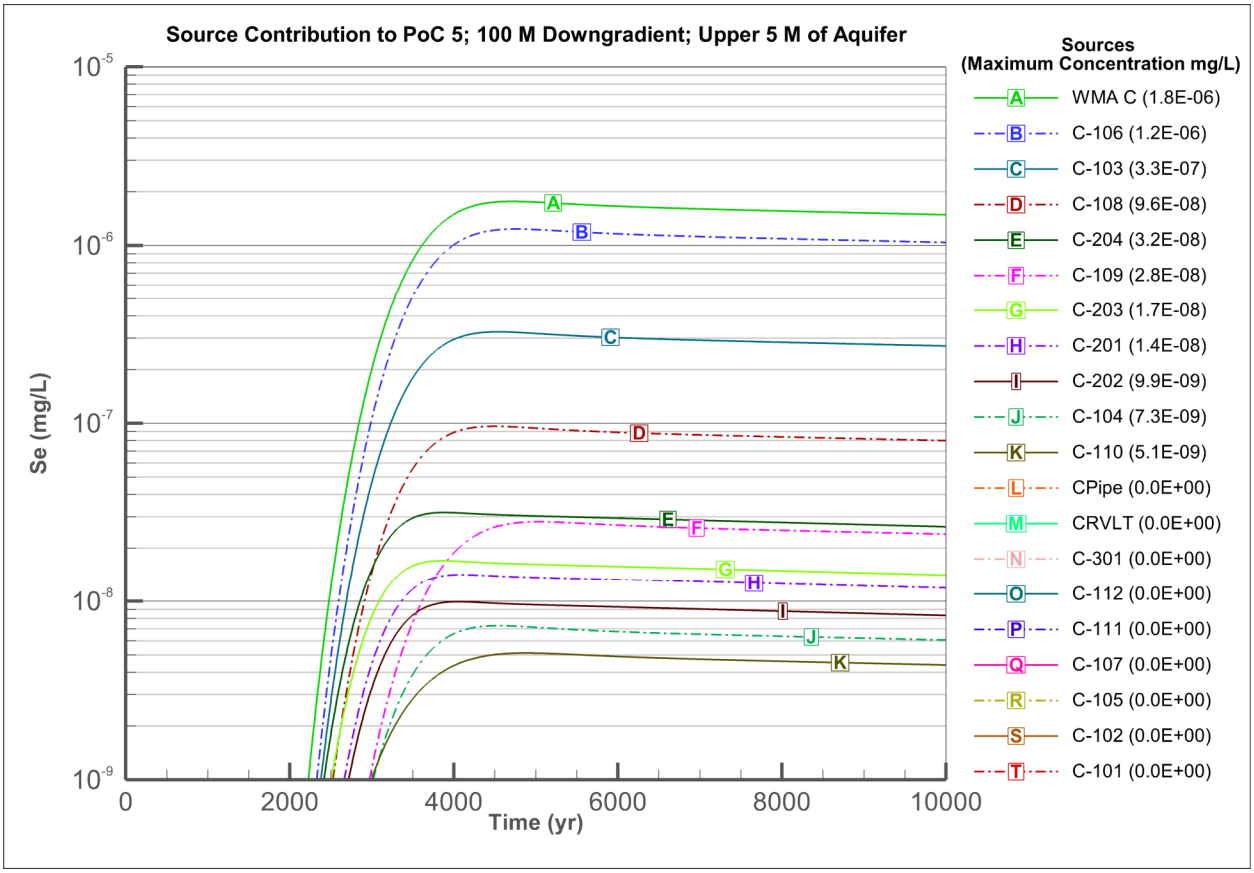

PoC = Point of Calculation WMA = Waste Management Area

Plot of breakthrough curves for nitrate at different PoCals (PoCal 3, 4, 5, and 6) at different downgradient locations (e.g., fenceline, 100 m, and 200 m) illustrate small differences in nitrate concentrations in modeling results at different PoCals and downgradient locations from WMA C (see Figure 8-24).

## 8.3 ASSESSMENT OF IMPACTS TO WATER RESOURCES

In this section, the assessment of impacts to water resources is evaluated. Two different evaluations are presented for this assessment. A summary of both the cancer risk and non-cancer hazards based on the EPA tap water scenario are presented. The 2007 MTCA risk-based criteria are based on a target risk level of $1 \times 10^{-6}$ for carcinogens and an HQ of 1 for noncarcinogens.

**Figure 8-16. Groundwater Concentration of Selenium ($K_d$ = 0.1 mL/g) According to Each Source at Point of Calculation 5 Where the Maximum Concentration Occurs 100 meters Downgradient from Waste Management Area C.**

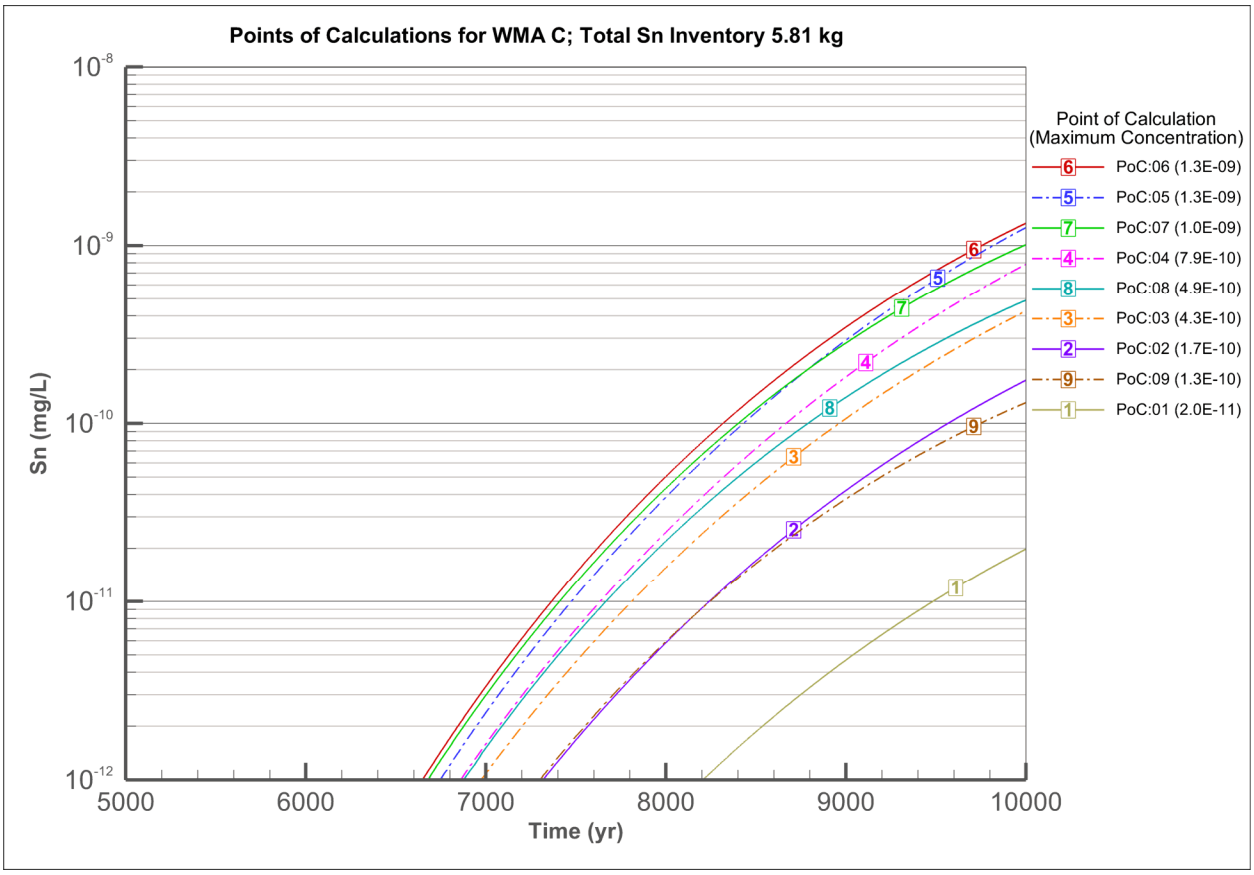



PoC = Point of Calculation WMA = Waste Management Area

Cancer risk and non-cancer hazards are based on the EPA tap water (residential) scenario. Cancer risk and non-cancer hazard are calculated by taking the concentration at the PoCal and calculating a cancer risk and HQ for each contaminant. The cumulative risk and HI is the sum of cancer risk and HQ for all contaminants evaluated. The results of these calculations are presented in this chapter and compared to the $10^{-4}$ risk range for radionuclides, $10^{-5}$ cumulative risk range for hazardous chemicals, and an HI of 1 for non-cancer hazards.

Groundwater concentrations are presented as a set of deterministic "base case" results that represent reasonable maximum exposure estimates for the input parameters, and for a situation in which all the safety functions discussed in Chapter 1 behave as expected. These results are supported by a suite of sensitivity cases (see Section 9.0), which have been selected to evaluate the importance of the safety functions. They are also supported by probabilistic analyses completed for the WMA C PA (RPP-ENV-58782, Section 8.1 Uncertainty Analysis) that evaluated the importance of parameter uncertainty, and which demonstrated that the base case represents a central tendency of the range of outputs from the probabilistic analysis.

**Figure 8-17. Maximum Predicted Groundwater Concentration of Tin ($K_d$ = 0.5 mL/g) at All Points of Calculation 100 meters Downgradient from Waste Management Area C.**

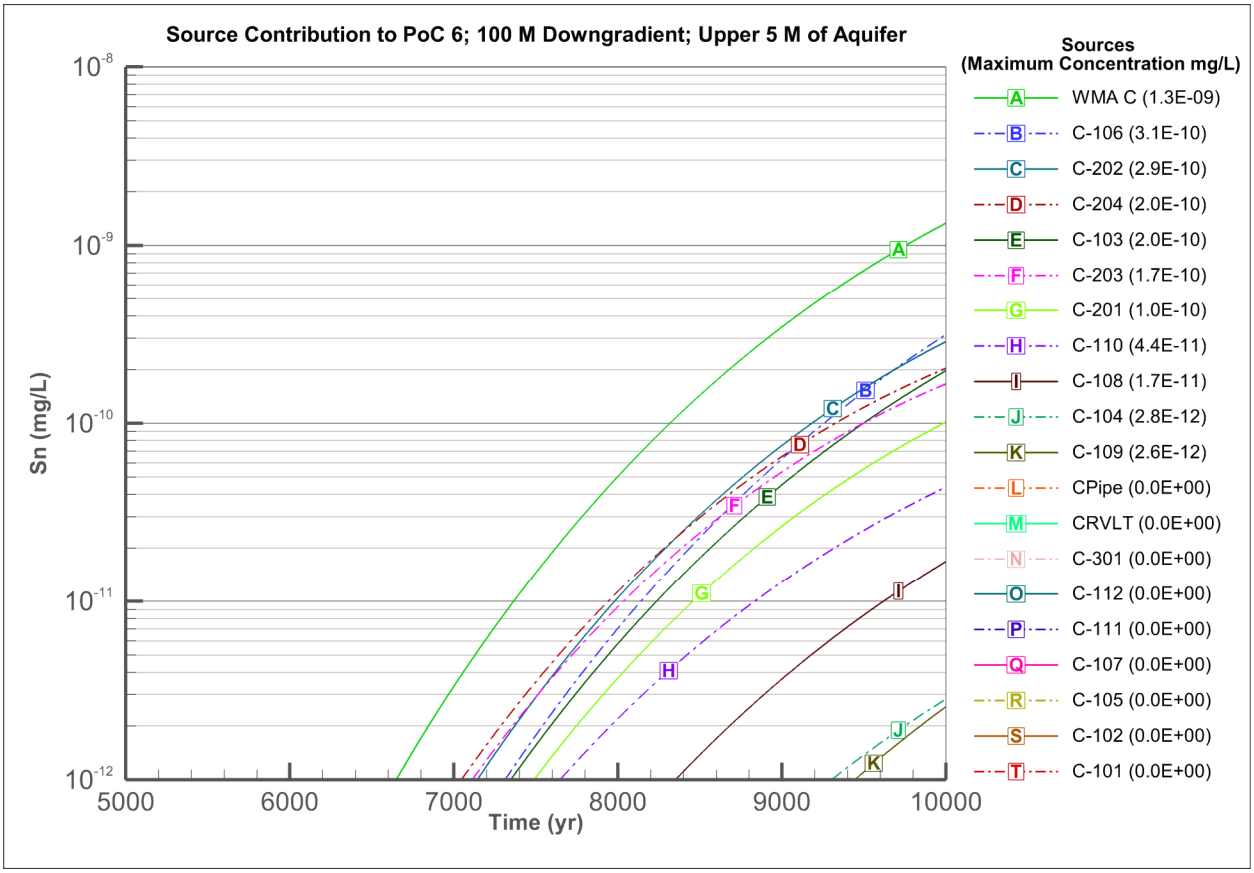



WMA = Waste Management Area

The EPA tap water (residential) scenario is associated with the groundwater protection pathway, with the groundwater concentrations calculated according to the methodology presented in Chapter 7. This methodology implements the groundwater protection requirements, which require a comparison of the peak concentration in the groundwater at all PoCals and then choosing the PoCal containing the highest concentration along the flux plane located 100 m downgradient of the WMA C. Groundwater concentrations do not take account of any dilution that may occur in the well as it is pumped.

The equations and inputs used to calculate cancer risk and non-cancer hazards were also presented in Section 7 of this document. For the analysis of cancer risk and non-cancer hazards, peak groundwater concentrations are used as the concentrations at the wellhead, to which the resident receptor has the potential for exposure. The exposure inputs used for the tap water scenario are estimates of reasonable maximum exposure. This approach has been taken to maintain consistency between the groundwater protection performance objectives of the RCA with the all-pathways dose performance objective presented in the WMA C PA (RPP-ENV-58782, Section 7.3.1).

**Figure 8-18. Groundwater Concentration of Tin ($K_d$ = 0.5 mL/g) According to Each Source at Point of Calculation 3 Where the Maximum Concentration Occurs 100 meters Downgradient from Waste Management Area C.**




PoC = Point of Calculation WMA = Waste Management Area

### 8.3.1 Summary of EPA Tap Water Cancer Risks

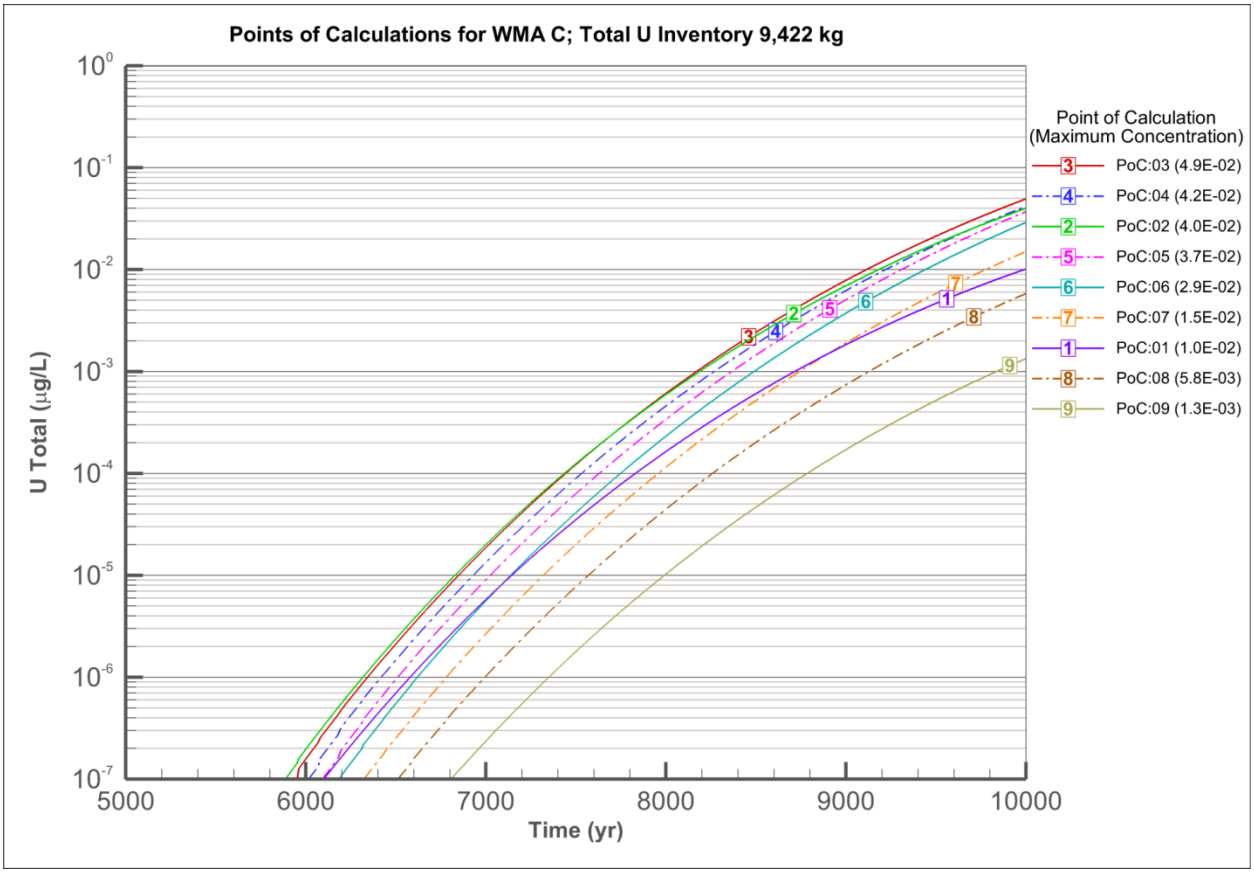
Radiological cancer risks are presented in Figure 8-25 for the 100-m distance for each PoCal. The peak cumulative radiological cancer risk occurs at PoCal 4. The cumulative radiological cancer risk results for PoCal 4 are presented in Figure 8-26 for all radionuclides that produced a nonzero cancer risk result within 10,000 years. The peak radiological cancer risk summed over all radionuclides is $1.58 \times 10^{-6}$, which occurs between 1,510 years and 1,590 years after closure. This risk estimate is within the acceptable risk range of $1 \times 10^{-4}$ to $1 \times 10^{-6}$. The key contributing radionuclide at all times is $^{99}$Tc. Minor contributors to the total radiological cancer risk at times beyond the 1,000 years are $^{79}$Se, $^{129}$I, $^{126}$Sn, and uranium isotopes. A summary of the peak radiological cancer risk and time of peak occurrence is presented in Table 8-4.

### 8.3.2 Summary of EPA Tap Water Non-Cancer Hazards

Cumulative non-cancer hazards are presented in Figure 8-27 at the 100-m distance for each PoCal. The peak cumulative non-cancer HI occurs at PoCal 4. The cumulative non-cancer hazard results for PoCal 4 are presented in Figure 8-28 for all chemicals that produced a nonzero

hazard result within 10,000 years. The peak chemical non-cancer HI summed over all chemicals is about 0.07, which occurs at 1,440 years after closure. This HI is less than the target HI of 1. The key contributing chemicals at all times are fluoride (27% contribution), nitrite (54% contribution), nitrate (11% contribution), and cyanide (8% contribution). A summary of the peak chemical non-cancer HQs and time of peak occurrence is presented in Table 8-5. Additionally, Table 8-6 presents a summary of chemical non-cancer HQs and time of peak for all PoCals.

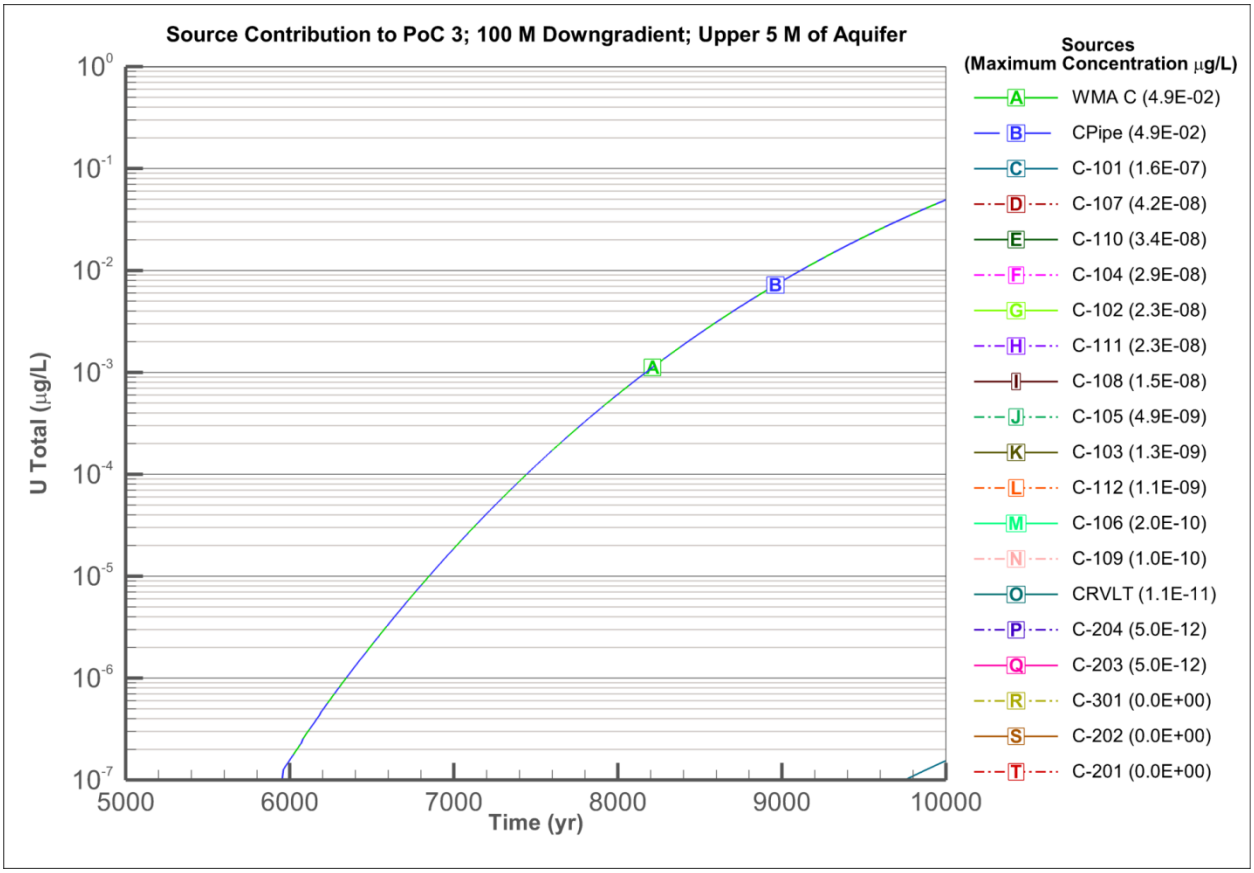
**Figure 8-19. Maximum Predicted Groundwater Concentration of Uranium ($K_d$ = 0.6 mL/g) at All Points of Calculation 100 meters Downgradient from Waste Management Area C.**




WMA = Waste Management Area

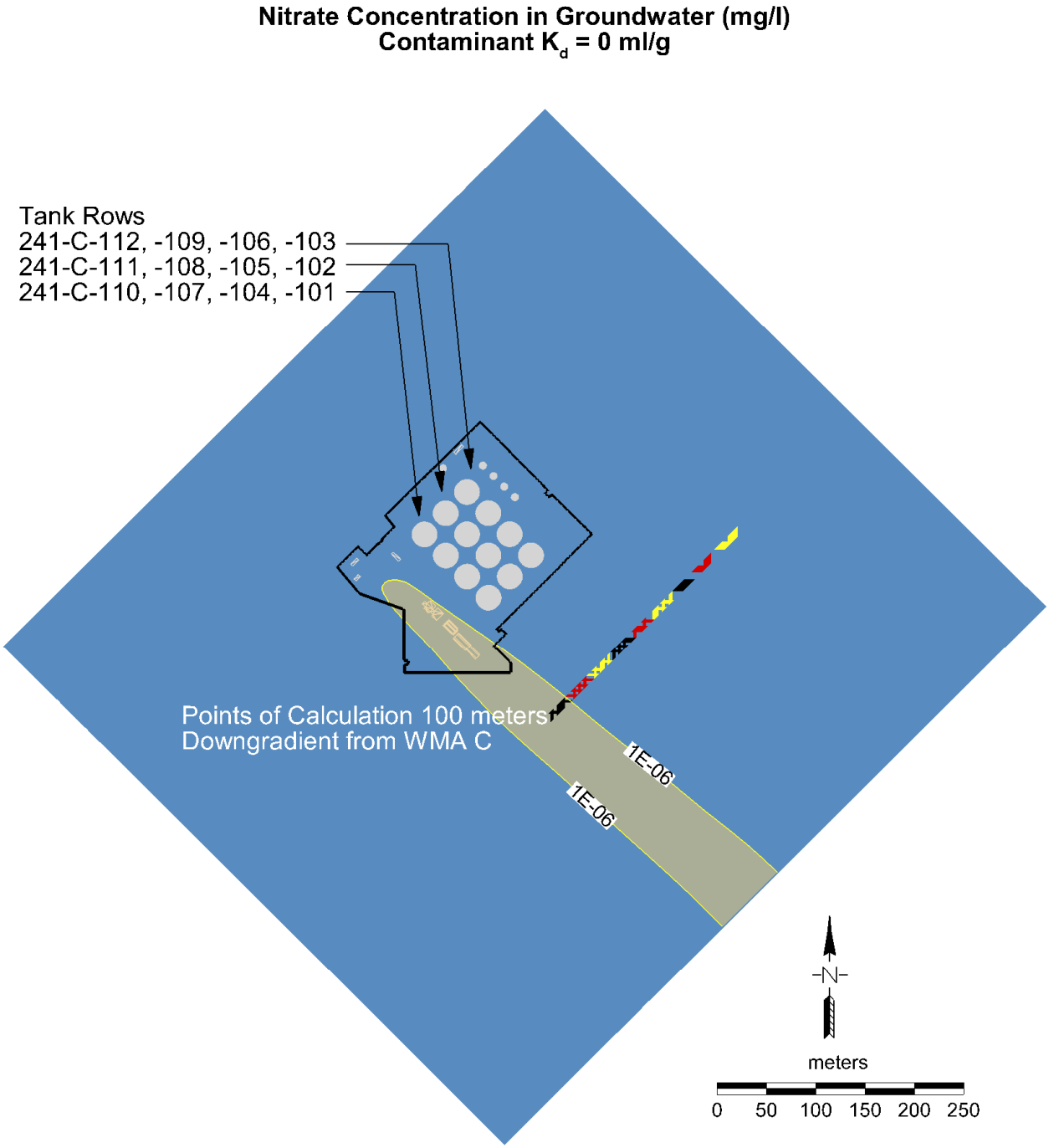
Peak cumulative chemical cancer risk is not discussed because carcinogenic chemicals did not arrive at any PoCal with concentration values above 0.

**Figure 8-20. Groundwater Concentration of Uranium ($K_d$ = 0.6 mL/g) According to Each Source at Point of Calculation 3 Where the Maximum Concentration Occurs 100 meters Downgradient from Waste Management Area C.**




PoC = Point of Calculation

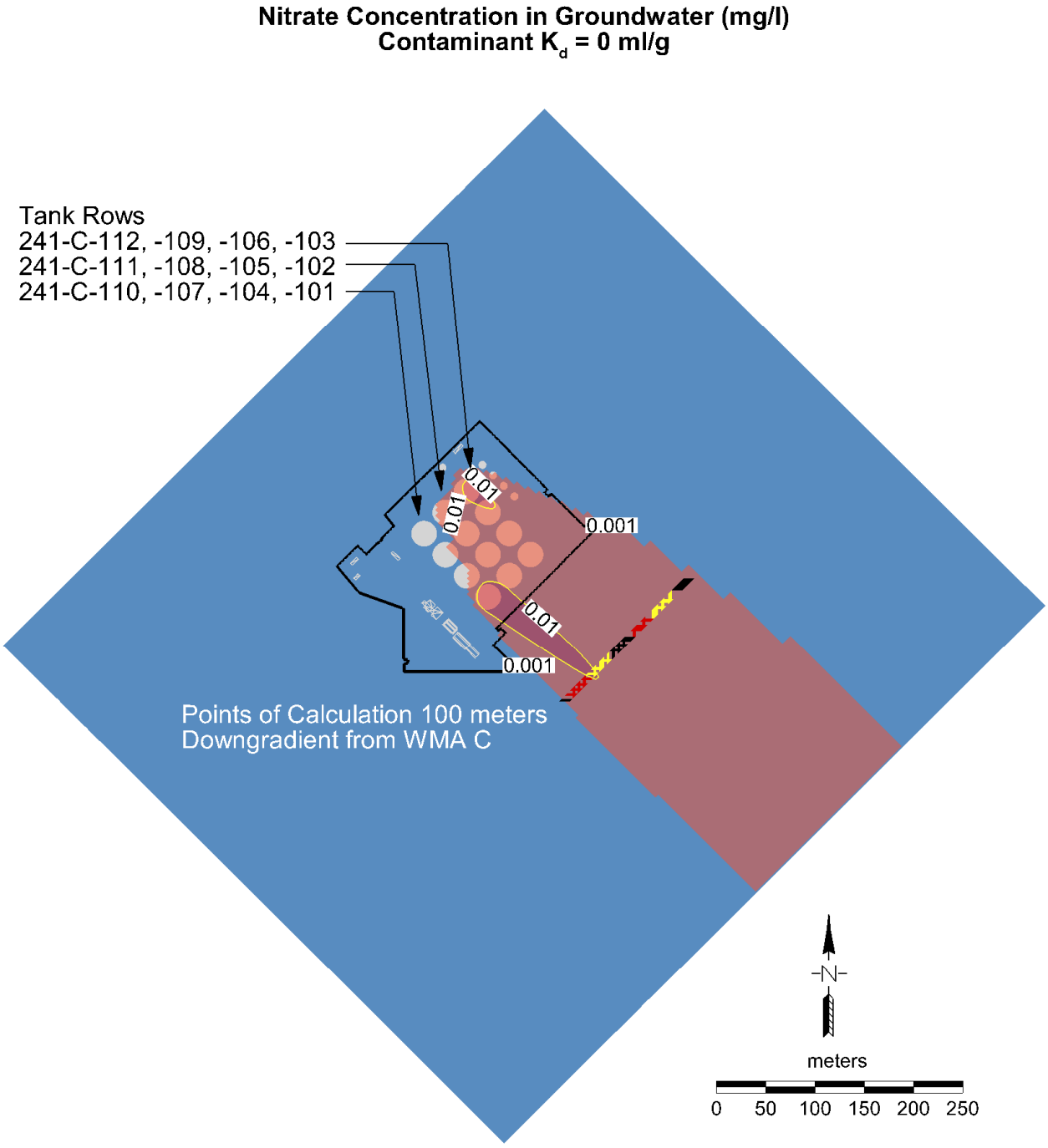
**Figure 8-21. Extent of Nitrate Plume in Groundwater 500 Years after Closure at the End of the Surface Barrier Design Life.**




End of barrier design life

WMA = Waste Management Area

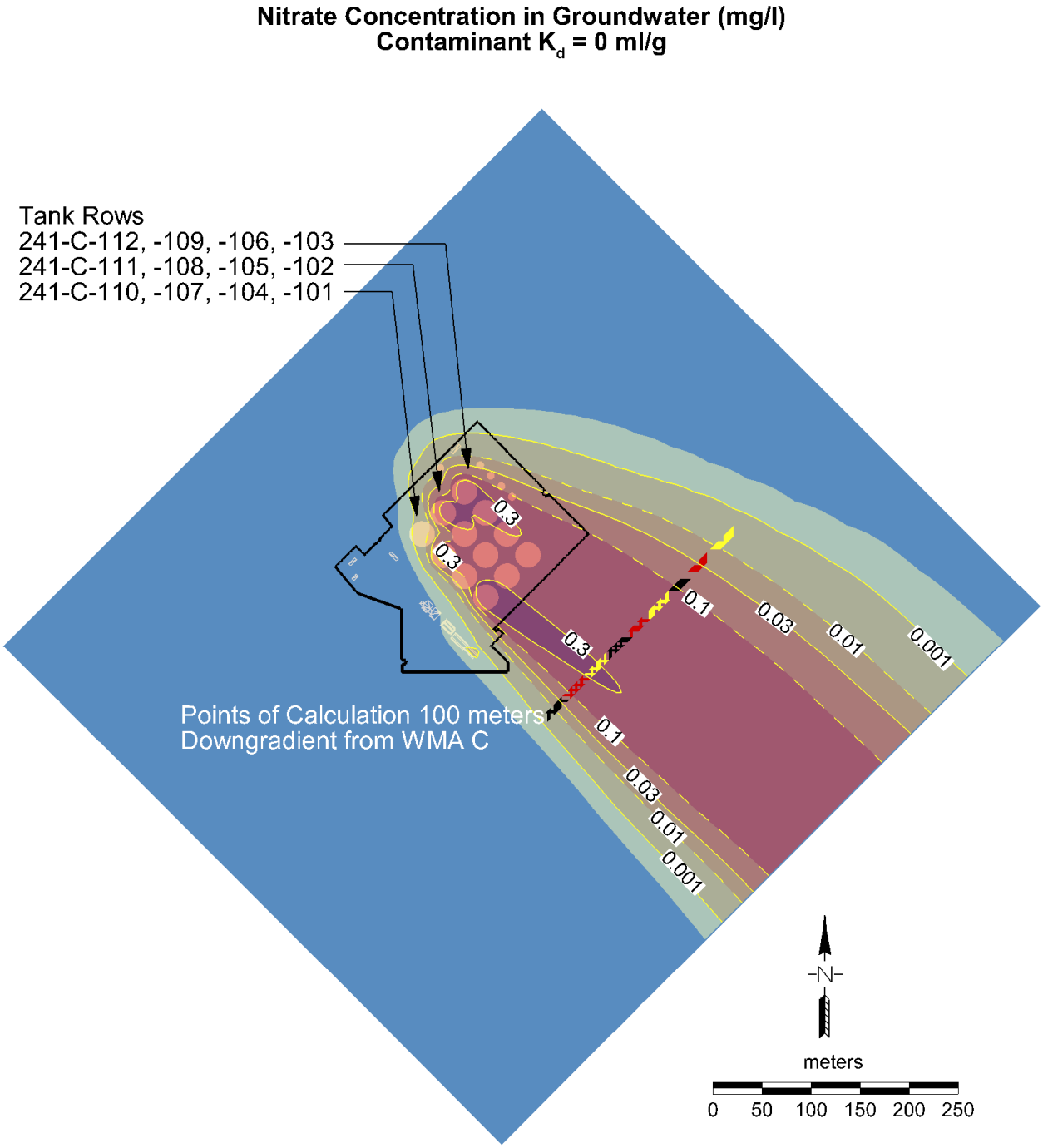
**Figure 8-22. Extent of Nitrate Plume in Groundwater 1,000 Years after Closure at the End of the 0- to 1,000-Year Post-Closure Time Frame.**




End of the 1,000 Year Compliance Period

WMA = Waste Management Area

**Figure 8-23. Extent of Nitrate Plume in Groundwater 1,375 Years after Closure at the Time of the Maximum Concentration at the 100-meter Point of Calculation.**




Approximate time of peak concentration at point of calculation

WMA = Waste Management Area

**Figure 8-24. Nitrate Concentration Breakthrough Curves in Groundwater after Closure at Different Points of Calculation and Downgradient Locations.**

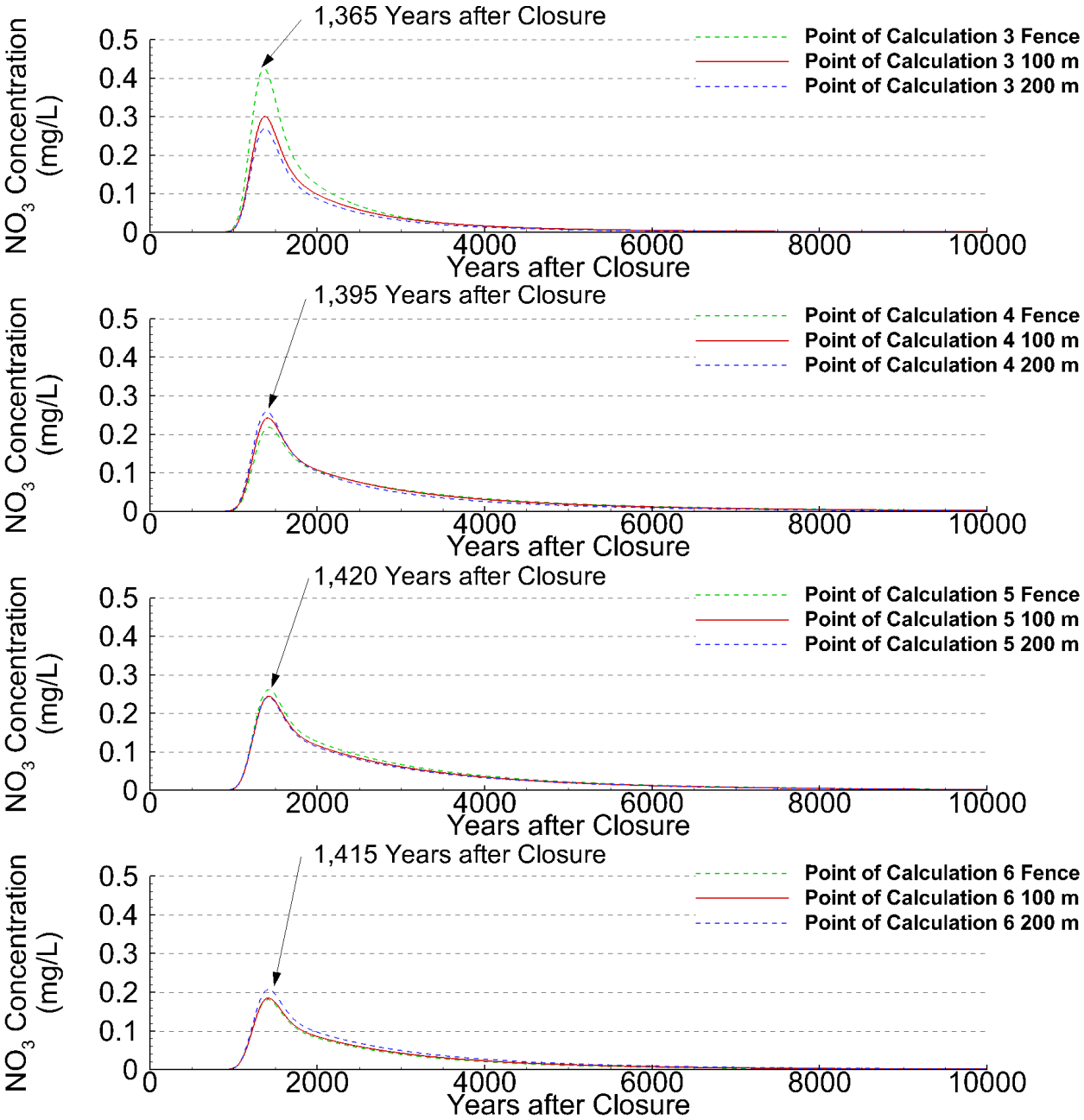
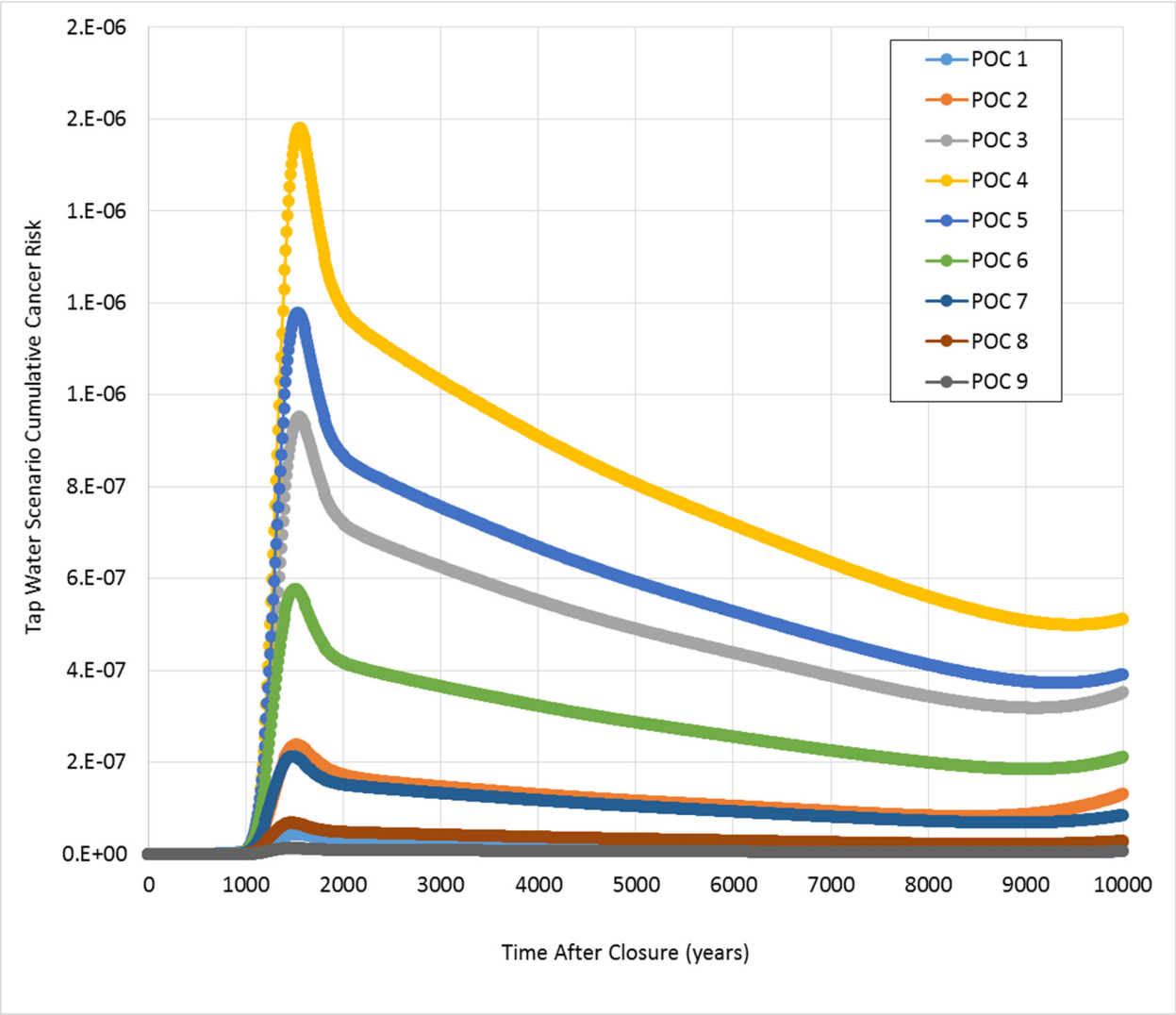
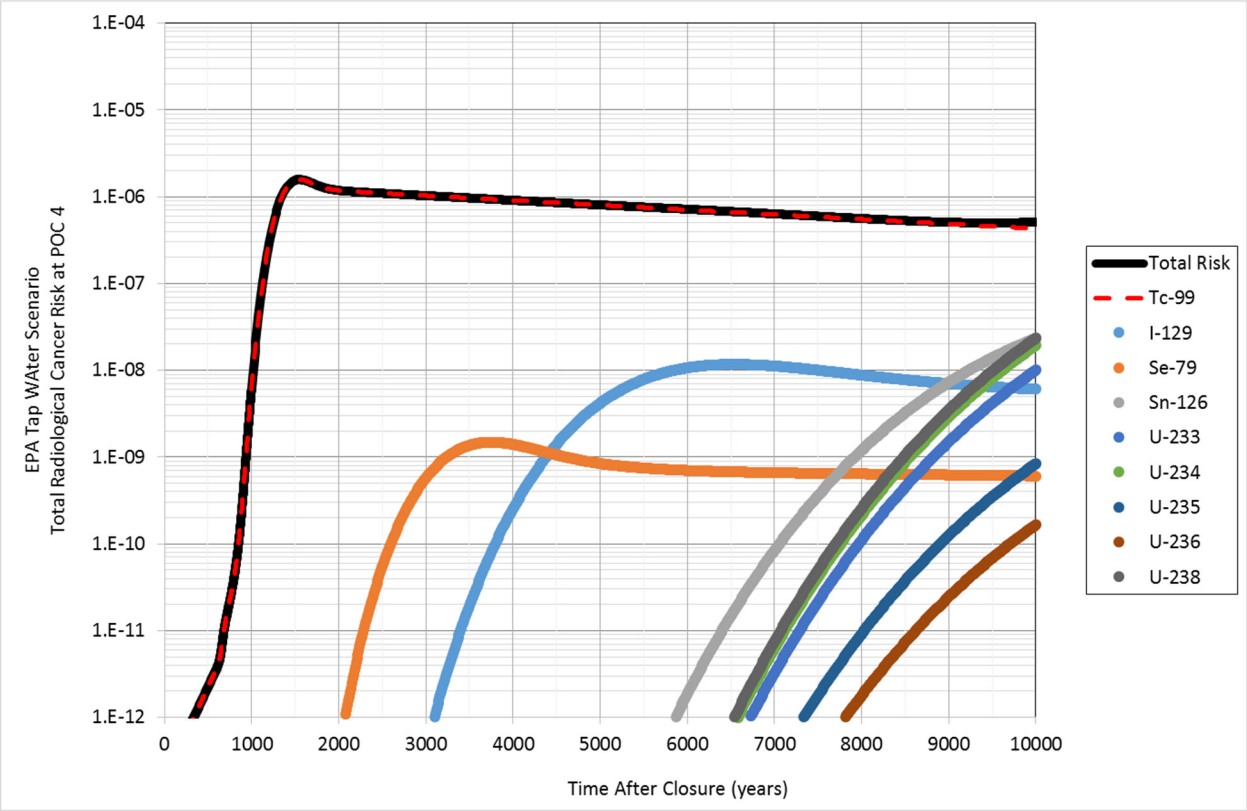


**Figure 8-25. EPA Tap Water (Residential) Scenario Radiological Cancer Risk as a Function of Time for All Points of Calculation at the 100-meter Distance.**




EPA = U.S. Environmental Protection Agency POC = Point of Calculation

**Figure 8-26. EPA Tap Water (Residential Scenario) Radiological Cancer Risk Results for the Peak Groundwater Concentration at Point of Calculation 4.**

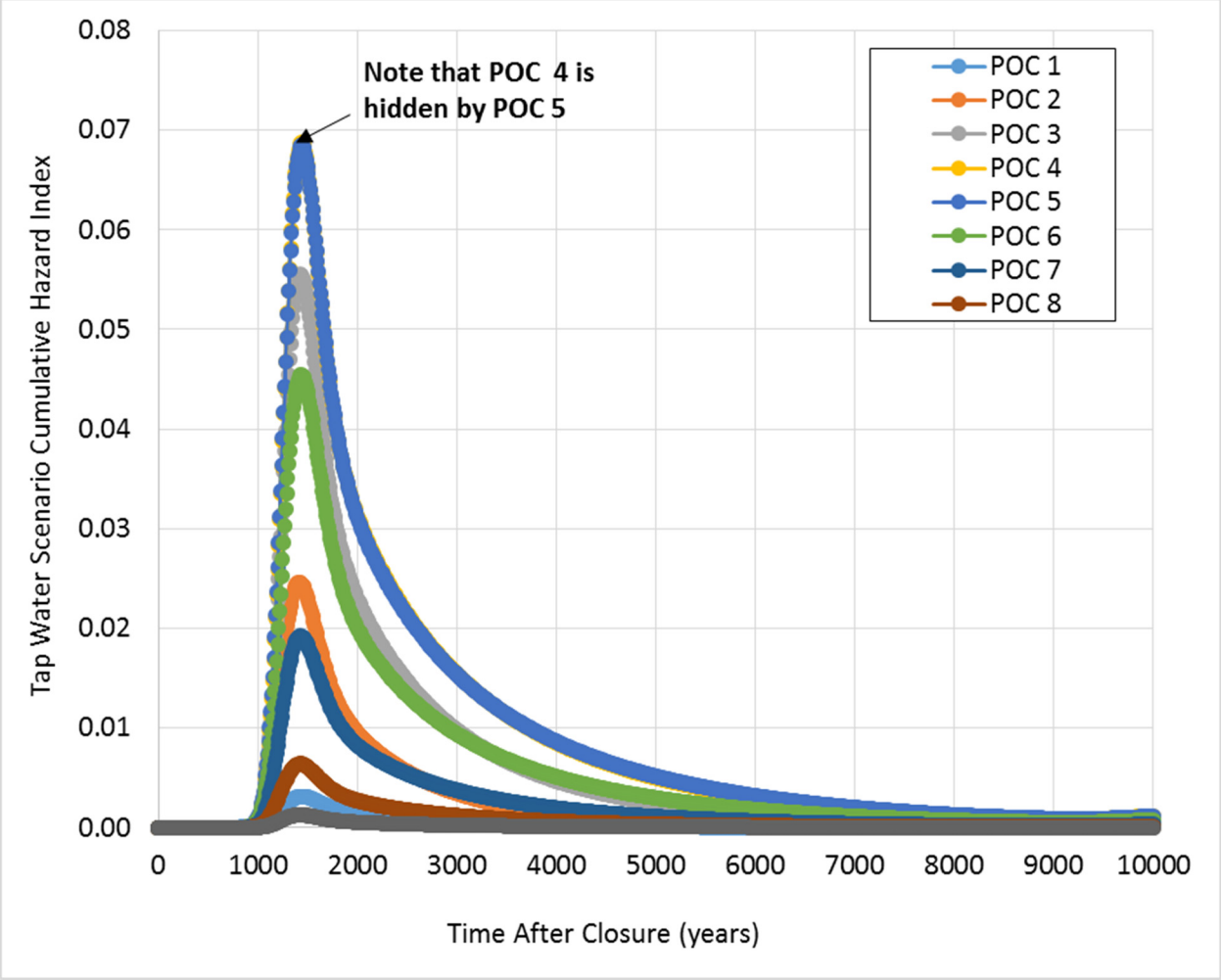



EPA = U.S. Environmental Protection Agency POC = Point of Calculation

**Table 8-4. Summary of Peak Total Radiological Cancer Risk and the Time of Occurrence for All Radionuclides Giving Nonzero Risk in the Base Case Analysis.**

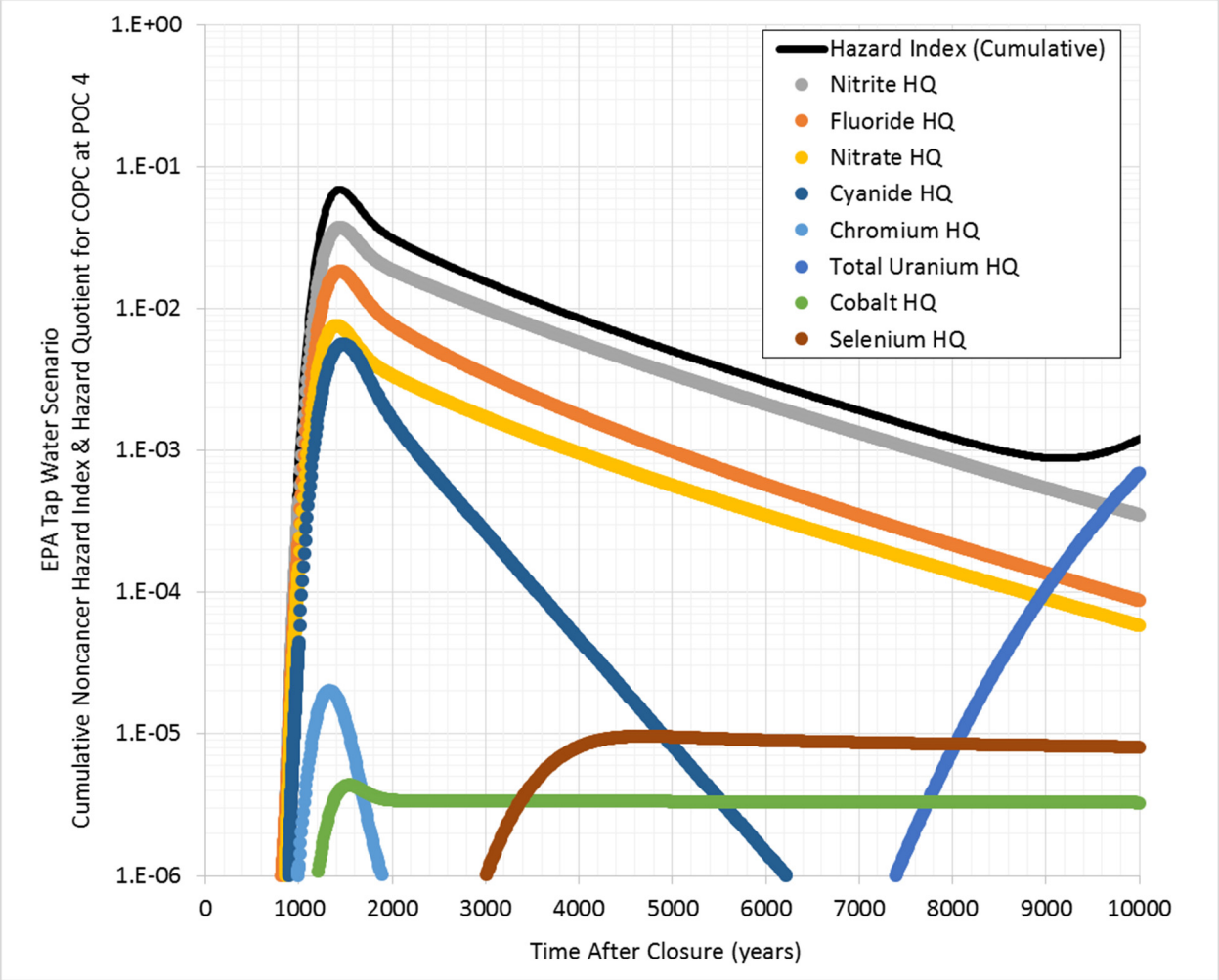
| Radionuclide | Peak Total Risk | Time of Peak (years) |
|---|---|---|
| I-129 | 1.2E-8 | 6,430 to 6,650 |
| Se-79 | 1.5E-9 | 3,690 to 3,820 |
| Sn-126 | 2.3E-8 | 10,000 |
| Tc-99 | 1.6E-6 | 1,530 to 1,570 |
| U-233 | 1.0E-8 | 10,000 |
| U-234 | 2.0E-8 | 10,000 |
| U-235 | 8.4E-10 | 10,000 |
| U-236 | 1.7E-10 | 10,000 |
| U-238 | 2.4E-8 | 10,000 |

**Figure 8-27. EPA Tap Water (Residential) Scenario Cumulative Non-Cancer Hazard Index as a Function of Time for All Points of Calculation at the 100-meter Distance.**




EPA = U.S. Environmental Protection Agency POC = Point of Calculation

**Figure 8-28. EPA Tap Water (Residential Scenario) Cumulative Non-Cancer Hazard Index and Hazard Quotient for each Constituent of Potential Concern for the Peak Groundwater Concentration at Point of Calculation 4.**




EPA = U.S. Environmental Protection Agency HQ = Hazard Quotient POC = Point of Calculation

**Table 8-5. Summary of Peak Chemical Hazard Quotients and Time of Occurrence for All Chemicals Giving Nonzero Hazard in the Base Case Analysis.**

| Chemical | Peak Hazard Quotient | Approximate Time of Peak (years) |
|---|---|---|
| Chromium | 2.0E-05 | 1,330 |
| Fluoride | 1.8E-05 | 1,440 |
| Nitrite | 3.7E-02 | 1,440 |
| Nitrate | 7.6E-03 | 1,410 |
| Cobalt | 4.4E-06 | 1,530 to 1,550 |
| Cyanide | 5.6E-03 | 1,470 to 1,480 |
| Selenium | 9.6E-06 | 4,630 to 4,780 |
| Tin | 6.6E-11 | 10,000 |
| Uranium | 6.9E-04 | 10,000 |

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**Table 8-6. Summary of Peak Chemical Hazard Quotients and Time of Occurrence for All Chemicals Giving Nonzero Hazard in the Base Case Analysis.**

| Constituent of Potential Concern | PoCal 1 | | PoCal 2 | | PoCal 3 | | PoCal 4 | | PoCal 5 | | PoCal 6 | | PoCal 7 | | PoCal 8 | | PoCal 9 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | HQ | Peak Year | HQ | Peak Year | HQ | Peak Year | HQ | Peak Year | HQ | Peak Year | HQ | Peak Year | HQ | Peak Year | HQ | Peak Year | HQ | Peak Year |
| Chromium | 7.50E-06 | 1,420 – 1,430 | 1.10E-05 | 1,330 | 1.50E-05 | 1,310 – 1,320 | 1.90E-05 | 1,330 | ***2.00E-05*** | 1,330 | 1.50E-05 | 1,320 – 1,330 | 6.70E-06 | 1,320 | 2.50E-06 | 1,310 | 5.40E-07 | 1,310 |
| Cobalt | 5.80E-08 | 1,580 – 1,590 | 5.20E-07 | 1,520 – 1,570 | 1.60E-06 | 1,530 | 5.40E-06 | 1,530 – 1,550 | 9.80E-06 | 1,530 – 1,540 | 8.80E-06 | 1,490 – 1,500 | 5.30E-06 | 1,450 | 2.50E-06 | 1,430 – 1,440 | 6.00E-07 | 1,410 – 1,440 |
| Cyanide | 8.80E-06 | 1,450 – 1,460 | 1.00E-04 | 1,440 | 5.00E-04 | 1,440 | 0.0017 | 1,480 | ***0.0029*** | 1,500 | 0.0023 | 1,500 – 1,510 | 9.20E-04 | 1,500 | 2.90E-04 | 1,490 – 1,500 | 5.60E-05 | 1,490 |
| Fluoride | 0.0016 | 1,490 – 1,500 | 0.0072 | 1,460 | 0.018 | 1,450 | 0.023 | 1,440 | ***0.024*** | 1,430 | 0.018 | 1,420 – 1,430 | 0.0083 | 1,420 | 0.0029 | 1,410 – 1,420 | 6.00E-04 | 1,410 |
| Nitrate | 6.60E-04 | 1,370 | 0.0072 | 1,360 | 0.012 | 1,370 | 0.0095 | 1,410 | ***0.0095*** | 1,420 | 0.0072 | 1,410 – 1,420 | 0.0034 | 1,410 | 0.0012 | 1,410 | 2.40E-04 | 1,400 |
| Nitrite | 0.0017 | 1,430 | 0.016 | 1,420 | 0.039 | 1,430 | **0.047** | 1,440 | *0.04* | 1,440 | 0.023 | 1430 | 0.0088 | 1,420 | 0.0028 | 1,420 | 5.40E-04 | 1,410 |
| Selenium | 6.00E-08 | 4,600 – 4,770 | 5.90E-07 | 4,580 – 4,670 | 2.40E-06 | 4,610 – 4,670 | 1.20E-05 | 4,690 – 4,700 | 2.30E-05 | 4,680 – 4,750 | 1.60E-05 | 4,640 – 4,750 | 8.00E-06 | 4,620 – 4,630 | 3.40E-06 | 4,470 – 4,580 | 8.60E-07 | 4,380 – 4,420 |
| Tin | 2.10E-12 | 10,000 | 1.80E-11 | 10,000 | 4.50E-11 | 10,000 | 8.20E-11 | 10,000 | 1.40E-10 | 10,000 | 1.40E-10 | 10,000 | 1.00E-10 | 10,000 | 5.10E-11 | 10,000 | 1.40E-11 | 10,000 |
| Uranium | 1.7E-04 | 10,000 | 6.67E-04 | 10,000 | 8.3E-04 | 10,000 | 6.9E-04 | 10,000 | 6.2E-04 | 10,000 | 4.8E-04 | 10,000 | 2.5E-04 | 10,000 | 9.7E-05 | 10,000 | 2.2E-05 | 10,000 |
| Total HI* | 3.13E-03 | 1,440 | 2.47E-02 | 1,440 | 5.55E-02 | 1,440 | 6.88E-02 | 1,440 | 6.85E-02 | 1,440 | 4.54E-02 | 1,440 | 1.92E-02 | 1,440 | 6.40E-03 | 1,440 | 1.28E-03 | 1,440 |

HQ = hazard quotient
PoCal = Point of Calculation

* The total hazard index is given at the approximate time of the peak hazard index, it is not the sum of the peak HQ, because the peaks do not always coincide.

# 9.0 SENSITIVITY ANALYSIS FOR THE GROUNDWATER PATHWAY

Sensitivity analyses evaluate changes in calculated groundwater impacts that result from changes in input parameter estimates. Parameter value ranges used in these analyses were selected by one of several methods. As discussed in Section 1, during the scoping process leading up to the implementation of the integrated PA, stakeholders expressed specific interest in seeing sensitivity results of specific sets of input parameters. In addition to these agreed sets of sensitivity analyses, additional sensitivity cases were identified during the implementation of the RCA to evaluate the importance of specific safety functions on the behavior of the disposal system. The result is a set of sensitivity analyses intended to represent the effects of changing a broad set of input assumptions. The sensitivity analyses are generally intended to evaluate changes in the underlying assumptions upon which the model is based, and intended to demonstrate the effect the alternative assumptions have on the groundwater concentrations at the PoCal.

Primary sources of alternative modeling assumptions are natural system heterogeneities, long-term engineered surface barrier performance, and human actions. Such assumptions can be categorized as scenario or model uncertainties, and as such are not readily amenable to the use of probabilistic methods (NCRP Report 152; "Decision analysis for low-level radioactive waste disposal facilities" [Kozak 1994]). Consequently, these analyses are run as deterministic sensitivity analyses, without assigning a likelihood of occurrence to a particular result other than (in some cases) a qualitative evaluation of its likelihood.

The sensitivity analyses quantify the ranges of calculated groundwater concentration outcomes due to single-parameter or multiple-parameter changes that represent an underlying shift in the conceptual model. With respect to the defense-in-depth concept, the analyses quantify the impacts that alternative views of the natural and engineered barriers have on groundwater concentrations in the total system performance. These analyses are an effective tool for supporting closure action decisions for WMA C, because they demonstrate the complementary and redundant nature of the safety functions evaluated in this assessment.

The set of sensitivity analyses is presented in Table 9-1. Each sensitivity analysis is assigned a shorthand designator so it can be easily referenced. A brief explanation of each sensitivity analysis is also provided in the table, to provide insight into the alternative assumptions it is intended to evaluate. Depending on the nature of the sensitivity analysis, it was either run in STOMP© or using the GoldSim© abstraction of the STOMP© model; the selection of how to run the analysis was made solely for pragmatic considerations. It is much easier and faster to run the GoldSim© model, so when possible, that is the preferred approach. However, when the sensitivity case involved changes in the underlying flow field, by necessity the analysis could only be done using STOMP©.

In Table 9-1, the sensitivity analyses are subdivided into several categories corresponding to the categories of safety functions they are intended to evaluate.

The sensitivity cases conducted using the 3-D STOMP© model can be grouped in three categories: (1) changes in aquifer properties, (2) changes in recharge, and (3) changes in

vadose zone geology and hydrologic parameters. The sensitivity analysis for the aquifer parameters examines the impacts associated with COPC transport and mixing in the aquifer between WMA C and the PoCal 100 m (328 ft) downgradient of the facility. The recharge category of sensitivity simulations addresses elements associated with the surface barrier function and the impacts of changes in recharge rate estimates during both pre- and post-design life performance periods of the surface barrier. The hydrologic cases examine the impacts of changes in the hydrologic parameters and address those elements of the defense-in-depth associated with the vadose zone function. This category includes the evaluation of Alternative Geologic Model II and the hypothesized presence of a clastic dike within the WMA C fenceline. The sensitivity cases conducted using the system GoldSim© model can be grouped into four categories: (1) changes in the inventory estimate, (2) changes in tank degradation time, (3) changes in grout diffusion parameters, and (4) changes in dissolved concentration limited transport for COPCs. These four sensitivity cases were compared to the system model base case. Because the screening analysis and base case results indicate that only the most mobile COPCs break through to a peak concentration in groundwater within the 10,000-year sensitivity evaluation time frame, comparative results are presented for COPCs with $K_d$ values equal to zero; in particular, nitrate.

**Table 9-1. Summary of Sensitivity Cases. (3 sheets)**

| Sensitivity Case Shorthand | Explanation | Model |
|---|---|---|
| **Surface Barrier Flow Safety Function** | | |
| inf01 | All parameters same as base case, except that post-design surface barrier net infiltration = 1.0 mm/yr. This is a case in which the surface barrier continues to provide limitation to flow beyond its design life. | STOMP© |
| inf02 | All parameters same as base case, except that post-design surface barrier net infiltration = 5.2 mm/yr. This is a case in which the surface barrier behaves worse than expected after its design life, and allows more infiltration than the base case Hanford infiltration. | STOMP© |
| inf03 | All parameters same as base case, except that operational period net infiltration = 140 mm/yr, and post-institutional control net infiltration = 100 mm/yr. This corresponds to future scenarios in which land use or vegetative cover are significantly different and disadvantageous compared to the base case. This may include vegetative progression, migration of sand dunes onto Waste Management Area (WMA) C, or agricultural irrigation on the site. | STOMP© |
| unc01 | All parameters same as base case, except that net infiltration for all surfaces outside WMA C = 0.5 mm/yr for all times. This corresponds to future scenarios in which land use or vegetative cover are significantly different and advantageous compared to the base case, but the cover continues to have a nominal functionality. | STOMP© |
| unc02 | All parameters same as base case, except that net infiltration for all surfaces outside WMA C = 100 mm/yr for all times. This corresponds to future scenarios in which land use or vegetative cover are significantly different and disadvantageous compared to the base case, but the cover continues to have a nominal functionality. | STOMP© |

**Table 9-1. Summary of Sensitivity Cases. (3 sheets)**

| Sensitivity Case Shorthand | Explanation | Model |
|---|---|---|
| **Aquifer Dilution Safety Function** | | |
| gwp01 | All parameters same as base case, except that aquifer flow parameters are 5th percentile values. This corresponds to altered aquifer flow producing minimal aquifer dilution compared to the base case. | STOMP© |
| gwp03 | All parameters same as base case, except that aquifer flow parameters are 95th percentile values. This corresponds to altered aquifer flow producing a higher level of aquifer dilution compared to the base case. | STOMP© |
| **Vadose Zone Flow and Dispersion Safety Functions** | | |
| vzp01 | All parameters same as base case, except that vadose zone hydraulic properties are 5th percentile values. This is an exploration of the effect of vadose zone parameters. | STOMP© |
| vzp02 | All parameters same as base case, except that vadose zone hydraulic properties are 50th percentile values (median). This is an exploration of the effect of vadose zone parameters. | STOMP© |
| vzp03 | All parameters same as base case, except that vadose zone hydraulic properties are 95th percentile values. This is an exploration of the effect of vadose zone parameters. | STOMP© |
| vzp04 | All parameters same as base case, except that the geologic model is Alternative II with 5th and 95th percentile values of H2 Sand applied to H2 Fine and H2 Coarse Sand, respectively. This is an exploration of the effect of vadose zone parameters. | STOMP© |
| vzp05 | All parameters same as base case, except that the geologic conceptualization includes clastic dikes. This is an alternative conceptual model representing an unknown feature below the site. | STOMP© |
| **Inventory Estimate** | | |
| inv1 | All parameters same as base case, except that the estimated inventory is based on the upper bound values. This is an exploration of the effect of alternative inventory assumptions. | GoldSim© |
| **Grout Flow Safety Function** | | |
| grt1 | All parameters same as base case, except that after 5,000 years the grout volumes become active and the flow properties change to Hanford H2 sand values, with a step function change in the flow rate occurring at this time. This may represent an alternative in which the grout degradation is more rapid than the base case, either through weathering processes that are not included in the base case, or if failure occurs from unanticipated seismic activity. | GoldSim© |
| grt2 | All parameters same as base case, except that after 1,000 years the grout volumes become active and the flow properties change to Hanford H2 sand values, with a step function change in the flow rate occurring at this time. This may represent an alternative in which the grout degradation is more rapid than the base case, either through weathering processes that are not included in the base case, or if failure occurs from unanticipated seismic activity. | GoldSim© |

**Table 9-1. Summary of Sensitivity Cases. (3 sheets)**

| Sensitivity Case Shorthand | Explanation | Model |
|---|---|---|
| grt3 | All parameters same as base case, except that after 500 years the grout volumes become active and the flow properties change to Hanford H2 sand values, with a step function change in the flow rate occurring at this time. This may represent an alternative in which the grout degradation is more rapid than the base case, either through weathering processes that are not included in the base case, or if failure occurs from unanticipated seismic activity. | GoldSim© |
| grt4 | All parameters same as base case, except that after 0 years the grout volumes become active and the flow properties change to Hanford H2 sand values, with a step function change in the flow rate occurring at this time. | GoldSim© |
| **Tank Flow Safety Function** | | |
| dif1 | All parameters same as base case, except that the release function is based on diffusion coefficient 1E-7 $cm^2/s$. This case represents the tank and base mat in worse condition than the base case, but still limited by diffusion. | GoldSim© |
| dif2 | All parameters same as base case, except that the release function is based on linearly changing diffusion coefficient over 500 years from 1E-14 to 3E-8 $cm^2/s$. This case represents the tank and base mat degrading over 500 years, but still limited by diffusion. | GoldSim© |
| dif3 | All parameters same as base case, except that the tanks remain intact (no release) for 5,000 years, followed by advective and diffusive release beginning immediately. This case represents the steel shell remaining intact for longer than the base case, potentially allowing ingrowth of uranium progeny, followed by advective and diffusive release with associated potential for higher releases of the progeny. | GoldSim© |
| **Residual Chemistry Safety Function** | | |
| rls1 | All parameters same as base case, except that the there is no dissolved concentration limit for chromium within the waste. This case evaluates a more conservative release function compared to the base case. | GoldSim© |

GoldSim© simulation software is copyrighted by GoldSim Technology Group LLC of Issaquah, Washington (see http://www.goldsim.com).
Subsurface Transport Over Multiple Phases (STOMP)© is copyrighted by Battelle Memorial Institute, 1996.

TC&WM EIS = Tank Closure and Waste Management Environmental Impact Statement (DOE/EIS-0391, 2012, "Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington," U.S. Department of Energy, Washington, D.C.)

## 9.1 AQUIFER DILUTIONS SENSITIVITY ANALYSES

The aquifer property sensitivity evaluations address the safety function component related to dilution caused by the groundwater flux in the aquifer. The parameters that determine the groundwater flux and the amount of dilution that occurs in the aquifer are the hydraulic conductivity and hydraulic gradient. In a natural system, the two parameters offset one another. If the groundwater flux through an aquifer volume remains constant, then in areas with high

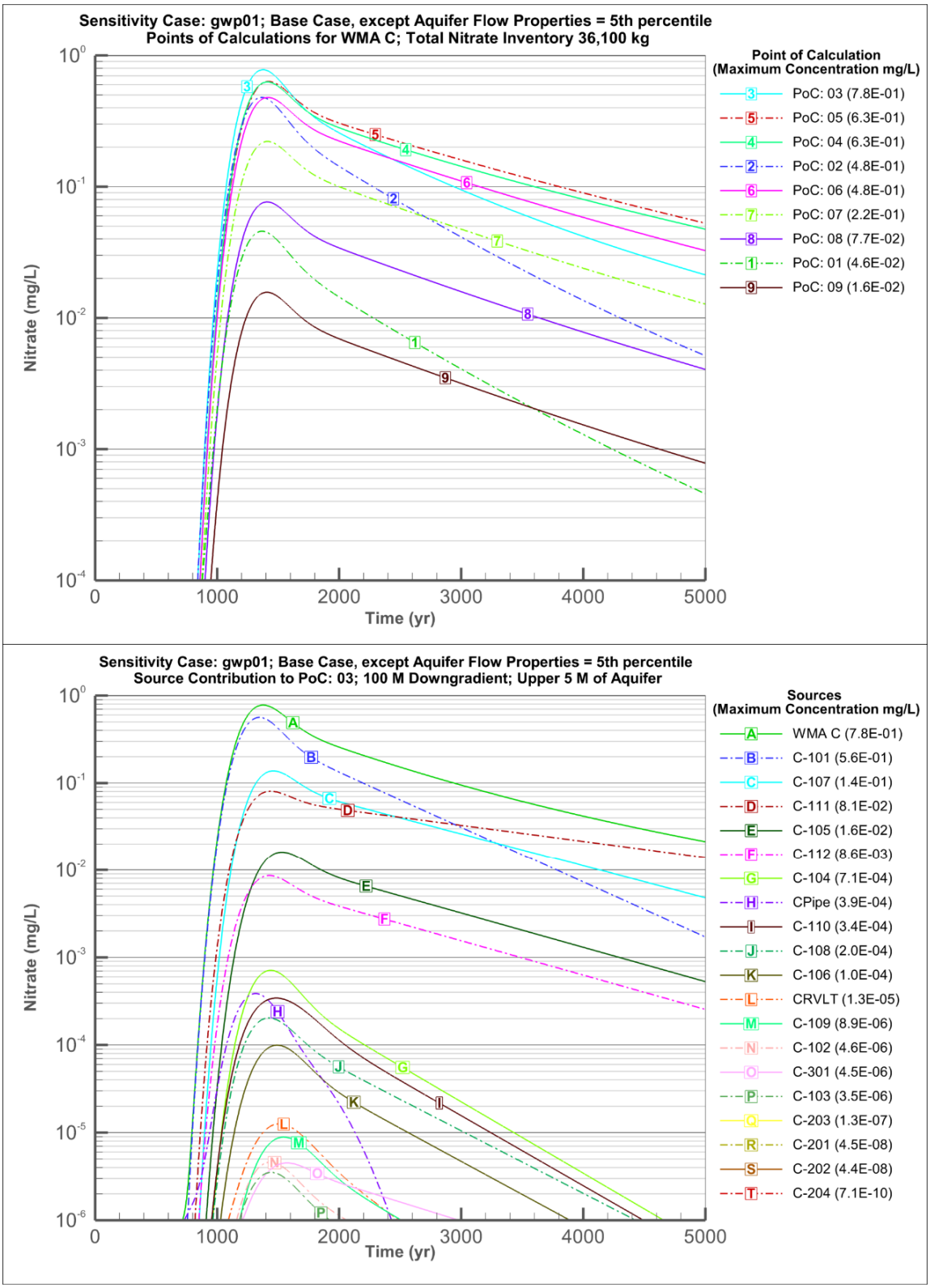
hydraulic conductivity, the hydraulic gradient will be less, and vice versa. They are considered to be coupled parameters because changes to the flux term caused by changes made to one term are inseparable from changes made to the other term. These parameters act inversely proportional to one another, and the same change in the flux can be made by making the same proportional change to either parameter. Therefore, only one of the parameters, e.g., hydraulic conductivity, needs to be varied to produce the variability in the flux necessary to conduct the sensitivity analysis. For this sensitivity evaluation, the hydraulic conductivity is varied.

The sensitivity analysis includes two values of hydraulic conductivity, the 5$^{th}$ percentile value (4,200 m/day [13,800 ft/day] [gwp01]) and the 95$^{th}$ percentile value (17,800 m/day [58,400 ft/day] [gwp03]). The results provide some insight into the dilution mechanism of the aquifer (Table 9-2). Figure 9-1 and 9-2 show the overall results for WMA C at the nine PoCals for the 5$^{th}$ and 95$^{th}$ percentile values, respectively, with a breakdown by source at the maximum PoCal. Figure 9-3 shows a comparison of the specific results for tank C-101 and the pipelines at the maximum PoCal. Tank C-101 has the largest estimated residual inventory of nitrate, and the release from the pipelines is approximated as being advection-controlled instead of diffusion-controlled release used in the tanks. The results of the evaluation using the 5$^{th}$ percentile value are a factor of 2.6 greater than the base case, and the hydraulic conductivity is a factor of 2.6 less than the base case value. Similarly, the results of the evaluation using the 95$^{th}$ percentile value are a factor of 1.6 less than the base case, and the hydraulic conductivity is a factor of 1.6 greater than the base case value. The amount of dilution appears inversely proportional to the flux through an aquifer as determined from the hydraulic conductivity. The proportionality is observed in the tank C-101 and pipeline residuals evaluations. The results of the 5$^{th}$ percentile hydraulic conductivity evaluation indicate an approximate factor of 2.6 increase in the peak concentration compared to the base case, and the results of the 95$^{th}$ percentile hydraulic conductivity evaluation indicate an approximate factor of 1.6 decrease in the peak concentration compared to the base case. These results indicate that the aquifer flow parameters that affect the flux rate of water have an inversely proportional impact on the groundwater concentration.

**Table 9-2. Aquifer Property Sensitivity Evaluation**

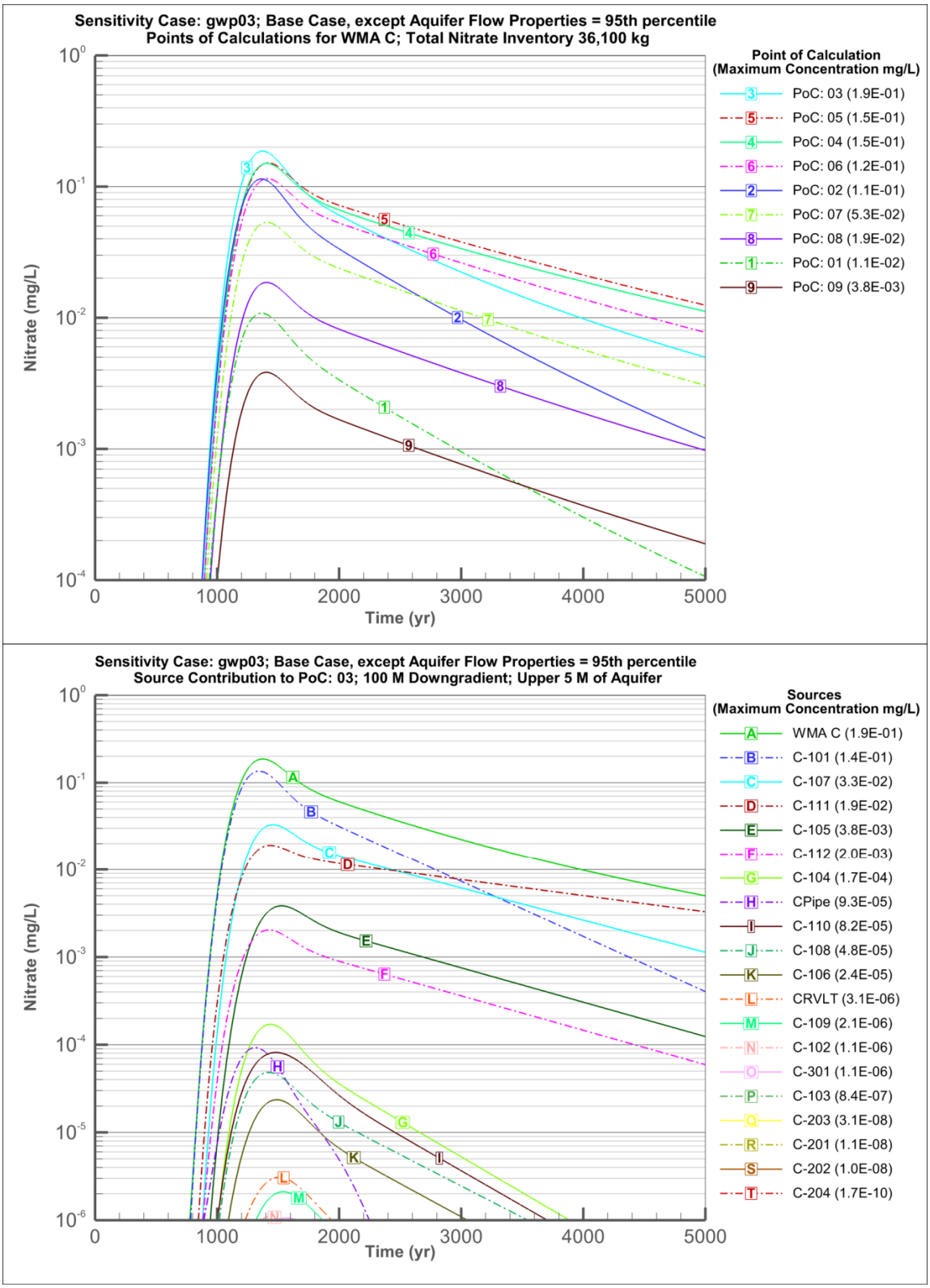
| Aquifer Property | Sensitivity Case Shorthand | Time of Arrival of Maximum Concentration at Downgradient Point of Calculation (Years after Closure) | Nitrate Maximum Concentration at Downgradient Point of Calculation (mg/L) |
|---|---|---|---|
| 5th Percentile Hydraulic Conductivity Value | gwp01 | 1,375 | 0.78 |
| Median Hydraulic Conductivity Value | bas01 | 1,375 | 0.30 |
| 95th Percentile Hydraulic Conductivity Value | gwp03 | 1,370 | 0.19 |

**Figure 9-1. Aquifer Property Sensitivity Analysis Results of the Nitrate Concentration in Groundwater for the 5th Percentile (gwp01) Hydraulic Conductivity Values.**



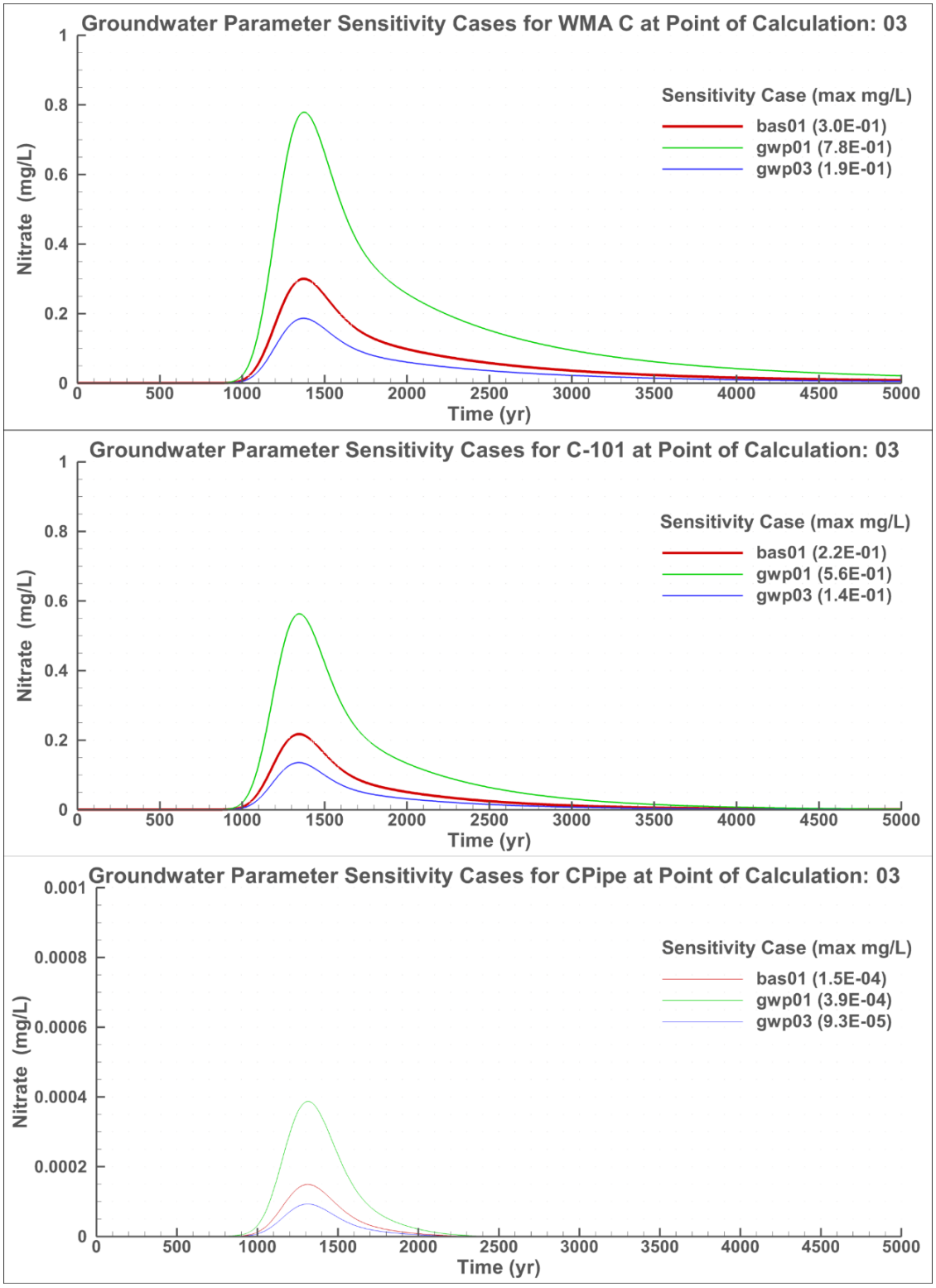

PoC = Point of Calculation WMA = Waste Management Area

**Figure 9-2. Aquifer Property Sensitivity Analysis Results of the Nitrate Concentration in Groundwater for the 95th Percentile (gwp03) Hydraulic Conductivity Values.**




PoC = Point of Calculation WMA = Waste Management Area

**Figure 9-3. Comparison of the Aquifer Property Sensitivity Analysis Results of the Nitrate Concentration in Groundwater for the Base Case, 5th Percentile (gwp01), and 95th Percentile (gwp03) Hydraulic Conductivity Values at Point of Calculation 4.**




CPipe = WMA C Pipeline WMA = Waste Management Area

## 9.2 SURFACE BARRIER FLOW SENSITIVITY ANALYSES

In this evaluation, recharge-related parameters were varied to examine the impact of temporal and spatial variations in recharge at the 100 m (328 ft) PoCal. The recharge sensitivity evaluations address the safety function related to surface barrier flow. Because of the spatial component of this analysis, it was conducted using STOMP©. For this analysis, the vadose zone and aquifer hydraulic properties remain unchanged from their base case values.

Five recharge sensitivity cases were evaluated. Cases inf01 and inf02 address the minimum and maximum estimated values of net infiltration (recharge) after the design life of the surface barrier. Case inf03 represents significantly different conditions on the cover, with very high infiltration rate characteristic of infiltration rates for bare soil that existed during the operational period. This case involves the assumption of present day estimates of tank farm recharge resuming at WMA C after a 100-year period of institutional controls. Inclusion of case inf03 is due to a specific request by Ecology during the scoping session meetings. Cases unc01 and unc02 address variability in recharge estimates outside WMA C. Case unc02 also evaluates the potential effects on groundwater impacts of including additional water at the edge of the cover. This case can be used to approximate the effect of runoff from the top surface of the barrier and additional recharge through the side slopes and at the base of the barrier on groundwater results.

The peak groundwater concentration of nitrate ranges between 0.16 and 0.79 mg/L for these cases (Table 9-3). This includes recharge rates applied to areas outside of WMA C, ranging from 0.5 mm/yr to 100 mm/yr (0.02 in./yr to 3.94 in./yr) to evaluate the impact the outside recharge rates have on the results. The latter of these two cases also addresses the concern that increased recharge may occur through the side slopes and around the base of the surface barrier.

Figure 9-4 and 9-5 show the overall results for nitrate at the nine PoCals for the minimum and maximum estimated values of post-design life barrier net infiltration, respectively, with a breakdown by source at the maximum PoCal. Figure 9-6 shows a comparison of the specific nitrate results for tank C-101 and the pipelines at the maximum PoCal. For the case with the post-design life recharge rate set to the minimum value, the maximum concentration of nitrate decreases from the base case value of 0.30 mg/L to 0.16 mg/L, a decrease of 47%. For the case with the maximum post-design life recharge rate, the peak groundwater concentration of nitrate increases from the base case value of 0.30 mg/L to 0.39 mg/L, an increase of 30% (Table 9-3).

Recharge in the areas outside WMA C has an inverse relationship with the results: peak nitrate concentration in groundwater decreases as recharge in the areas outside WMA C increases. The magnitude of the increase or decrease is within the range of values determined from the WMA C surface barrier evaluation (Table 9-3). For very high infiltration, characteristic of alternative assumptions about future surface conditions leading to extreme infiltration, the peak groundwater concentration of nitrate increases by approximately 150% from the base case results, and arrives at the PoCal approximately 75 years after the barrier ceases to exist (Table 9-3).

**Table 9-3. Recharge Sensitivity Evaluation.**

| Sensitivity Case Shorthand | Pre-WMA C and Undisturbed Ground Recharge Rate Percentile (Value) | Recharge Rate of WMA C Ground During Operations Percentile (Value) | Design Life Surface Barrier and Degraded Liner Recharge Rate Percentile (Value) | Post-Design Life Surface Barrier Recharge Rate Percentile (Value) | Time of Arrival of Maximum Concentration at Downgradient Point of Calculation (Years after Closure) | Nitrate Maximum Concentration at Downgradient Point of Calculation (mg/L) |
|---|---|---|---|---|---|---|
| bas01 | 3.5 mm/yr | 100 mm/yr | 0.5 mm/yr | 3.5 mm/yr | 1,375 | 0.30 |
| inf01 | 3.5 mm/yr | 100 mm/yr | 0.5 mm/yr | 1.0 mm/yr | 1,367 | 0.16 |
| inf02 | 5.2 mm/yr[a] | 100 mm/yr | 0.5 mm/yr | 5.2 mm/yr | 1,145 | 0.39 |
| inf03 | 3.5 mm/yr | 140 mm/yr | 0.5 mm/yr | 100 mm/yr[b] | 175 | 0.79 |
| unc01 | 3.5 mm/yr[c] | 100 mm/yr[c] | 0.5 mm/yr[c] | 3.5 mm/yr[c] | 1,510 | 0.31 |
| unc02 | 3.5 mm/yr[d] | 100 mm/yr[d] | 0.5 mm/yr[d] | 3.5 mm/yr[d] | 900 | 0.25 |

[a]Only recharge in the area that will be occupied by Waste Management Area (WMA) C is 5.2 mm/yr. Recharge everywhere else remains the base case value of 3.5 mm/yr.

[b]Post-design recharge begins 100 years after closure.

[c]Recharge in the areas not occupied by WMA C is 0.5 mm/yr.

[d]Recharge in the areas not occupied by WMA C is 100 mm/yr.

## 9.3 VADOSE ZONE FLOW AND DISPERSION SENSITIVITY ANALYSIS

The vadose zone hydraulic properties were varied to determine the impact that the inherent variability in these parameters has on the groundwater results. This set of vadose zone hydraulic properties sensitivity evaluations address the safety functions associated with flow and dispersion in the vadose zone. Four vadose zone parameters were varied: van Genuchten α and n (coupled), saturated moisture content ($\theta_s$), residual moisture content ($\theta_r$), and fitted saturated hydraulic conductivity ($K_s$). The parameters were varied in accordance with the percentile relationships determined in the PA uncertainty analysis (see RPP-ENV-58782, Section 8.1.3.4 Uncertainties in Vadose Zone Hydraulic Properties). Therefore, for the evaluations using the 5$^{th}$ percentile values, all of the geologic soil units were assigned their 5$^{th}$ percentile values. It is important to note that the percentiles refer to sets of parameter values and not to the properties individually (as discussed in Section 7.3.2 and Appendix B). Thus, the maximum van Genuchten residual saturation parameter does not necessarily represent the largest value of $\theta_r$, but instead represents the value associated with the fitted unsaturated hydraulic conductivity curve that produces the highest flow velocity at the pre-Hanford operations recharge rate. The values of four vadose zone parameters—van Genuchten α and n (coupled), $\theta_s$, $\theta_r$, and fitted saturated hydraulic conductivity ($K_s$)—varied for the three percentile cases (5$^{th}$ [vzp01], median

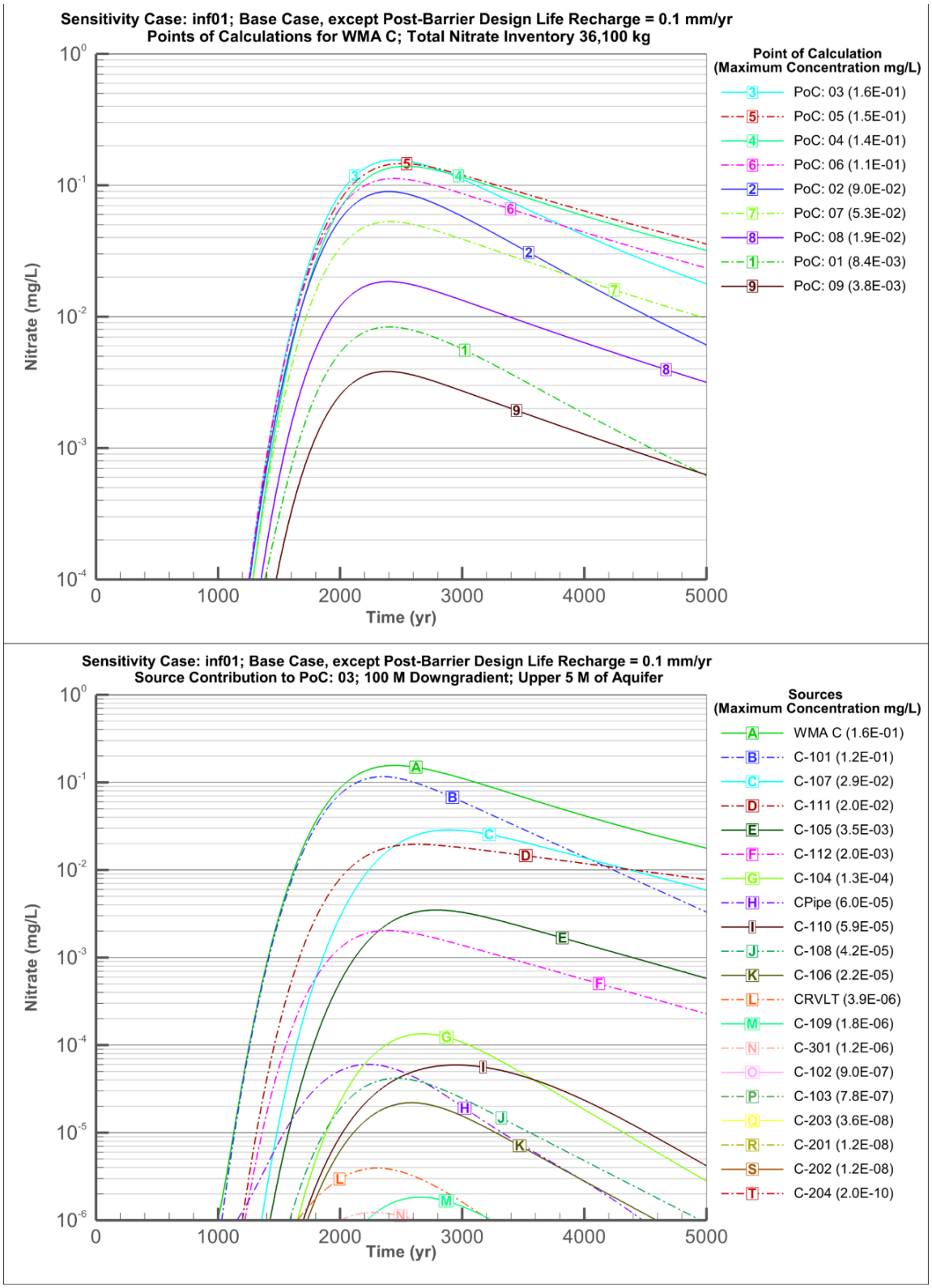
[vzp02], and 95th [vzp03]) are presented in Table 9-4. These evaluations used the base case recharge values and time sequence.

The vadose zone evaluation also included two alternate conceptual models of the geology. One alternative, referred to as Alternative II (vzp04), considers the Hanford H2 Sand unit to consist of three subunits that each possess different hydraulic characteristics. Most of the formation remains identified as H2 Sand, and the hydraulic properties for it remain unchanged from the base case analysis. Near the base of the Hanford H2 Sand unit in Alternative II are fine and coarse sand subunits. For this sensitivity evaluation, these subunits are assigned the Hanford H2 Sand 5th and 95th percentile hydraulic property sets, respectively. The second alternative conceptual model of the geology includes clastic dikes that extend the length and width of WMA C throughout the vadose zone to the capillary fringe of the aquifer (vzp05). For the sensitivity case, the length of the dike is assumed to extend for 7.6 m (25 ft), and the 3-D model discretization imposes a minimum width of 3.8 m (12 ft) for the dike. Although a width of 3.8 m (12 ft) is more representative of a planar feature than a dike, finer resolution of the model grid is not practicable with the available computational resources. The planar area of the dike is 29 $m^2$ (312 $ft^2$), which is comparable to a 1-m (3.3-ft)-wide dike that extends the entire diameter of the tank (23 $m^2$ [246 $ft^2$]). Clastic dikes of this size typically occur in sand, silt, and only occasionally in gravel (BHI-01103); therefore, the model representation of the dike extends throughout the depth of the Hanford H2 Sand. The hydraulic parameters assigned to the clastic dike material were selected to determine whether the flux conditions exist at WMA C such that the clastic dikes provide a preferential flow path for the residual waste. Thus, the set of clastic dike hydraulic parameters from among the samples listed in PNNL-23711, "Physical, Hydraulic, and Transport Properties of Sediments and Engineered Materials Associated with Hanford Immobilized Low-Activity Waste" that produced the highest pore water velocity at the undisturbed recharge rate of 3.5 mm/yr were assigned to the clastic dike material.

Figures 9-7 through 9-9 show the overall results for nitrate at the nine PoCals for the 5th, median, and 95th percentile values, respectively, with a breakdown by source at the maximum PoCal. Figure 9-10 shows a comparison of the specific nitrate results for tanks C-101, C-111, and the pipelines at the maximum PoCal. The peak groundwater concentration ranges between 0.18 and 0.41 mg/L for these cases (Table 9-5). The median hydraulic property values produce peak concentration results very similar to the base case results (0.27 mg/L arriving 1,215 years after closure compared to 0.30 mg/L arriving 1,375 years after closure for the base case; see Table 9-5). The range of results for the vadose zone sensitivity analysis produced a similar range of results to that of the recharge estimates.

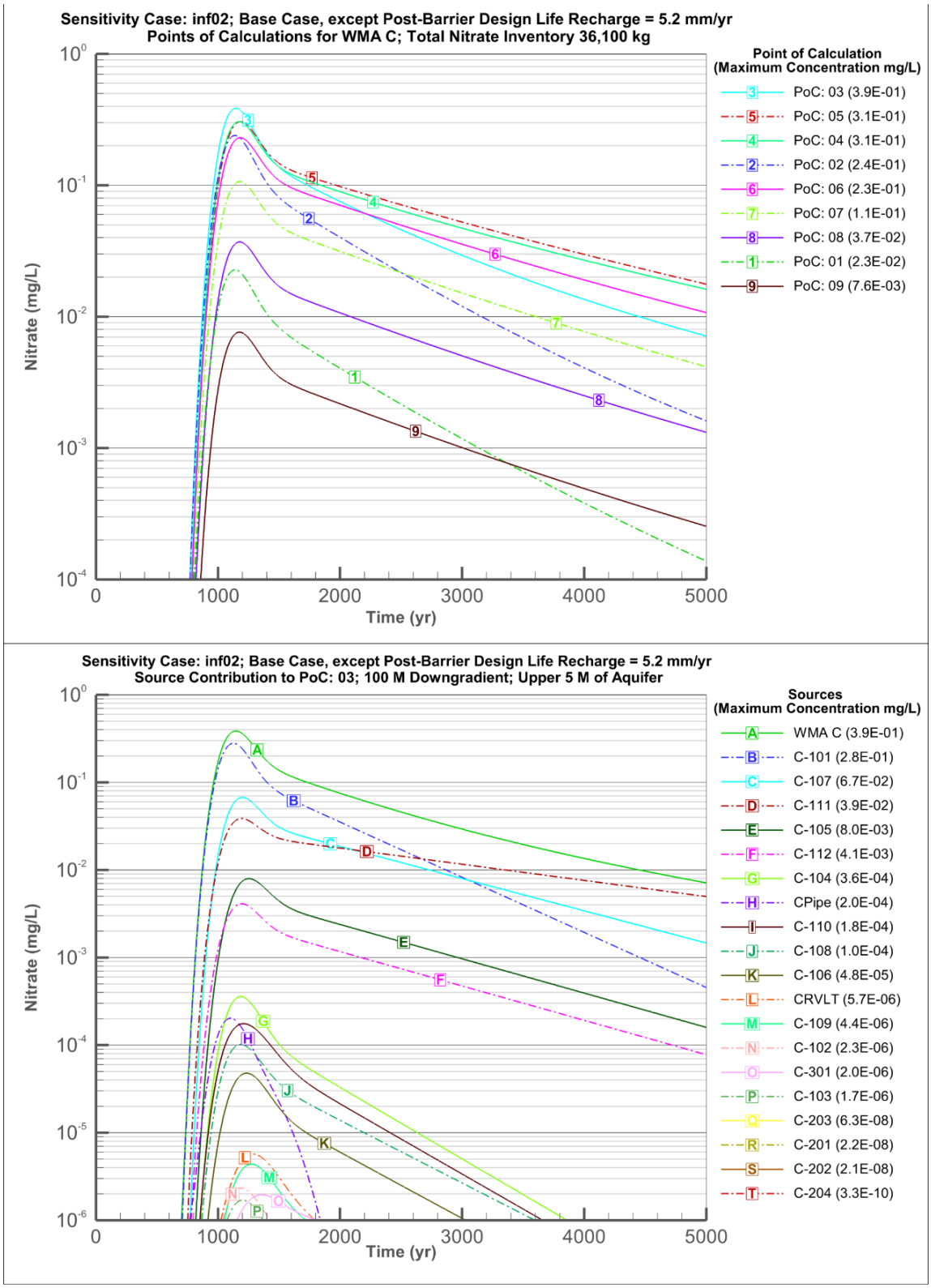
This evaluation of the alternative conceptual model of the geology indicates that these heterogeneous features do not strongly affect the results of the RCA. Figure 9-11 and 9-12 show the overall results for WMA C at the nine PoCals for Alternative Model II and for the clastic dike analysis, respectively, with a breakdown by source at the maximum PoCal. Figure 9-13 shows a comparison of the specific results for tanks C-101 and the pipelines at the maximum PoCal (i.e., PoCal 03). The peak concentration values show little change from the base case value, although the Alternative Geologic Model II analysis shows a slightly reduced travel time (Table 9-5).

**Figure 9-4. Recharge (Net Infiltration) Sensitivity Analysis Results of the Nitrate Concentration in Groundwater for the Minimum (inf01) Post-Design Life Value.**



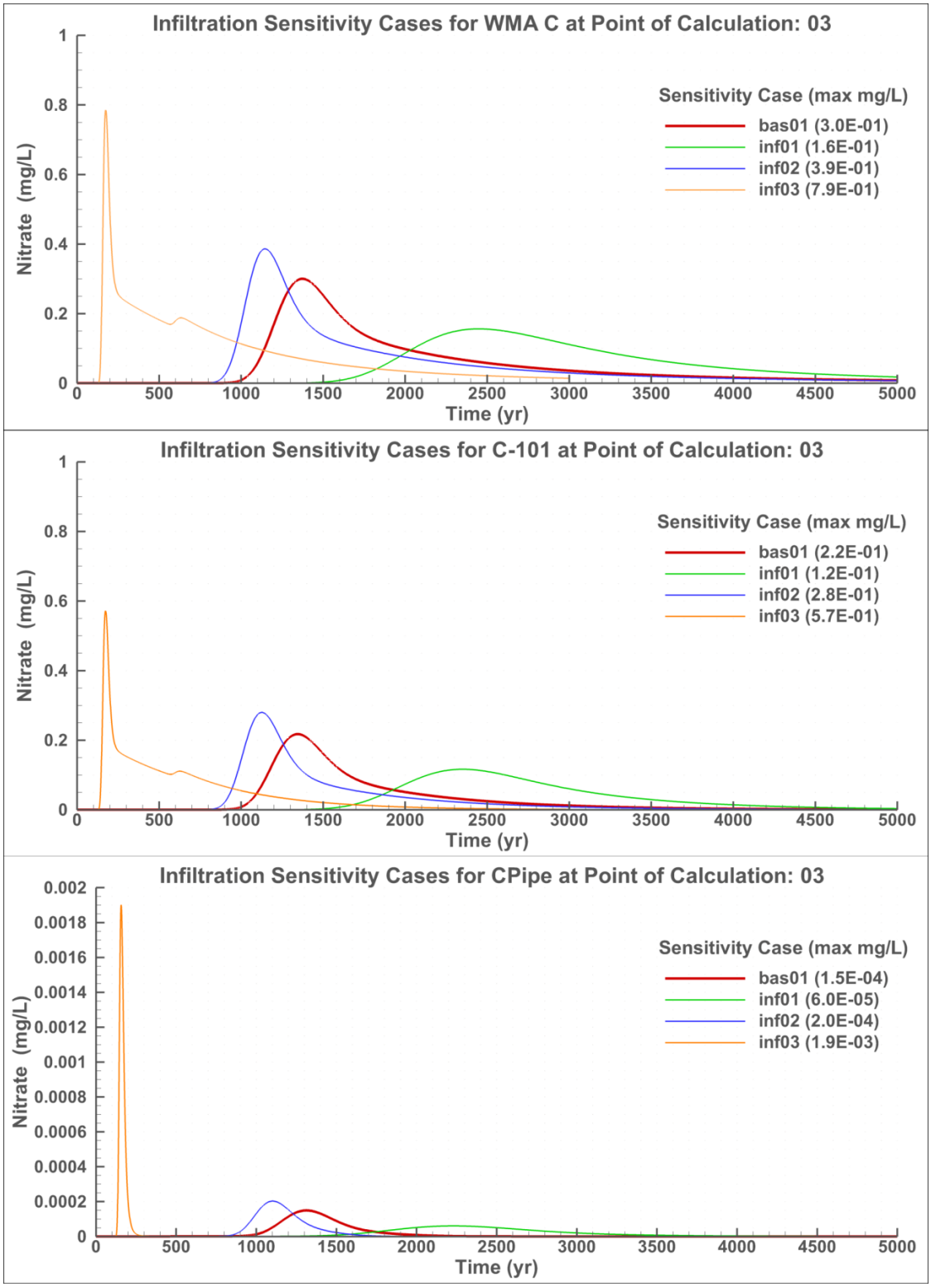

PoC = Point of Calculation WMA = Waste Management Area

**Figure 9-5. Recharge (Net Infiltration) Sensitivity Analysis Results of the Nitrate Concentration in Groundwater for the Maximum (inf02) Post-Design Life Value.**




PoC = Point of Calculation WMA = Waste Management Area

**Figure 9-6. Comparison of Recharge (Net Infiltration) Sensitivity Analysis Results of the Nitrate Concentration in Groundwater for the Base Case, Minimum (inf01), and Maximum (inf02) Post-Design Life Values.**




CPipe = WMA C Pipeline WMA = Waste Management Area

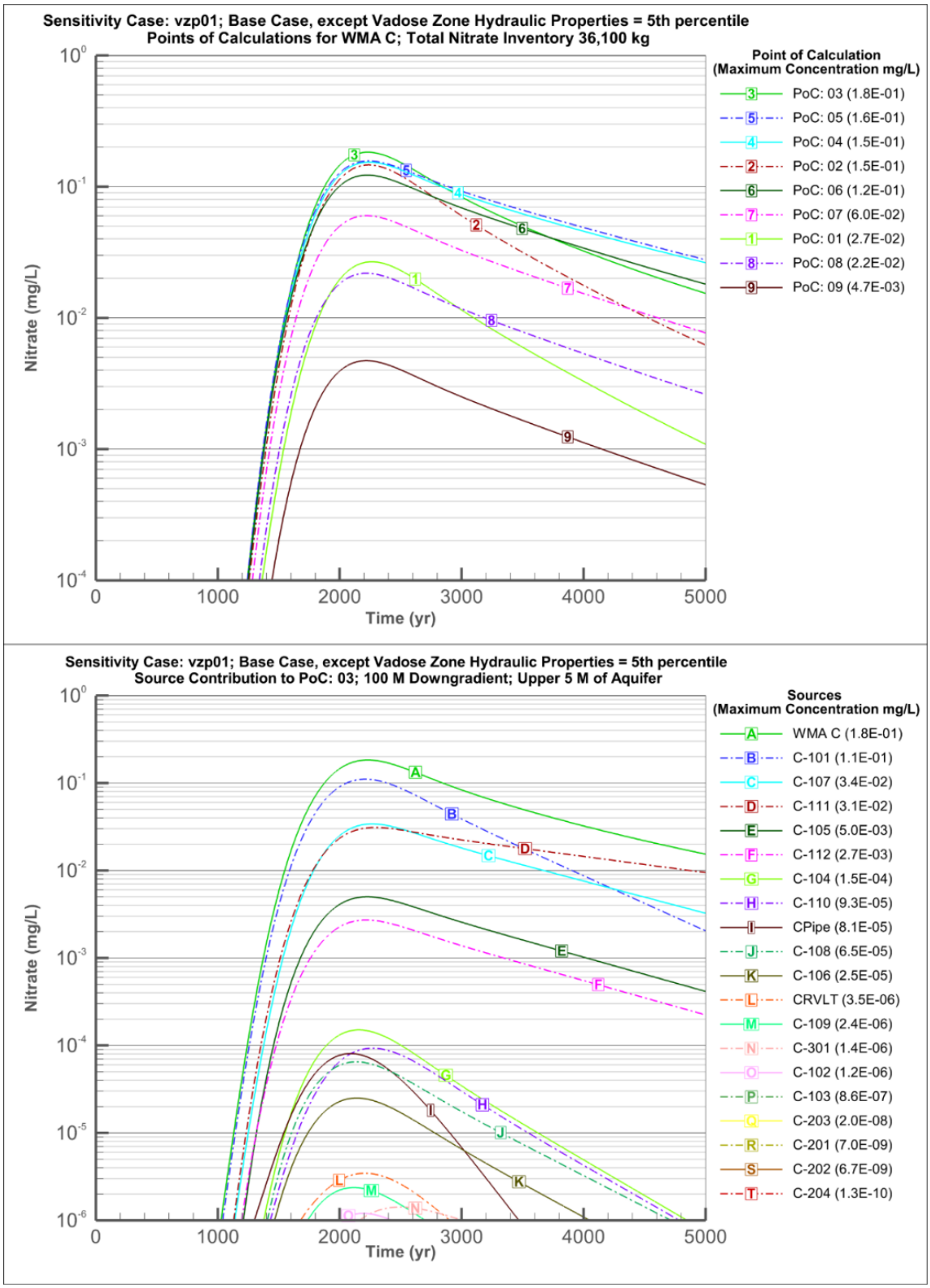
**Table 9-4. van Genuchten-Mualem Parameters Corresponding to the Percentiles Selected from the Vertical Pore Water Velocity Cumulative Distribution Functions.**

| Strata (tension) | Percentile | $K_s$ (cm/s) | $\theta_s$ | $\theta_r$ | α (1/cm) | n |
|---|---|---|---|---|---|---|
| Backfill | 5th Percentile* | 7.91E-06 | 0.2217 | 1.23E-02 | 0.0026 | 1.441 |
| | 25th Percentile | 1.08E-05 | 0.1319 | 1.57E-02 | 0.0031 | 1.31 |
| | 50th Percentile** | 7.31E-05 | 0.203 | 5.94E-03 | 0.0086 | 1.577 |
| | 75th Percentile | 1.98E-04 | 0.1409 | 1.42E-02 | 0.0123 | 1.47 |
| | 95th Percentile*** | 3.13E-04 | 0.1287 | 1.35E-02 | 0.0298 | 1.635 |
| | Base Case | 5.60E-04 | 0.138 | 1.00E-02 | 0.021 | 1.374 |
| Hanford H1/H3 | 5th Percentile* | 7.78E-05 | 0.2887 | 3.24E-02 | 0.0121 | 1.335 |
| | 25th Percentile | 5.14E-06 | 0.2118 | 2.08E-02 | 0.0062 | 1.733 |
| | 50th Percentile** | 1.49E-04 | 0.1735 | 3.06E-02 | 0.0124 | 1.603 |
| | 75th Percentile | 1.58E-03 | 0.3094 | 7.01E-03 | 0.0238 | 1.717 |
| | 95th Percentile*** | 2.99E-04 | 0.1024 | 1.45E-02 | 0.0152 | 1.76 |
| | Base Case | 7.70E-04 | 0.1712 | 1.11E-02 | 0.036 | 1.491 |
| Hanford H2 | 5th Percentile* | 1.79E-03 | 0.3541 | 2.89E-02 | 0.0402 | 1.633 |
| | 25th Percentile | 1.15E-03 | 0.2893 | 2.99E-02 | 0.0266 | 1.971 |
| | 50th Percentile** | 2.20E-02 | 0.3304 | 2.72E-02 | 0.1253 | 1.889 |
| | 75th Percentile | 3.79E-02 | 0.3474 | 2.05E-02 | 0.0966 | 1.966 |
| | 95th Percentile*** | 1.68E-02 | 0.2652 | 2.11E-03 | 0.1076 | 1.724 |
| | Base Case | 4.15E-03 | 0.3152 | 3.92E-02 | 0.0631 | 2.047 |

Note: The connectivity parameter ℓ is assumed to be 0.5 for all strata and all percentile values.

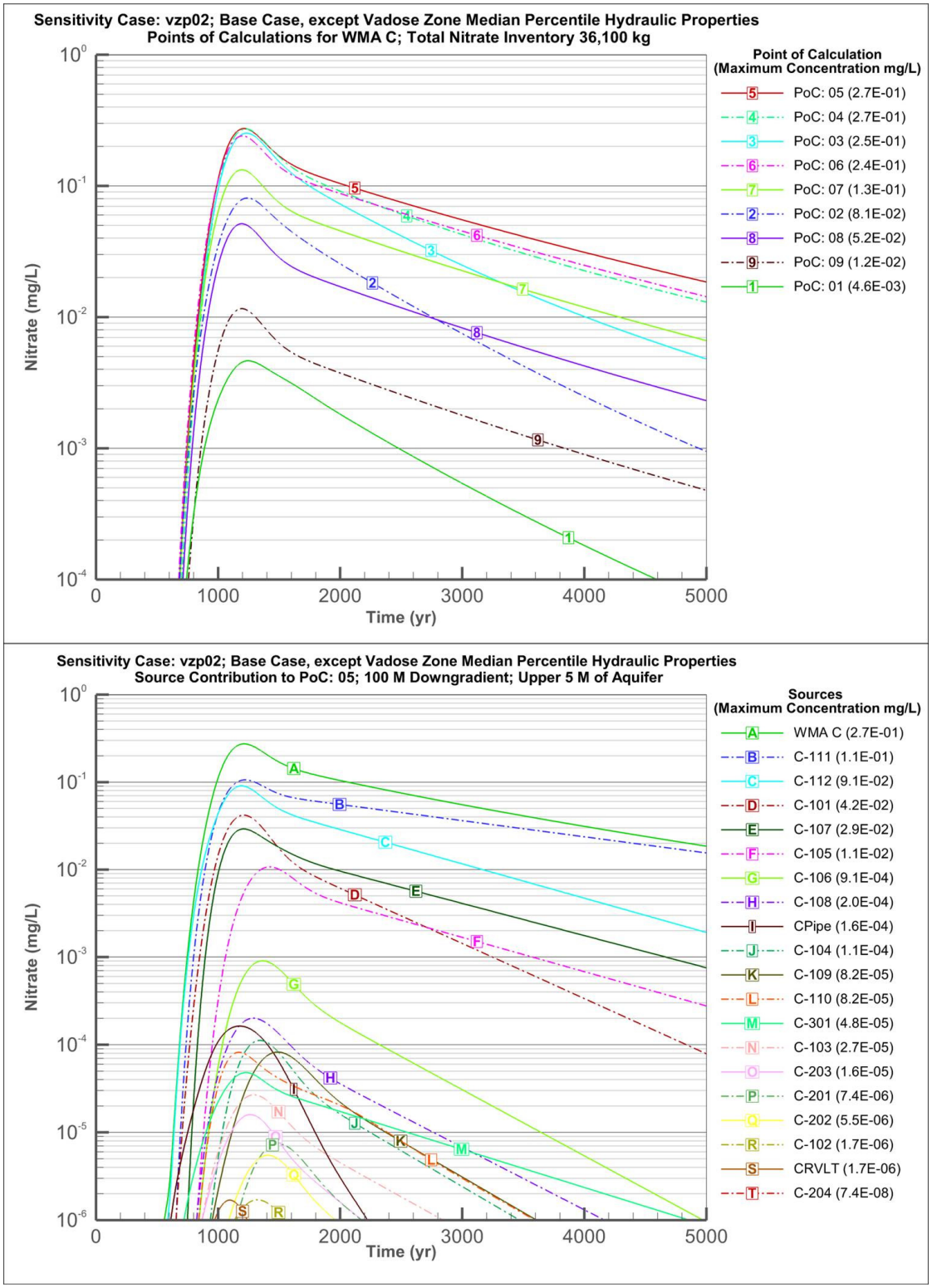
*Parameters associated with vadose zone sensitivity case, vzp01.
**Parameters associated with vadose zone sensitivity case, vzp02.
***Parameters associated with vadose zone sensitivity case, vzp03.

**Figure 9-7. Vadose Zone Property Sensitivity Analysis Results of the Nitrate Concentration in Groundwater for the 5th (vzp01) Percentile Hydraulic Parameter Values.**



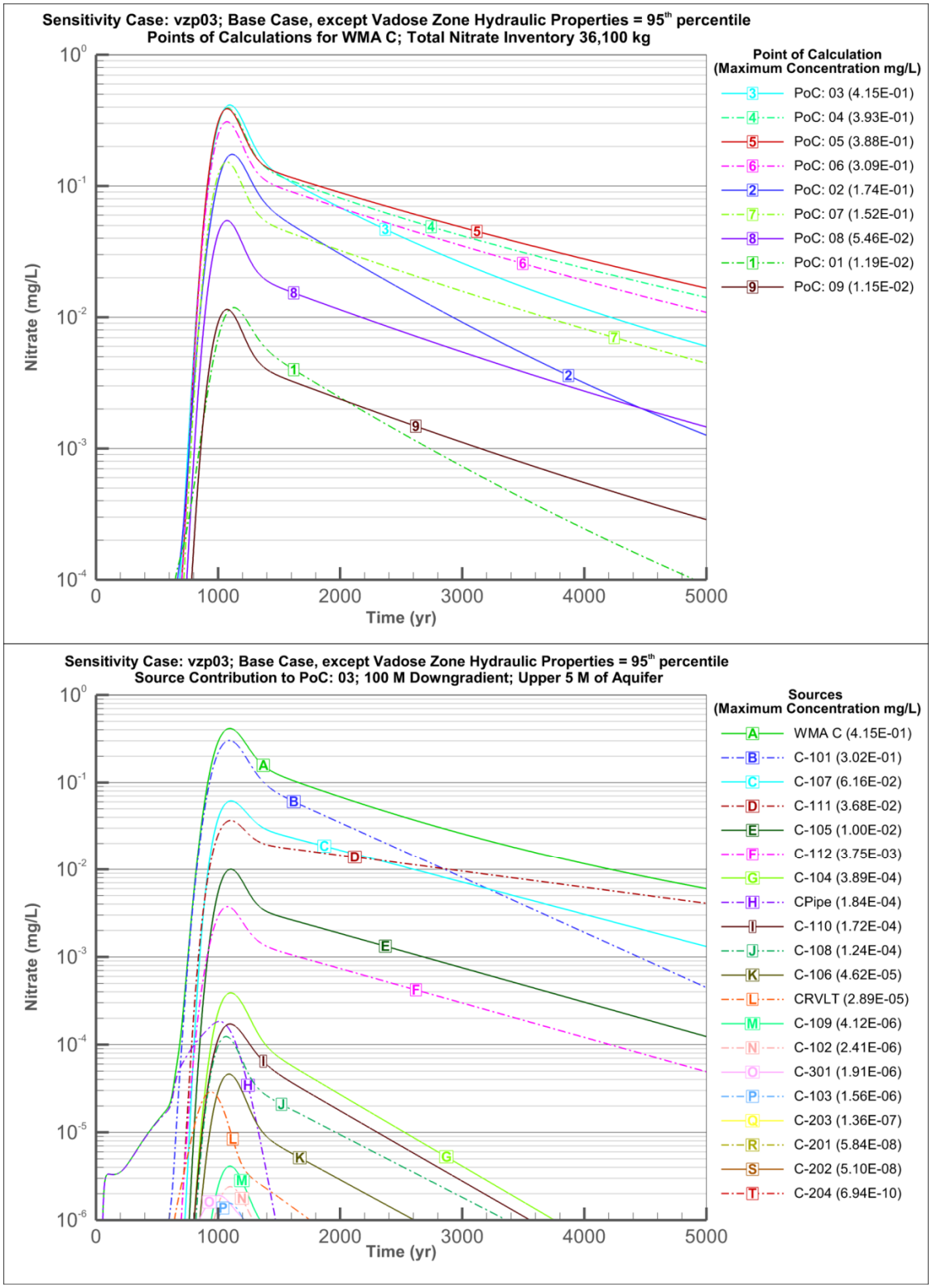

PoC = Point of Calculation WMA = Waste Management Area

**Figure 9-8. Vadose Zone Property Sensitivity Analysis Results of the Nitrate Concentration in Groundwater for the Median (vzp02) Percentile Hydraulic Parameter Values.**



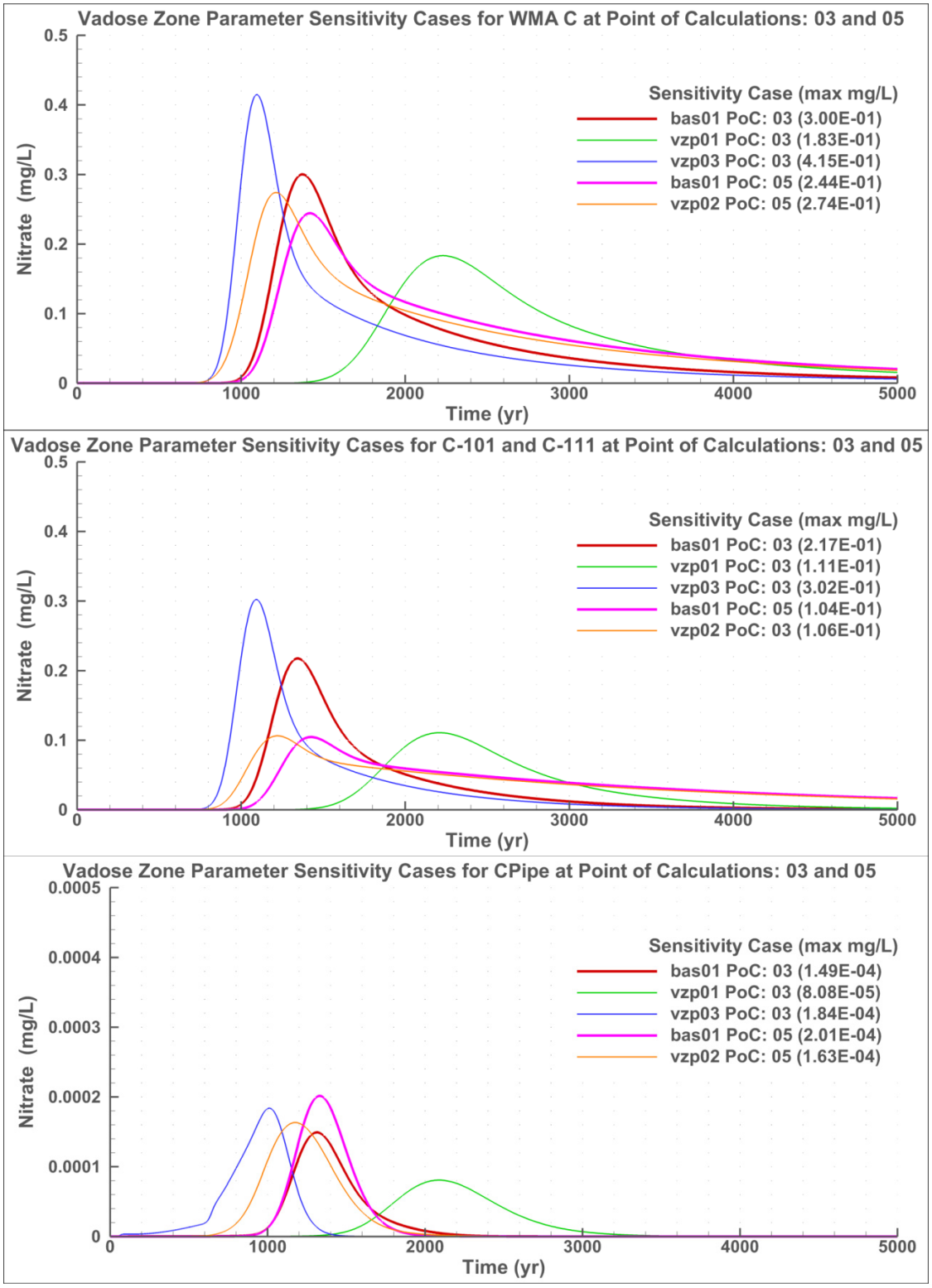

PoC = Point of Calculation WMA = Waste Management Area

**Figure 9-9. Vadose Zone Property Sensitivity Analysis Results of the Nitrate Concentration in Groundwater for the 95th (vzp03) Percentile Hydraulic Parameter Values.**




PoC = Point of Calculation WMA = Waste Management Area

**Figure 9-10. Comparison of Vadose Zone Property Sensitivity Analysis Results of the Nitrate Concentration in Groundwater for the Base Case, 5th (vzp01), Median (vzp02), and 95th Percentile (vzp03) Hydraulic Parameter Values.**




CPipe = WMA C Pipeline WMA = Waste Management Area

**Table 9-5. Vadose Zone Sensitivity Evaluations.**

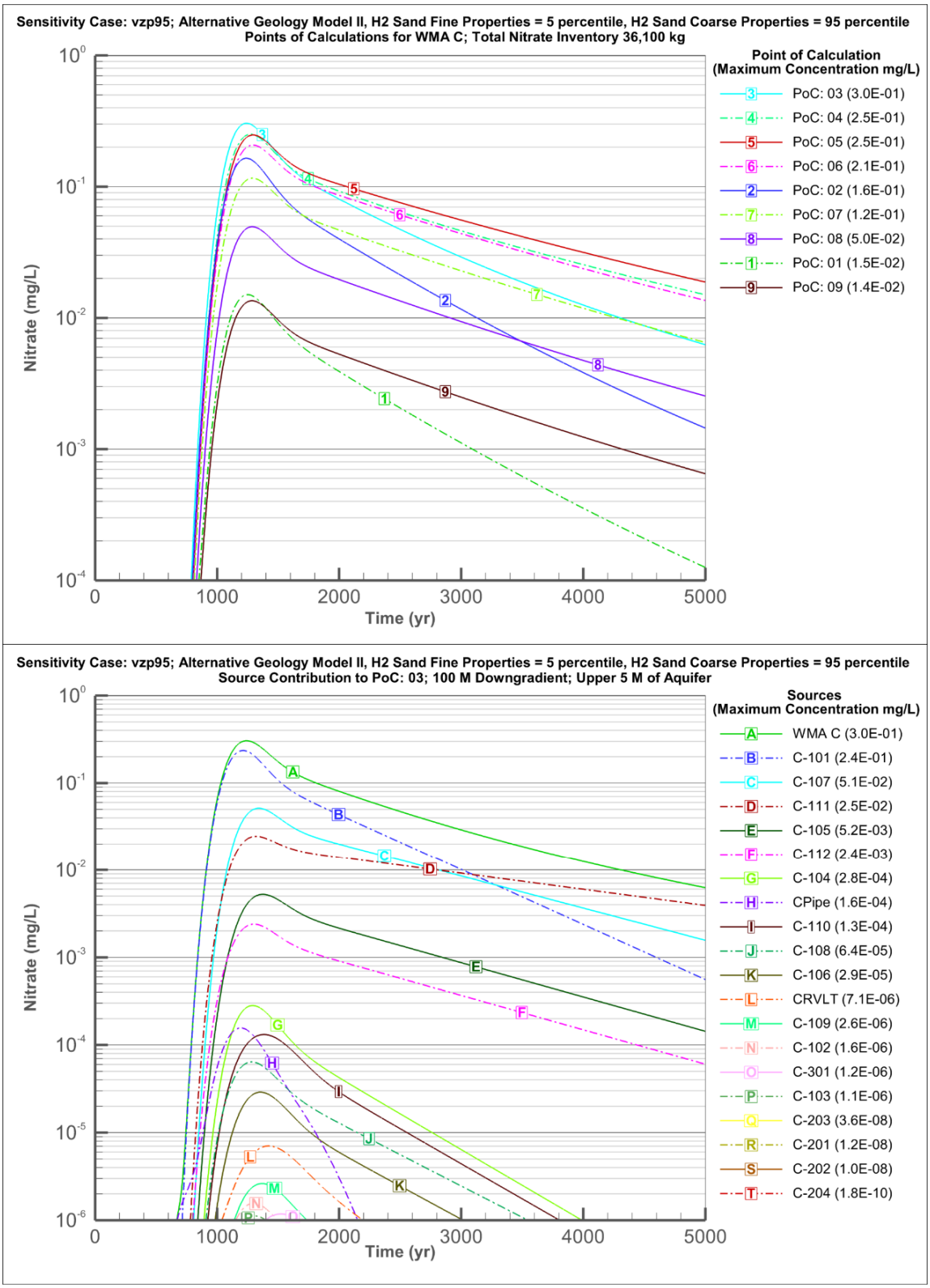
| Vadose Zone Sensitivity | Sensitivity Case Shorthand | Time of Arrival of Maximum Concentration at Downgradient Point of Calculation (Years after Closure) | Nitrate Maximum Concentration at Downgradient Point of Calculation (mg/L) |
|---|---|---|---|
| Base Case | bas01 | 1,375 | 0.30 |
| 5th Percentile Parameter Values | vzp01 | 2,230 | 0.18 |
| Median Percentile Parameter Values | vzp02 | 1,215 | 0.27 |
| 95th Percentile Parameter Values | vzp03 | 1,095 | 0.41 |
| Alternative Geologic Model II | vzp04 | 1,240 | 0.30 |
| Presence of Clastic Dike | vzp05 | 1,395 | 0.30 |

## 9.4 INVENTORY SENSITIVITY ANALYSES

An upper bound estimate of inventory is provided in Section 3.2.2.3 for both the retrieved tanks with a post-retrieval sample and for tanks undergoing retrieval (see Tables 3-16 and 3-17). For retrieved tanks (C-101, C-107, and C-112) without a post-retrieval sample, an upper bound could not be estimated for many constituents in these tanks (Section 3.2.2.3.2). A sensitivity case (inv01) was performed by replacing the base case nitrate inventory with the upper bound value to evaluate the impact in terms of groundwater concentration at the PoCal. Additionally, the residual volume based on the upper bound estimate was also updated to be consistent with the change in inventory. A summary of the nitrate inventory used in the base case and this bounding case is provided in Table 9-6. All other parameters were kept the same as in the system model base case.

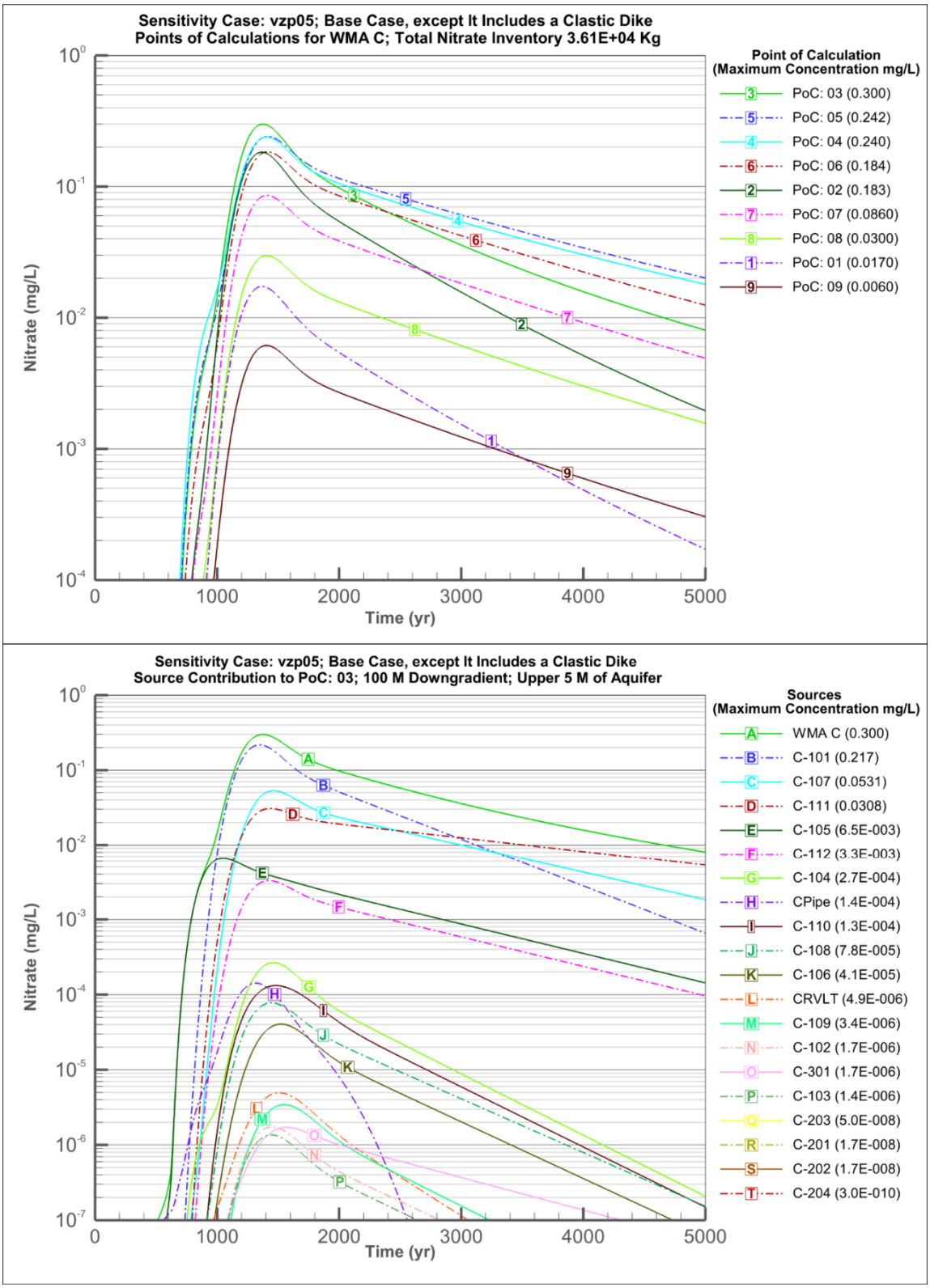
The upper bound residual inventory for nitrate for all sources within WMA C was estimated at about 66,000 kg. In comparison, the estimated total nitrate inventory for the base case was about 36,100 kg. Figure 9-14(a) presents the results of the sensitivity case compared to the system-model base case. The peak groundwater concentration increased by approximately 19% (Table 9-7), while the approximate increase in total inventory was about 83%. This results primarily from the spatial distribution of tanks where the inventory increase occurred. Since the largest increase in inventory occurs in tanks C-102 (from 0.09 kg to 22,000 kg) and C-105 (from 783 kg to 8,140 kg), the PoCals of the highest concentrations change spatially compared to the base case, resulting in only 19% overall increase. Note that the base case inventory for these tanks at closure was estimated as the tanks had not been retrieved.

**Figure 9-11. Alternative Geologic Model Evaluation Results of the Nitrate Concentration in Groundwater for the Alternative Geologic Model (vzp04) Geologic Conceptualization.**



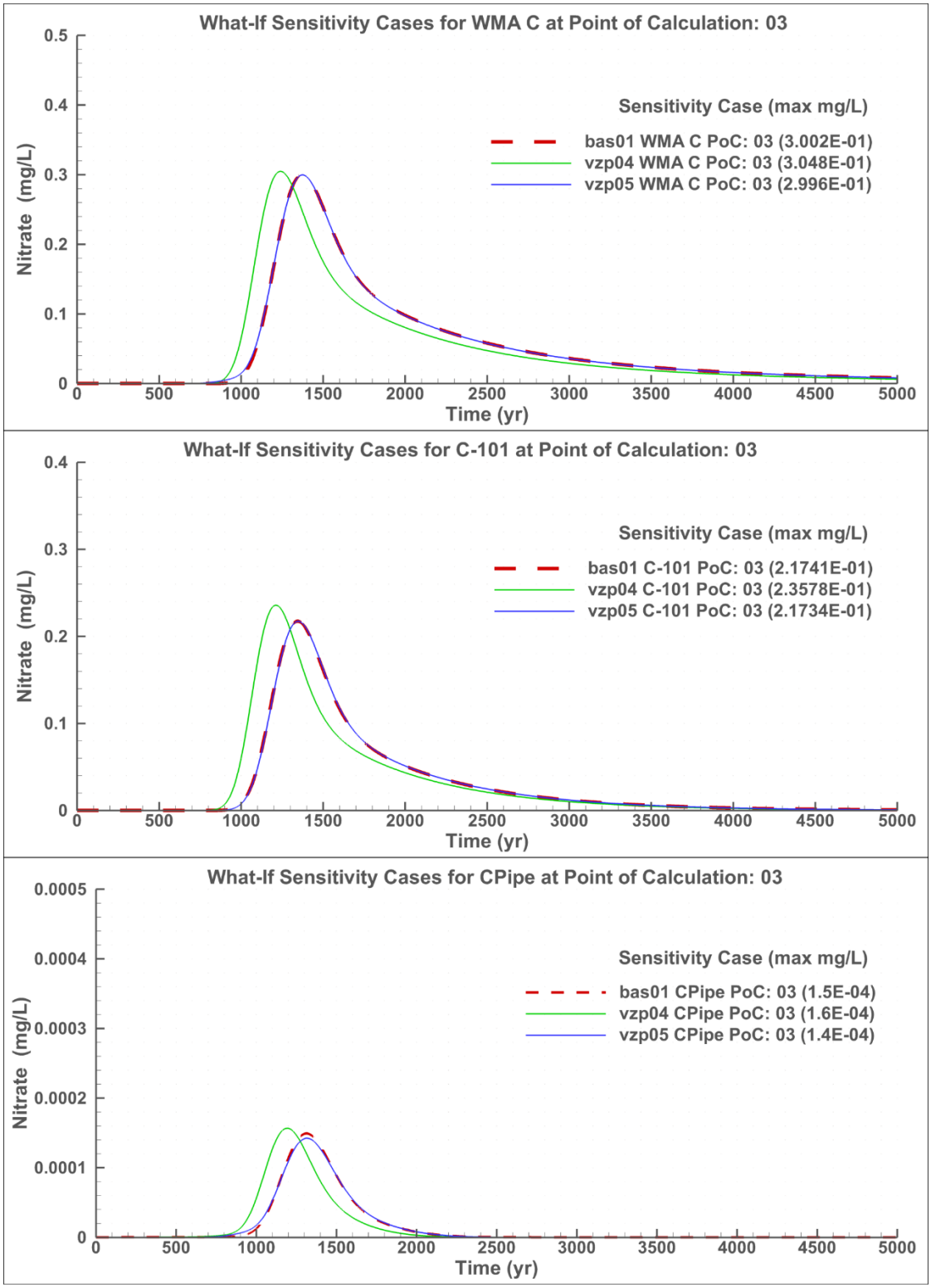

PoC = Point of Calculation WMA = Waste Management Area

**Figure 9-12. Alternative Geologic Model Evaluation Results of the Nitrate Concentration in Groundwater for the Hypothesized Clastic Dike (vzp05) Geologic Conceptualization.**




PoC = Point of Calculation WMA = Waste Management Area

**Figure 9-13. Comparison of the Results of the Nitrate Concentration in Groundwater for the Alternative Geologic Model (vzp04) and the Hypothesized Clastic Dike (vzp05) Geologic Conceptualizations.**




Cpipe = WMA C Pipeline WMA = Waste Management Area

**Table 9-6. Summary of Nitrate Inventory Used in Base Case and Bounding Inventory Sensitivity Case, inv1.**

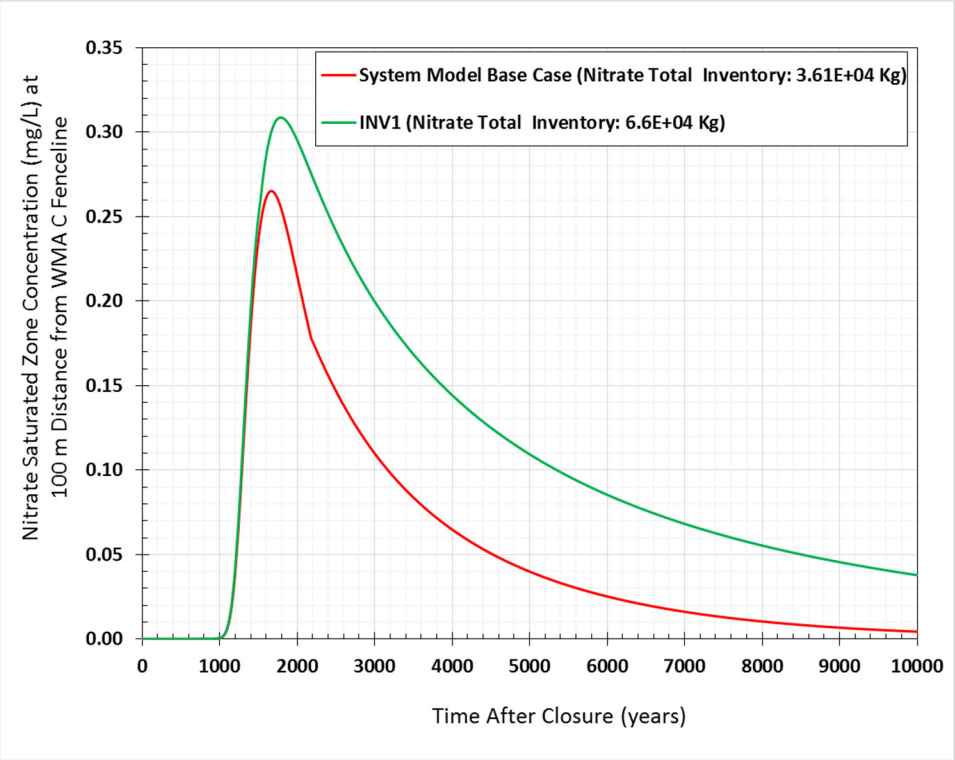
| | Nitrate Inventory (in kg) | | | |
|---|---|---|---|---|
| | **Base Case** | **Inventory Table Taken From** | **Sensitivity Case, inv1** | **Inventory Table Taken From** |
| **241-C-103** | 8.71E-01 | Table 3-13[a] | 1.10E+00 | Table 3-16[a] |
| **241-C-104** | 9.38E+00 | Table 3-13[a] | 1.30E+01 | Table 3-16[a] |
| **241-C-106** | 3.48E+01 | Table 3-13[a] | —[b] | Table 3-16[a] |
| **241-C-108** | 9.16E+00 | Table 3-13[a] | 1.15E+01 | Table 3-16[a] |
| **241-C-109** | 4.52E+00 | Table 3-13[a] | 5.79E+00 | Table 3-16[a] |
| **241-C-110** | 6.73E+00 | Table 3-13[a] | 1.33E+01 | Table 3-16[a] |
| **241-C-201** | 1.35E+00 | Table 3-13[a] | 2.11E+00 | Table 3-16[a] |
| **241-C-202** | 1.25E+00 | Table 3-13[a] | 1.73E+00 | Table 3-16[a] |
| **241-C-203** | 3.76E+00 | Table 3-13[a] | —[b] | Table 3-16[a] |
| **241-C-204** | 2.22E-02 | Table 3-13[a] | 2.23E-02 | Table 3-16[a] |
| **241-C-101** | 8.20E+03 | Table 3-13[a] | 8.20E+03 | Table 3-13[a] |
| **241-C-107** | 3.59E+03 | Table 3-13[a] | 3.59E+03 | Table 3-13[a] |
| **241-C-112** | 8.76E+03 | Table 3-13[a] | 8.76E+03 | Table 3-13[a] |
| **241-C-102** | 9.54E-02 | Table 3-14[a] | 2.22E+04 | Table 3-17[a] |
| **241-C-105** | 7.81E+02 | Table 3-14[a] | 8.14E+03 | Table 3-17[a] |
| **241-C-111** | 1.47E+04 | Table 3-14[a] | 1.47E+04 | Table 3-17[a] |
| **Catch Tank 241-C-301[c]** | 7.50E+00 | Table 3-15[a] | 7.50E+00 | Table 3-15[a] |
| **244-CR Process Tank Vault[c]** | 7.69E+00 | Table 3-15[a] | 7.69E+00 | Table 3-15[a] |
| **Pits[d]** | 2.27E-01 | Table 3-15[a] | 2.27E-01 | Table 3-15[a] |
| **Diversion Boxes[d]** | 4.40E-01 | Table 3-15[a] | 4.40E-01 | Table 3-15[a] |
| **Pipelines[d]** | 1.14E+01 | Table 3-15[a] | 1.14E+01 | Table 3-15[a] |

Source: RPP-RPT-42323, "Hanford C-Farm Tank and Ancillary Equipment Residual Waste Inventory Estimates."

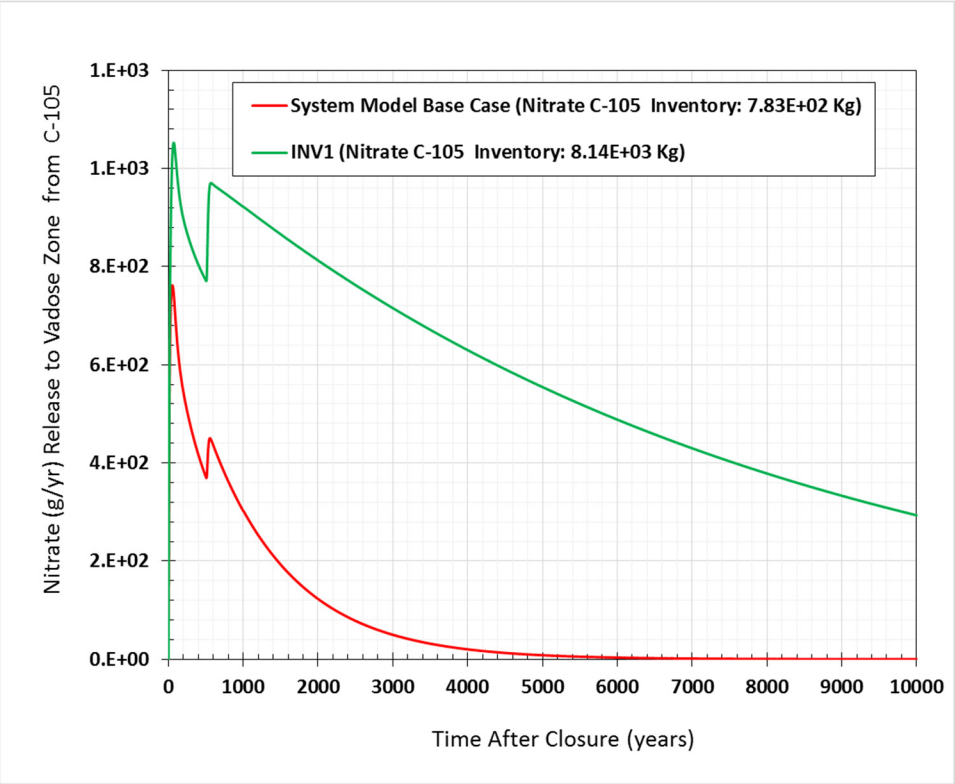
[a] September 1, 2014 Best-Basis Inventory (BBI), includes tank 241-C-106 for which retrieval completion is under review.
[b] Concentration less than analytical detection limit.
[c] Assumes 90% retrieval for C-301 catch tank and 244-CR Process Tank Vault. Note: Current volumes and inventories for these tanks are 10 times the values shown in this table.
[d] Estimated waste volumes and inventories at closure for pits, diversion boxes and pipelines.

**Figure 9-14. Comparison of Base Case and INV1 Case (a) Nitrate Concentration at 100-meter Boundary (b) Nitrate Release to Vadose Zone from Tank 241-C-105.**

(a)




(b)




WMA = Waste Management Area

**Table 9-7. Inventory Estimate Sensitivity Evaluation.**

| Inventory | Sensitivity Case Shorthand | Time of Arrival of Maximum Concentration at Downgradient Point of Calculation (Years after Closure) | Maximum Concentration at Downgradient Point of Calculation (mg/L) |
|---|---|---|---|
| Upper bound Inventory for Nitrate | inv1 | 1,790 | 0.31 |
| System model base case | bas01 | 1,670 | 0.26 |

Figure 9-14(b) presents the source term release rate of nitrate from tank C-105 (a representative tank) to the vadose zone immediately below the tank. This release rate is higher for the higher residual inventory case and indicates that source term release provides the predominant control on the observed differences in groundwater concentrations at the PoCal. For the upper bounding inventory, the peak concentration is slightly delayed compared to the base case, due to the longer time it takes for the source to be depleted.

## 9.5 GROUT FLOW SENSITIVITY ANALYSES

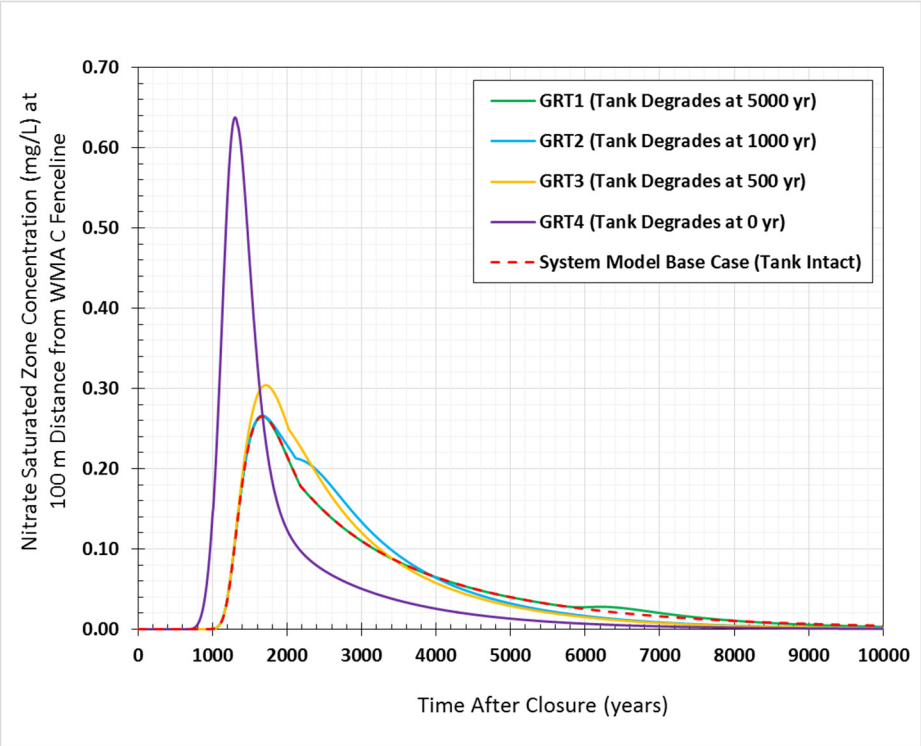
In the base case, the grouted tanks were assessed to remain intact throughout the 10,000-year simulation time. To assess the impact of early failure of the tank due to unforeseen events, sensitivity cases are performed where the infill grout in the tank is assumed to provide no barrier to flow through the tank. For this purpose, the grout properties are replaced by H2 sand properties, and flow through the tank is initiated at the following three degradation times:

1. Tank Degrades at 5,000 years after closure (grt1)
2. Tank Degrades at 1,000 years after closure (grt2)
3. Tank Degrades at 500 years after closure (grt3)
4. Tank Degrades at 0 years after closure (grt4).

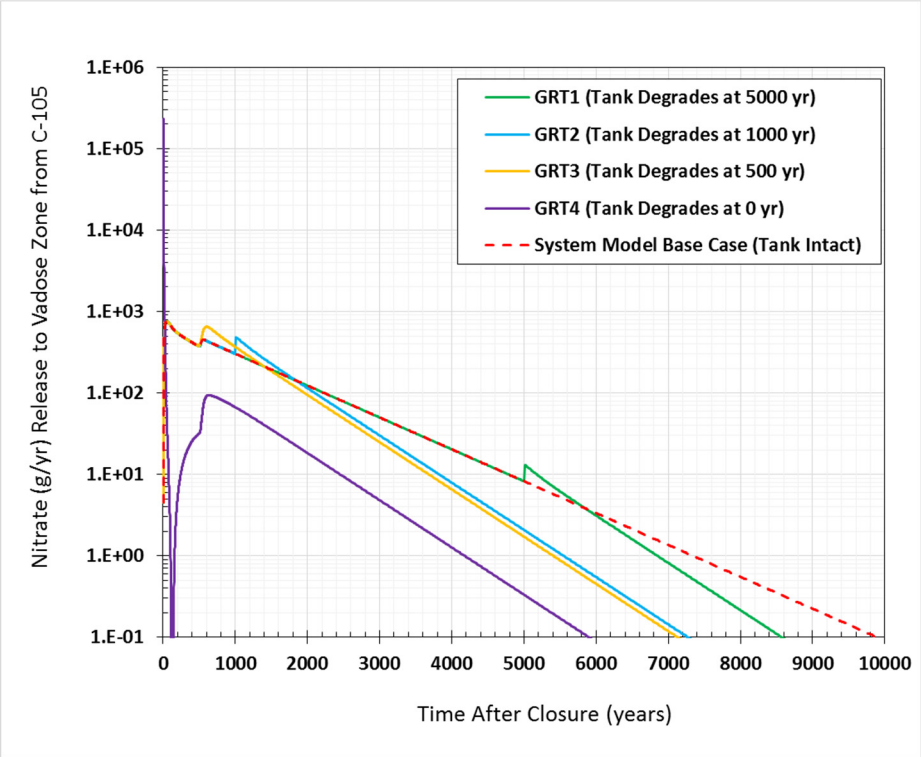
Figure 9-15(a) presents the nitrate concentration in the saturated zone at the PoCal (cumulative for all the sources). The magnitude in peak concentration (and peak release rate) in the saturated zone reduces with the delayed tank degradation time, due to inventory depletion from diffusive release prior to the start of advection (Table 9-8). For the case where the tank grout is degraded at closure (0 years), the peak concentration in the saturated zone is about a factor of two higher than the case where the tank grout is degraded at 500 years after closure but the magnitude remains small for both cases. The peak concentration for the case where the tank is degraded at closure occurs around 1,300 years, indicating delayed transport through the vadose zone.

**Figure 9-15. Comparison of Base Case and GRT1, GRT2, GRT3, GRT4 Case (a) Nitrate Concentration at 100-meter Boundary (b) Nitrate Release to Vadose Zone from Tank 241-C-105.**

(a)




(b)




WMA = Waste Management Area

**Table 9-8. Grout Flow Safety Function Sensitivity Evaluation.**

| Tank Degradation Time | Sensitivity Case Shorthand | Time of Arrival of Maximum Concentration at Downgradient Point of Calculation (Years after Closure) | Maximum Concentration at Downgradient Point of Calculation (mg/L) |
|---|---|---|---|
| Tank Degrades at 5,000 yr | grt1 | 1,670 | 0.26 |
| Tank Degrades at 1,000 yr | grt2 | 1,670 | 0.27 |
| Tank Degrades at 500 yr | grt3 | 1,710 | 0.30 |
| Tank Degrades at 0 yr | grt4 | 1,300 | 0.64 |
| System model base case | bas01 | 1,670 | 0.26 |

Figure 9-15(b) presents the nitrate release from tank C-105 to the vadose zone immediately below the tank for the three cases in comparison to the base case. Release rate from tank C-105 is presented as a representative example of the source-term release from a tank. Although the release characteristics will be similar for other tanks, the magnitude of the release rates will be different due to varying initial concentrations. Where the tank grout is degraded at closure (0 years) the nitrate release rate from the tank at early times is much higher, primarily due to advection, and drops sharply as the mass is depleted. This is in contrast to the release rate from the tanks that are assumed to degrade later, where the release occurs by diffusion (same as base case) until the tank degrades, and by both advection and diffusion after the tank degradation. Until the degradation time, the tank release curves track the base case results. For the case where the release occurs at closure (0 years) the mass is depleted from the source initially and then, due to relatively slower transport in the vadose zone, there is backward diffusion of mass resulting from reversal of concentration gradients that is then swept away by advection.

## 9.6 TANK FLOW SENSITIVITY ANALYSES

Diffusive release through the base of the tank (made up of grout and concrete layer) is the primary release mechanism to the natural system. The effective diffusion coefficient through the concrete and grout layer is a key parameter in determining the diffusive flux. For the base case, an effective diffusion coefficient of $3 \times 10^{-8}$ cm$^2$/s was used, and the following three sensitivity cases were analyzed to evaluate the impact of changing the effective diffusion coefficient.

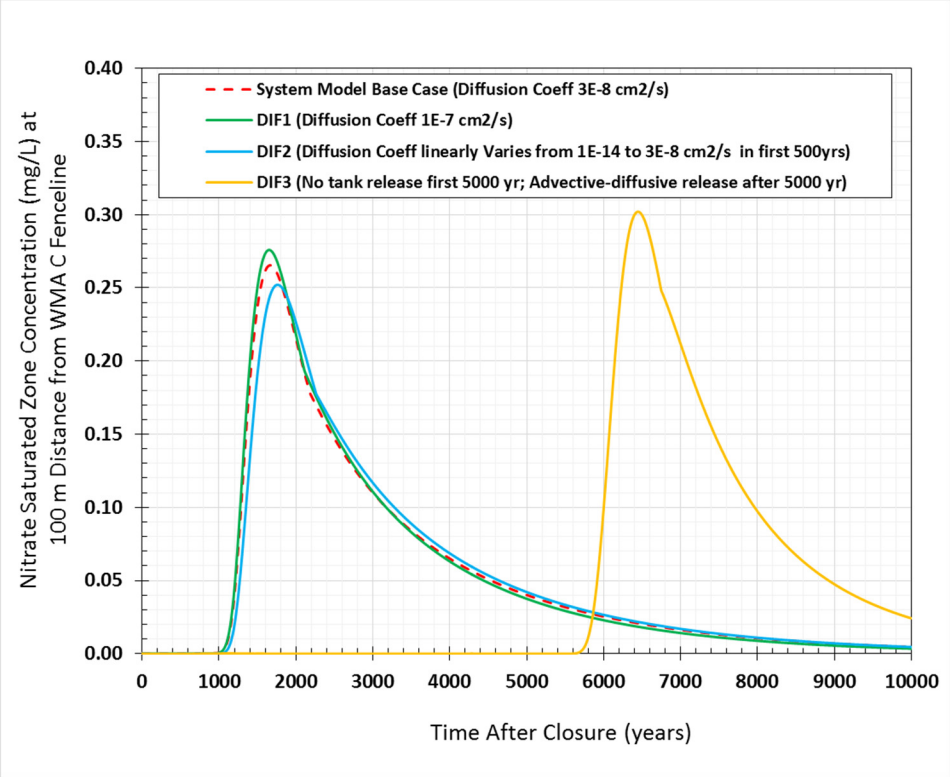
1. Effective diffusion coefficient for the grout is changed to $1 \times 10^{-7}$ cm$^2$/s (dif1).

2. Effective diffusion coefficient for the grout varies linearly from $1 \times 10^{-14}$ to $3 \times 10^{-8}$ cm$^2$/s in the first 500 years after closure, and remains constant afterwards at $3 \times 10^{-8}$ cm$^2$/s (dif2).

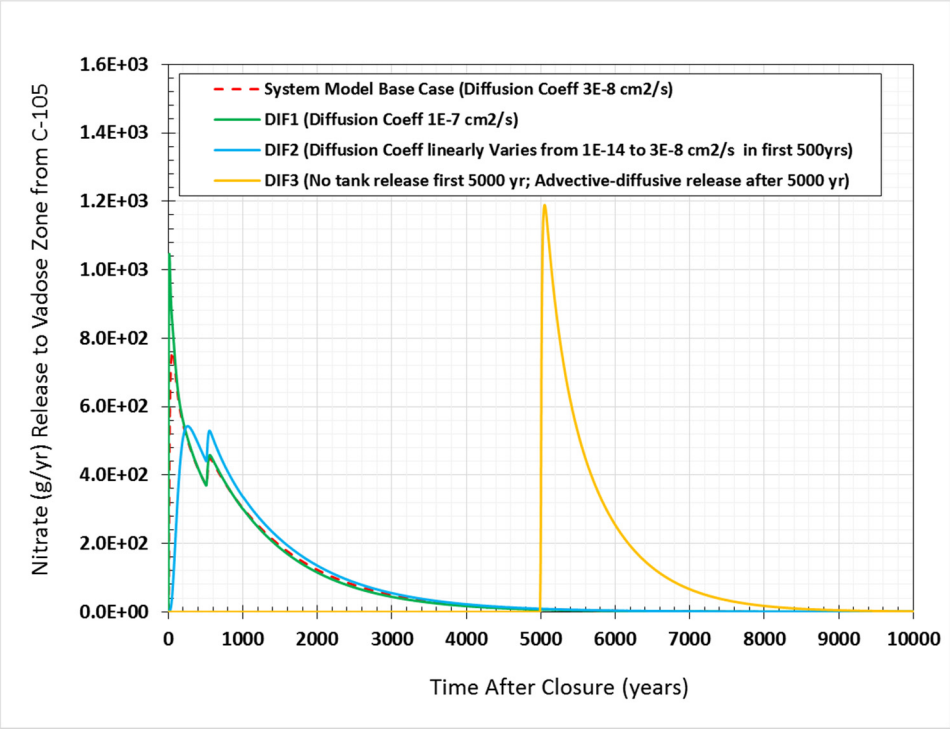
3. Tanks (including 244-CR vault) remain fully intact with no advective or diffusive release until 5,000 years. The tank becomes fully degraded at 5,000 years, resulting in both advective and diffusive releases. The effective diffusion coefficient remains the same as the base case (dif3).

**Figure 9-16. Comparison of Base Case and DIF1, DIF2, DIF3 Case (a) Nitrate Concentration at 100-meter Boundary (b) Nitrate Release to Vadose Zone from Tank 241-C-105.**

(a)




(b)




WMA = Waste Management Area

**Table 9-9. Tank Flow Safety Function Sensitivity Evaluation.**

| Tank Flow | Sensitivity Case Shorthand | Time of Arrival of Maximum Concentration at Downgradient Point of Calculation (Years after Closure) | Maximum Concentration at Downgradient Point of Calculation (mg/L) |
|---|---|---|---|
| Diffusion coefficient 1E-7 $cm^2/s$ | dif1 | 1,650 | 0.27 |
| Linearly changing diffusion coefficient over 500 years from 1E-14 to 3E-8 $cm^2/s$ | dif2 | 1,760 | 0.25 |
| Tanks remain intact (no release) for 5,000 years, followed by advective release beginning immediately | dif3 | 6,450 | 0.30 |
| System model base case | bas01 | 1,670 | 0.26 |

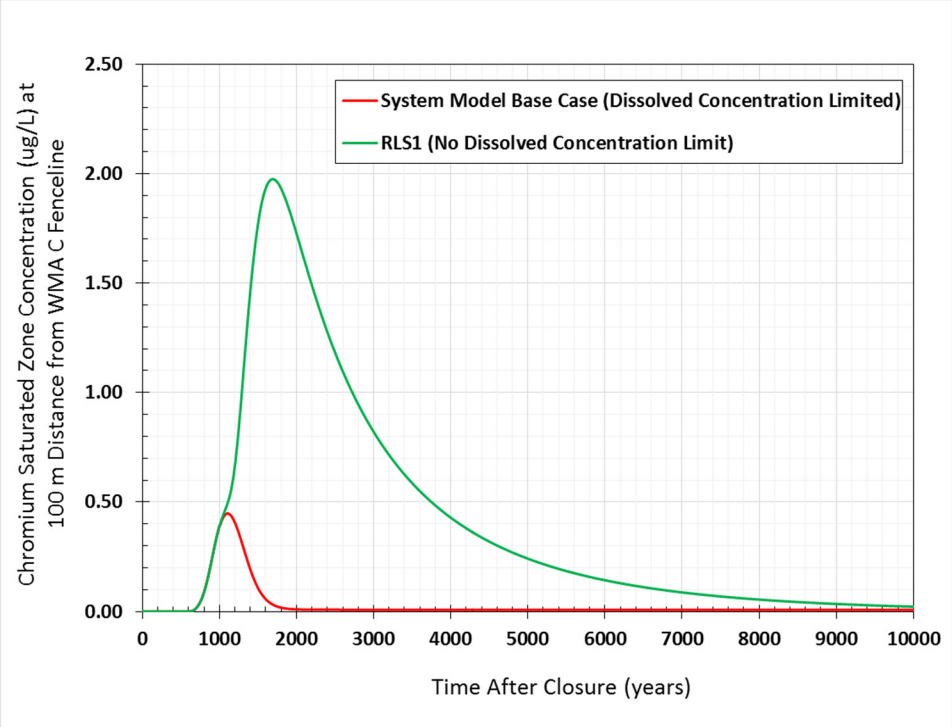
Figure 9-16(a) presents the nitrate concentration in the saturated zone at the PoCal, and Figure 9-16(b) presents the nitrate release from tank C-105 to the vadose zone immediately below the tank for the three cases in comparison to the base case. For the dif1 case, the higher diffusion coefficient results in a higher diffusive release and marginally higher peak concentration (Table 9-9). Following the peak value, the curves follow the same trend as the base case. For the dif2 case, due to lower diffusion coefficient in the first 500 years, the diffusive flux is lower and therefore the peak concentration is slightly lower than the base case (Table 9-9). For the dif3 case, since no release is allowed from the grouted tank sources in the first 5,000 years, the only release prior to this time is from the pipeline source that results in a small groundwater concentration [Figure 9-16(a)]. After 5,000 years, both advective and diffusive releases start, resulting in a higher peak concentration than the base case (Table 9-9).

## 9.7 EVALUATION OF DISSOLVED CONCENTRATION LIMITS FOR TRANSPORT OF CHROMIUM

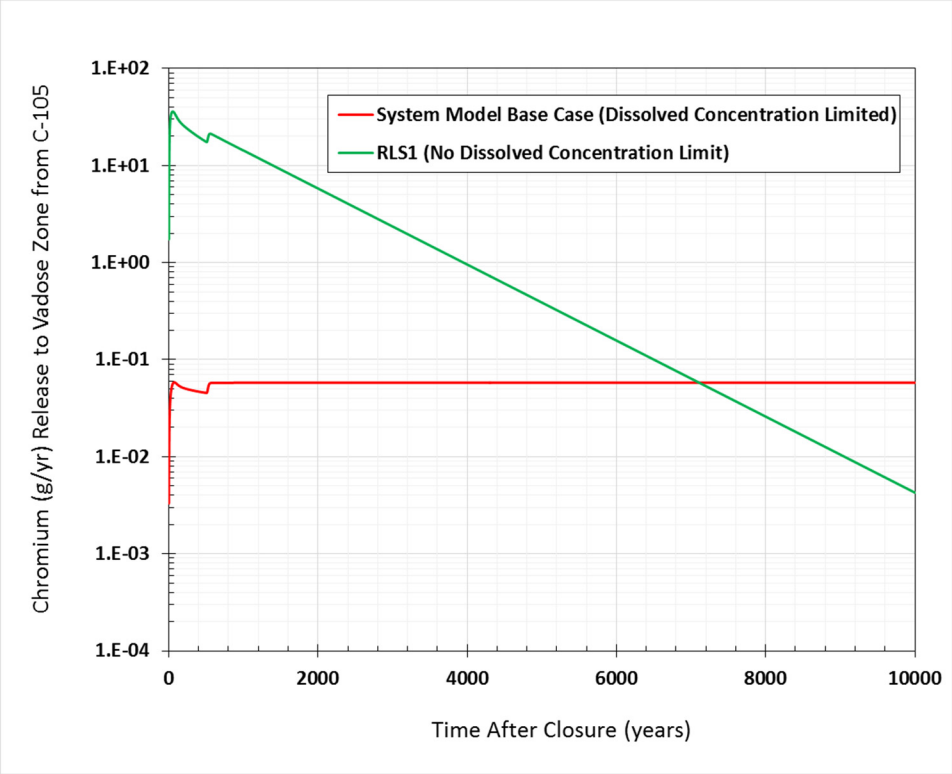
Dissolved concentration limits are applied in determining the source term release for chromium. As described in Section 7.3.1, a dissolved concentration limit of 2,000 µg/L was applied to the source-term release models for chromium. In this sensitivity analysis (rls1), this limit is removed to evaluate the impact on saturated zone concentration at the PoCal.

**Figure 9-17. Comparison of Base Case and RLS1 Case for (a) Chromium Concentration at 100-meter Boundary and (b) Chromium Release to Vadose Zone from Tank 241-C-105.**

(a)




(b)




WMA = Waste Management Area

Figure 9-17(a) shows the comparison of groundwater concentration between the base case and the sensitivity case where the dissolved concentration limit for chromium has been removed. With no dissolved concentration limit, the groundwater concentrations increase (peak concentration increased by factor of four) but the magnitude remains relatively small (< 2 µg/L). Figure 9-17(b) presents the release of chromium to the vadose zone from the bottom of tank C-105. For the base case, the chromium release is steady as it is controlled by the dissolved concentration limit imposed in the source term, but for the sensitivity case, the release rate is significantly higher due to removal of such limits. The steady decline observed for the sensitivity case reflects depletion of mass within the tank. Despite the large increase in source term release for the sensitivity case, the effect on groundwater concentrations are relatively minor. Note that no retardation onto the tank base mat is considered for chromium.

# 10.0 EVALUATION AND INTERPRETATION OF RESULTS AGAINST REGULATORY STANDARDS FOR GROUNDWATER

In this section, the results of the RCA are consolidated and compared against the regulatory standards for groundwater to interpret their meaning and significance. The goals of this section are as follows.

- To compare the results of the RCA against the applicable standards for risk and hazard quotients/indices using the EPA tap water scenario, Federal and State MCLs, and 2007 MTCA Method B groundwater cleanup levels.

- To provide a basis to conclude that the performance of waste residuals in tanks and ancillary equipment left at WMA C at closure has been adequately addressed, and that the results provide a sufficient basis for concluding that the closed facility meets the regulatory standards defined for the EPA tap water scenario; Title 40 CFR, Part 141, "National Primary Drinking Water Regulations" (40 CFR 141); and the WAC 173-340-720 at the PoCal.

- To provide context for the results of the sensitivity analyses and the support they provide to the conclusion that release of hazardous chemical and dangerous waste constituents remaining in the tank and ancillary residuals at a closed WMA C meets the regulatory standards defined for the EPA tap water scenario, 40 CFR 141 and WAC 173-340-720 at the PoCal.

- To provide results and interpretation of potential human health impacts for the three periods of analysis: 1) 0 to 1,000 years post-closure period; 2) 1,000 to 10,000 years post-closure period; and 3) the period beyond 10,000 years post-closure.

The comparison and interpretation of results for the RCA are presented in the following subsections.

- Assessment of impacts to water resources including:
    - An evaluation of risk and hazard impacts from groundwater use using the EPA Tap Water scenario
    - A comparison of peak predicted groundwater concentrations to Federal and State MCLs and 2007 MTCA Method B groundwater cleanup levels.
- Sensitivity analyses for the groundwater pathway. Sensitivity analyses include cases that evaluate the effect of specific safety functions on the behavior of the disposal system.

This section also includes a summary-level discussion of future uses of the RCA results and future anticipated work.

## 10.1 ASSESSMENT OF IMPACTS TO WATER RESOURCES

In this section, the assessment of impacts to water resources is evaluated. Two types of evaluations are used to assess impacts. The first evaluation uses peak predicted groundwater concentrations to calculate cancer risks and non-cancer hazards based on the EPA tap water (residential) scenario. Results of the modeling analysis at the PoCal 100 m downgradient of the WMA C fenceline are compared against the regulatory standards for cumulative cancer risks of less than the $10^{-4}$ risk range for radionuclides and less than the $10^{-5}$ risk range for hazardous chemicals, and non-cancer hazards are less than an HI of 1.

The second evaluation compares peak predicted hazardous chemical and dangerous waste constituent concentrations in groundwater to available Federal and State drinking water standards including:

- 40 CFR 141, "National Primary Drinking Water Regulations" (i.e., maximum contaminant levels)

- 2007 MTCA (WAC 173-340-720, "Groundwater Cleanup Standards").

The State of Washington has adopted the 40 CFR 141 national primary drinking water regulations (revised as of July 1, 2009) for hazardous substances as defined in WAC 246-290, "Group A Public Water Supplies" [WAC 246-290-025, "Adoption by Reference" and WAC 246-290-310, "Maximum Contaminant Levels (MCLs) and Maximum Residual Disinfectant Levels (MRDLs)"]. The 2007 MTCA Method B groundwater cleanup levels are based on a target risk level of $1 \times 10^{-6}$ for carcinogens and an HQ of 1 for noncarcinogens.

Groundwater concentrations from the base case are evaluated to assess the impacts to water resources. The base case is a single deterministic evaluation of future dose to the public as a result of the anticipated retrieval and closure actions taken on tanks and ancillary facilities and equipment at WMA C. The base case results do not necessarily, or intend to, represent a best estimate or central tendency value. The base case represents the conditions in which the safety functions behave as expected as the facility evolves into the future. The selection of base case assumptions and parameters consider the best available information, while adopting some conservative bias to account for uncertainty, with the intent to provide reasonable assurance that future impacts to the public do not exceed the regulatory standards for an EPA tap water scenario, 40 CFR 141, and WAC 173-340-720 at the PoCal. The base case in the RCA provides a means to demonstrate that these regulatory standards are satisfied at the PoCal. The evaluation of base case results provides a means to:

1) Compare facility performance quantitatively to the above-listed regulatory standards

2) Demonstrate that there is a reasonable expectation that the facility will meet these established regulatory standards.

Sensitivity analysis is carried along with the base case to provide additional evidence that the facility has a reasonable expectation of meeting the regulatory standards. Sensitivity analysis

provides a quantitative basis for identifying those parameters and processes most important to system performance, particularly with respect to remaining below the regulatory standards. The sensitivity analysis is also used to evaluate uncertainties in the evolution of safety functions as the disposal system evolves in the future.

The composite results of the base case along with sensitivity analyses provide the overall body of evidence that supports the conclusion that the facility has a reasonable expectation of meeting the regulatory standards.

### 10.1.1 Summary of Cancer Risk and Non-Cancer Hazard Impacts using EPA Tap Water (Residential) Scenario

The EPA tap water (residential) scenario is associated with the groundwater protection pathway, with the groundwater concentrations calculated according to the methodology presented in Section 7. This methodology implements the groundwater protection requirements, which require a comparison of the peak concentration in the groundwater at all points along the plane of PoCals 100 m downgradient of the facility. Groundwater concentrations do not take account of any dilution that may occur in the well as it is pumped.

The equations and inputs used to calculate cancer risk and non-cancer hazards were also presented in Section 7. For the analysis of cancer risk and non-cancer hazards, peak groundwater concentrations are used as the concentrations at the wellhead, to which the resident receptor has the potential for exposure. The exposure inputs used for the tap water scenario are estimates of reasonable maximum exposure. This approach has been taken to maintain consistency between the groundwater protection regulatory standards and the all-pathways dose performance objective presented in the WMA C PA (RPP-ENV-58782, Table 2-1).

**10.1.1.1 Summary of Cancer Risks.** Cancer risks, resulting from the EPA tap water scenario, are summarized in Table 10-1 for the 100-m distance for each PoCal. The peak cumulative cancer risk in space is found at PoCal 4. Note that PoCal 4 is used as the compliance point for the WMA C PA (RPP-ENV-58782) all-pathways analysis. The primary carcinogens giving rise to the cancer risk are radiological carcinogens.

Peak cumulative cancer risk from hazardous carcinogens are not discussed because carcinogenic chemicals do not arrive at any PoCal during the 0- to 10,000-year period of analysis.

The maximum radiological cancer risk results and their time of occurrence are provided in Table 10-1 for all radionuclides that produced a nonzero cancer risk result within 10,000 years. The peak radiological cancer risk summed over all radionuclides is $1.58 \times 10^{-6}$, which occurs around 1,500 years. This risk estimate is within the acceptable risk range of $1 \times 10^{-4}$ to $1 \times 10^{-6}$. The highest radiological cancer risk within the 1,000-year time period is $6.20 \times 10^{-9}$, which occurs at 1,000 years after closure. This risk estimate is less than the lower end of the acceptable risk range of $1 \times 10^{-4}$ to $1 \times 10^{-6}$. The key contributing radionuclide at all times is $^{99}$Tc. Minor contributors to the total radiological cancer risk at times beyond the 1,000-year post-closure period are $^{79}$Se, $^{129}$I, $^{126}$Sn, and uranium isotopes.

**Table 10-1. Summary of Peak Total Radiological Cancer Risk and the Time of Occurrence for All Radionuclides Giving Nonzero Risk in the Base Case Analysis.**

| Radionuclide | Peak Total Risk at 1,000 years after Closure | Peak Total Risk Between 1,000 and 10,000 years after Closure | Time of Peak (years) |
|---|---|---|---|
| I-129 | 0 | 1.2E-8 | 6,430 to 6,650 |
| Se-79 | 0 | 1.5E-9 | 3,690 to 3,820 |
| Sn-126 | 0 | 2.3E-8 | 10,000 |
| Tc-99 | 6.2E-9 | 1.6E-6 | 1,530 to 1,570 |
| U-233 | 0 | 1.0E-8 | 10,000 |
| U-234 | 0 | 2.0E-8 | 10,000 |
| U-235 | 0 | 8.4E-10 | 10,000 |
| U-236 | 0 | 1.7E-10 | 10,000 |
| U-238 | 0 | 2.4E-8 | 10,000 |
| Radionuclide Target Risk Range = 1E-6 to 1E-4 | | | |

**10.1.1.2 Summary of Non-Cancer Hazards.** A summary of the peak chemical non-cancer HQs and time of peak occurrence is presented in Table 10-2. The peak cumulative non-cancer HI in space is found at PoCal 4. These non-cancer HQs results are presented in Table 10-2 for all chemicals that produced a nonzero HQ result within 10,000 years. The peak chemical non-cancer HI summed over all chemicals is 0.069, which occurs at 1,440 years after closure. This HI is less than the target HI of 1. The highest chemical non-cancer HI within the 1,000-year period is 0.061, which occurs at 1,000 years after closure. This HI is also less than the target HI of 1. The key contributing chemicals at all times are fluoride (27% contribution), nitrite (54% contribution), nitrate (11% contribution), and cyanide (8% contribution). .

### 10.1.2 Comparison of Peak Groundwater Concentrations to Maximum Contaminant Levels and 2007 Model Toxics Control Act Method B Cleanup Levels

Peak groundwater concentrations for all PoCals along the 100-m distance were compared to available Federal and State MCLs and to the 2007 MTCA Method B groundwater cleanup levels.

Similar to the EPA tap water (residential) scenario evaluation, the groundwater concentrations are calculated according to the methodology presented in Section 6. Groundwater cleanup levels were calculated using the equations and inputs described in the 2007 MTCA (WAC 173-340-720). Peak groundwater concentrations were not within the 1,000-year period; therefore, the entire 10,000-year modeling time frame was used for comparison purposes.

For each COPC and PoCal, the Federal MCL, the 2007 MTCA Method B groundwater cleanup level, peak groundwater concentration (within 10,000-year modeling time frame), and corresponding peak year is provided in Table 10-3. The results of the comparison indicate that—although chromium (total), cobalt, cyanide, fluoride, nitrate, nitrite, selenium, and tin reach

groundwater within the 10,000-year time frame—all concentrations are less than the MCL (if available) and the 2007 MTCA Method B groundwater cleanup level. Boron, iron, manganese, mercury, nickel, lead, strontium, and TBP do not reach groundwater within the 10,000-year time frame.

**Table 10-2. Summary of Peak Chemical Hazard Quotients and Time of Occurrence for All Chemicals Giving Nonzero Hazard in the Base Case Analysis.**

| Chemical | Peak Non-Cancer Hazard Quotient at 1,000 years after Closure | Peak Hazard Quotient Between 1,000 and 10,000 years after Closure | Time of Peak (years) |
|---|---|---|---|
| Total Chromium | 0.0000012 | 0.00002 | 1,320 to 1,340 |
| Chromium VI | | 0.01 | 1,320 to 1,340 |
| Fluoride | 0.00024 | 0.018 | 1,440 |
| Nitrite | 0.00044 | 0.037 | 1,440 |
| Nitrate | 0.00015 | 0.0076 | 1,410 |
| Cobalt | 0.000000025 | 0.0000044 | 1,530 to 1,550 |
| Cyanide | 0.000044 | 0.0056 | 1,470 to 1,480 |
| Selenium | 0 | 0.0000096 | 4,630 to 4,780 |
| Selenium | 0 | 6.6E-11 | 10,000 |
| Total Uranium | 0 | 0.001 | 10,000 |
| Target Hazard Quotient = 1 | | | |
| | **Peak Non-Cancer Hazard Index at 1,000 years after Closure** | **Peak Hazard Index Between 1,000 and 10,000 years after Closure** | **Time of Peak (years)** |
| Non-Cancer Hazard Index | 0.061 | 0.069 | 1,440 |
| Target Hazard Index = 1 | | | |

## 10.2 SUMMARY OF SENSITIVITY ANALYSES FOR THE GROUNDWATER PATHWAY

In this section, a summary of the sensitivity analyses presented in Section 8 is provided. Sensitivity analyses are generally intended to evaluate changes in the underlying assumptions upon which the base case model is based, and to demonstrate the effect the alternative assumptions have on the groundwater concentrations at the PoCals used in the RCA.

Sensitivity cases were conducted using the 3-D STOMP© model or the GoldSim©-based system model. For purposes of illustrating the effect of changes in model parameters and assumptions used in the sensitivity cases, results of the sensitivity cases were compared to base results, largely using results for nitrate as a basis for evaluating the effects of changes. In one sensitivity

case examining the effects of rate-limiting releases from the waste residual, results for chromium were used in the comparison.

**Table 10-3. Summary of Maximum Contaminant Levels, 2007 Model Toxics Control Act Method B Groundwater Cleanup Levels, Peak Chemical Concentrations, and Time of Occurrence for All Chemicals in the Base Case Analysis.**

| Constituent of Potential Concern | Federal and State[a] MCL (µg/L) | 2007 MTCA Method B Groundwater Cleanup Levels[b,c] (µg/L) | Peak Concentration Between 0 and 10,000 Years after Closure (µg/L) | Peak Year |
|---|---|---|---|---|
| Boron | — | 3,200 | 0.00E+00 | — |
| Chromium Total | 100 | 24,000 | 4.9E-01 | 1,330 |
| Chromium VI | — | 48 | 4.9E-01 | 1,330 |
| Cobalt | — | 4.8 | 4.70E-05 | 1,530 – 1,540 |
| Cyanide | 200 | 4.8 | 1.40E-02 | 1,500 |
| Fluoride | 4,000 | 960 | 2.30E+01 | 1,430 |
| Iron | — | 11,200 | 0.00E+00 | — |
| Manganese | — | 384 | 0.00E+00 | — |
| Mercury | 2 | 4.8 | 0.00E+00 | — |
| Nickel | — | 320 | 0.00E+00 | — |
| Nitrate | 45,000 | 113,600 | 2.44E+02 | 1,420 |
| Nitrite | 4,500 | 4,800 | 7.50E+01 | 1,440 |
| Lead | — | 15 | 0.00E+00 | — |
| Selenium | 50 | 80 | 1.80E-03 | 4,680 – 4,750 |
| Strontium | — | 9,600 | 0.00E+00 | — |
| Tin | — | 9,600 | 1.3E-6 | 10,000 |
| Total Uranium | 30[d] | 48 | 0.049 | 10,000 |
| Tributyl phosphate | — | 9.72 | 0.00E+00 | — |

[a] Washington Administrative Code (WAC) 246-290-310, "Maximum Contaminant Levels (MCLs) and Maximum Residual Disinfectant Levels (MRDLs)."

[b] ECF-100NPL-10-0462, Rev. 2, "Calculation of Standard Method B Groundwater Cleanup Levels for Potable Groundwater for the 100 Areas and 300 Area Remedial Investigation/ Feasibility Study Reports."

[c] The value for lead was obtained for 2007 Model Toxics Control Act (MTCA) WAC 173-340-900, "Tables" Table 720-1 Method A Cleanup Levels for Groundwater.

[d] 40 CFR 141, "National Primary Drinking Water Regulations."

WAC = Washington Administrative Code

The 3-D STOMP© model cases were grouped into three categories: (1) changes in aquifer properties, (2) changes in recharge, and (3) changes in vadose zone geology and hydrologic parameters. Results of these three sensitivity cases were compared to comparable results from the base case. The sensitivity cases conducted using the GoldSim© model were grouped into four categories: (1) changes in the inventory estimate, (2) changes in tank degradation time, (3) changes in grout diffusion parameters, and (4) changes in rate-limited transport for a key COPC (specifically chromium). Results for these four sensitivity cases were compared to comparable results derived from the system-level model evaluation of the base case.

Comparative results for each sensitivity case focus on changes in nitrate or chromium concentrations relative to the base case (from 3-D STOMP© or the GoldSim©-based system model). A summary description of the sensitivity cases, the peak concentrations for each of the sensitivity cases, and the year of the peak groundwater concentration is presented in Table 10-4. Peak nitrate concentrations for all of the sensitivity cases compared to the 3-D STOMP©-base case ranged between 1.9 times less and 2.6 times greater than the base case. Peak nitrate concentrations for all of the sensitivity cases compared to the system model base case ranged between 1.1 times less than the base case and 1.5 times greater than the base case. All nitrate as nitrogen concentrations are below the MCL value of 10,000 mg/L.

## 10.3 USE OF RCRA CLOSURE ANALYSIS RESULTS

Results of the RCA have substantiated that landfill closure of residual wastes in WMA C can meet applicable regulatory standards (i.e., target risk, hazard quotients/indices and groundwater MCLs) related to impacts from hazardous chemical and dangerous waste constituents. The results of this RCA of residual waste left in tanks and ancillary equipment can be used to support decisions regarding further retrieval from the remaining tanks undergoing retrieval and in supporting determinations that sufficient retrieval has been accomplished prior to proceeding with landfill closure of WMA C.

The key results from the RCA that support these decisions are the base case and the range of sensitivity analysis cases, including the sensitivity analysis case in which no further retrieval was assumed for three of the tanks undergoing retrieval at the time of this analysis (see sensitivity case INV01 summarized in Table 10-4). This analysis case showed that the landfill-closed WMA C disposal system could meet regulatory standards related to groundwater impacts from hazardous chemical and dangerous waste constituents without further retrieval.

In addition to considerations that are embedded in the retrieval process, it is anticipated that the RCA will be used to support optimization activities related to development of the final detailed design of the facility. This can be done using the results of the RCA to establish functional requirements for the design features, such as a functional requirement for infiltration through the surface cover barrier.

The RCA will provide the technical basis for subsequent decision documents (i.e., RCRA Closure Plans and Permit Modifications) in order for these documents to assure compliance with WAC 173-303-610, WAC 173-303-640 (8), and WAC 173-303-665 (6).

**Table 10-4. Summary of Sensitivity Analysis Cases. (3 sheets)**

| Analysis Case | Description | Peak Concentration | Peak Year |
|---|---|---|---|
| STOMP© 3-D Base Case – bas01 | | 0.30 mg/L | 1,375 |
| **Aquifer flow property** | **Change in nitrate concentrations caused by groundwater flux in the aquifer: two sensitivity cases for the hydraulic conductivity value.** | | |
| Sensitivity – gwp01 | 5th percentile hydraulic conductivity value – 4,200 m/day. | 0.78 mg/L – 2.6 times greater than base case. | 1,375 – same as base case. |
| Sensitivity – gwp03 | 95th percentile hydraulic conductivity value – 17,800 m/day. | 0.19 mg/L – 1.9 times less than base case. | 1,375 – same as base case. |
| **Recharge sensitivity and surface barrier flow** | **Change in nitrate concentrations resulting from surface barrier flow: five sensitivity cases associated with net infiltration (recharge) after the design life of the surface barrier.** | | |
| Sensitivity – inf01 | All recharge rates same as base case except post-design life surface barrier (1 mm/year) is less than base case. | 0.16 mg/L – 1.9 times less than base case. | 1,367 – 8 years earlier than base case. |
| Sensitivity – inf02 | Recharge rates the same as base case except for pre-WMA C/undisturbed ground (5.2 mm/year) and post-design life surface barrier (5.2 mm/year) are greater than base case. | 0.39 mg/L – 1.3 times greater than base case. | 1,145 – 230 years earlier than base case. |
| Sensitivity – inf03 | Recharge rates the same as base case except WMA C ground during operations (140 mm/year) and post-design life time periods (100 mm/year 100 years after closure) represent bare soil and are greater than base case. | 0.79 mg/L – 2.6 times greater than base case. | 175 – 1,200 years earlier than base case. |
| Sensitivity – unc01 | Recharge rates the same as base case except recharge in the areas not occupied by WMA C is 0.5 mm/year. | 0.31 mg/L – approximately equal to base case. | 1,510 – 135 years after base case. |
| Sensitivity – unc02 | Recharge rates the same as base case except recharge in the areas not occupied by WMA C is 100 mm/year. | 0.25 mg/L – 1.2 times less than base case. | 900 – 475 years earlier than base case. |
| **Vadose zone hydraulic property** | **Change in nitrate concentrations resulting from flow and dispersion in the vadose zone: five sensitivity cases associated with variations in van Genuchten α and n (coupled), saturated moisture content ($\theta_s$), residual moisture content ($\theta_r$), fitted saturated hydraulic conductivity ($K_s$), Alternative Geological Model II, and the presence of a clastic dike.** | | |
| Sensitivity — vzp01 | 5th percentile parameter values | 0.18 mg/L – 1.7 times less than base case. | 2,230 – 855 years after base case. |
| Sensitivity — vzp02 | Median percentile parameter values | 0.27 mg/L – 1.1 times less than base case. | 1,215 – 160 years earlier than base case. |
| Sensitivity – vzp03 | 95th percentile parameter values | 0.41 mg/L – 1.4 times greater than base case. | 1,095 – 280 years earlier than base case. |

**Table 10-4. Summary of Sensitivity Analysis Cases. (3 sheets)**

| Analysis Case | Description | Peak Concentration | Peak Year |
|---|---|---|---|
| Sensitivity – vzp04 | Alternative Geological Model II. | 0.30 mg/L – equal to base case. | 1,240 – 135 years earlier than base case. |
| Sensitivity – vzp05 | Presence of clastic dike. | 0.30 mg/L – same as base case. | 1,375 – same as base case. |
| **Upper bound inventory estimate** | **Change in nitrate concentrations from replacing base case nitrate inventory with the upper bound inventory: one sensitivity case.** | | |
| Sensitivity – inv2 | Nitrate inventory increased from 36,100 kg to 66,000 kg. | 0.31 mg/L – 1.5 times greater than system model base case. | 1,790 – 120 years after system model base case. |
| System Model Base Case – bas01 | | 0.21 mg/L | 1,670 |
| **Grout flow safety function** | **Change in nitrate concentrations resulting from increased grout degradation times: three sensitivity cases.** | | |
| Sensitivity – GRT1 | Tank degrades 5,000 years after closure. | 0.26 mg/L – ~1.2 times system model base case. | 1,670 – about same as system model base case. |
| Sensitivity – GRT2 | Tank degrades 1,000 years after closure. | 0.27 mg/L – ~1.3 times system model base case. | 1,670 – about same system model base case. |
| Sensitivity – GRT3 | Tank degrades 500 years after closure. | 0.30 mg/L – ~1.4 times greater than system model base case. | 1,710 – 40 years after system model base case. |
| Sensitivity – GRT4 | Tank degrades 0 years after closure. | 0.64 mg/L – ~3 times greater than system model base case | 1,300 – 370 years before system model base case. |
| **Tank flow safety function** | **Change in nitrate concentrations resulting from the variation in the grout effective diffusion coefficients: three sensitivity cases.** | | |
| Sensitivity – DIF1 | Effective diffusion coefficient changed to 1E-07 $cm^2$/sec. | 0.23 mg/L – 1.1 times greater than system model base case. | 1,730 – 40 years earlier than system model base case. |
| Sensitivity – DIF2 | Effective diffusion coefficient varies linearly from 1E-14 to 3E-8 $cm^2$/s in the first 500 years after closure and remains constant afterwards at 3E-8 $cm^2$/s. | 0.20 mg/L – 1.1 times less than system model base case. | 1,820 – 50 years after system model base case. |
| Sensitivity – DIF3 | No release for 5,000 years, followed by advective release immediately at 5,000 years. | 0.26 mg/L – 1.2 times greater than system model base case. | 6,630 – 4,560 years after system model base case. |

**Table 10-4. Summary of Sensitivity Analysis Cases. (3 sheets)**

| Analysis Case | Description | Peak Concentration | Peak Year |
|---|---|---|---|
| **Rate-limited transport for chromium** | **Change in chromium concentrations resulting from removal of the waste form degradation and the dissolved concentration limit of 2,000 µg/L: one sensitivity case** | | |
| System Model Base Case – bas01 | | 0.45 mg/L | 1,100 |
| Sensitivity – RLS1 | No dissolved concentration limit. | 1.95 mg/L – 4.3 times greater than system model base case. | 1,650 – 550 years after system model base case. |

3-D = three-dimensional
Subsurface Transport Over Multiple Phases (STOMP)© is copyrighted by Battelle Memorial Institute, 1996.
WMA = Waste Management Area

In addition, results of the RCA will be used to provide supplemental information to support decisions related to not only the final waste residuals left at closure within tanks and ancillary equipment, but the potential use of corrective measures associated to past tank waste leaks and losses that have contaminated vadose zone soils in the immediate vicinity of WMA C.

## 10.4 FUTURE WORK

The current RCA is based on current available information based on partial retrieval of residual wastes from WMA C. The retrieval process continues for the three tanks (C-102, C-015, and C-111) and the RCA will be updated to reflect updated inventory information when the tanks are considered to be fully retrieved and sample-based inventories are available. Additionally, detailed design of the closure system needs to be performed, including the specific grout formulation to be used in filling the tanks, along with the detailed design of the final closure engineered surface cover system. These detailed designs may require updates of the RCA.

Grout infill material and the tank concrete shell diverts any infiltrating water from flowing through the tank. Understanding the long-term degradation rates of these cementitious materials under Hanford shallow vadose zone conditions should be considered as an area of future research.

In addition to the results developed for this document, the RCA will complement results developed in the PA of radiological impacts from tank waste residuals done under DOE M 435.1-1 Chg 1 [IV.P.(4)]. This radiological impacts PA process includes a requirement for PA maintenance to evaluate the impact of design and operational changes and to incorporate any new information regarding waste forms, site characteristics, etc. In addition to a PA maintenance plan, required documentation in support of the Tier 1 Closure Authorization Statement (CAS) for WMA C includes, a closure plan, monitoring plan, and annual reports documenting any recent changes to the plans for the facility or changes in the understanding of

the environmental impacts from the facility. The path forward in the near term includes the following:

- Preparation of an updated PA that addresses key findings, secondary issues, and observations provided by the Low-Level Waste Disposal Facility Federal Review Group (LFRG) during its review of this document

- Development of an additional revision of the PA that resolved review comments by outside agency comments (NRC, State Regulators, Public)

- Development and implementation of a change control process to address potential effects of changes in closure actions and decisions that could affect the validity of the analyses and conclusions of this RCA and associated PA.

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# 11.0 QUALITY ASSURANCE

Model development and application for the WMA C PA was performed under a general project plan for modeling for RCRA closure analyses and DOE O 435.1 PAs. This general project plan implements the requirements of Title 10, CFR, Part 830, "Nuclear Safety Management" (10 CFR 830) Subpart A, "Quality Assurance Requirements"; DOE O 414.1D, Quality Assurance; and State and Federal environmental regulations. Additionally, this general project plan follows EPA guidance provided in EPA/240/R-02/007, Guidance for Quality Assurance Project Plans for Modeling, EPA QA/G-5M. It addresses as relevant and important all nine "Group A" elements presented in EPA/240/B-01/003, EPA Requirements for Quality Assurance Project Plans, EPA QA/R-5. The nine elements include problem definition and background, quality objectives and criteria for measurements and data acquisition leading to model inputs and outputs, data validation and usability, references, documentation and records management, special training requirements and certifications for modelers, and assessments and reports to management. The model documentation requirements identified during project planning align with DOE management expectations for compliance listed in Revision 1 of EM-QA-001, EM Quality Assurance Program, Attachment H, "Model Development, Use, and Validation."

## 11.1 ENVIRONMENTAL MODEL LIFECYCLE QUALITY ASSURANCE PROCESS

The development, application, and preservation of environmental models used to support regulatory decision-making and analysis is conducted under a general project plan that implements the requirements of DOE O 414.1D and the direction related to modeling in EM-QA-001, as well as EPA guidance provided in EPA/240/R-02/007. This plan provides for modeling to be performed in a framework for quality assurance of the full lifecycle, with integrated control of models, implementing software, applications, and supporting information as depicted in Figure 11-1.

Highlights of the general plan requirements under which the WMA C PA was developed include the following.

- Training is stipulated in the general plan for modelers to complete that ensured the requirements and quality assurance process for model development and application are communicated.

- Software used to implement environmental models is controlled per the requirements of DOE O 414.1D (refer to Section 11.2, below, for further details on this with respect to this PA). Modeling software management is provided at the Hanford Site by CHPRC as part of that contractor's integration role for Hanford Site modeling activities. CHPRC's controlled software management procedure implements the DOE O 414.1D software requirements. This control includes configuration management of code; use of a central registry for software registration, grading and classification, approval tracking, and use logging; and software quality assurance documentation requirements. Software users are required to complete software-specific training assignments, obtain code from the

software owner (configuration management system), complete installation testing for specific computers per the test plan, and submit software installation and checkout documentation to record tested installations.

- A process for model documentation, control, and preservation is specified (refer to Section 11.3, below, for further details on this with respect to the WMA C PA). Features of this process include documentation of model development in model package reports (a quality configuration item); documentation of model applications in an Environmental Model Calculation File (EMCF, also a quality configuration item); and preservation of models, model applications, and model basis information (non-direct measurements) in an integrated archive. Full checking and senior review of model package reports and EMCFs is required as part of this process.

The general plan follows the EPA guidance in structure, and provides for flexibility to support with a specific plan for modeling projects that require additional quality assurance/quality control requirements. The WMA C PA modeling work was developed under the general plan and a complementary project-specific plan.

## 11.2 CONTROLLED SOFTWARE USE

Software used for model implementation was managed following a controlled software management procedure (PRC-PRO-IRM-309, "Controlled Software Management") that implements the requirements of 10 CFR 830 Subpart A, "Quality Assurance"; DOE O 414.1D; and State and Federal environmental regulations. This controlled software management procedure directs management of all software including configuration control, evaluation, implementation, acceptance and installation testing (verification and validation), and operation and maintenance. Software used to implement the models and perform calculations was approved for use under this controlled software management procedure that also implements the requirements of, and is compliant with, DOE management expectations for compliance listed in Revision 1 of EM-QA-001, Attachment G, "Software Quality Requirements."

The WMA C PA relies on two primary controlled-use software packages to simulate the flow and transport in the subsurface, simulate source term releases, conduct inadvertent intruder calculations, and simulate air-pathway transport in order to calculate doses resulting from the disposal of waste at the facility. These primary software packages are STOMP© and GoldSim© Pro, which are qualified for controlled use at the Hanford Site in accordance with their respective software management and testing plans. These software packages are registered in the Hanford Information Systems Inventory (HISI). HISI provides the platform for tracking all software in use at the Hanford Site. For safety software (which includes STOMP© and GoldSim© Pro), the HISI entry is used to record approval for use of software versions, to maintain a registry of authorized users, and to log all instances of the software's usage. Software is maintained using the established Hanford Site configuration management system, MKS Integrity™[1], which is the Hanford Site standard for preserving and managing source code and executable versions of

[1] MKS Integrity, Integrity, and all other PTC product names and logos are trademarks or registered trademarks of Parametric Technology Corporation or its subsidiaries in the United States and in other countries.

software. MKS Integrity™ provides a "checkpoint" feature that locks files at particular points, such as when an executable has passed quality assurance testing, been documented in an acceptance test report, and been approved for use.

Software-specific descriptions, and associated quality assurance documentation for each software package used in the PA, are summarized below for the primary model implementation software packages used for the WMA C PA (STOMP© and GoldSim©).

### 11.2.1 Subsurface Transport Over Multiple Phases

The vadose zone fate and transport calculations are performed using "CHPRC Build 4" of the STOMP© simulator software (PNNL-12030; PNNL-15782, "STOMP Subsurface Transport Over Multiple Phases: User's Guide Version 4.0"). STOMP© is registered in the HISI under identification number 2471. The STOMP© simulator was developed at PNNL, which maintains a program to test STOMP© code to meet ANSI/ASME NQA-1-2008, "Quality Assurance Requirements for Nuclear Facility Applications" software requirements, as well as the requirements specified under DOE O 414.1D for Safety Software. The "Water" and "Water-Transport" operational modes of STOMP© were used for the WMA C PA, and all code elements of those modes that were used have been ANSI/ASME NQA-1-2008 tested by PNNL. STOMP© use for the WMA C PA is managed and controlled such that the computational needs filled by use of STOMP© (and any associated utility codes) and the specific roles and responsibilities for management and the modeling staff and subcontractors have been identified and traced. These responsibilities include modeler training, source code installation and testing, preserving the software and verification test results, operation and maintenance of the original Fortran source code and executable files provided by PNNL, validation and verification that the PNNL quality assurance documentation demonstrate that STOMP© meets the CHPRC modeling needs and purposes, reporting and documenting any software errors (none were encountered during the development of the WMA C PA), management of the STOMP© input files, and contingency and disaster recovery (which was not encountered during development of the WMA C PA). Acceptance and installation tests of the STOMP© simulation software demonstrate that it is appropriate for its intended uses for the WMA C PA and that it has been successfully installed on computing systems used for STOMP© simulations to develop the WMA C PA.

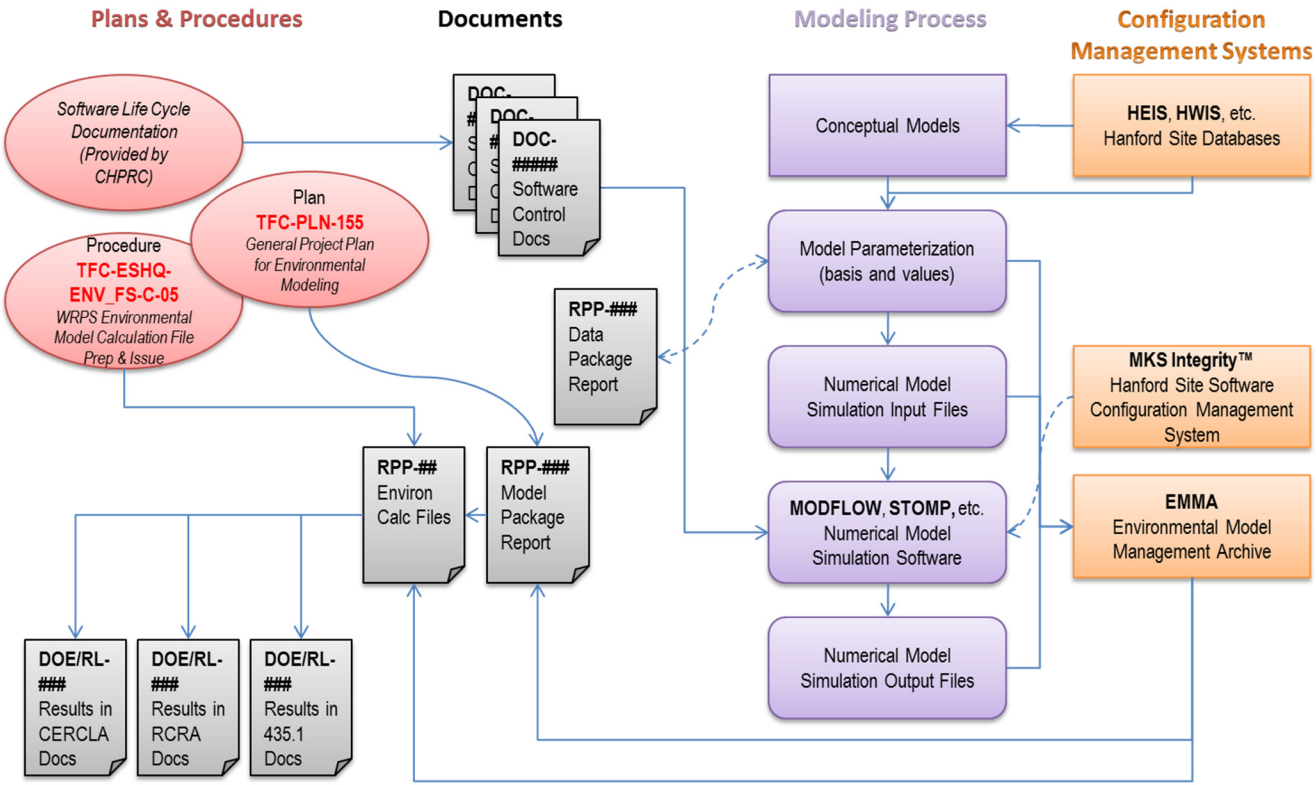
STOMP© was executed on two independent computer systems. The first of these is the GREEN Linux®[2] system that is owned and managed by INTERA, Incorporated, which is a subcontractor to WRPS. The GREEN system is physically located at INTERA's Richland, Washington office, and is comprised of a Dell™[3] PowerEdge™ R510 with two 6-core Intel® Xeon®[4] X5660 processors @ 2.80GHz and 48 GB of RAM. The second system used was the Tellus Subsurface Simulation Platform, a Linux® cluster system that is owned and managed by CHPRC to support Hanford Site integrated environmental modeling needs. The Tellus cluster system is comprised of a Dell™ PowerEdge™ M1000e blade enclosure with 16 Dell™ PowerEdge™ M610 and 1 Dell™ PowerEdge™ M710 blade servers. The M610 blade servers each have 6-core Intel® Xeon X5670 processors @ 2.93 GHz (12MB cache) and 96 GB of RAM.

[2] Linux® is a registered trademark of Linus Torvalds in the U.S. and other countries.

[3] Dell and PowerEdge are trademarks of Dell Inc.

[4] Intel and Xeon are trademarks of Intel Corporation in the U.S. and other countries.

**Figure 11-1. Lifecycle Quality for Environmental Models.**




435.1 = DOE O 435.1, 2001, Radioactive Waste Management, U.S. Department of Energy, Washington, D.C.
CERCLA = Comprehensive Environmental Response, Compensation, and Liability Act of 1980, 42 USC 9622, et seq.
CHPRC = CH2M HILL Plateau Remediation Company
HEIS = Hanford Environmental Information System
HWIS = Hanford Well Information System
RCRA = Resource Conservation and Recovery Act of 1976, 42 USC 6901, et seq.

References:

TFC-ESHQ-ENV_FS-C-05, "WRPS Environmental Model Calculation Preparation and Issuance," Washington River Protection Solutions LLC (WRPS) Tank Farms, Richland, Washington.
TFC-PLN-155, "General Project Plan for Environment Modeling," Washington River Protection Solutions LLC (WRPS) Tank Farms, Richland, Washington.

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MODFLOW software has been developed and distributed by the U.S. Geological Survey, Washington, D.C.
Battelle Memorial Institute (Battelle) retains copyright on all versions, revisions, and operational modes of the Subsurface Transport Over Multiple Phases (STOMP©) software simulator, as permitted by the U.S. Department of Energy. STOMP© is used here under a limited government use license.

DOE/RL-2011-50 contains a summary of the main model attributes and code selection criteria that serve as the basis for the demonstration of the adequacy of the STOMP© code for use in vadose zone modeling at the Hanford Site. The results of the evaluation in DOE/RL-2011-50 show that the STOMP© code is capable of meeting or exceeding the identified attributes and criteria.

### 11.2.2 GoldSim©

Software development of Goldsim© Pro meets ANSI/ASME NQA-1-2008 software requirements, as well as the requirements specified under DOE O 414.1D for Safety Software. Goldsim© Pro use at the Hanford Site is managed and controlled such that the computational needs filled by use of Goldsim© Pro (and any associated utility codes) and the specific roles and responsibilities for management and the modeling staff and subcontractors have been identified and traced. These responsibilities include modeler training, source code installation and testing, preserving the software and verification test results, validation and verification that the Goldsim© Pro quality assurance documentation demonstrate that Goldsim© Pro meets identified modeling needs and purposes, reporting and documenting any software errors (none were encountered during the development of the WMA C PA), management of the Goldsim© Pro input files, and contingency and disaster recovery (which was not encountered during the development of the WMA C PA). Acceptance and installation tests of the Goldsim© Pro simulation software demonstrate that it is appropriate for its intended uses for the WMA C PA and that it has been successfully installed on the computing systems used to conduct WMA C PA modeling.

### 11.2.3 Other Hanford Site Tank Waste Management Software Tools

The PA effort makes use of other tank waste management software tools available at the Hanford Site in the preparation of model inputs.

**11.2.3.1 Tank Waste Information Network System/Best Basis Inventory.** TWINS is a web-based database system providing access to Hanford tank waste data, documents, graphics, photos and reports via the Hanford Local Area Network (HLAN) and to approved offsite users via the Internet. This legacy software was developed over time and contains a number of primary databases, reporting tools, and support tools. The database system consists of the Tank Characterization Database, Tank Vapor Database, BBI Estimates and BBI Model tool, the Automated Tank Characterization Report system, Data Source Access, Automated Statistics tool, and Automated Vector creation tool. These systems were developed by various projects over a number of years and have been consolidated within the TWINS architecture. A system description can be found in RPP-RPT-39487, “TWINS Software Description.” TWINS changes are tracked in accordance with internal WRPS procedures used for TWINS software change control.

Except as noted, BBI estimates with radionuclides decayed to January 1, 2020 were used as source terms for the PA. The BBI is developed using applicable output from the Tank Characterization Database, Automated Statistics tool, Automated Vector creation tool and BBI Model tool. The BBI values are based on sample- and/or model-based composition estimates multiplied by waste volume estimates. Best-Basis process outputs are described in Section 3.2.2.

The BBI was developed in accordance with RPP-7625, "Guidelines for Updating Best-Basis Inventory" and TFC-ENG-CHEM-P-53, "Best-Basis Inventory Evaluations." BBI Model tool output was downloaded to a spreadsheet which was reviewed and checked in accordance with internal WRPS procedures used in the preparation and review of engineering calculations and incorporated into RPP-RPT-42323. Output from RPP-RPT-42323 is included in Tables 3-13 through 3-16 in this report.

**11.2.3.2 Hanford Tank Waste Operations Simulator.** The HTWOS model is a dynamic flowsheet mass balance model that tracks and predicts the movement of waste over the full River Protection Project mission (that is, from current tank contents through treatment to disposal). It establishes the timing of key process steps and the life-cycle system mass balance using a well-defined set of assumptions (the current set being described in Revision 6 of ORP-11242, "River Protection Project System Plan"). The various processes are modeled in sufficient detail to estimate the overall timing of each process and the quantities and composition of the primary and secondary waste streams, taking into account the interactions, including recycle, between the various processes and unit operations. The HTWOS model and validation of the model is described in RPP-RPT-39908, "Hanford Tank Waste Operations Simulator Model (HTWOS) Version 3.0 Verification and Validation Report." The HTWOS spreadsheet output for residual inventories is SVF-2109, Rev. 0, "Tank_Residuals_4MinTimestep(6Melters)-mmr-11-031-6.5-8.3r1-2011-03-18-at-01-31-58_M1.xlsm."

HTWOS residual inventories provided lower bound inventory estimates in the PA for tanks not yet retrieved as of September 1, 2014 (see Section 3.2.2.3.3). The HTWOS model is controlled in accordance with RPP-50816, "Software Management Plan for Grade D Custom Developed Hanford Tank Waste Operations Simulator (HTWOS)." The HTWOS output was downloaded to a spreadsheet to back decay values to January 1, 2020 and scale the values for a waste volume of 360 $ft^3$. The spreadsheet was reviewed and checked in accordance with internal WRPS procedures used in the preparation and review of engineering calculations and incorporated into RPP-RPT-42323. HTWOS residual inventory estimates are included in Table 3-17 in this report.

**11.2.3.3 Video Camera Computer-Aided Design Modeling System.** The CCMS was used to estimate the volume of residual waste in retrieved tanks. The CCMS approach consists of obtaining in-tank videos showing the location of residual solids and liquid waste remaining in a tank after retrieval. The videos are reviewed and a 3-D CAD drawing of the residual waste is developed using a template of an empty tank. The volume of the residual waste is then calculated using CAD software. The CCMS approach and quality assurance/quality control requirements are described in RPP-52784, "Video camera/CAD Modeling System for Retrieval: HISI #3254 Software Management Plan." CCMS modelers are trained and qualified in accordance with internal WRPS procedures used for post-retrieval volume determinations. Uncertainty in CCMS estimates is described in RPP-23403, "Single-Shell Tank Component Closure Data Quality Objectives." Actual and upper bound volumes based on CCMS estimates are documented in applicable waste volume reports and incorporated into the BBI.

**11.2.3.4 Other Legacy Software.** This section provides information about legacy software tools, namely the HDW software and the ORIGEN2 software, that are cited in the PA but are not currently managed as controlled use software.

**11.2.3.4.1 Hanford Defined Waste Model.** The HDW model (RPP-19822) uses a spreadsheet format to combine tank waste transfer and process information with Hanford Site irradiated fuel and separation plant process records from the ORIGEN2 model (RPP-13489) to produce total chemical and radionuclide compositions by waste type. These estimates comprise 46 radionuclides (the standard radioisotopes in the BBI), 33 nonradioactive species (24 of the 25 standard chemicals from the BBI plus citrate, N-[hydroxyethyl]-ethylenediaminetriacetic acid, ethylenediaminetetraacetic acid, glycolate, acetate, dibutyl phosphate, butanol, ammonia, and ferrocyanide) and four properties (density, water wt%, total organic carbon wt% and sludge void fraction [total organic carbon is a standard constituent in BBI]).

The HDW model concentration estimates are considered to have higher uncertainty compared to sample-based concentrations and are used in BBI to fill gaps where sample data do not exist for a waste type and/or constituent. RPP-19822 (HDW model, Revision 5) was checked in accordance with company procedures (see RPP-19822, Appendix G). Revision 5 uses the same software and formulas as Revision 4, but includes updated ORIGEN2 results and tank waste process inputs to estimate tank waste type compositions and does not include the supernatant mixing model, tank waste layering model, or tank-specific inventory estimates in Revision 4. Additional description of the waste type compositions model is provided in LA-UR-96-3860, "Hanford Tank Chemical and Radionuclide Inventories: HDW Model Rev. 4."

**11.2.3.4.2 Oak Ridge Isotope Generation and Depletion Code 2.** The primary radionuclide input to the HDW model consists of a file of "pre-decayed" isotopic inventories (Fuel Activity Records) generated using the ORIGEN2 and Radioactive Decay (DK) and Processing (PRO) (DKPRO) codes. The ORIGEN2 code is used to calculate initial radionuclide inventories as a function of fuel type, fuel burn-up, and reactor type, with subsequent decay and processing computed by the DKPRO code. Input to the DKPRO code includes an archive file of separations processing records by fuel batch, a file of processing directives, a file of summary directives, and a set of ORIGEN2 inventory files representing unprocessed radionuclide inventories. The ORIGEN2 and DKPRO software and outputs are described in RPP-13489. Review and checking ORIGEN2 results and verification and validation of DKPRO code is presented in Appendices A and F of RPP-13489.

## 11.3 MODEL DOCUMENTATION, CONTROL, AND PRESERVATION

The four basic model components necessary to provide traceable, reproducible models are (1) the basis for the model inputs, including data packages, (2) the models themselves, (3) the applications of the models, and (4) the implementing software.

As noted above regarding controlled software use, software used for the development of the WMA C PA is maintained using the established Hanford Site configuration management system, MKS Integrity™. However, models are comprised of more than just software. Control and preservation of the other three identified model components (basis, models, and applications) are necessary as well. Under the general project plan for modeling for RCRA closure analyses and DOE O 435.1 PAs followed for development of the WMA C PA, these components are maintained in the WRPS Environmental Model Management Archive (EMMA). The EMMA is

the approved means to maintain traceability and reproducibility for these model components by providing for version documentation and preservation of the model basis, inputs, and output, along with identification of the software packages and specific versions used. The EMMA is fundamentally a highly disciplined file system, with defined structure, controls on staging and uploading content, requirements for content preservation, and an active backup plan that ensures the EMMA is frequently synchronized to a controlled, managed disk space inside HLAN. EMMA's organization aligns to the three components mentioned: basis, models, and applications.

- The EMMA "basis" bin includes Electronic Model Data Transmittal coversheets to document preserved data and information that form the basis of model parameterization.

- The EMMA "model" bin includes model package reports that provide the description and explanation of the modeling objectives, conceptualization, implementation, uncertainty and sensitivity evaluations, version configuration control, and the limitations of the models. Model input files that form the specific version of a configuration-controlled model are preserved with the model package report that documents that specific model and version.

- The EMMA "application" bin includes documentation of model applications. While the model package reports include information regarding the complete configuration managed version of the WMA C PA models, the EMCF documents information on specific cases analyzed with the models. This includes the application of the STOMP© and Goldsim© Pro models used to perform the calculations for the WMA C PA.

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Mr. Marcel Bergeron has more than 35 years of experience in a wide variety of subsurface investigations and studies at radioactive and hazardous waste facilities and contaminated sites. He is experienced in planning and implementation of environmental characterization and risk assessment investigations in a variety of roles including as a technical contributor, a project and task manager, and a line manager. He has performed quantitative analysis of subsurface systems using analytical and numerical models and visualization tools. He has significant technical project experience in managing technical teams, schedules, and budgets for multi-disciplinary projects and communication of project results with clients, regulators, and stakeholders.

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Mr. Connelly provided technical support to the RCA/performance assessment (PA) team for the Tank Farm Vadose Zone Project and is a contributing author to this document. He has over 16 years of experience in environmental geohydrology including project management, groundwater modeling, and using computer techniques to analyze and interpret field data for remedial action and site characterization activities.

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Dr. Matthew Kozak has more than 27 years of experience in the areas of performance assessment of near-surface and geological radioactive waste repositories, regulatory development, dose assessment for residual contamination of soils and buildings, toxic materials risk assessment, and mixed waste issues. He is the author of over 100 publications on these topics. He has supported national programs in the U.S. and countries in Europe, Asia, and Africa to site, develop, construct, and analyze facilities for disposal of radioactive waste.

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For this document, Dr. Kozak developed the safety function concepts used in the identification of features, events, and processes used in this RCA. He also prepared and technically supported the overall document preparation and review including the specific preparation of Appendix A (Key Assumptions in the RCRA Closure Analysis) and Appendix H (List of Features, Events and Processes Applied to Waste Management Area C RCRA Closure Analysis/Performance Assessment).

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For this document, Dr. Mehta has been one of the principal investigators, performing the flow and transport abstraction modeling for sensitivity analysis and risk/hazard impact calculations, focusing on project coordination, reviews, and overall document preparation.

For this document, Dr. Mehta was the lead author on Section 6 (Waste Characteristics) and 7 (Analysis of Risk and Hazard Impacts) and was a significant contributor to Section 8 (Results of Analysis), Section 9 (Sensitivity Analysis of the Groundwater Pathway), and Section 10 (Performance Evaluation and Interpretation of Results).

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Mr. McMahon specializes in hydrologic data collection, analysis, and interpretation, and groundwater and vadose zone numerical modeling to support groundwater and vadose remedial projects. He has experience with a number of vadose zone and groundwater modeling packages. His other duties include directing hydrologic data collection efforts, analyzing and interpreting hydrologic data, assessing the effectiveness of groundwater remedial actions, developing work plans for data collection and interpretation, and performing numerical modeling to predict facility impacts to the aquifer to support remediation and construction decisions.

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For this document, Ms. Morgans provided technical support in the development of exposure parameters and equations presented in Section 7.3.3. Exposure scenarios included in the PA include the All-Pathways Representative Person Scenario, the Atmospheric Pathway, and the hypothetical Inadvertent Intruder scenarios. The exposure scenario included in the RCRA closure analysis includes the EPA tap water (resident) scenario used in the RCRA analysis.

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In this document, Ms. Singleton provided technical support in the development of waste inventories and screening analysis and supported the preparation of Sections 3.2.2 (Waste Inventory), Section 4.0. (Comparison of Tank Residuals with WAC 173-340 Soil Cleanup Levels) and 5.0 (Screening Analysis). Ms. Singleton also provided technical assistance in the overall document preparation and the specific preparation of 7.0 (Analysis of Risk and Hazard Impacts) and Appendix E (Other Supporting Risk Information).

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# APPENDIX A

# KEY ASSUMPTIONS IN THE RCRA CLOSURE ANALYSIS

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# LIST OF TERMS

## Abbreviations and Acronyms

| | |
|---|---|
| DOE | U.S. Department of Energy |
| RCA | Resource Conservation and Recovery Act of 1976 (RCRA) Closure Analysis |
| WMA | Waste Management Area |

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# APPENDIX A

## KEY ASSUMPTIONS IN THE RCRA CLOSURE ANALYSIS

In this Appendix, a set of key assumptions used in the base case analysis of the Resource Conservation and Recovery Act of 1976 (RCRA) Closure Analysis (RCA) are listed. However, it is emphasized that the structure of the RCA is founded on the extensive use of sensitivity analyses that explore the consequences if alternative assumptions are used. The alternative analyses include sensitivity cases evaluating conditions well outside the range of the base case analysis. In all cases, the calculations produced results that are below the performance measures. Therefore, it is not possible to identify key assumptions or design variables that must be met in order to meet the regulatory goals of DOE O 435.1, Radioactive Waste Management.

- It has been assumed that the landfill closure of Waste Management Area (WMA) C occurs in 2020, consistent with planning assumptions in DOE/EIS-0391, "Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington." The results of the performance assessment are not significantly affected by alternative assumptions about closure timing.

- The Central Plateau has been designated Industrial-Exclusive for the indefinite future, based on several Records of Decision [64 FR 61615, "Record of Decision: Hanford Comprehensive Land-Use Plan Environmental Impact Statement (HCP EIS)"; 73 FR 55824, "Amended Record of Decision for the Hanford Comprehensive Land-Use Plan Environmental Impact Statement"]. This area, which includes the 200 East and 200 West Areas, includes WMA C. There is no stated intention to release the Central Plateau from this designation or from U.S. Department of Energy (DOE) control at any time in the future. Despite this designation, it is assumed in this analysis that institutional control and societal memory of the disposal activities are lost 100 years after site closure, for consistency with DOE O 435.1 requirements. This assumption is necessary to allow future hypothetical individuals to come onto the Central Plateau and engage in activities that might result in exposure.

- In the base case, the land use and land cover, including the barrier, remain shrub steppe indefinitely after closure. Alternative infiltration rates in the future are included in alternative analysis cases, which are intended to address a variety of potential future conditions, including progression to different land uses and land covers.

- The engineered cover for WMA C is not yet designed but is assumed to be similar to the Modified RCRA Subtitle C Barrier that limits infiltration through the waste primarily by evapotranspiration processes (i.e., surface barrier) based on the work done for the Hanford Prototype barrier (DOE/ORP-2008-01, RCRA Facility Investigation Report for Hanford Single-Shell Tank Waste Management Areas, Appendix C). These processes are not modeled directly for this report, but those processes have been studied through field measurements, tracer studies, and numerical models to estimate net infiltration (PNNL-14744, "Recharge Data Package for the 2005 Integrated Disposal Facility Performance Assessment"; PNNL-14960, "200-BP-1 Prototype Hanford Barrier Annual

Monitoring Report for Fiscal Year 2004"; "Multiple-Year Water Balance of Soil Covers in a Semiarid Setting" [Fayer and Gee 2006]). Instead, the recommended net infiltration rates from those reports are applied to the area under the engineered cover and are varied spatially and temporally as appropriate according to the estimated or assumed time-dependent performance of a surface barrier.

- The design life of the cover is assumed to be 500 years in the base case, following which the infiltration through the cover is assumed to return to the site-wide average infiltration rate for undisturbed soil. Alternative infiltration rates in the future are included in alternative analysis cases, which are intended to address a variety of potential future conditions, including progression to different land uses and land covers.

- It is assumed the tanks will be filled with grout according to the basic assumptions outlined for landfill closure in DOE/EIS-0391 (2012). The specific formulation of the grout has not yet been established, but consistent with DOE/EIS-0391 (2012), it is assumed the fill material for the tanks will be similar to the cold-cap grout formulation developed by the U.S. Army Corps of Engineers for the Hanford Grout Vault Program. This type of grout is assumed to behave chemically like ordinary cementitious material. It has been assumed that the grout formulation does not provide any specific or unusual chemical conditions, such as reducing conditions.

- Radionuclide and chemical release mechanisms from the sources are assumed to occur by one of two mechanisms: (a) the entire inventory of the residual waste is assumed to be instantly available for release and transport out of the tanks, or (b) a semi-empirical release function is applied based on leach tests performed on residual waste from WMA C.

- Transport of contamination from the tanks is assumed to be primarily controlled by diffusion from the grouted tanks through the base mat below the tank. Alternative assumptions are included as sensitivity cases that evaluate the consequences of hydraulic failure (i.e., fracturing) of the grouted tanks and base mat.

- The specific formulation of the grout has not yet been established, and site-specific measurements of the chemical influence of the grout have not been performed. The chemical effect of the grout is represented by contaminant-specific distributions of distribution coefficients ($K_d$), which have been developed from international literature on sorption of radionuclides on cementitious materials. These values are generally consistent with, or more conservative than, comparable values used for the facility-specific grout at the Savannah River F and H tank farm performance assessments [WSRC-STI-2007-00369, "Hydraulic and Physical Properties of Tank Grouts and Base Mat Surrogate Concrete for FTF Closure" and WSRC-STI-2007-00607, "Chemical Degradation Assessment of Cementitious Materials for the HLW Tank Closure Project (U)"].

- Release and migration from one WMA C source does not alter similar processes occurring in the other sources.

- The post-retrieval inventory of contaminants in WMA C is assumed to be uniformly distributed throughout the waste residual volume. The residual volume in the tanks is assumed to be a uniform layer distributed at the bottom of the tanks. In pipelines and ancillary equipment, the residual waste is assumed to be distributed in a homogeneous layer across WMA C at the depth of the pipelines.

- Progeny radionuclides with a half-life of less than two years are assumed to be in secular equilibrium with their parent, which allows a reduction in the number of species tracked but still accounts for the radiological effects of the progeny.

- Inventories of contaminants in retrieved tanks are based on post-retrieval sampling and measurements. It is assumed that the sampling results are representative of the entire waste residual. Inventories for tanks that have not yet completed retrieval use the best estimates of post-retrieval conditions available at this time. These data have been estimated as of September 30, 2014. Additional sensitivity cases were identified in the 2009 to 2011 working sessions to evaluate alternative inventory assumptions.

- The vadose zone is modeled as an aqueous-gas porous media system where flow and transport through the gas phase are assumed to be negligible.

- Hydraulic property heterogeneity is assumed to be insignificant within. Hence, each assigned its upscaled, effective hydraulic properties. These properties have been updated from the input parameters presented in the 2009 and 20011 data packages based on consideration from field data for moisture content, as discussed in Appendix B.

- Post-closure groundwater flow beneath WMA C is assumed to be northwest to southeast and parallel to the four tank arrays of 100-series tanks in WMA C. The justification for this assumption is found in RPP-RPT-46088, "Flow and Transport in the Natural System at Waste Management Area C." Groundwater flow parameters have been derived from the Central Plateau groundwater model (CP-47631, "Model Package Report: Central Plateau Groundwater Model Version 6.3.3").

- Distribution coefficients ($K_d$) are used to represent sediment-contaminant chemical interaction that best represent plausible levels of reactivity. Groups of radionuclides that show similar levels of chemical reactivity with Hanford soils and sediments were assigned the same $K_d$ values. Justification for the selected parameter values is found in RPP-RPT-46088; PNNL-16663, "Geochemical Processes Data Package for the Vadose Zone in the Single-Shell Tank Waste Management Areas at the Hanford Site"; and PNNL-17154, "Geochemical Characterization Data Package for the Vadose Zone in the Single-Shell Tank Waste Management Areas at the Hanford Site." In addition, uncertainties in $K_d$ values have been assessed as part of the uncertainty analysis.

- The point of calculation used in the calculation of the groundwater concentration corresponds to the location 100 m (328 ft) downgradient from the facility per DOE O 435.1. For the purpose of calculating groundwater concentrations for comparison with groundwater protection requirements, it is necessary to identify the peak location in

space at which the concentration occurs. The approach for identifying the location of peak groundwater concentrations is described in Section 7.3.2.2.

- Assumptions used in the exposure scenarios to define input parameter values are based on appropriate regulatory guidance as detailed in RPP-ENV-58813, "Exposure Scenarios for Risk and Performance Assessments in Tank Farms at the Hanford Site, Washington." These values represent conservative inputs to the exposure scenario calculations characteristic of a highly exposed individual.

- Age- and gender-weighted intake rates are generally developed for a Representative Person in accordance with the recommendations described in DOE-STD-1196-2011, Derived Concentration Technical Standard. The 95$^{th}$ percentile intake rates were obtained from EPA/600/R-090/052F, Exposure Factors Handbook: 2011 Edition, National Center for Environmental Assessment, based on available information. Even though mean intake rates were available, the 95$^{th}$ percentile values from the underlying distribution were chosen conservatively to maximize the likely exposure. Typically, the 95$^{th}$ percentile intakes rates weighted by age and gender are calculated (Appendix P of RPP-ENV-58813). The exceptions to this approach were the indoor inhalation rate (taken directly from a reference source) and the soil ingestion rates (where simple age weighting is performed for children and adults).

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# APPENDIX B

# BASIS FOR DEVELOPMENT OF VADOSE ZONE HYDRAULIC PROPERTIES AT WASTE MANAGEMENT AREA C

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# LIST OF TERMS

## Abbreviations and Acronyms

| | |
|---|---|
| ACM-I/ACM1 | Alternative Geologic Model I |
| ACM-II/ACM2 | Alternative Geologic Model II |
| ERDF | Environmental Restoration Disposal Facility |
| HSU | hydrostratigraphic unit |
| IDF | Integrated Disposal Facility |
| MC | Monte Carlo |
| MPa | megapascal |
| PA | performance assessment |
| RCRA | Resource Conservation and Recovery Act of 1976 |
| RETC | RETention Curve |
| S&L | Sisson and Lu |
| SST | single-shell tank |
| WMA | Waste Management Area |

# APPENDIX B

# BASIS FOR DEVELOPMENT OF VADOSE ZONE HYDRAULIC PROPERTIES AT WASTE MANAGEMENT AREA C

This appendix provides a description of the basis for the selection of hydraulic properties for hydrostratigraphic units (HSUs) identified at Waste Management Area (WMA) C. No WMA C site-specific data are available that can be used to directly develop estimates of hydraulic properties needed for the Resource Conservation and Recovery Act of 1976 (RCRA) Closure Analysis (RCA). As a result, a process has been developed for identifying surrogate hydraulic properties based on samples collected at other sites within the 200 Areas that are considered to be representative of sediments characteristic of the major HSUs identified at WMA C. The selected properties were then used to simulate a WMA C vadose zone flow field and the simulation results were cross-checked against field moisture contents for different WMA C units. This step allowed an updating of the properties by incorporating data sets developed from data collected at other nearby sites within the 200 Areas that are consistent with WMA C field data.

The following information is included in this Appendix:

- WMA C moisture content database, its consistency with nearby field data, and a summary of available data on 241-C Tank Farm (C Farm) soil-water matric potential and their impact on the selection of moisture characteristic data for RCA modeling (see Section B.1 below)

- Evaluation of laboratory measurements for vadose zone soil moisture retention, saturated and unsaturated hydraulic conductivity for samples in the vicinity of C Farm and 200 Areas (see Section B.2 below) as the basis for the selection of hydraulic properties for the major HSUs identified at WMA C (see Section B.2 below)

- Comparison of observed and simulated moisture content using selected hydraulic properties (see Section B.2.1.1 below)

- Moisture characteristic curves for major HSUs identified for Alternative Geologic Models I and II (see Section B.2.1.2 below)

- Effective (upscaled) moisture retention, saturated and unsaturated hydraulic conductivity, bulk density, diffusivity, and macrodispersivity estimates for various strata (see Sections B.3 and B.4 below).

## B.1 MOISTURE CONTENT MEASUREMENTS AT WASTE MANAGEMENT AREA C

As part of WMA C site characterization, an extensive database of moisture content information is available for various HSUs. The moisture content database was developed as part of a direct push campaign conducted at WMA C in 2008, and understood as being long after the occurrence

of past leaks and discharges at the farm. A summary of these measurements for the WMA C area and associated statistics presented in this Appendix is provided in RPP-CALC-60450, "Process for Determining the Volumetric Moisture Content for the Vadose Zone Geologic Units Underlying Waste Management Area."

The spatial distribution of all moisture measurements collected in and around WMA C is shown in Figure B-1(a); the database includes moisture content data collected both within the footprint of the single-shell tanks (SSTs) (i.e., where the backfill is thickest) [Figure B-1(b)] and outside this area (where the backfill is thin or non-existent) [Figure B-1(c)]. The green line on Figure B-1(b) and (c) reflects the approximate demarcation of areas inside and outside of the SST footprint. In each of the four plots on Figure B-1, the size of the circles depicted at each borehole is indicative of the magnitude of moisture content. The larger-diameter circles (higher moisture content) are more prevalent in the shallower units and outside the farm. Figure B-1(d) is a perspective view looking north-northwest, showing both the vertical direct pushes, drywells, groundwater well, characterization borehole, and slant direct pushes.

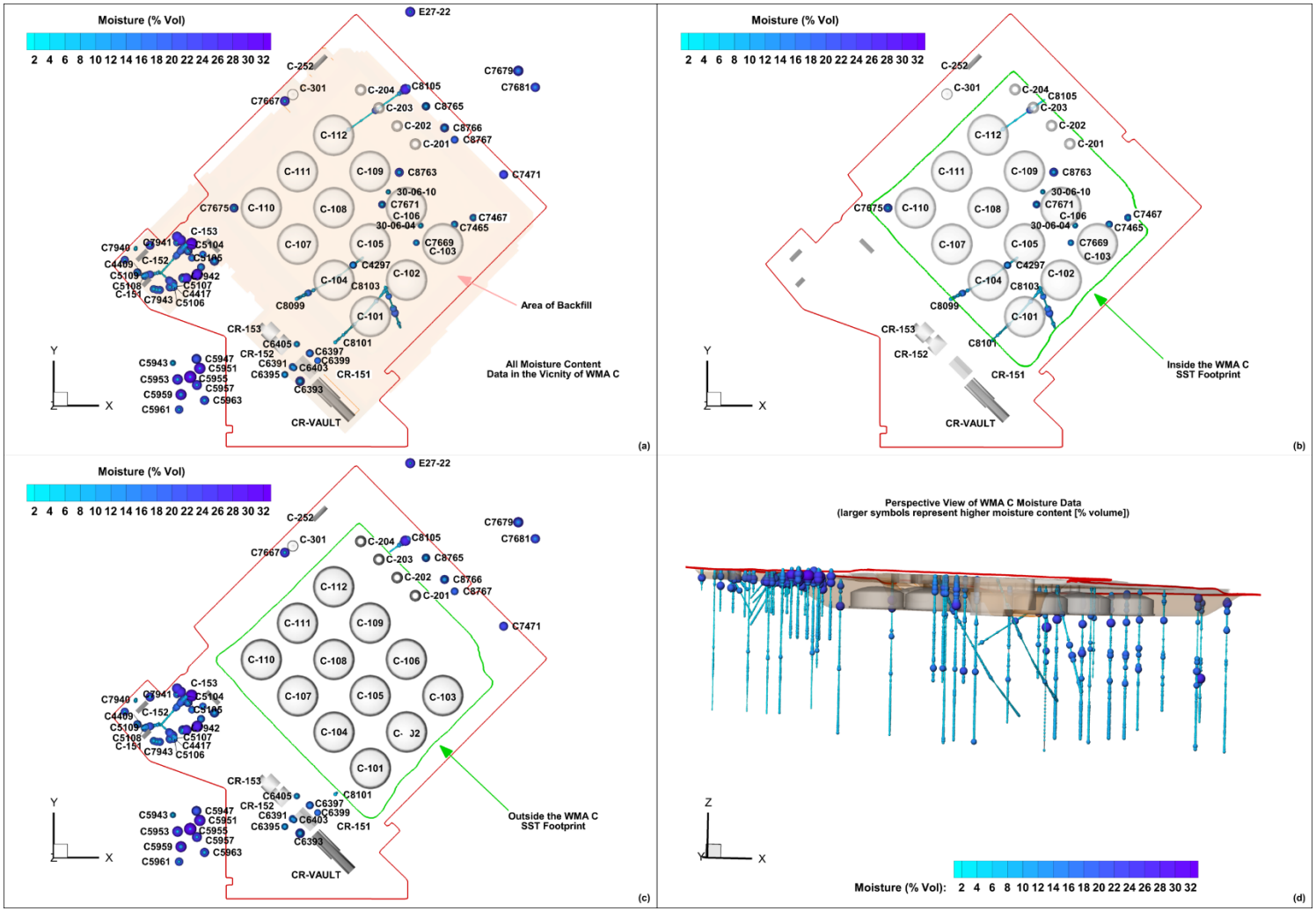
A summary of the statistics of the moisture content measurements by major HSUs is provided in Table B-1. Overall, the moisture content data show considerable variability: the range varies from a low of 0.11 (% volume) to as high as 30.64 (% volume) (Table B-1).

### B.1.1 Moisture Content Measurements for Hanford H2 Sand-Dominated Unit

The Hanford H2 (sand-dominated) unit is the dominant unit at WMA C in terms of vadose zone thickness. The largest number of the moisture content measurements is associated with the Hanford H2 unit (Table B-1).

Figure B-1(a) and (b) show the location of where moisture content measurements were made in the Hanford H2 unit relative to the green line that marks the boundary of where the backfill is thickest (i.e., within the footprint of the SSTs). Figure B-2a shows the histogram for H2 moisture data for all measurements inside and outside of the SST footprint. Figure B-2b shows the histogram for measurements inside the SST footprint, whereas Figure B-2c shows the histogram for measurements outside the SST footprint. While the average for all H2 measurements (inside as well as outside of SST footprint) is ~5.15 (% volume) (Figure B-2a), inside the tank farm, the average is 5.09 (% volume), with the range varying from ~1.86% to 19.9% and a variance of 3.03% (Figure B-2b). Outside the SST footprint, the average is 5.17 (% volume), with the range varying from ~1.06% to 26.32% and a variance of 3.39% (Figure B-2c). The statistics suggest that the averages for moisture content measurements inside and outside the SST footprint are not significantly different. The variance for measurements inside the SST footprint is lower, compared to variance for measurements outside the SST footprint. This may simply be a reflection of a smaller sample size (a count of 5,143 inside of the SST footprint versus a count of 15,733 outside of the SST footprint), or may reflect differences in media heterogeneities within the H2 unit.

**Figure B-1. Distribution of Moisture Content Measurements Collected in and around Waste Management Area C (a) Plan View with All Moisture Content Data, (b) Plan View with All Moisture Content Data Inside the Single-Shell Tank Footprint, (c) Plan View with All Moisture Content Data Outside the Single-Shell Tank Footprint and (d) a Side View Looking Northwest.**

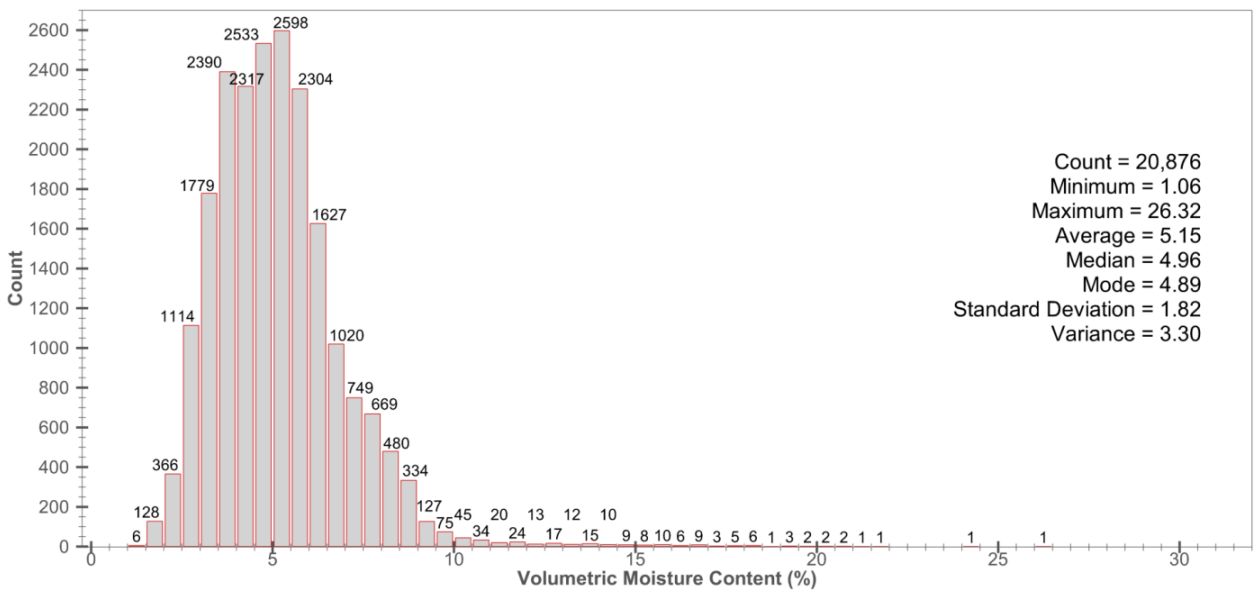



SST = single-shell tank WMA = waste management area

**Table B-1. Summary Statistics for Waste Management Area C Moisture Content (% Volume) Database.**

| Unit | Count | Minimum | Maximum | Average |
|---|---|---|---|---|
| Backfill | 4,052 | 0.11 | 30.61 | 8.09 |
| H1 | 7,977 | 0.13 | 30.64 | 5.88 |
| H2 | 20,876 | 1.06 | 26.32 | 5.15 |
| H3 | 7 | 5.54 | 7.09 | 6.18 |
| All Units | 32,912 | 0.11 | 30.64 | 5.69 |

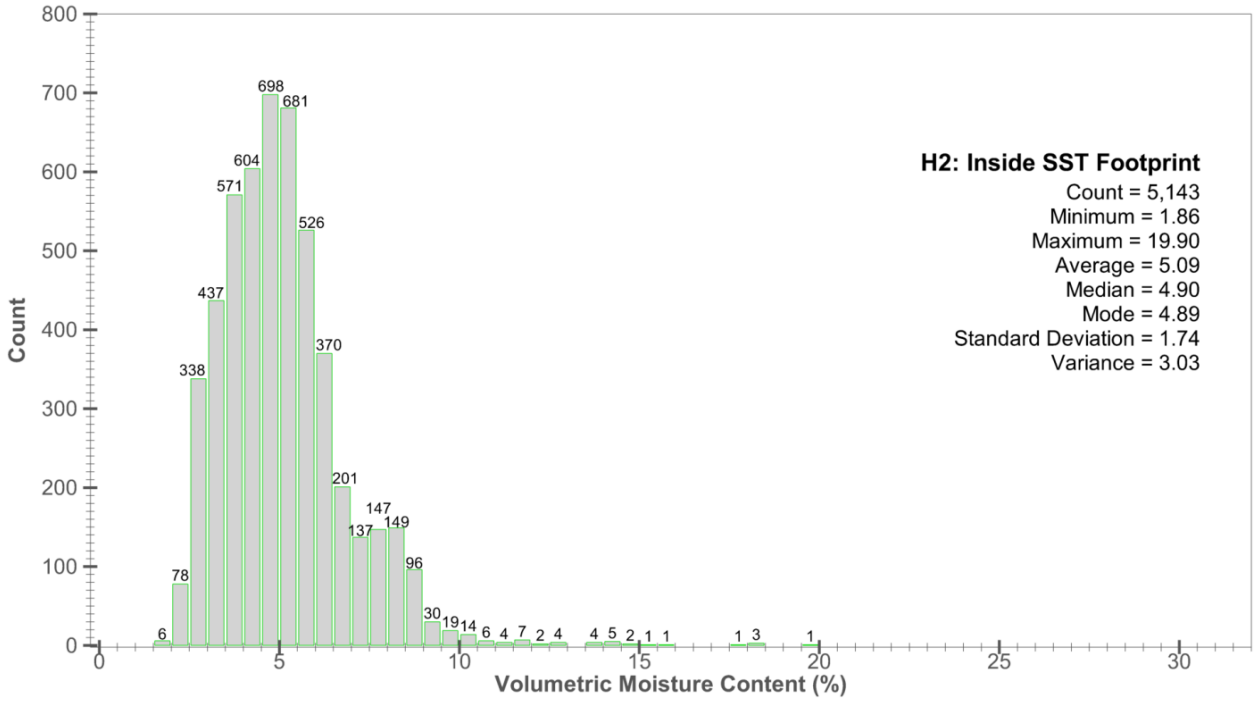
**Figure B-2a. Waste Management Area C Moisture Content Histogram for All H2 Data (Includes the Data from Both Inside and Outside of the Single-Shell Tank Footprint).**




**B.1.1.1 Comparison with Sisson and Lu Site Moisture Content Measurements.** In this section of the Appendix, the moisture content measurements for the Hanford H2 unit at WMA C are compared to, and checked for consistency against, another extensive set of moisture content measurements collected at the nearby Sisson and Lu (S&L) field injection site in 200 East Area (Figure B-3). Unlike WMA C, soil hydraulic properties data are available for the S&L site (PNNL-14284, "Laboratory Measurements of the Unsaturated Hydraulic Properties at the Vadose Zone Transport Field Study Site"; "Evaluation of van Genuchten-Mualem relationships to estimate unsaturated hydraulic conductivity at low water contents" [Khaleel et al. 1995]). Furthermore, unlike WMA C, moisture content measurements are available before and after application of anthropogenic recharge at the S&L site. Thus, the S&L site serves as a backdrop for WMA C moisture measurements for Hanford H2 unit. Details of the S&L site, field injections and the spatio-temporal distribution of observed moisture plume are described elsewhere ("Stochastic analysis of moisture plume dynamics of a field injection experiment"

[Ye et al. 2005]; PNNL-13795, "Vadose Zone Transport Field Study: Soil Water Content Distributions by Neutron Moderation").

**Figure B-2b. Waste Management Area C Moisture Content Histogram for H2 Data Within the Single-Shell Tank Footprint.**

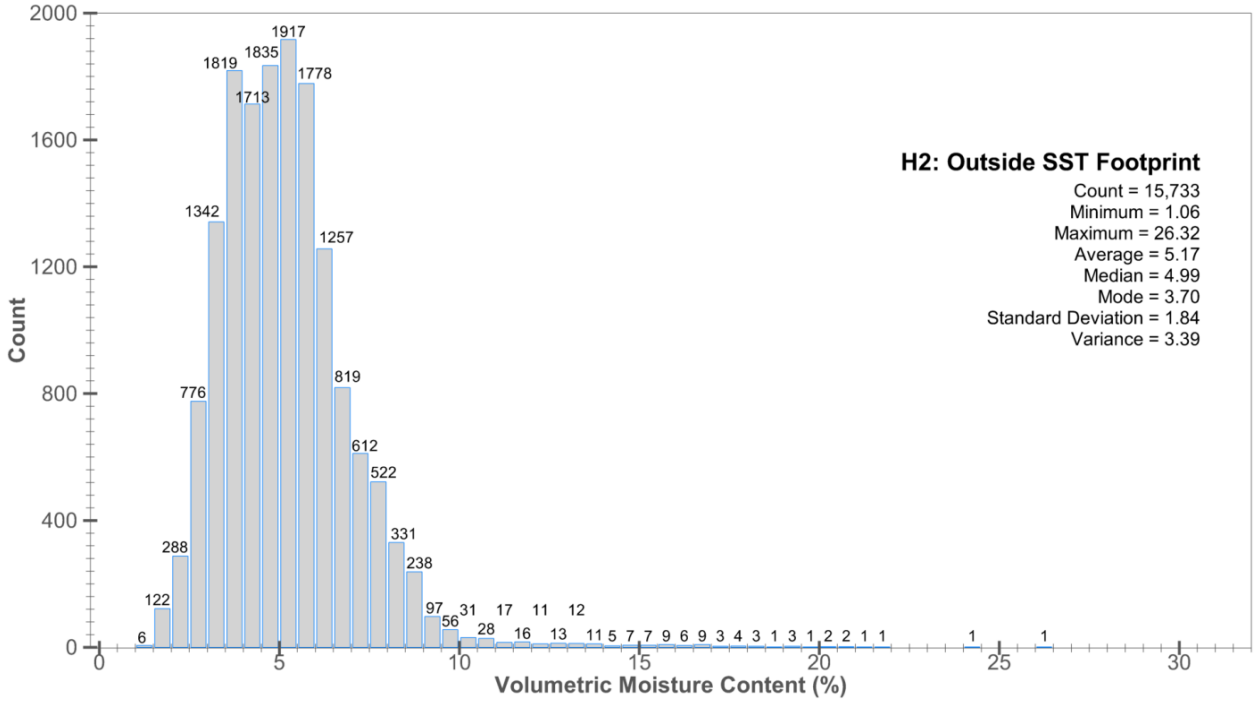



SST = single-shell tank

Figure B-4 shows the composite set of all moisture content measurements collected before and after injection at the S&L site. The S&L site initial moisture content data were collected on May 5, 2000 [Figure B-4(a)] and post-injection and post-redistribution data were collected about two months later [Figure B-4(b)]. These measurements are all within an HSU that would correlate with the Hanford H2 sand unit identified at WMA C. The S&L moisture content profiles are in general agreement with the known stratigraphic cross-section (Ye et al. 2005), with larger moisture content values being associated with the fine-textured sediments and smaller values being associated with the coarse-textured sediments. In addition to the 2000 S&L field experiment, data also exist on the 1980 field experiment conducted at the same site (RHO-ST-46P, "Field Calibration of Computer Models for Application to Buried Liquid Discharges: A Status Report"). Although not shown here, the 1980 moisture content measurements are nearly identical to the 2000 moisture content measurements. The consistency in the moisture content profiles over the 20-year time interval suggests that, in the absence of anthropogenic recharge, the moisture content distribution is under a state of natural equilibrium with meteoric recharge. The S&L moisture content profiles (Figure B-4) clearly illustrate the impact of media heterogeneities and natural capillary breaks ("Simulating field-scale moisture flow using a combined power-averaging and tensorial connectivity-tortuosity approach" [Zhang and Khaleel 2010]; Ye et al. 2005). During and following field injections, the capillary breaks created due to textural discontinuities allow flow to occur laterally until the pressure head in the fine layer is sufficient to overcome the entry pressure head of the underlying coarse layer.

Nonetheless, as indicated in Figure B-4, the pre- and post-injection moisture plumes are essentially confined within three layers (i.e., two fine-textured layers and a coarse-textured layer that is sandwiched in between the two fine-textured layers).

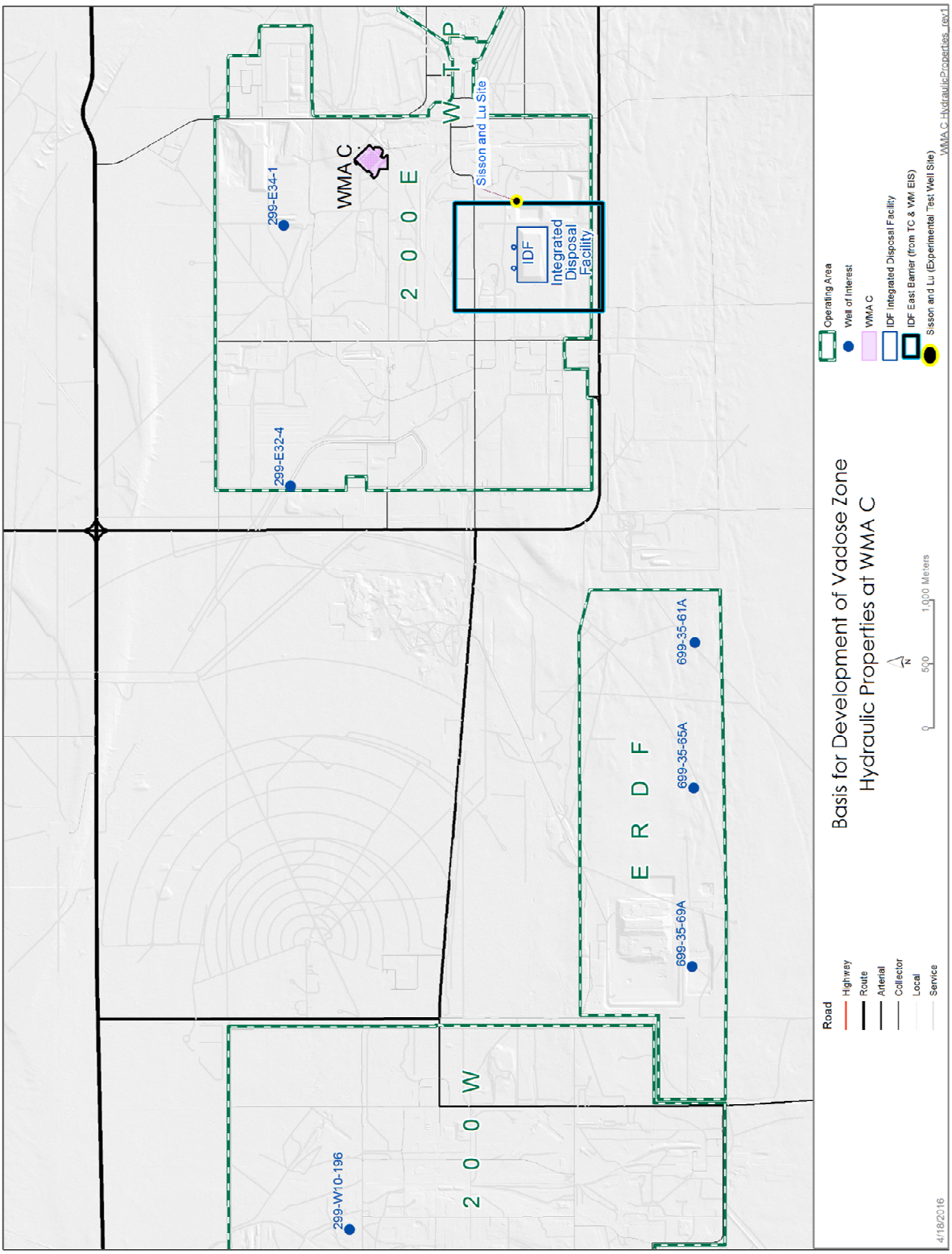
**Figure B-2c. Waste Management Area C Moisture Content Histogram for H2 Data Outside of the Single-Shell Tank Footprint.**




SST = single-shell tank

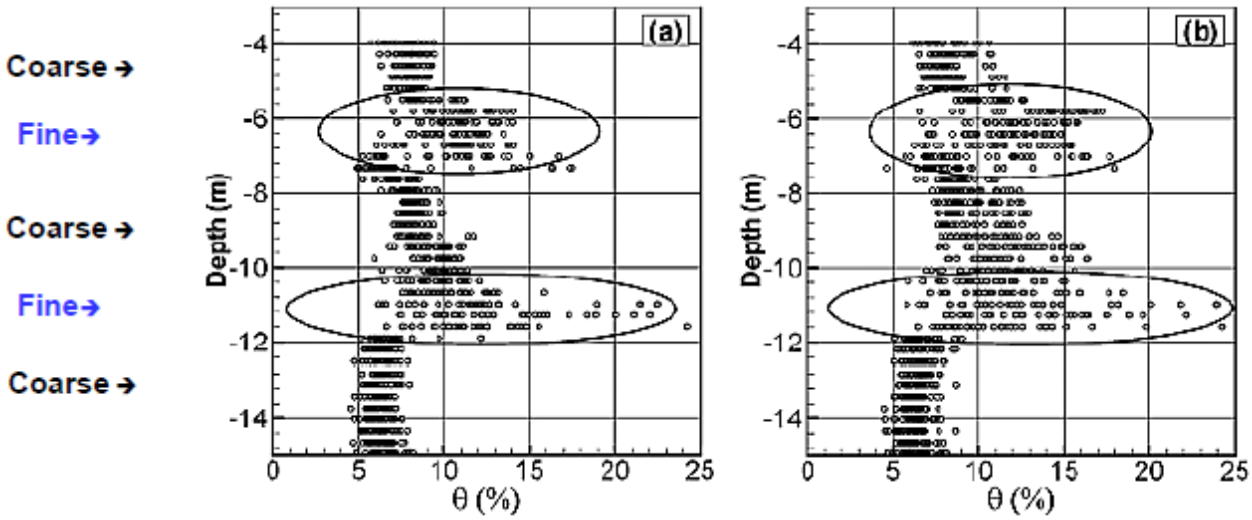
At WMA C, the volumetric moisture content for the Hanford H2 unit inside the tank farm (see Figure B-2c) ranges from 1.86 to 19.90 with a mean of 5.09 (% volume), whereas at the S&L site the volumetric moisture content ranges from 4.60 to 24.50 with a mean of 8.92 (% volume) (Ye at al. 2005). Even though the natural recharge at the two sites are not identical and the sediment textural data are different, the WMA C H2 unit moisture contents compare well and show similar trends relative to variability with field-measured H2 moisture contents at the nearby S&L site. However, the S&L mean moisture content is much higher than the WMA C (inside the tank farm) mean value. This is consistent with the ubiquitous occurrence of fine-textured units at the S&L site (Ye at al. 2005), and the apparent non-occurrence of such units at WMA C. These data show that the field measurements at both WMA C and S&L sites are significantly impacted by small-scale heterogeneities. However, if the moisture content data is used as a surrogate for characterizing media heterogeneities, the higher mean (~8.92 [% volume]) moisture values at the S&L site suggest that the Hanford H2 unit is much coarser at WMA C than at the nearby S&L site. Therefore, while the comparison with the S&L site generally corroborates the understanding of the WMA C H2 unit, the S&L site is not a useful surrogate for development of hydraulic properties for the Hanford H2 sand unit at WMA C. Furthermore, the comparison demonstrates that substantial variability can occur in the H2 unit over fairly short spatial distances.

**Figure B-3. Location of Sisson and Lu Site, Integrated Disposal Facility and Selected Boreholes in 200 Area.**




ERDF = Environmental Restoration Disposal Facility WMA = Waste Management Area
TC & WM EIS = Tank Closure and Waste Management Environmental Impact Statement

**Figure B-4. (a) Pre- and (b) Post-Injection Moisture Plumes for the Field Injection Experiment in the 200 East Area.**

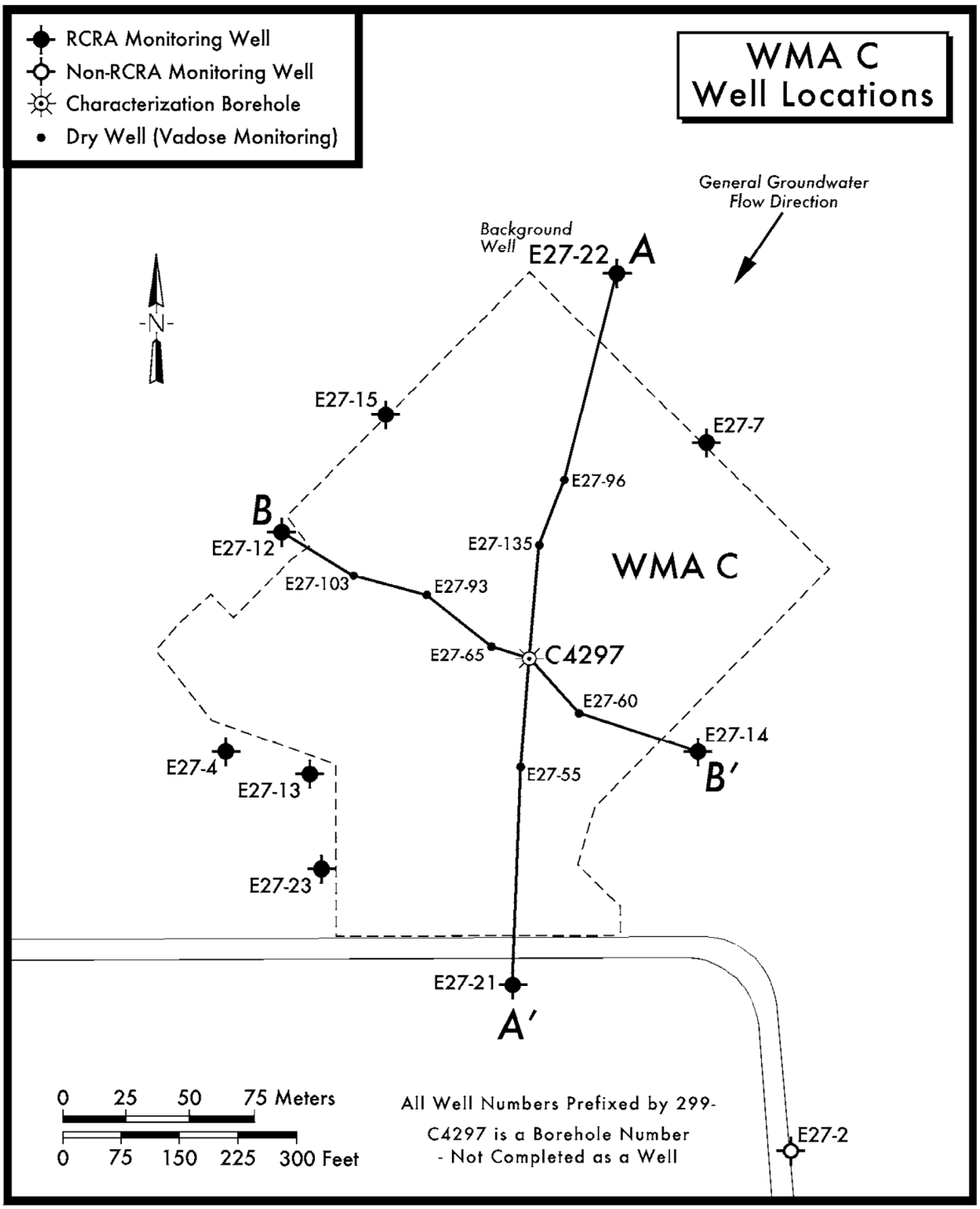



Profiles of volumetric moisture content (%) measured on (a) May 5, 2000, and (b) July 31, 2000. The figures illustrate the fact that, in the absence of anthropogenic recharge, moisture contents at the field site are in equilibrium with natural recharge at the site.
Reference: "Stochastic analysis of moisture plume dynamics of a field injection experiment" (Ye et al. 2005).

**B.1.1.2 Soil-Moisture and Matric Potential Data for Borehole Samples Inside and Outside the Tank Farm.** In addition to the moisture content measurements developed from neutron logging of direct push boreholes presented in Section B.1, additional moisture content data as well as matric potential information are available for two individual boreholes. Boreholes C4297 (inside the tank farm near tank C-105) and 299-E27-22 (RCRA borehole just outside the tank farm) (Figure B-5) provide moisture content (gravimetric) measurements as well as matric potential (using filter paper) data (PNNL-15503, "Characterization of Vadose Zone Sediments Below the C Tank Farm: Borehole C4297 and RCRA Borehole 299-E27-22"). The two sets of data on moisture content and matric potential were collected to evaluate differences between one being outside the farm (a lower expected average moisture content and a more negative matric potential) and the other inside the farm (a higher expected average moisture content and a less negative matric potential indicative of a draining soil profile). However, as stated earlier (Section B.1.1), the averages for moisture content measurements inside and outside the SST footprint were not significantly different.

The moisture content profiles for the two boreholes are shown in Figures B-6a and B-6b, respectively. Zones with relatively high moisture are illustrated via a light blue bar immediately to the right of the lithologic log in these diagrams. The moisture content and lithological data are generally consistent; the elevated levels of moisture in the vadose zone at C Farm are associated with fine-grained lenses of fine sand and/or silt. Most of these occur within the Hanford formation H2 unit, although there is also one at the base of the backfill in borehole C4297, and within the H1 unit in RCRA borehole 299-E27-22, which is consistent with the concentration of moisture at an abrupt, large contrast in grain size. This is illustrated at the 82-ft depth in RCRA borehole 299-E27-22 (Figure B-6b), where there is a sharp contact between gravelly sand overlying fine to coarse sand (PNNL-15503).

**Figure B-5. Borehole Location Map for Waste Management Area C.**

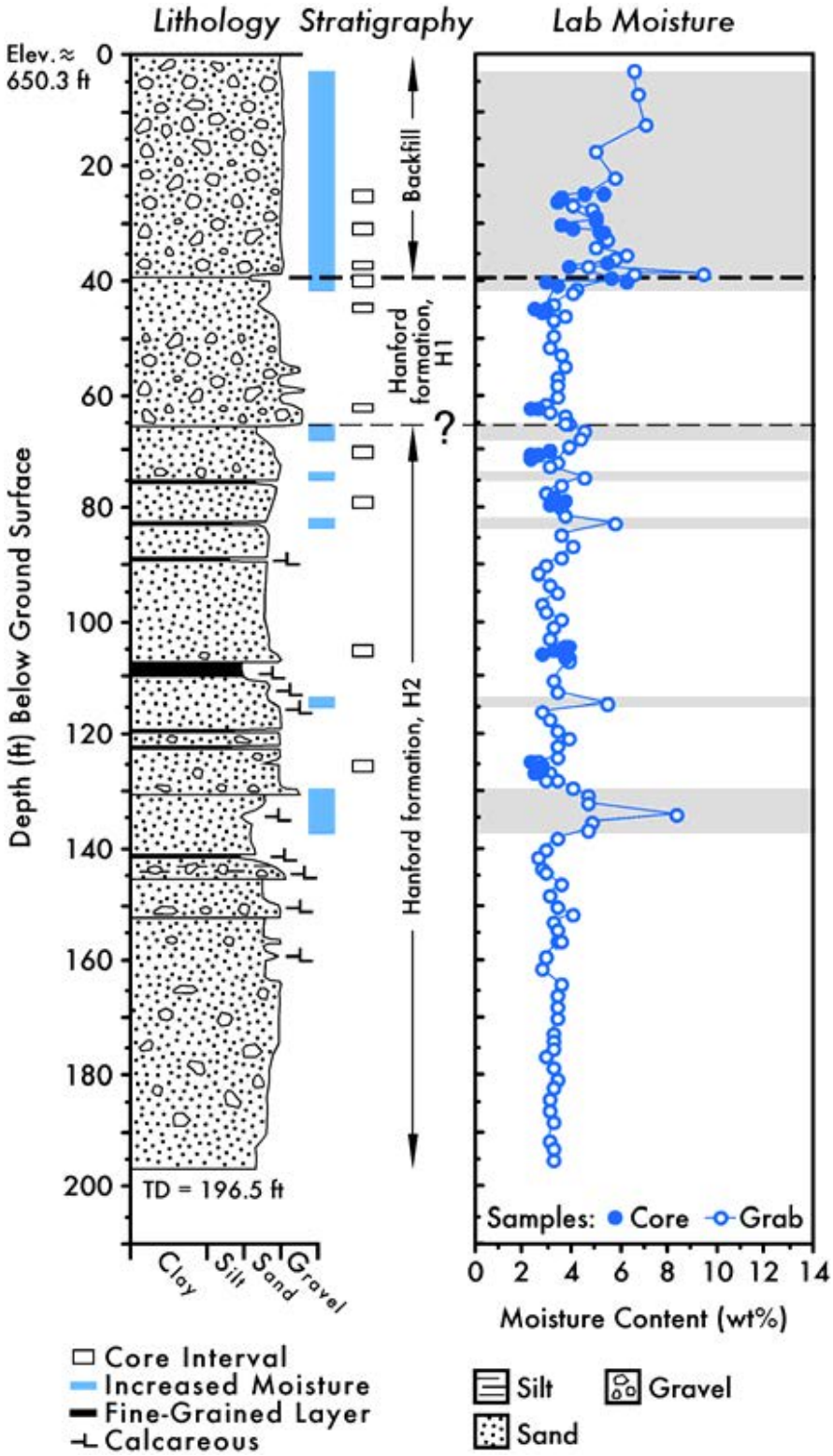



RCRA = Resource Conservation and Recovery Act of 1976 WMA = Waste Management Area

Source: PNNL-15503, "Characterization of Vadose Zone Sediments Below the C Tank Farm: Borehole C4297 and RCRA Borehole 299-E27-22."

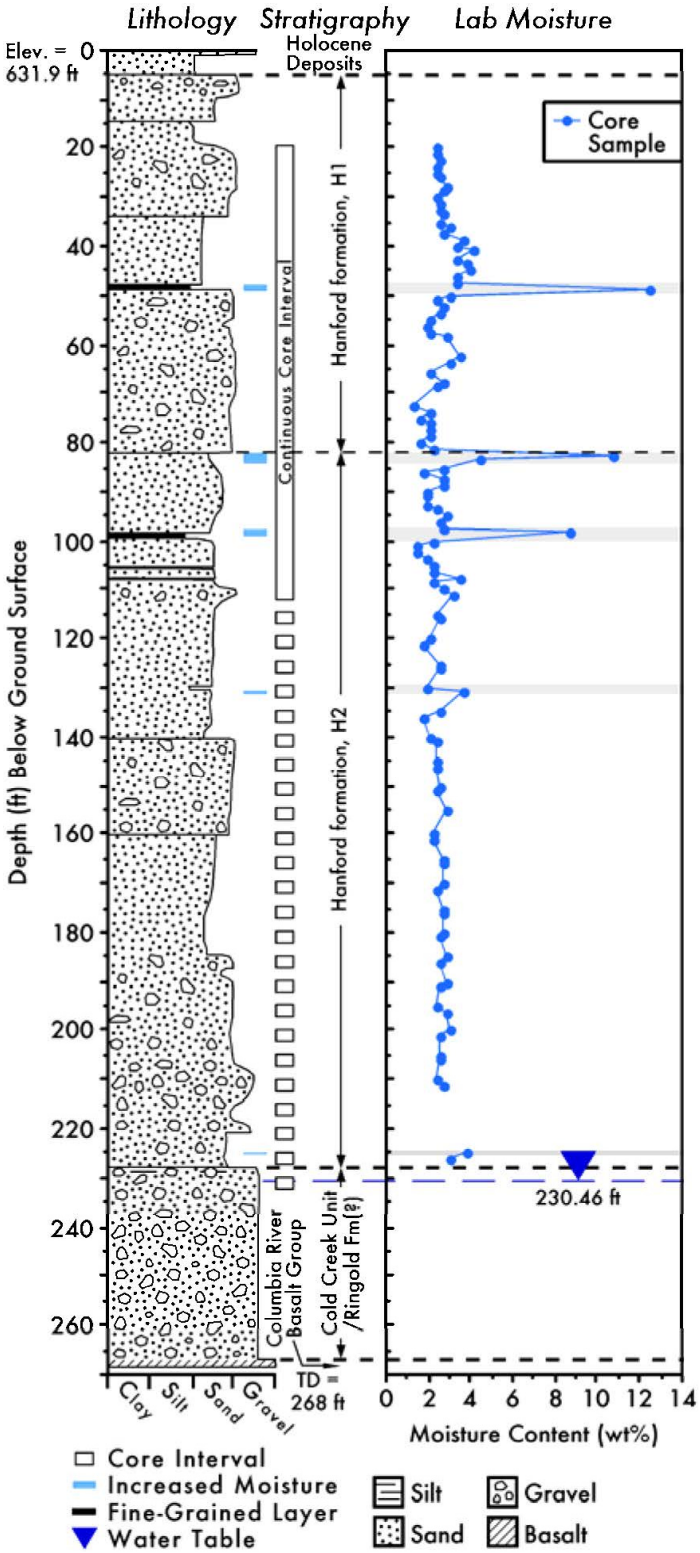
Note: Cross-sections AA' and BB' are Figures 2.4 and 2.5, respectively, in PNNL-15503.

**Figure B-6a. Borehole C4297 Lithology and Gravimetric Moisture Content Measurements (the shaded areas in light blue and gray are regions of increased moisture).**




Reference: PNNL-15503, "Characterization of Vadose Zone Sediments Below the C Tank Farm: Borehole C4297 and RCRA Borehole 299-E27-22."

**Figure B-6b. Borehole 299-E27-22 Lithology and Gravimetric Moisture Content Measurements (the shaded areas in light blue and gray are regions of increased moisture).**




Reference: PNNL-15503, "Characterization of Vadose Zone Sediments Below the C Tank Farm: Borehole C4297 and RCRA Borehole 299-E27-22."

The distribution of moisture in the vadose zone at these two borehole locations was developed by gravimetric moisture measured directly from core samples in the laboratory (Figures B-6a and B-6b). Moisture data based on grab sampling is only available for one of the two boreholes (C4297), and these data generally corroborate the laboratory-measured moisture content measurements (Figure B-6a). However, several pronounced spikes that appear on the laboratory-moisture plot do not appear in the moisture log. This is likely the result of a number of thin (a few inches or less) fine-grained layers that were preferentially sampled during core processing. These thin layers are not visible on the geophysical log because the neutron flux is averaged over a larger area beyond the limits of the fine-grained layer, including adjacent relatively dry layers. Thus, the resulting field logging signal is dampened. In general, the neutron-moisture log appears to accurately reflect the relative bulk moisture content, and can confidently be used as a substitute to estimate bulk moisture conditions when core samples are unavailable. However, most thin (<6 in.) moist zones go undetected on neutron-moisture logs (PNNL-15503).

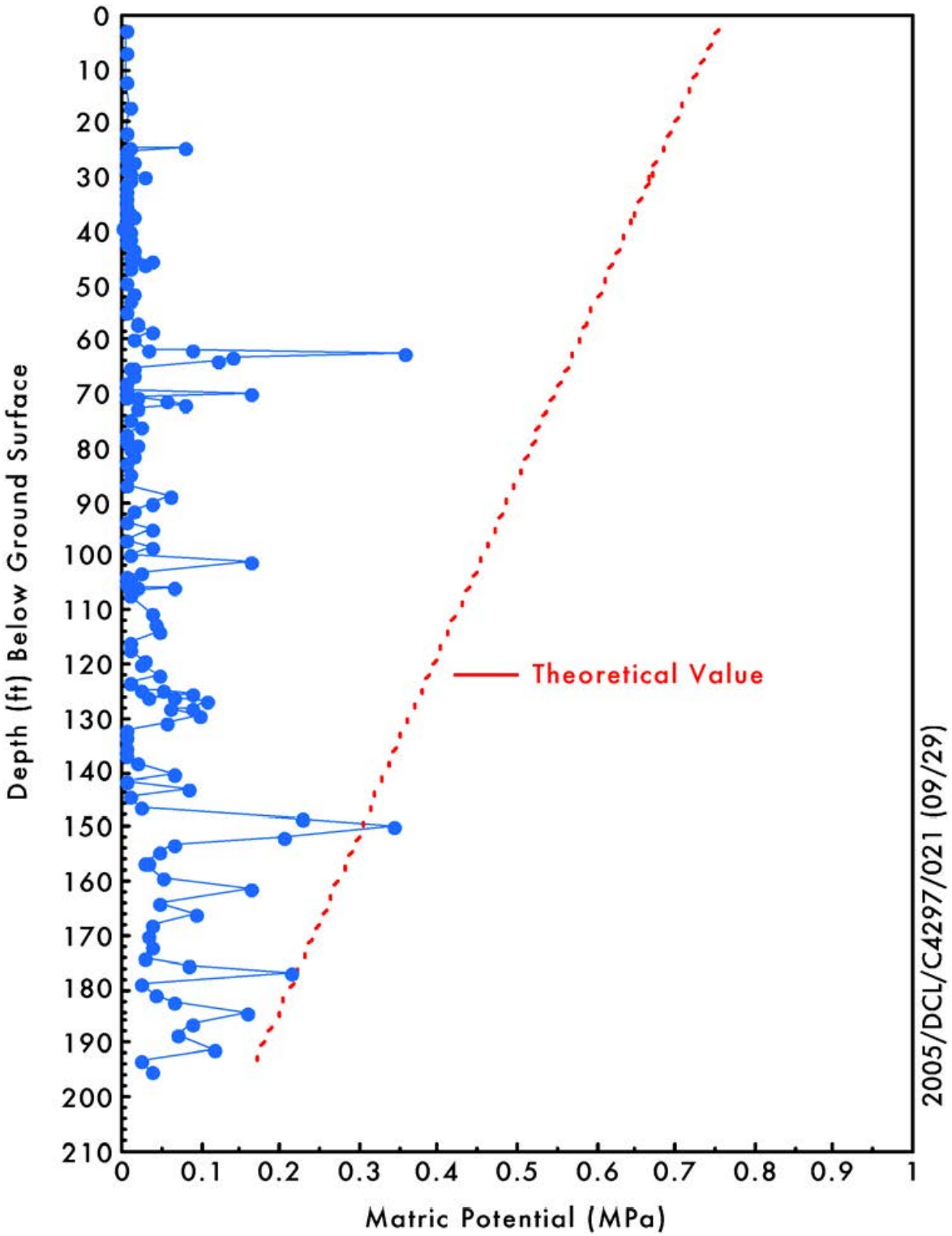
While the moisture content profiles provide useful information, the moisture profiles, by themselves, cannot be used to describe the soil-water energy status and the vadose zone flow dynamics. Data on soil-moisture matric potentials are needed to establish the energy level and the subsequent flow status. A simple measure of direction of flow can be approximated by plotting field-measured matric potentials versus the height above the water table. The hydraulic potential at any given elevation is given by the sum of matric potential and gravitational potential and the flux is calculated from the Darcy-Buckingham law (Soil Physics [Jury and Horton 2004]).

Figures B-7a and B-7b illustrate the respective filter paper-based matric potential measurements, as a function of depth for sediment samples from the two boreholes: C4297 (inside the farm) and 299-E27-22 (outside the farm), with the potentials (MPa) shown as absolute values (PNNL-15503). With the filter paper technique, the moisture in a filter material reaches equilibrium with the surrounding environment. In both figures, the red line, labeled “theoretical value” is the theoretical line that represents the steady-state equilibrium condition. Matric potential values to the left of the theoretical line suggest a draining profile. The general trend for the data is that the measured potentials for both boreholes are consistent with those of a draining profile.

For borehole 299-E27-22 (Figure B-7b), matric potentials for three of the samples (27.0, 72.0, and 74.5 ft below ground surface) suggest very dry conditions; these appear to be erroneous because of inadvertent drying of the samples or weighing errors. The matric suction values are generally below 0.5 MPa (~5,000 cm) for the sediment profile in borehole 299-E27-22 as well as borehole C4297.

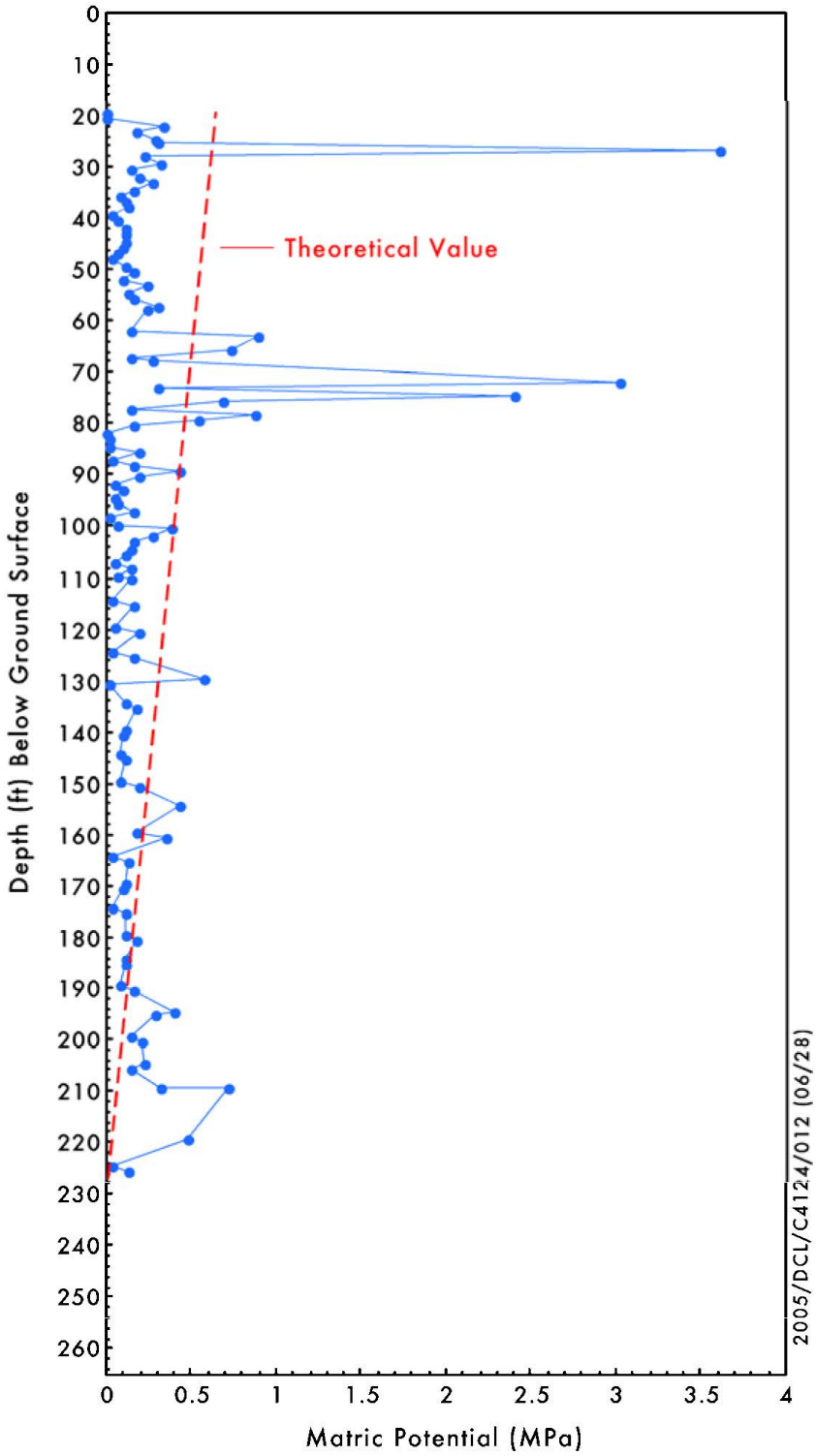
Filter paper-based soil matric potentials are point measurements, and are not consistent with the use of averaged upscaled (effective) properties (Section 7) for the large blocks used in the RCA simulations. In addition, the error bar for filter paper measurements is rather large (0.1 to 0.2 MPa). Soil moisture measurements are typically more accurate than matric potential measurements, and the matric potential variability is typically larger than the soil moisture variability. Overall, however, the WMA C moisture and tension data appear to be internally consistent and represent a relatively dry moisture regime.

**Figure B-7a. Matric Potentials Measured by Filter Paper Technique on Core Samples from Borehole C4297.**
**Matric potentials are presented as absolute values.**




Reference: PNNL-15503, "Characterization of Vadose Zone Sediments Below the C Tank Farm: Borehole C4297 and RCRA Borehole 299-E27-22."

**Figure B-7b. Matric Potentials Measured by Filter Paper Technique on Core Samples from Borehole 299-E27-22. Matric potentials are presented as absolute values.**




Reference: PNNL-15503, "Characterization of Vadose Zone Sediments Below the C Tank Farm: Borehole C4297 and RCRA Borehole 299-E27-22."

Table B-2 summarizes the mean moisture content and mean filter paper-based matric potential measurements for the two borehole samples. The data show a drier moisture content for measurements outside the farm compared to those inside the farm. A comparison of the moisture and matric potential profiles for the two boreholes is shown in Figures B-8a and B-8b, respectively.

**Table B-2. Mean Moisture and Matric Potentials for Borehole Samples Inside and Outside of Waste Management Area C.**

| Borehole | C4297 (inside tank farm) | 299-E27-22 (outside tank farm) |
|---|---|---|
| Mean moisture content (% volume)* | 0.060 | 0.046 |
| Mean matric potential (-cm) | 498.45 | 1,616.43 |

*Gravimetric data were converted to volumetric moisture content using an assumed sediment bulk density of 1.7 g $cm^{-3}$.

Reference: PNNL-15503, "Characterization of Vadose Zone Sediments Below the C Tank Farm: Borehole C4297 and RCRA Borehole 299-E27-22."

As stated earlier, matric potential measurements for both boreholes suggest a draining soil profile (PNNL-15503). Intuitively, it might be postulated that the higher mean observed moisture and a less negative mean matric potential inside the farm is due to the combined effects of both natural recharge and the operational use of water during the period of past tank farm operations. However, whereas the mean moisture contents for the two borehole samples suggest a slightly higher moisture content from measurements inside the tank farm, the much more negative mean matric potential for outside borehole samples (Table B-2) could simply be a reflection of differences in moisture retention characteristics for the two datasets, albeit being of similar lithology.

### B.1.2 Moisture Content Measurements for Hanford H1, Hanford H3 and Backfill Gravelly Units

The statistics of moisture content measurement for Hanford H1 and H3 gravelly units and backfill gravelly unit are summarized in Table B-1. As indicated in Table B-1, unlike moisture content measurements made in the H1 gravelly unit, the sample size of moisture content measurements made in the H3 gravelly unit is too small to generate any meaningful statistics.

**B.1.2.1 Hanford H1 Gravelly Unit.** Figure B-9a shows the histogram for all moisture content measurements made in the H1 gravelly unit inside and outside the tank farm (Figure B-2c). Figure B-9b shows the histogram for measurements inside the SST footprint, whereas Figure B-9c shows the histogram for measurements outside the SST footprint. While the average for all H1 measurements is about 5.88% on a volume basis (Figure B-9a), inside the tank farm the average is 4.24 (% volume), with the range varying from ~1.47% to 23.11% and a variance of 3.76% (Figure B-9b). Outside of the SST footprint the average is 6.41 (% volume), with the range varying from ~0.13% to 30.64% and a large variance of 15.42% (Figure B-9c). Once again, similar to H2 data and contrary to expectation, the statistics suggest a considerably higher H1 average moisture content for measurements outside the SST footprint, compared with the average for measurements inside the SST footprint. The variance for H1 measurements

outside the SST footprint is higher, compared to variance for measurements inside the SST footprint. This might simply be a reflection of a smaller sample size (a count of 1,921 inside versus a count of 6,056 outside), and/or media heterogeneities that are prevalent within the H1 unit.

It is questionable as to whether the observed high moisture contents (e.g., 30.64 [% volume] for the gravel-dominated H1 unit) are reflective of the natural moisture regime. As discussed earlier, other moisture data in the nearby S&L test site suggest that, in the absence of anthropogenic recharge, the moisture profiles are typically in equilibrium with meteoric recharge. Furthermore, in the absence of anthropogenic recharge, moisture contents correlate with sediment texture (i.e., coarse-textured sediments have a lower moisture content and fine-textured sediments have a higher moisture content) (Figure B-4). Nonetheless, none of the S&L moisture content measurements for the fine-textured horizons approach as high as 30.64% (% volume); such an unusually high value for the gravel-dominated H1 unit is considered an outlier.

**B.1.2.2 Backfill Gravelly Unit.** In general, tank farm backfill materials consist of unstructured, poorly-sorted mixtures of gravel, sand, and silt removed during tank excavation, and then later used as fill around the tanks. Backfill materials extend to depths of ~50 ft (~15.24 m) within the tank farms. Most or all of the recent deposits of eolian sand and silt material found elsewhere across the Hanford Site have been removed and replaced with backfill in the immediate vicinity of the tank farms.

For the backfill unit, the average moisture content is 8.08 (% volume) (Table B-1), and is the highest among averages for all the units. The backfill unit also has the lowest measured moisture content of 0.11 (% volume) among all units. The maximum measured moisture content for backfill is 30.61 (% volume).

Figure B-10a shows the histogram for all moisture content measurements made in the backfill gravelly unit inside and outside the tank farm (Figure B-2c). Figure B-10b shows the histogram for measurements inside the SST footprint, whereas Figure B-10c shows the histogram for measurements outside the SST footprint. While the average for all backfill measurements is about 8.09% (% volume) (Figure B-10a), inside the tank farm, the average is 6.61 (% volume), with the range varying from ~0.31% to 23.05% and a variance of 7.69% (Figure B-10b). Outside of the SST footprint, the average is considerably higher (9.30 [% volume]), with the range varying from ~0.11% to 30.61% and a large variance of 15.47% (Figure B-10c).

## B.2 LABORATORY-SCALE MEASUREMENTS FOR HYDRAULIC PROPERTIES

The purpose of this section is to summarize data sources and laboratory measurements of core-scale sample properties for different HSUs; these are later upscaled for use in WMA C RCA modeling (Section B.3 below). Core-scale measurements and their parameterization are described below for the following HSUs:

- Hanford H2 Sand Unit
- Hanford H1 and H3 Gravelly Units

- Backfill Gravelly Unit.

### B.2.1 Properties of the Hanford H2 Sand Unit

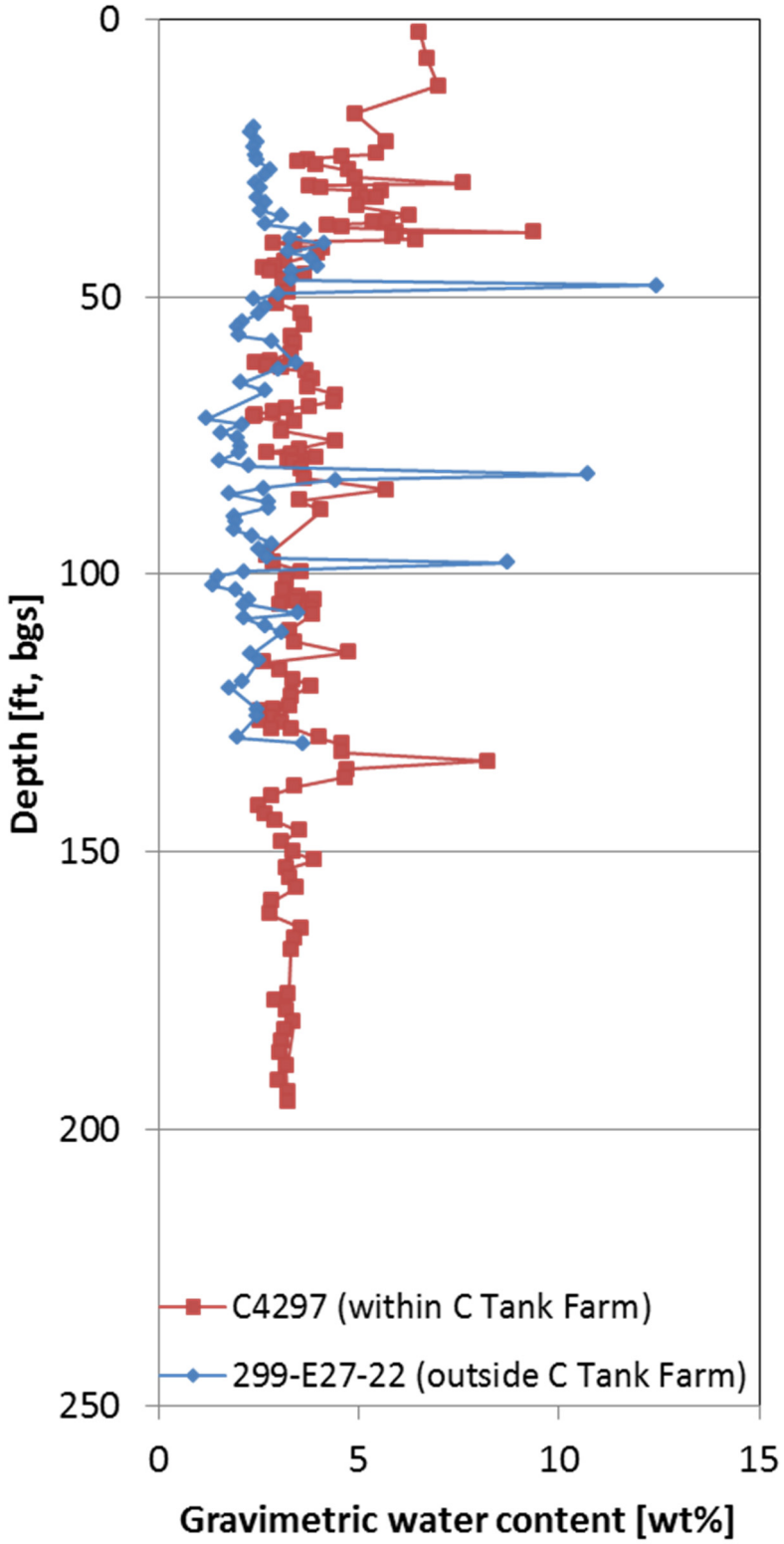
Figure B-11 shows a representative sample of sediments associated with the Hanford H2 sand-dominated unit identified at WMA C. Because site-specific hydraulic properties data are unavailable, the available hydraulic properties database for coarse sands as well as the WMA C moisture content distribution were used to identify and characterize hydraulic properties for the Hanford H2 sand unit identified at WMA C. Soils used to characterize the WMA C Hanford H2 unit properties were similar to those shown in Figure B-11. Using moisture as a proxy, the nearby 200 East Area Integrated Disposal Facility (IDF) site (Figure B-3) coarse sand unit correlates well with the Hanford H2 sand unit identified at WMA C; the IDF coarse sands were thus used as surrogate for the WMA C H2 sands. The primary mission of RCRA-permitted IDF (Figure B-3) is disposal of low-level wastes, mixed low-level wastes, and Immobilized Low-Activity Waste (i.e., the Hanford tank waste that has undergone separations treatment to remove the bulk of the radionuclides and then solidified at the Hanford Waste Treatment and Immobilization Plant).

As part of site characterization for IDF, sediment samples were obtained in fiscal years 1998, 2001 and 2002 via a borehole drilling and sampling program. The Hanford formation sandy H2 sequence identified at the IDF site is ~200 ft (~61 m) thick and, like WMA C, is the dominant facies at the site.

The laboratory procedures used to analyze the IDF H2 borehole samples and analysis of samples from the three boreholes are described in appendices found in RPP-20621, "Far-Field Hydrology Data Package for the Integrated Disposal Facility Performance Assessment." Briefly, the multistep and steady-state methods were used to obtain moisture retention and unsaturated conductivity data. The specific details for the two methods are described in RPP-20621 appendices. Both methods were performed on the same core using the same sensor locations. In addition to cumulative outflow, the multistep method provides water content-matric potential ($\theta$-$\psi$) pairs. These data were used in conjunction with a numerical inversion procedure ("Optimization of Hydraulic Functions from Transient Outflow and Soil Water Pressure Data" [Eching and Hopmans 1993]) to determine the optimal set of van Genuchten model ("A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils" [van Genuchten 1980]) parameters (RPP-20621). The steady-state method, described in "Hydraulic Conductivity and Diffusivity: Laboratory Methods" (Klute and Dirksen 1986), provides water content-matric potential-unsaturated conductivity ($\theta$-$\psi$-$K$) triplets; the method was primarily used as a check on the multistep method.

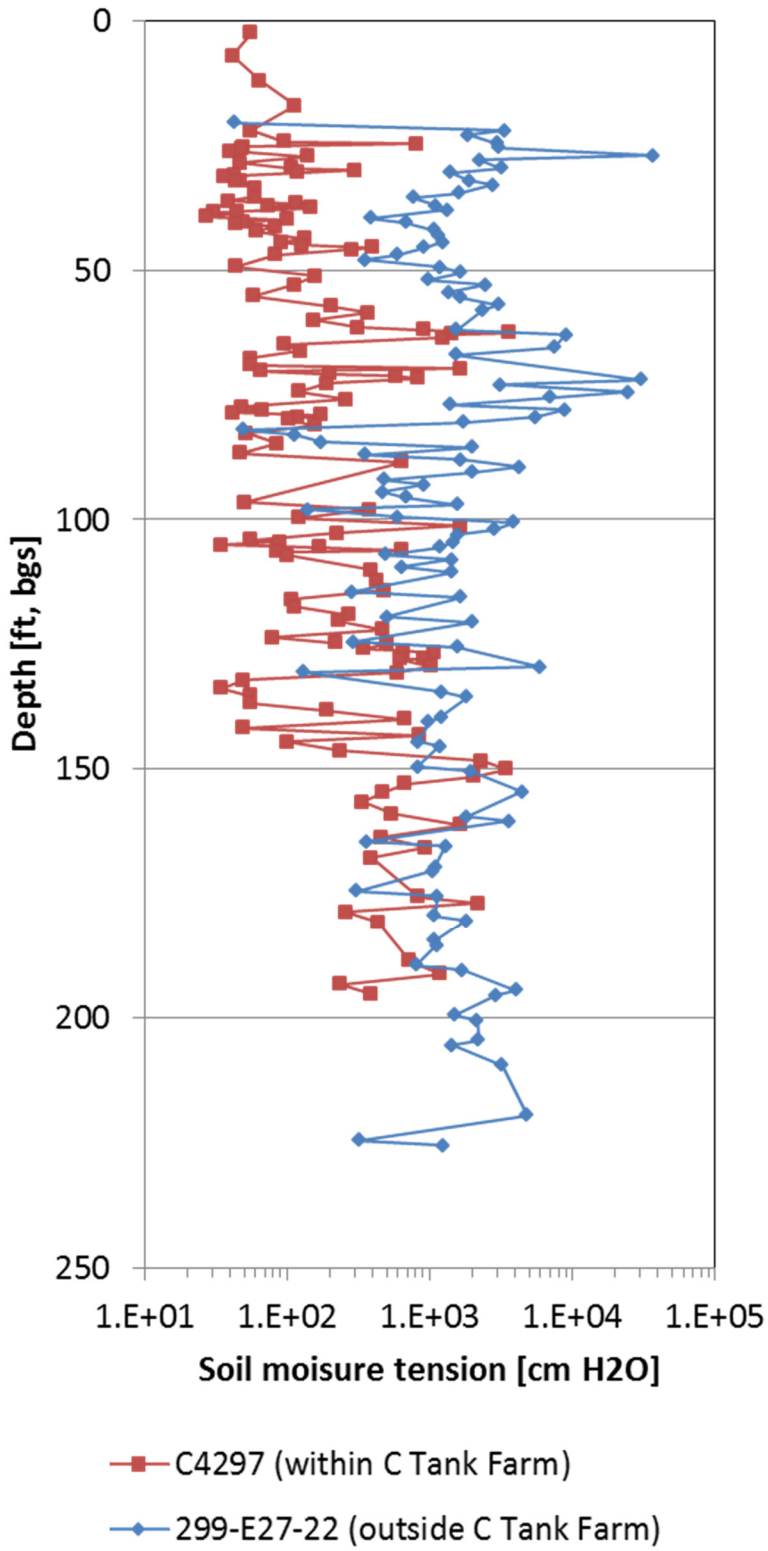
RPP-20621 (Tables 1 through 3) provides the van Genuchten model parameters determined using the numerical inversion procedure and data from the multistep test. The pore-size distribution parameter $\ell$ ("A New Model for Predicting the Hydraulic Conductivity of Unsaturated Porous Media" [Mualem 1976]) was kept fixed at 0.5. The fitted van Genuchten-Mualem parameters for the IDF H2 sandy sequence (44 samples) are reproduced in Table B-1.

**Figure B-8a. Comparison of Gravimetric Moisture Content Measurements for Boreholes C4297 and 299-E27-22.**




Reference: PNNL-15503, "Characterization of Vadose Zone Sediments Below the C Tank Farm: Borehole C4297 and RCRA Borehole 299-E27-22."

**Figure B-8b. Comparison of Soil Moisture Tension Measurements for Boreholes C4297 and 299-E27-22.**




Reference: PNNL-15503, "Characterization of Vadose Zone Sediments Below the C Tank Farm: Borehole C4297 and RCRA Borehole 299-E27-22."

**Figure B-9a. Waste Management Area C Moisture Content Histogram for All H1 Data (Includes the Data from Both Inside and Outside of the Single-Shell Tank Footprint).**

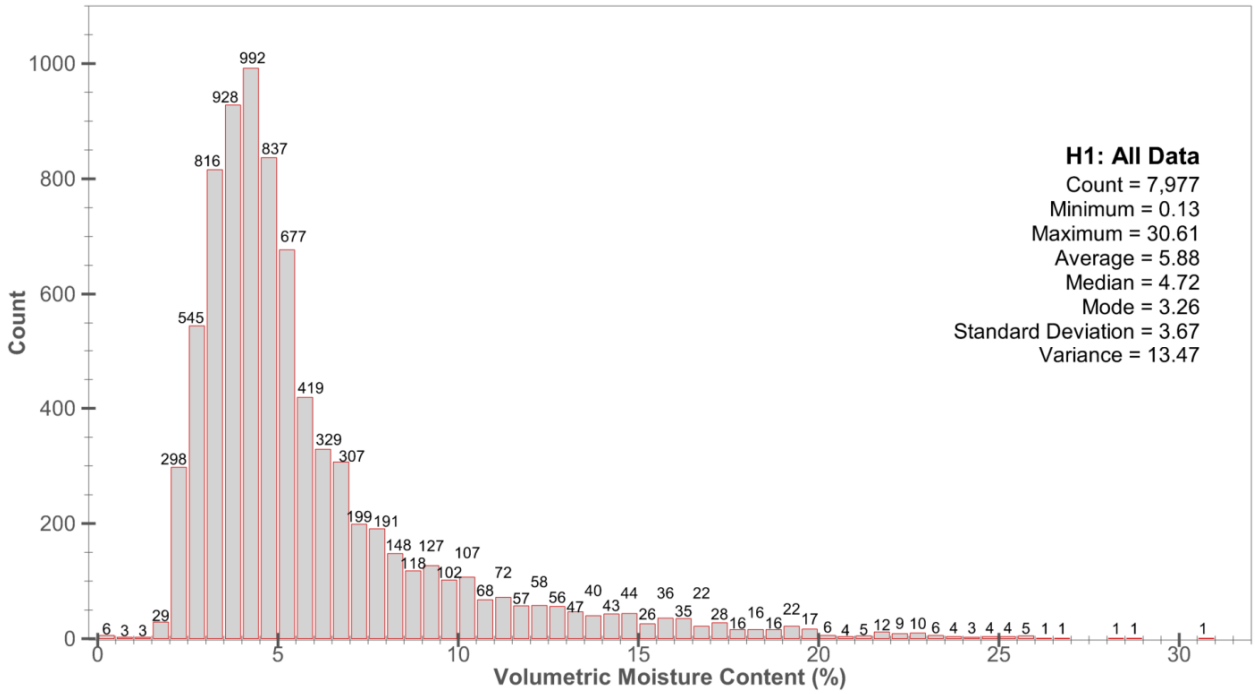
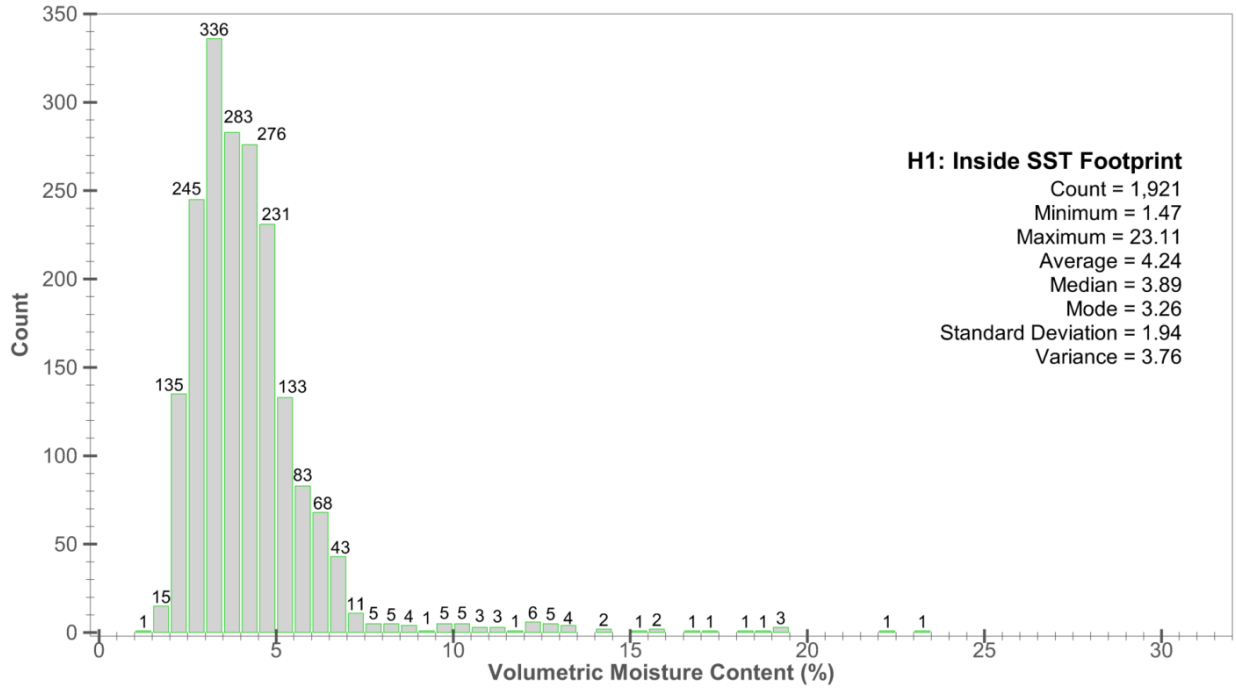
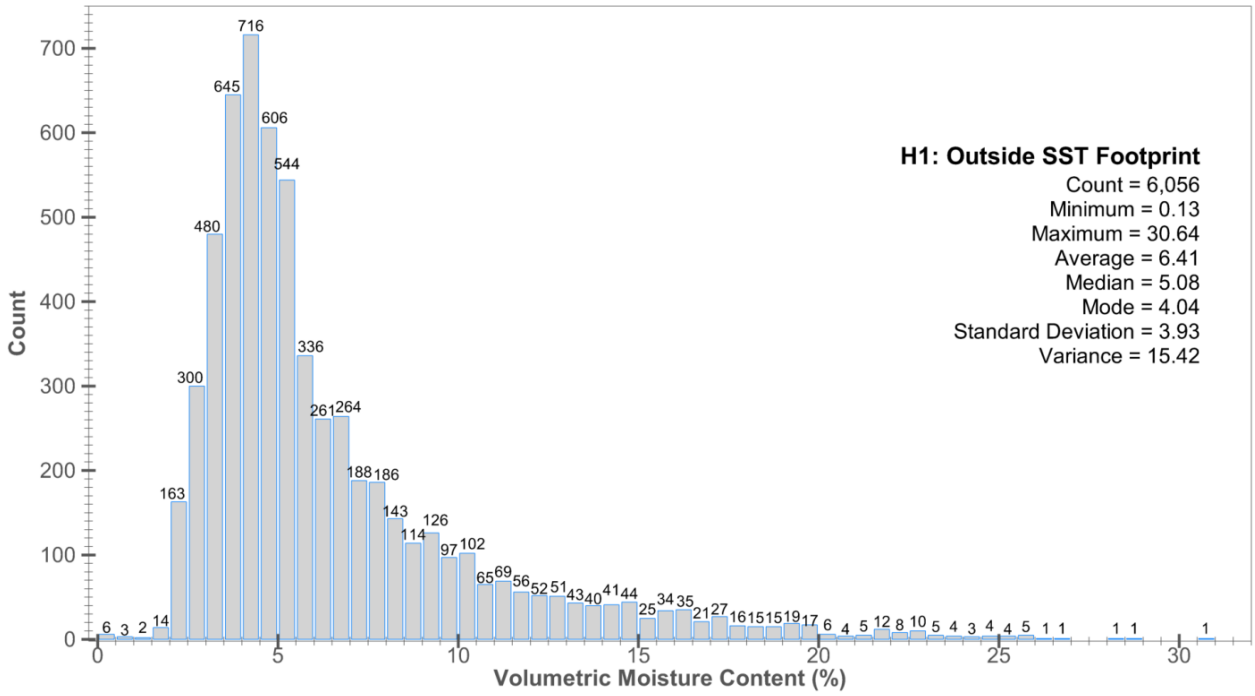



**Figure B-9b. Waste Management Area C Moisture Content Histogram for H1 Data Within the Single-Shell Tank Footprint.**




SST = single-shell tank

**Figure B-9c. Waste Management Area C Moisture Content Histogram for H1 Data Outside of the Single-Shell Tank Footprint.**




SST = single-shell tank

**Figure B-10a. Waste Management Area C Moisture Content Histogram for All Backfill Data (Includes the Data from Both Inside and Outside of the Single-Shell Tank Footprint).**

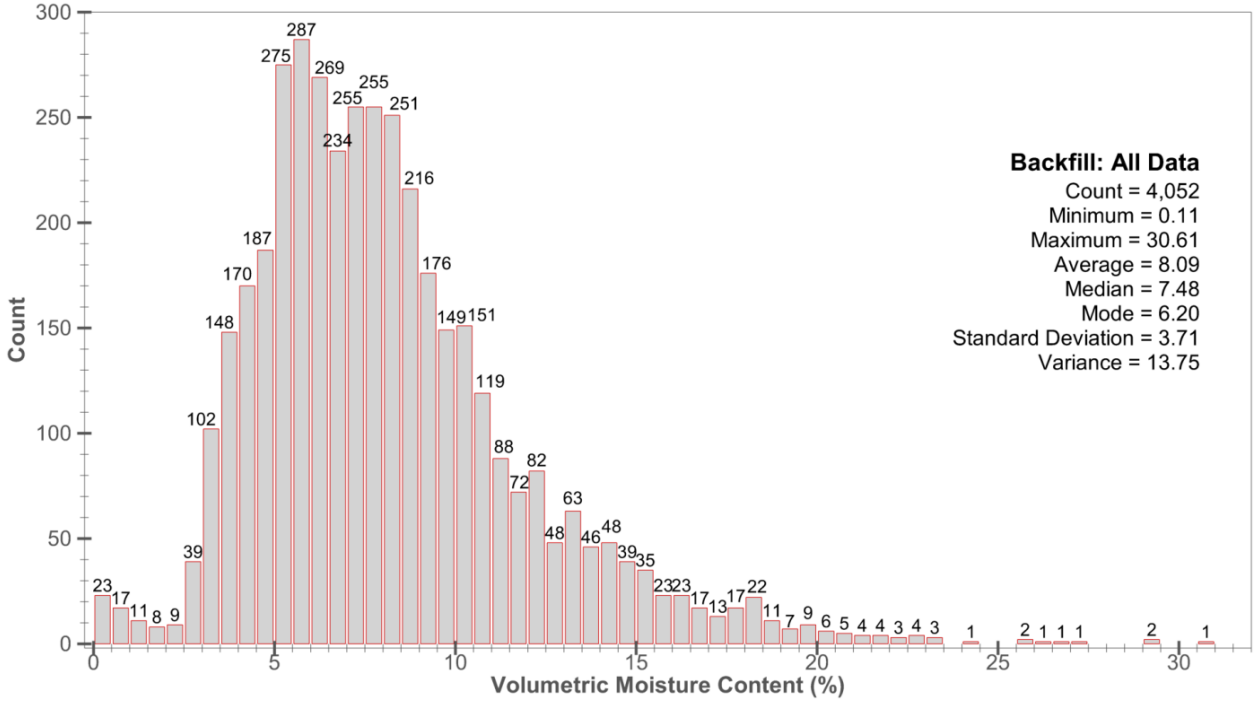
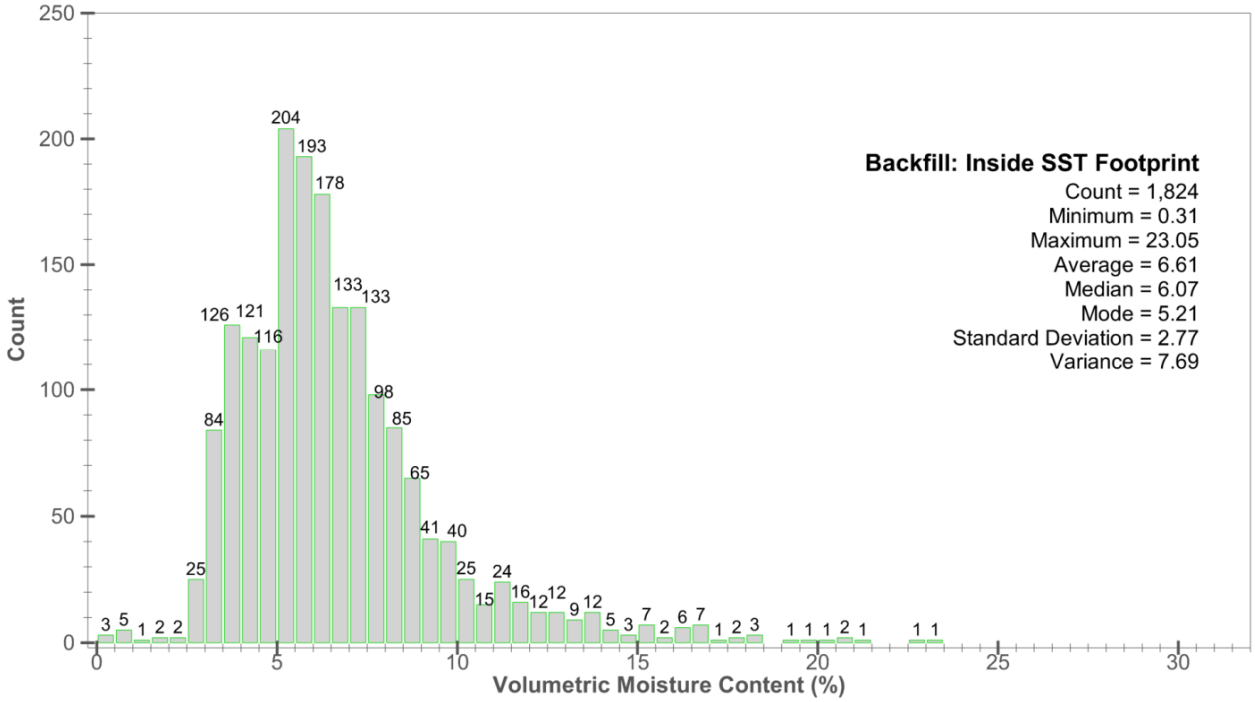
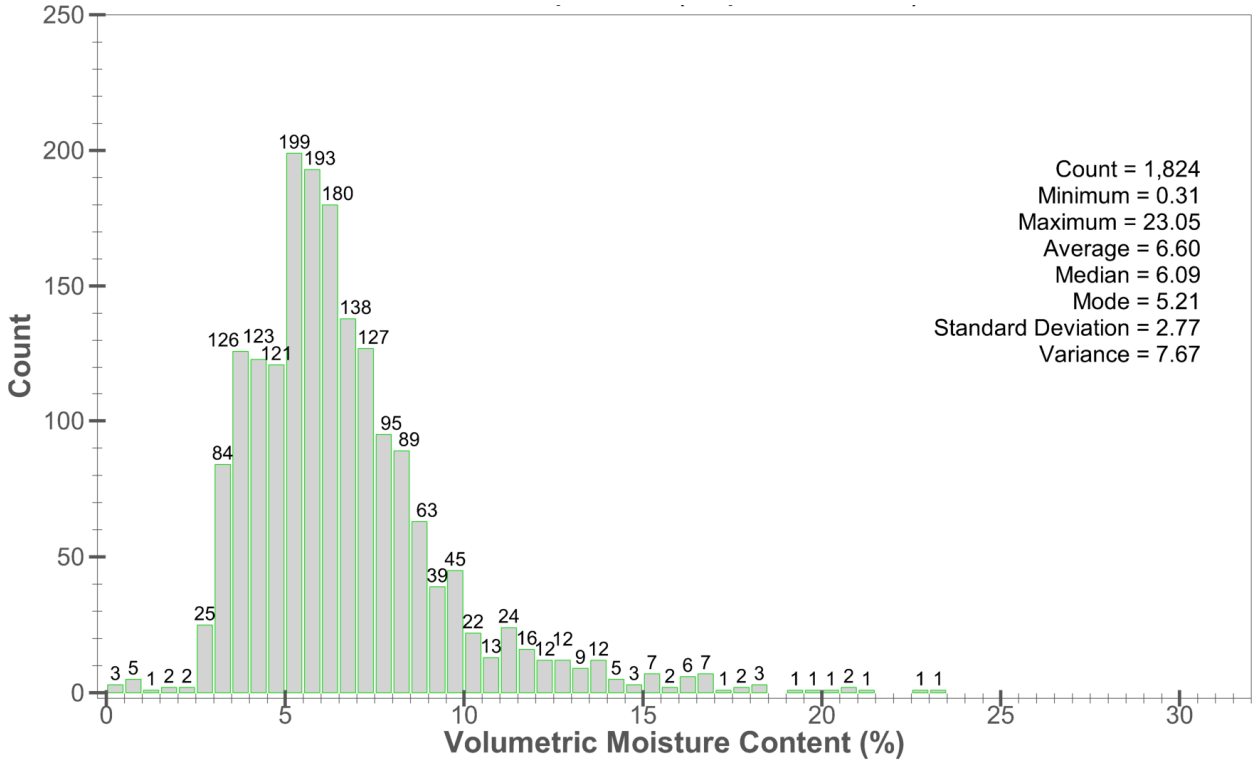


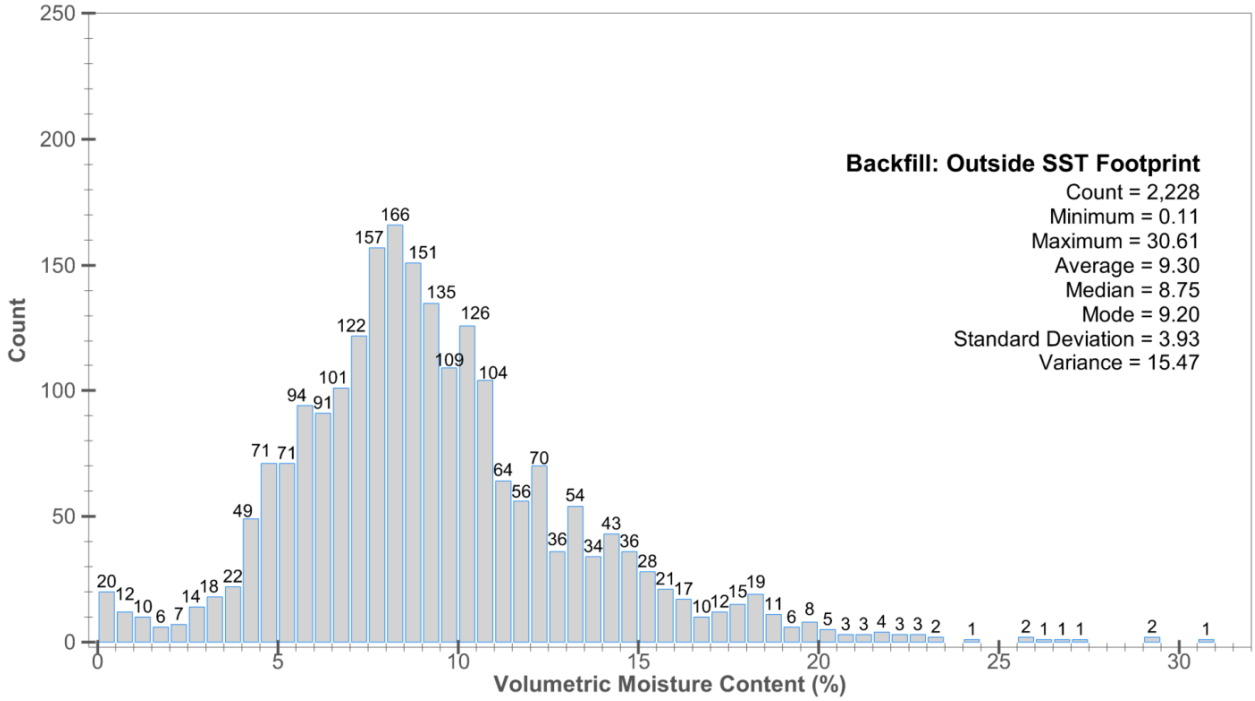
**Figure B-10b. Waste Management Area C Moisture Content Histogram for Backfill Data Inside of the Single-Shell Tank Footprint.**




SST = single-shell tank

**Figure B-10c. Waste Management Area C Moisture Content Histogram for Backfill Data Outside the Single-Shell Tank Footprint.**



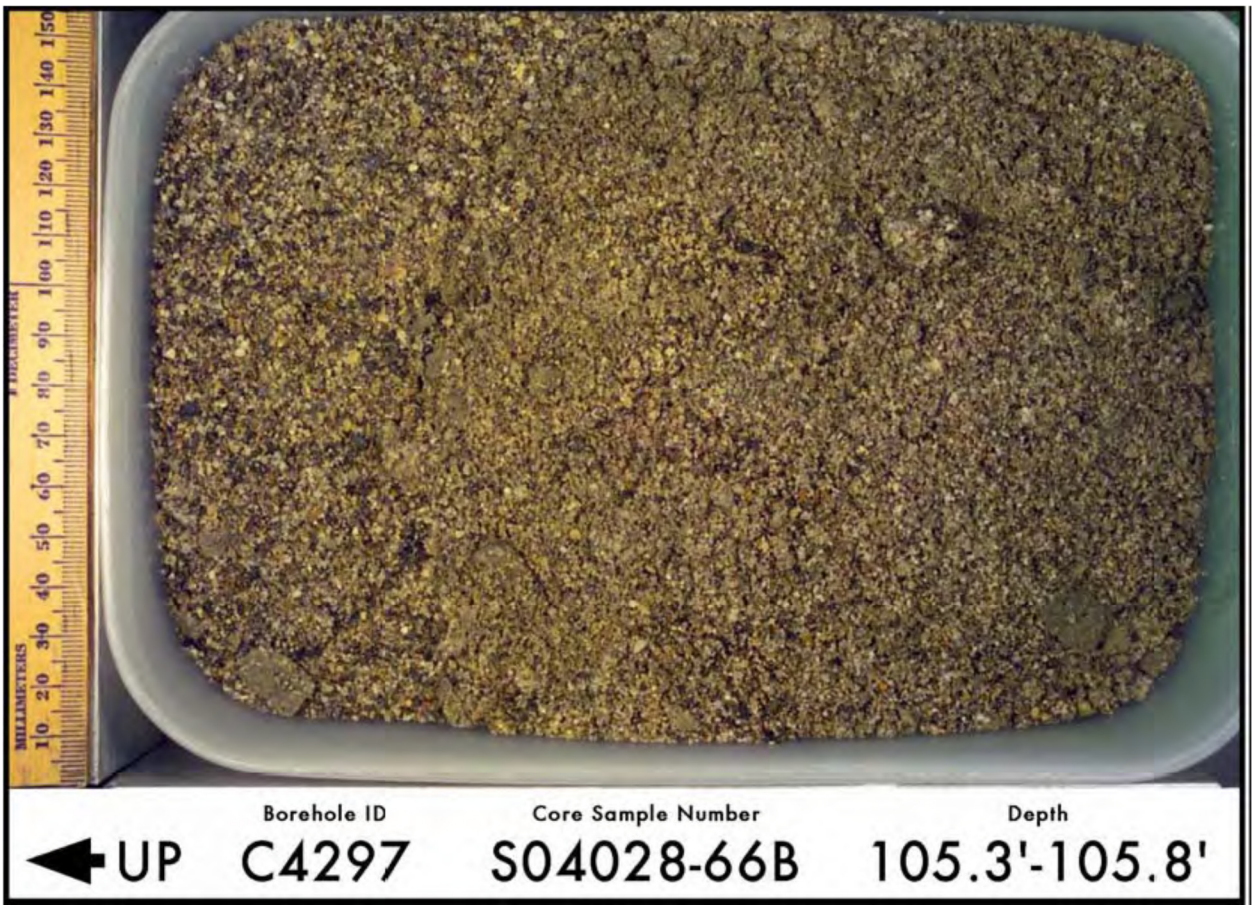

SST = single-shell tank

The IDF H2 samples contain very little gravel (>2-mm size) (RPP-20621). To account for the presence of gravel fraction for WMA C samples, the IDF H2 moisture retention data (Table B-3) were corrected ("Correcting laboratory-measured moisture retention data for gravels" [Khaleel and Relyea 1997]). Table B-4 data suggest that the gravel fraction for the H2 unit can range from less than 1% to about 25%. Also, borehole logs (PNNL-15503) suggest the presence of a high gravel fraction, and many WMA C H2 samples are characterized as "sandy pebble gravel" and "pebbly sand." A gravel fraction of 20% was assumed and applied to correct the IDF retention data. The fitted moisture retention curves and unsaturated conductivity curves for H2 sandy sequence as well as the WMA C H2 composite curves are shown in Figures B-12 and B-13, respectively. To obtain the composite curves, all measurements for an equivalent homogeneous medium (EHM) were pooled and the composite van Genuchten parameters were obtained via RETC (RETention Curve) code (EPA/600/2-91/065, The RETC Code for Quantifying the Hydraulic Functions of Unsaturated Soils) and a simultaneous fit of both moisture retention and unsaturated conductivity data. The composite curves account for gravel correction (Khaleel and Relyea 1997).

**B.2.1.1 Comparison of Simulated and Observed Moisture Content.** As stated earlier, the selected properties were used to simulate a vadose zone flow field and the simulation results were cross-checked against WMA C field-measured moisture contents. Figure B-14 shows a comparison of measured moisture profile for borehole C4297 (Figure B-5) and the simulated steady-state moisture profile for WMA C. As indicated, for an expected long-term recharge estimate of 3.5 mm/yr, the simulated H2 moisture profile compares well with the measurements. Overall, the simulated H2 moisture content of ~6 (% volume) is in agreement with the average

WMA C H2 moisture of ~5.15 (% volume) (Table B-1). As stated in Section B.1.1, the averages for moisture content measurements for H2 inside and outside the SST footprint were not significantly different even though the recharge conditions outside the farm are different (lower infiltration) from those inside the farm (higher infiltration). As expected, the field-measured moisture contents are significantly impacted by small-scale heterogeneities and exhibit considerable variability (Figure B-14). To the contrary, the RCA simulations are based on upscaled or effective hydraulic properties; each heterogeneous formation is replaced by its homogeneous equivalent, and the upscaled or effective flow parameters are used to represent the EHM. This effectively results in a smoothing of the model estimates (Figure 7-3). Therefore, the variability of field-measured moisture contents, induced by media heterogeneities, is inherently larger in comparison to that based on RCA simulations using homogenized upscaled properties, and the ensemble average, embedded in EHM approximation, cannot capture the field-scale variability.

**Figure B-11. Waste Management Area C Hanford H2 Sand-Dominated Core.**




Reference: PNNL-15503, "Characterization of Vadose Zone Sediments Below the C Tank Farm: Borehole C4297 and RCRA Borehole 299-E27-22."

Similar comparison was also made for other units using their selected properties (presented below); for a recharge estimate of 3.5 mm/yr, the steady-state simulated moisture contents and the field-measured average moisture contents (Table B-1) compared well.

**Table B-3. van Genuchten Parameters (Based on the Multistep Method) and Saturated Hydraulic Conductivity Data for 44 Integrated Disposal Facility Borehole Samples from the H2 Sandy Sequence. (2 sheets)**

| Sample | $\theta_s$ (cm$^3$/cm$^3$) | $\theta_r$ (cm$^3$/cm$^3$) | $\alpha$ (1/cm) | $n$ (-) | Saturated Hydraulic Conductivity (cm/s) |
|---|---|---|---|---|---|
| 7A[1] | 0.377 | 0.0404 | 0.0290 | 1.825 | 1.04E-03 |
| 10A[1] | 0.413 | 0.0279 | 0.1161 | 1.784 | 2.95E-03 |
| 12A[1] | 0.363 | 0.0309 | 0.0650 | 1.755 | 2.15E-03 |
| 14A[1] | 0.416 | 0.0324 | 0.0445 | 1.728 | 1.99E-03 |
| 15A[1] | 0.380 | 0.0254 | 0.0487 | 1.844 | 2.09E-03 |
| 16A[1] | 0.420 | 0.0228 | 0.0682 | 1.710 | 9.57E-03 |
| 17A[1] | 0.423 | 0.0382 | 0.0689 | 1.899 | 1.99E-03 |
| 19A[1] | 0.444 | 0.0279 | 0.2010 | 1.542 | 4.31E-03 |
| 20A[1] | 0.419 | 0.0321 | 0.0305 | 2.081 | 2.54E-03 |
| 21A[1] | 0.403 | 0.0276 | 0.0545 | 1.926 | 2.94E-03 |
| 22A[1] | 0.352 | 0.0252 | 0.1078 | 1.585 | 5.06E-03 |
| 23A[1] | 0.371 | 0.0411 | 0.0079 | 1.553 | 2.65E-04 |
| 24A[1] | 0.321 | 0.0413 | 0.0130 | 1.684 | 5.69E-04 |
| 25A[1] | 0.345 | 0.0267 | 0.0842 | 2.158 | 5.40E-03 |
| 27A[1] | 0.377 | 0.0354 | 0.0830 | 1.532 | 8.14E-03 |
| 29A[1] | 0.359 | 0.0317 | 0.0784 | 1.732 | 3.75E-03 |
| 31A[1] | 0.418 | 0.0444 | 0.0058 | 2.012 | 8.21E-04 |
| 32A[1] | 0.359 | 0.0401 | 0.0931 | 1.703 | 6.71E-03 |
| 34A[1] | 0.316 | 0.0324 | 0.0819 | 2.398 | 1.32E-02 |
| 35A[1] | 0.299 | 0.0428 | 0.0897 | 2.160 | 1.06E-02 |
| 45L[2] | 0.385 | 0.008 | 0.1039 | 1.737 | 3.24E-2 |
| 45U[2] | 0.385 | 0.005 | 0.088 | 1.664 | 3.24E-2 |
| 50L[2] | 0.420 | 0.025 | 0.073 | 1.710 | 1.75E-3 |
| 50U[2] | 0.420 | 0.013 | 0.045 | 1.667 | 1.75E-3 |
| 80L[2] | 0.359 | 0.031 | 0.0403 | 2.368 | 1.05E-3 |
| 80U[2] | 0.359 | 0.033 | 0.0313 | 2.572 | 1.05E-3 |

**Table B-3. van Genuchten Parameters (Based on the Multistep Method) and Saturated Hydraulic Conductivity Data for 44 Integrated Disposal Facility Borehole Samples from the H2 Sandy Sequence. (2 sheets)**

| Sample | $\theta_s$ (cm$^3$/cm$^3$) | $\theta_r$ (cm$^3$/cm$^3$) | $\alpha$ (1/cm) | $n$ (-) | Saturated Hydraulic Conductivity (cm/s) |
|---|---|---|---|---|---|
| 85L[2] | 0.406 | 0.023 | 0.1074 | 1.697 | 3.84E-2 |
| 85U[2] | 0.406 | 0.027 | 0.0847 | 1.595 | 3.84E-2 |
| 110L[2] | 0.412 | 0.039 | 0.0362 | 2.328 | 5.16E-4 |
| 110U[2] | 0.412 | 0.046 | 0.0268 | 3.182 | 5.16E-4 |
| 130L[2] | 0.358 | 0.032 | 0.0940 | 2.003 | 1.97E-2 |
| 130U[2] | 0.358 | 0.036 | 0.0674 | 1.934 | 1.97E-2 |
| 150L[2] | 0.431 | 0.015 | 0.0992 | 1.547 | 7.48E-3 |
| 150U[2] | 0.431 | 0.024 | 0.0703 | 1.514 | 7.48E-3 |
| 200L[2] | 0.410 | 0.002 | 0.0995 | 2.162 | 4.93E-2 |
| 215L[2] | 0.370 | 0.028 | 0.0448 | 1.918 | 2.24E-3 |
| 215U[2] | 0.370 | 0.023 | 0.0333 | 1.815 | 2.24E-3 |
| 230L[2] | 0.309 | 0.040 | 0.0472 | 1.658 | 3.56E-3 |
| 230U[2] | 0.309 | 0.038 | 0.0400 | 1.658 | 3.56E-3 |
| 251L[2] | 0.427 | 0.032 | 0.084 | 1.845 | 1.43E-2 |
| 261L[2] | 0.390 | 0.045 | 0.0191 | 2.485 | 5.54E-4 |
| C3826-171[3] | 0.382 | 0.0226 | 0.0390 | 1.840 | 7.96E-3 |
| C3827-63.5[3] | 0.444 | 0.0 | 0.0914 | 1.500 | 2.23E-2 |
| C3827-221[3] | 0.361 | 0.0220 | 0.0660 | 1.770 | 7.30E-3 |

[1]Fiscal year 1998 borehole.
[2]Fiscal year 2001 borehole.
[3]Fiscal year 2002 borehole.

Reference: RPP-20621, "Far-Field Hydrology Data Package for the Integrated Disposal Facility Performance Assessment."

**B.2.1.2 Alternative Geologic Model Properties.** The preceding sections have identified parameters for the soils in Alternative Geologic Model I (ACM-I). Alternative Geologic Model II (ACM-II) is a slight variation (see Section 7) of ACM-I. The primary difference between the two alternative models concerns whether or not a sandy gravel facies followed by a silty sandy layer exist at the bottom of the H2 unit in the vicinity of WMA C. Figure B-15 illustrates the moisture retention curves for ACM-II, whereas Figure B-16 illustrates the unsaturated conductivity curves for ACM-II.

**Table B-4. Wet Sieve Particle Size Distribution for Borehole 299-E27-22 Sediments.**

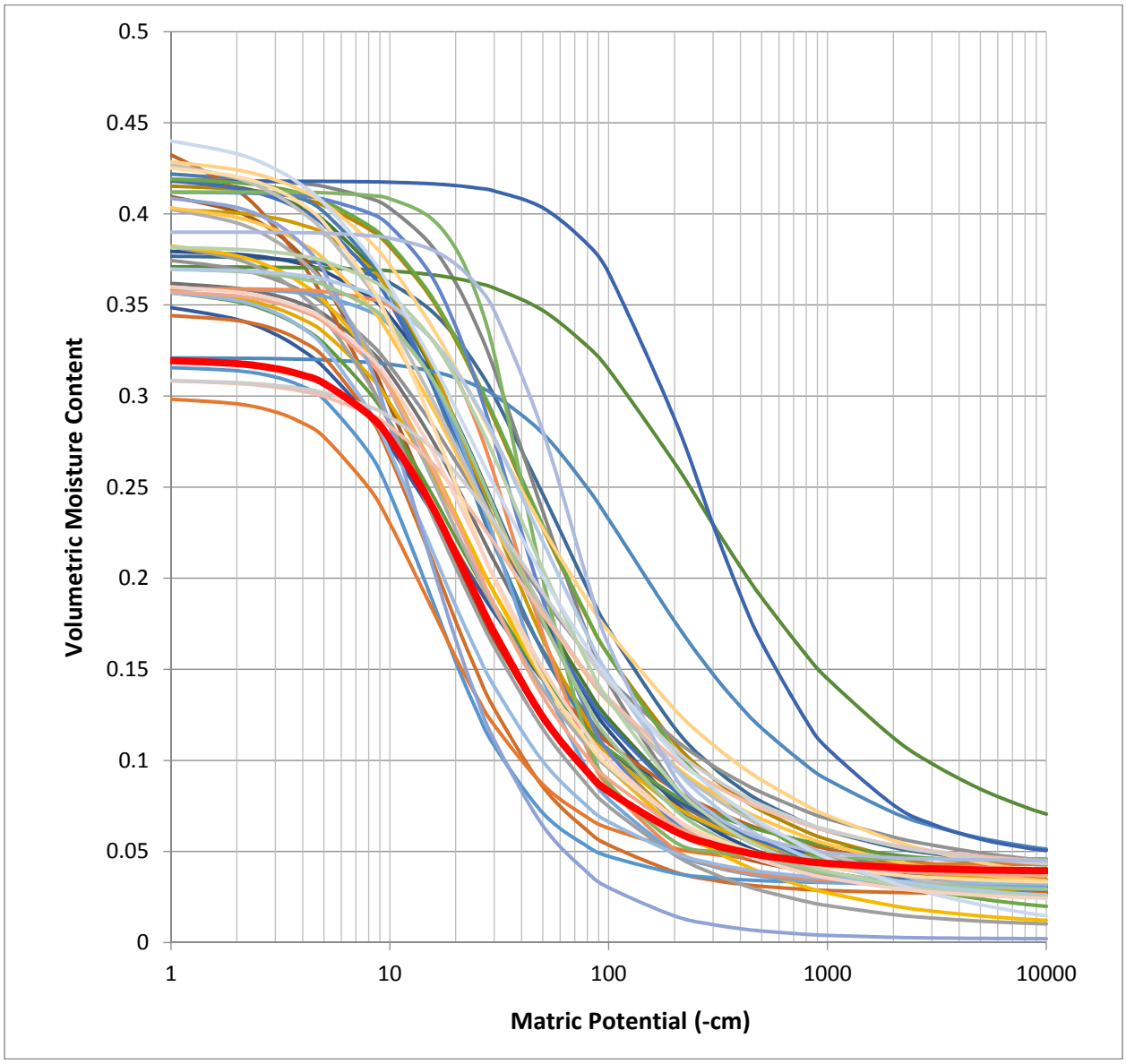
| Depth (ft bgs) | Stratigraphic Unit (Hanford formation) | Weight Percent | | |
|---|---|---|---|---|
| | | Gravel | Sand | Silt/Clay |
| 28.0 | H1 | 28.2 | 62.9 | 8.78 |
| 40.5 | H1 | 0.104 | 85.1 | 14.3 |
| 45.5 | H1 | 0.136 | 88.9 | 10.5 |
| 48.0 | H1 | 0 | 61.6 | 36.3 |
| 50.5 | H1 | 22.1 | 72.3 | 5.58 |
| 78.0 | H1 | 11.0 | 77.6 | 11.2 |
| 82.0 | H2 | 0.165 | 87.5 | 11.9 |
| 85.5 | H2 | 1.74 | 89.6 | 8.61 |
| 95.5 | H2 | 1.10 | 88.4 | 10.4 |
| 100.5 | H2 | 0.424 | 90.8 | 8.62 |
| 139.5 | H2 | 0.112 | 88.4 | 11.0 |
| 145.5 | H2 | 24.7 | 66.1 | 9.09 |
| 160.5 | H2 | 15.9 | 68.8 | 15.2 |
| 164.5 | H2 | 3.21 | 89.1 | 7.53 |
| 185.5 | H2 | 18.9 | 60.9 | 20.0 |
| 200.5 | H2 | 17.3 | 73.5 | 9.12 |
| 210.5 | H2 | 17.1 | 68.5 | 14.2 |
| 225.5 | H2 | 11.7 | 76.2 | 11.9 |

Reference: PNNL-15503, "Characterization of Vadose Zone Sediments Below the C Tank Farm: Borehole C4297 and RCRA Borehole 299-E27-22."

### B.2.2 Properties of the Hanford H1 and H3 Gravelly Units

Similar to the Hanford H2 sand-dominated unit, no site-specific data are available for the WMA C Hanford H1 and H3 gravelly units. However, as part of other Hanford Site projects, particle-size distribution, bulk density, saturated hydraulic conductivity, moisture retention, and unsaturated conductivity data have been collected for several borehole samples (Figure B-3) at other sites in the vicinity of C Farm and within the 200 Areas. These sites include the 218-E-12B and 218-E-10 low-level solid waste burial grounds in 200 East Area, the Environmental Restoration Disposal Facility site located in between the 200 West and 200 East Areas, and the 241-T-106 tank site located in 200 West Area. Borehole sediment samples from these sites were used as surrogates to represent the hydraulic properties for WMA C H1 and H3 gravel-dominated units.

**Figure B-12. Moisture Retention Data for H2 Unit (44 Samples). The Waste Management Area C H2 composite curve is shown in red.**

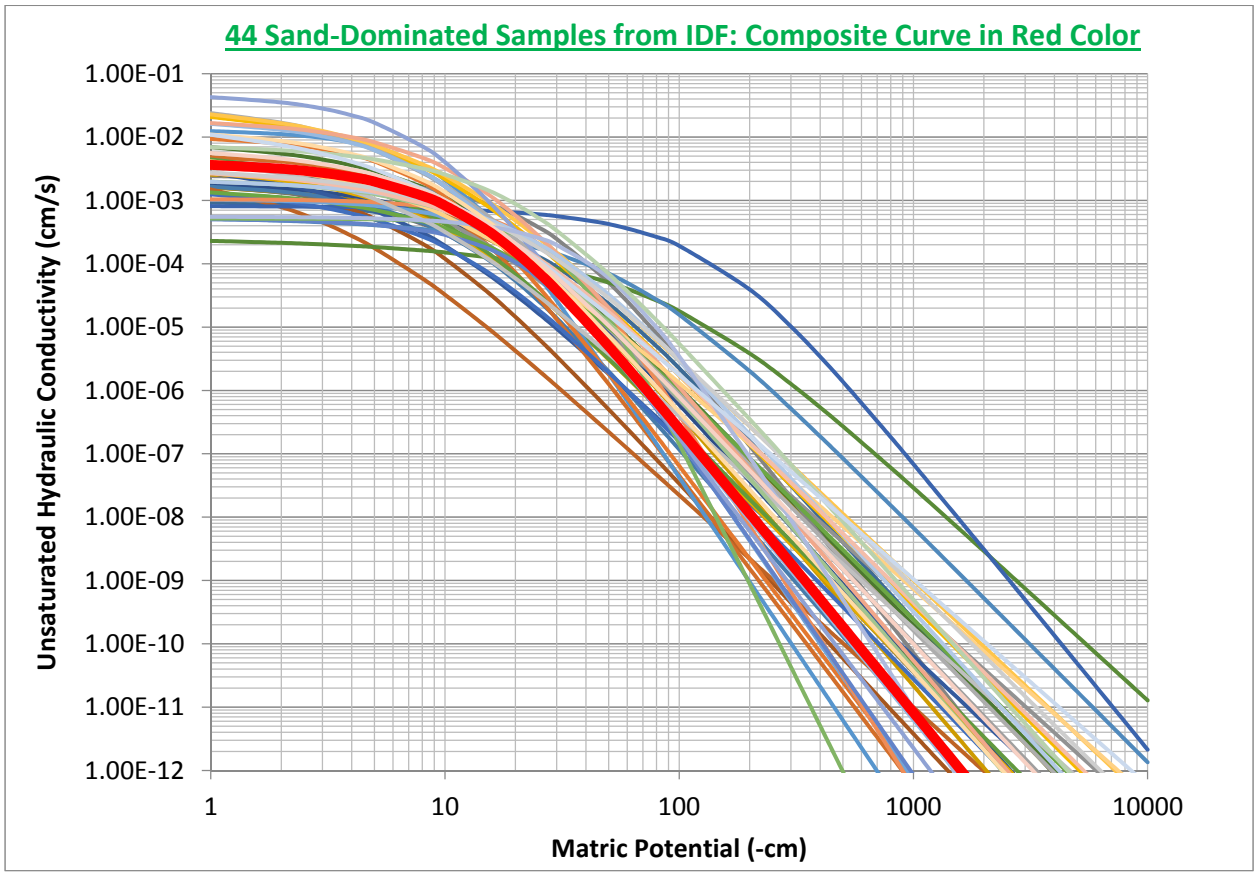



Reference: RPP-20621, "Far-Field Hydrology Data Package for the Integrated Disposal Facility Performance Assessment."

Unlike H2 sediments, both H1 and H3 sediments are comprised of a significant gravel (>2-mm size) fraction. To explore the impact of gravelly sediments for the drier moisture regime, a separate study was conducted ("Variability of Gardner's α for coarse-textured sediments" [Khaleel and Relyea 2001]); a total of 79 gravelly and sandy samples were analyzed in the laboratory. The gravel fraction for 41 samples ranged from 20 to 71% (by weight); the remaining 38 samples were sandy with very little gravel fraction (Figure B-17). A noteworthy feature of Figure B-17 is the fact that the variability in saturated conductivity is much greater than the variability in unsaturated conductivity near saturation. Furthermore, the measured unsaturated conductivities for the gravelly samples showed less variability for the drier moisture

regime, fell within a narrower range, and were well within the range of measured unsaturated conductivities for the sandy samples (see Figure B-17). Such a generic behavior for the gravelly sediments for the drier moisture regime prompted assigning similar properties for both H1 and H3 units.

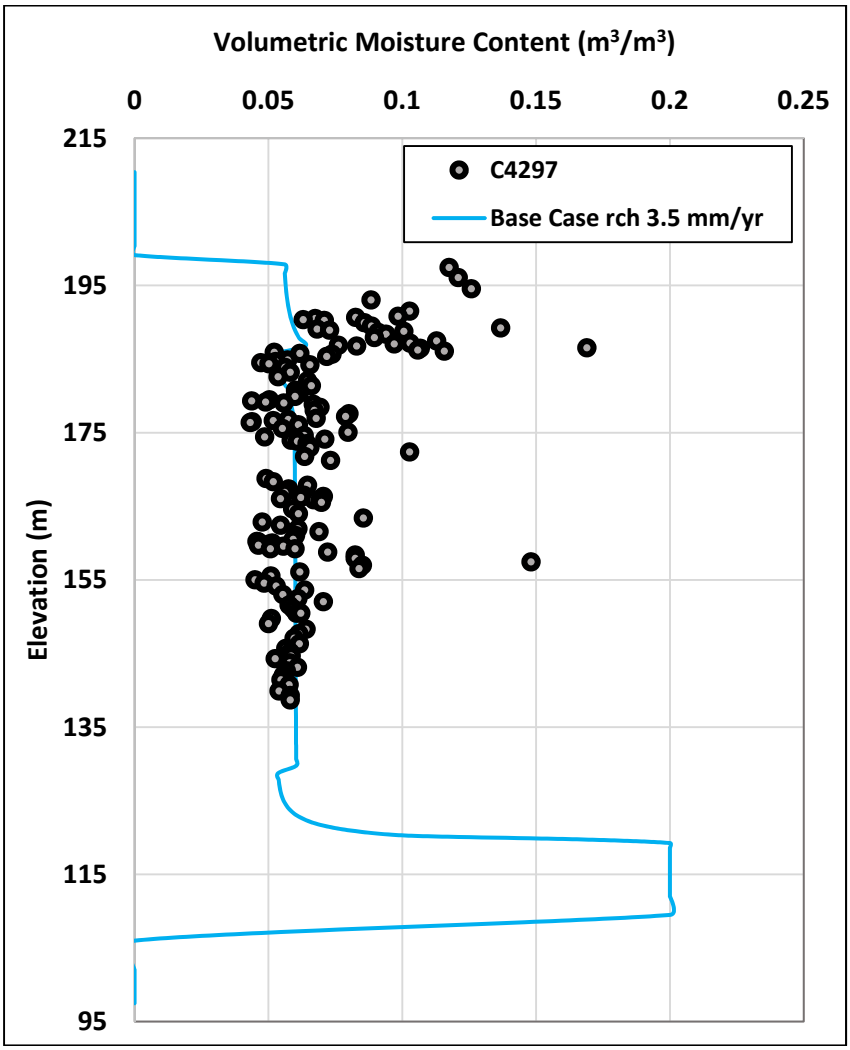
**Figure B-13. Unsaturated Hydraulic Conductivity Data for H2 Unit (44 Samples). The Waste Management Area C H2 composite curve is shown in red.**




Reference: RPP-20621, "Far-Field Hydrology Data Package for the Integrated Disposal Facility Performance Assessment."

Standard laboratory and Westinghouse Hanford Company quality assurance procedures (WHC-IP-0635, "Geotechnical Engineering Procedure Manual") were used to analyze the H1 and H3 sediment samples. The moisture retention data for the fine fraction (<2 mm) and the drainage cycle of up to -1,000 cm of pressure head were measured using "Tempe" pressure cells; the rest of the drainage data up to -15,000 cm was measured using the pressure plate extraction method ("Water Retention: Laboratory Methods" [Klute 1986]). A variation of the unit gradient method (Klute and Dirksen 1986, Khaleel et al. 1995) was used to measure unsaturated hydraulic conductivities for the bulk samples. The laboratory measured data on <2 mm size fraction were corrected for the gravel fraction ("Water Content" in Methods of Soils Analysis, Part 1—Physical and Mineralogical Methods [Gardner 1986]; Khaleel and Relyea 1997). No correction was needed for the saturated and unsaturated conductivities, since these were measured on the bulk sample.

**Figure B-14. Comparison of Simulated (Blue) and Observed (Circle) Moisture Content for Hanford H2 Sand-Dominated Unit.**




As was done for the Hanford H2 sandy unit, a simultaneous fit of both laboratory-measured moisture retention and unsaturated conductivity data was used; and all five unknown parameters (i.e., $\theta_r$, $\theta_s$, $\alpha$, n, and $K_s$), with m=1-1/n (van Genuchten 1980), were fitted to the data via RETC (EPA/600/2-91/065). The pore size distribution factor, $\ell$ (Mualem 1976), was kept fixed at 0.5 during the simultaneous fitting. The fitted parameters, based on moisture retention and unsaturated conductivity measurements for H1 and H3 units, are shown in Table B-5. The fitted retention and conductivity curves for H1 and H3 units are shown in Figure B-18 and Figure B-19, respectively.

### B.2.3 Properties for the Backfill Gravelly Unit

Because of high gravel content, the backfill hydraulic properties are expected to be similar to H1 and H3 gravelly media properties. Table B-6 catalogs the van Genuchten-Mualem parameters for samples that were selected from the 200 Areas database to represent the WMA C tank farm

backfill sediments. Because the backfill includes a significant gravel fraction, most of the samples (Table B-6) are repeats of the 17 samples used to represent the H1 and H3 gravelly units. The fitted retention and conductivity curves for the backfill unit are shown in Figure B-20 and Figure B-21, respectively.

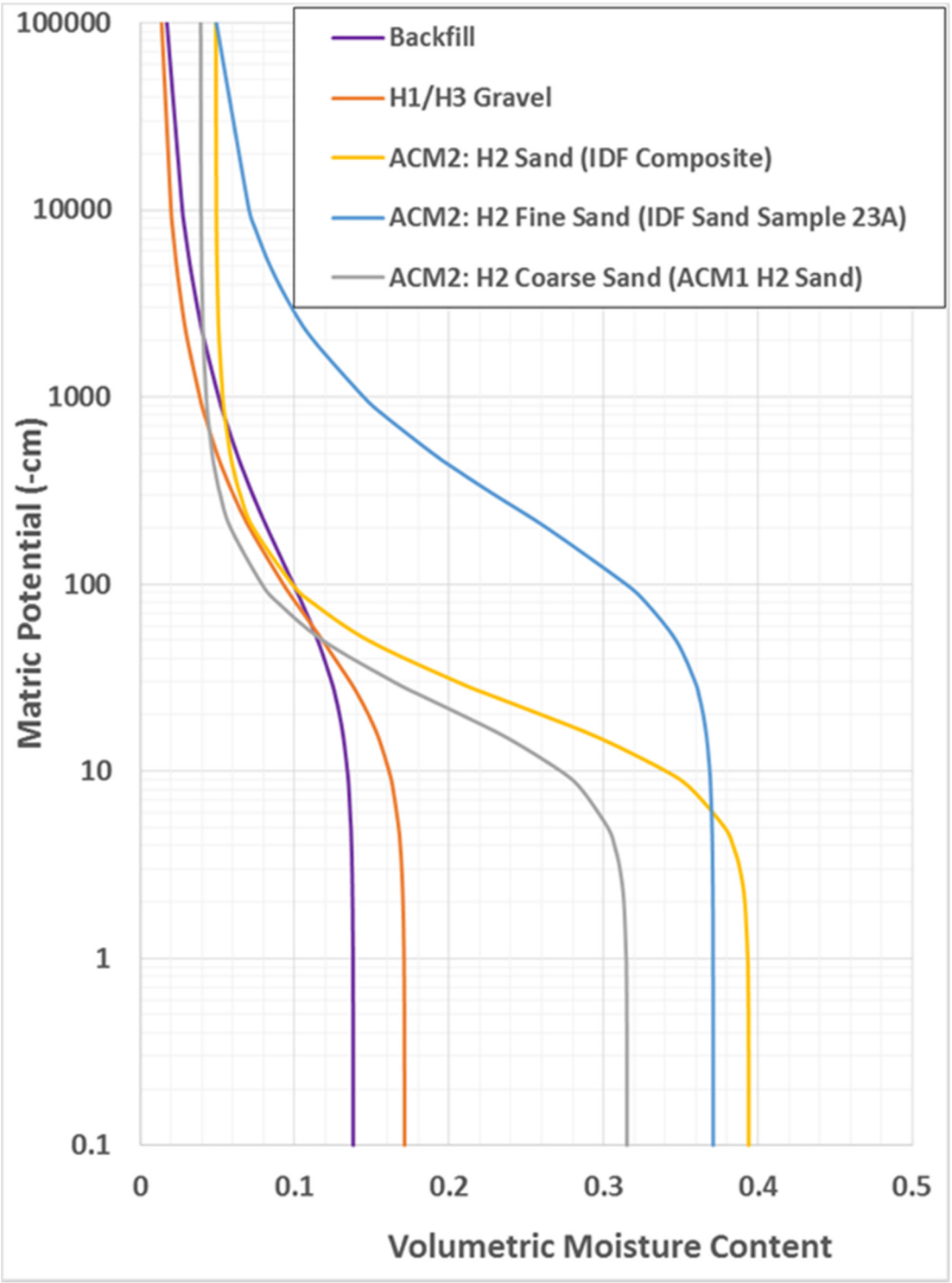
## B.3 EFFECTIVE (UPSCALED) FLOW PARAMETERS FOR VADOSE ZONE

Data on hydraulic properties, described in the preceding sections, were obtained via laboratory tests on core samples (scales of the order of a few centimeters). However, numerical models of fluid flow and contaminant transport in the unsaturated zone require specifying hydraulic properties for each discretized grid block (scales of the order of meters), which are much larger than the core scale at which the unsaturated properties are measured. The process of defining large-scale properties for the numerical grid blocks based on small, core-scale measurements is called upscaling ("Upscaled Flow and Transport Properties for Heterogeneous Unsaturated Media" [Khaleel et al. 2002]).

For stratified sediments such as those existing in the 200 Areas, the effective hydraulic conductivity tensor is anisotropic with a moisture-dependent (or tension-dependent) degree of anisotropy. The anisotropy ratio of horizontal hydraulic conductivity to vertical hydraulic conductivity increases with decreasing moisture content. Theoretical work on variable anisotropy includes, for example, "Stochastic Analysis of Unsaturated Flow in Heterogeneous Soils, 2. Statistically Anisotropic Media with Variable α" (Yeh et al. 1985), "Stochastic Modeling of Large-Scale Transient Unsaturated Flow Systems" (Mantoglou and Gelhar 1987), and "Estimation of effective unsaturated hydraulic conductivity tensor using spatial moments of observed moisture plume" (Yeh et al. 2005). Experimental studies supporting variable anisotropy include, for example, "Dependence of Anisotropy on Saturation in a Stratified Sand" (Stephens and Heermann 1988), "Effective Unsaturated Hydraulic Conductivity of Layered Sands" (Yeh and Harvey 1990), and "Hysteresis and State-Dependent Anisotropy in Modeling Unsaturated Hillslope Hydrologic Processes" (McCord et al. 1991). Variable, moisture-dependent anisotropy in unsaturated soils, in effect, is an effective, large-scale (macroscopic) flow property which results from media heterogeneities at a smaller scale, and provides a framework for upscaling laboratory-scale measurements to delineate the effective or upscaled properties for the large-scale vadose zone. A stochastic model (i.e., "Application of Stochastic Methods to Transient Flow and Transport in Heterogeneous Unsaturated Soils" [Polmann 1990]) is used to describe moisture- or tension-dependent anisotropy for WMA C sediments. Such an upscaling process recognizes the spatial variability inherent in heterogeneous media such as those existing at WMA C.

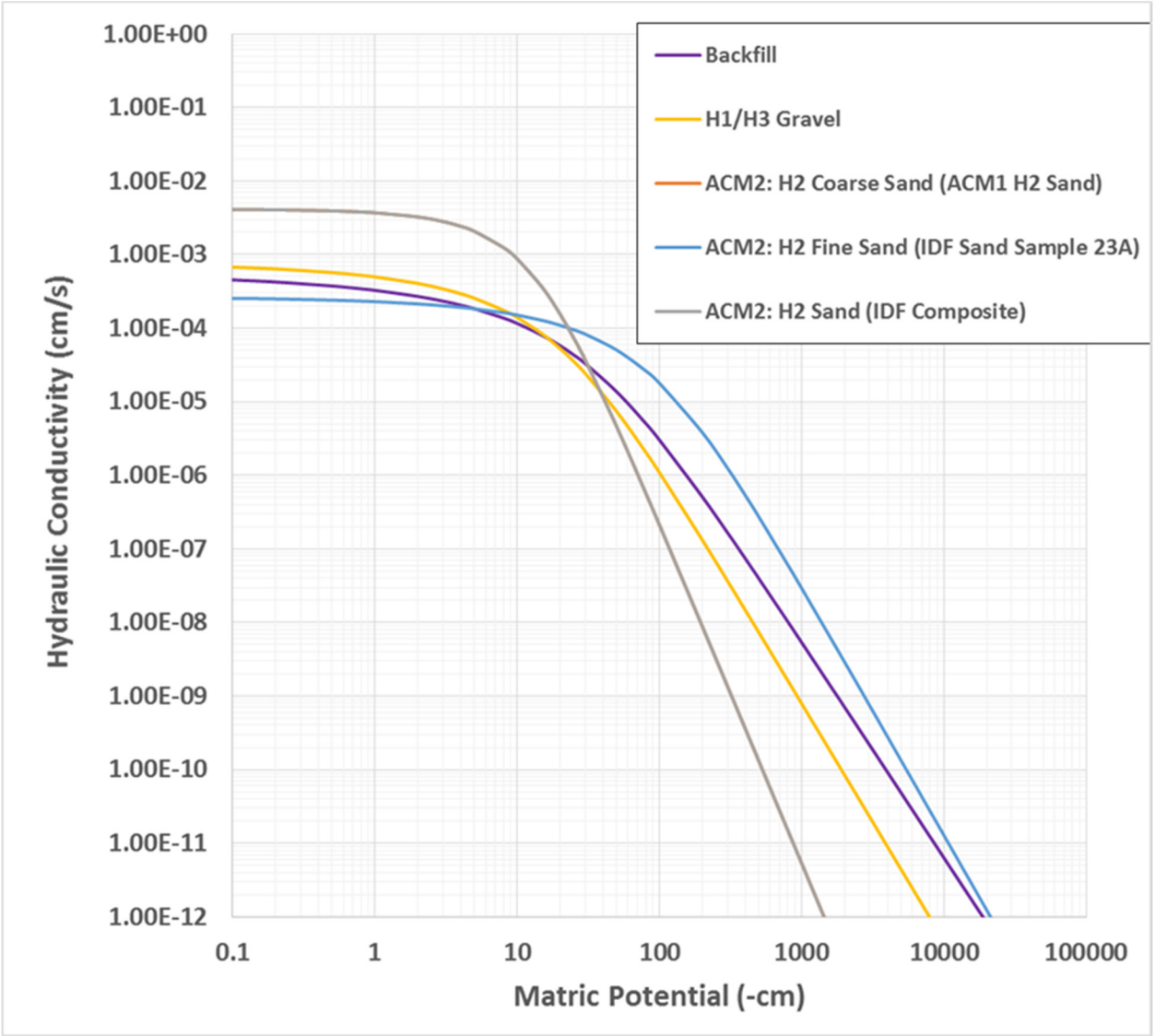
Effective or upscaled values of flow and transport parameters for the WMA C vadose zone are presented below. Specific upscaled flow parameters include moisture retention, saturated, and unsaturated hydraulic conductivity. Transport parameters (e.g., bulk density, diffusivity, sorption coefficients, and macrodispersivity) are discussed later in Section B.4.

**Figure B-15. Moisture Retention Curves for Various Hydrostratigraphic Units and Selected Properties for Alternative Geologic Model II.**




ACM1 = Alternative Geologic Model I
ACM2 = Alternative Geologic Model II
IDF = Integrated Disposal Facility

**Figure B-16. Unsaturated Hydraulic Conductivity Curves for Various Hydrostratigraphic Units and Selected Properties for Alternative Geologic Model II.**



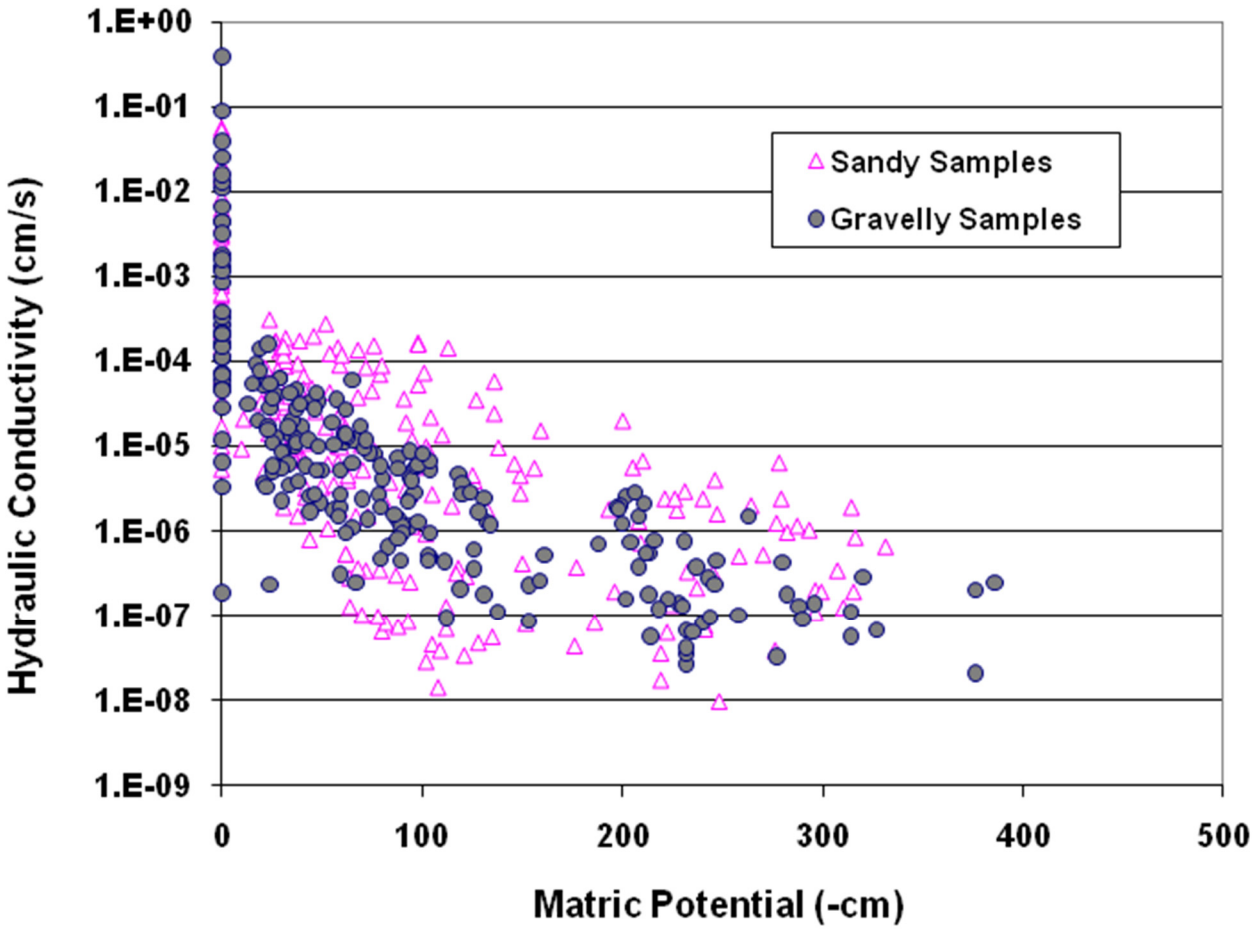

ACM1 = Alternative Geologic Model I
ACM2 = Alternative Geologic Model II
IDF = Integrated Disposal Facility

### B.3.1 Composite Macroscopic Relationships and Effective Parameters

The WMA C composite parameters for moisture characteristics are derived based on laboratory measurements presented in preceding sections. The fitted moisture retention curves (e.g., Figure B-12 for H2 unit) show spatial variability, albeit the degree of variation at a given tension is more modest than that of hydraulic conductivity (e.g., Figure B-13 for H2 unit). For both sandy (e.g., H2 unit) and gravelly (e.g., H1, H3, and backfill units) sediments, the composite van Genuchten parameters were obtained via RETC (EPA/600/2-91/065) and a simultaneous fit of both moisture retention and unsaturated conductivity predictions. The pore

size distribution factor ℓ (van Genuchten 1980) was kept constant at 0.5 during the simultaneous fitting.

**Figure B-17. Unsaturated Hydraulic Conductivity Measurements for Sand-dominated and Gravel-dominated Samples.**




Reference: "Variability of Gardner's α for coarse-textured sediments" (Khaleel and Relyea 2001).

The fitted composite van Genuchten-Mualem parameters for different HSUs are shown in Table B-7. Estimates for the equivalent horizontal and vertical hydraulic conductivities are discussed in Section B.3.2.

### B.3.2 Stochastic Model for Macroscopic Anisotropy

As discussed earlier, variable, tension-dependent anisotropy provides a framework for upscaling small-scale measurements to the effective or upscaled properties for the large-scale vadose zone. A stochastic model is used to describe tension-dependent anisotropy for sediments at C Farm.

Yeh et al. (1985) analyzed steady unsaturated flow through heterogeneous porous media using a stochastic model. Parameters such as hydraulic conductivity are treated as random variables rather than as deterministic quantities. The Gardner relationship ("Some Steady-State Solutions

of the Unsaturated Moisture Flow Equation with Application to Evaporation from a Water Table" [Gardner 1958]) was used by Yeh et al. (1985) to describe unsaturated hydraulic conductivity (K) as a function of saturated hydraulic conductivity ($K_s$) and tension (h), as shown in Equations B-1 and B-2.

$$K(h)=K_s\ exp(-\beta h) \tag{B-1}$$

Where β is a fitting parameter.

Equation B-1 can be written as

$$ln(K(h)) = ln(K_s) - \beta h \tag{B-2}$$

Equation B-2 is referred to as the log-linear model, since ln(K(h)) is linearly related to h through the constant slope β. However, such a constant slope is often inadequate in describing ln(K(h)) over ranges of tension of practical interest for field applications. As an alternative, the slope β can be approximated locally by straight lines over a fixed range of tension. The pseudo "ln($K_s$)" term in Equation B-2 can then be derived by extrapolating the local slopes back to zero tension.

Using a linear correlation model between the log-conductivity zero-tension intercept and β, Polmann (1990) presents a generalized model that accounts for the cross-correlation of the local soil property [i.e., ln($K_s$) and β] residual fluctuations. When compared with the uncorrelated ln($K_s$) - β model, a partial correlation of the properties is shown to have a significant impact on the magnitude of the effective parameters derived from the stochastic theory. The Polmann (1990) equations for deriving the effective parameters are shown in Equation B-3.

$$\begin{aligned}
&< LnK > = < LnK_s > - A < h > - \sigma^2_{LnKs}\lambda[p - p^2 < h > - \zeta^2 < h >]/(1 + A\lambda) \\
&\sigma^2_{LnK} = \sigma^2_{LnKs}[(1 - p < h >)^2 + \zeta^2 < h >^2]/(1 + A\lambda) \\
&K_h^{eq} = \exp[< LnK > + (\sigma^2_{LnK}/2)] \\
&K_v^{eq} = \exp[< LnK > - (\sigma^2_{LnK}/2)]
\end{aligned} \tag{B-3}$$

Where:

| | | |
|---|---|---|
| $\sigma^2_{LnK}$ | = | variance of log unsaturated conductivity (which depends on mean tension) |
| $<h>$ | = | mean tension (positive) = \|ψ\| |
| ψ | = | matric potential (negative) |
| $\sigma^2_{LnKs}$ | = | variance of pseudo "log saturated conductivity" |
| $<LnK_s>$ | = | mean of ln($K_s$) |
| $p$ | = | slope of the β versus ln($K_s$) regression line, where β is the slope of the unsaturated conductivity curve and approximated locally based on Gardner's (1958) exponential model |
| $\zeta$ | = | $\sigma_\delta/\sigma_{ln(Ks)}$ |

$\sigma_\delta$ = standard deviation of the residuals in the β versus ln($K_s$) regression
$A$ = mean slope, β, for ln(K) vs. h
$\lambda$ = vertical correlation lengths for ln($K_s$) (assumed to be same as that of β)
$K_h^{eq}$ = equivalent unsaturated horizontal conductivity
$K_v^{eq}$ = equivalent unsaturated vertical conductivity.

### B.3.3 Macroscopic Anisotropy Relations

Results of application of Equation B-3 for variable anisotropy are presented below. The data for individual HSUs (Tables B-3, B-5 and B-6) are used to obtain the Polmann parameters < ln($K_s$)>, $\sigma^2_{LnKs}$, p, ζ, and A (Equation B-3). The slope and pseudo ln($K_s$) estimates, discussed in the preceding section, are evaluated for the expected moisture regime of interest (i.e., relatively high tension range) (Table B-8). However, it should be noted that often no experimental data are available for unsaturated conductivities in the tension range of interest; β and ln($K_s$) estimates are then based on the fitted van Genuchten-Mualem curves.

An estimate of correlation length λ is needed for anisotropy calculations. Most of the measurements in the 200 Areas have been obtained at sampling intervals that are too coarse to yield a reasonable estimate for the correlation length. However, one data set is available that provides saturated conductivity estimates at about 30-cm intervals for a depth of 18 m within the Hanford formation; the site is located about 0.5 mi east of the IDF site (Figure B-3) in the 200 East Area. Figure B-22 shows the experimental variogram and the fitted theoretical variogram for saturated conductivities. The fitted variogram suggests a correlation length λ of about 50 cm (i.e., the distance at which the variogram drops to [1-(1/e)] times the sill) (Figure B-22). Correlation length λ for both ln($K_s$) and β were assumed to be equal.

Table B-9 lists the variable, macroscopic anisotropy parameter estimates for various WMA C units. The calculated macroscopic variable anisotropy relations for various HSUs are shown in Figures B-23, B-24, and B-25. A supporting document presents the anisotropy calculations (RPP-CALC-60452, "Moisture Dependent Anisotropy Calculations Supporting Waste Management Area C Performance Assessment").

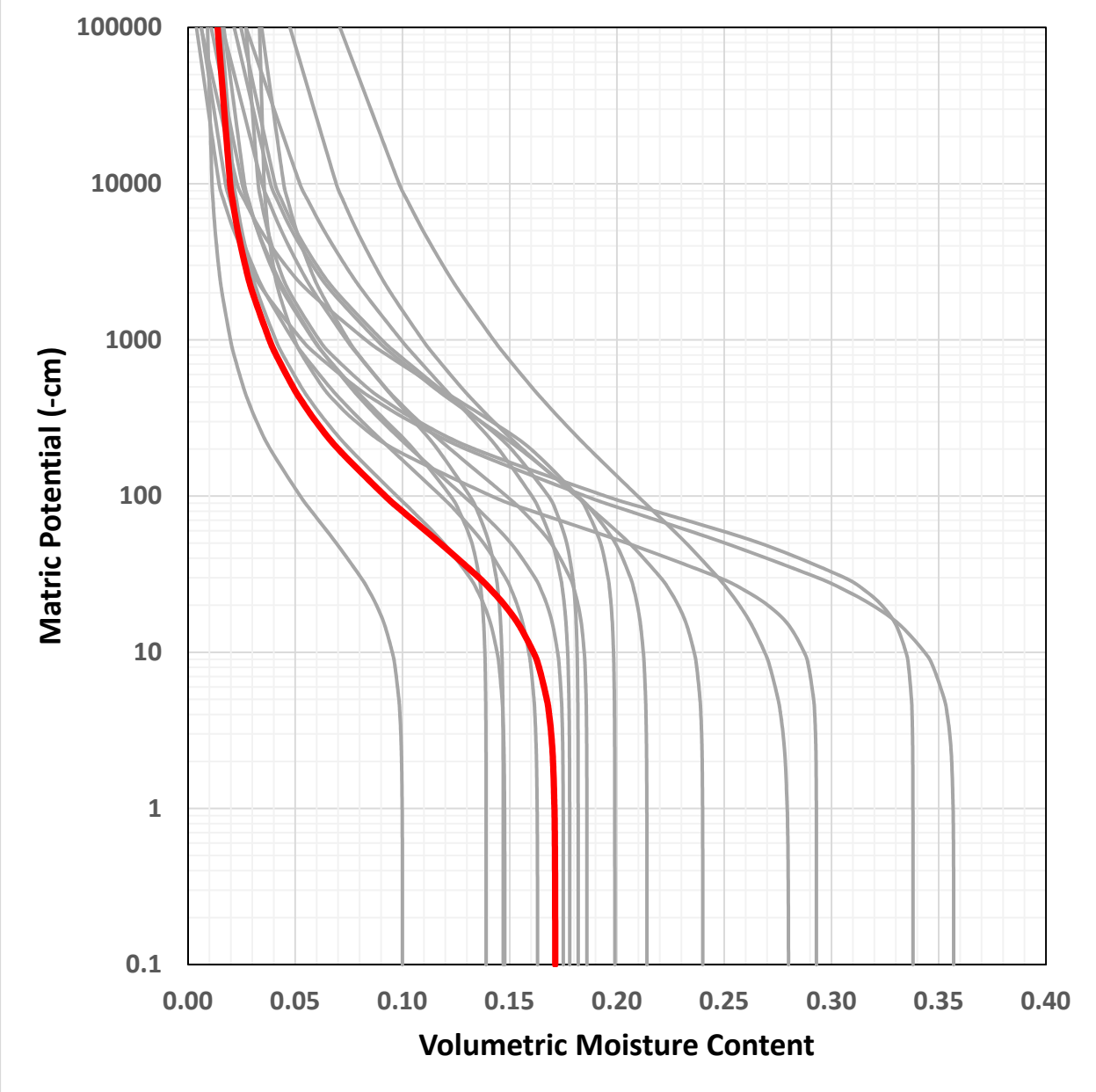
Note that values listed in Table B-7 are the composite van Genuchten-Mualem parameters for different units. Equation B-3 is used to assign the variable Polmann anisotropy (i.e., the ratio of equivalent unsaturated horizontal conductivity to equivalent unsaturated vertical conductivity) as a function of saturation. The van Genuchten-Mualem parameters in Table B-7 are then used to assign the actual unsaturated hydraulic conductivity estimates. The fitted $K_s$ values in Table B-7 represent the vertical components.

**Table B-5. van Genuchten Parameters, Fitted Saturated Hydraulic Conductivity, and Measured Bulk Density Data for H1/H3 Units (17 Samples).**

| Sample | Site/Operable Unit | Borehole Number | Depth m | Percent Gravel | Θs $cm^3/cm^3$ | Θr $cm^3/cm^3$ | α 1/cm | n | Fitted Ks cm/s | Bulk Density $g/cm^3$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 5-0150 | 218-E-12B | 299-E34-1 | 24.84 | 17 | 0.240 | 0.023 | 0.030 | 1.7077 | 1.47E-03 | 1.95 |
| 5-0157 | 218-E-10 | 299-E32-4 | 3.50 | 13 | 0.293 | 0.033 | 0.027 | 2.1675 | 7.77E-03 | 1.88 |
| 5-0152 | 218-E-12B | 299-E34-1 | 65.50 | 26 | 0.280 | 0.025 | 0.044 | 1.3253 | 2.43E-03 | 1.85 |
| 5-0158 | 218-E-10 | 299-E32-4 | 71.50 | 44 | 0.214 | 0.013 | 0.008 | 1.4226 | 1.38E-04 | 2.15 |
| 5-0148 | 218-E-12B | 299-E34-1 | 15.25 | 54 | 0.148 | 0.013 | 0.021 | 1.5589 | 2.72E-04 | 2.16 |
| 4-1080 | ERDF | 699-35-61A | 93.50 | 43 | 0.178 | 0.000 | 0.007 | 1.3819 | 8.11E-06 | 2.00 |
| 4-0791 | ERDF | 699-35-65A | 63.20 | 0 | 0.338 | 0.026 | 0.023 | 2.2565 | 6.81E-04 | 1.60 |
| 4-0792 | ERDF | 699-35-65A | 75.40 | 71 | 0.100 | 0.008 | 0.030 | 1.5858 | 3.42E-04 | 2.32 |
| 4-1076 | ERDF | 699-35-61A | 76.40 | 0 | 0.357 | 0.000 | 0.029 | 1.7015 | 1.23E-03 | 1.74 |
| 4-1079 | ERDF | 699-35-61A | 90.90 | 61 | 0.163 | 0.000 | 0.014 | 1.3079 | 1.18E-04 | 2.06 |
| 4-1013 | ERDF | 699-35-69A | 77.90 | 65 | 0.139 | 0.013 | 0.007 | 1.5656 | 1.06E-06 | 2.20 |
| 4-1012 | ERDF | 699-35-69A | 73.90 | 55 | 0.147 | 0.000 | 0.008 | 1.5109 | 4.50E-05 | 2.19 |
| 3-0668 | 241-T-106 | 299-W10-196 | 38.90 | 62 | 0.175 | 0.000 | 0.019 | 1.6124 | 1.63E-04 | 2.13 |
| 3-0682 | 241-T-106 | 299-W10-196 | 46.10 | 51 | 0.224 | 0.000 | 0.017 | 1.6577 | 2.37E-04 | 2.14 |
| 3-0210 | 241-T-106 | 299-W10-196 | 3.10 | 48 | 0.186 | 0.029 | 0.014 | 1.7674 | 1.96E-04 | 2.11 |
| 3-0688 | 241-T-106 | 299-W10-196 | 48.50 | 49 | 0.199 | 0.000 | 0.004 | 1.5321 | 2.60E-05 | 2.17 |
| 3-0690 | 241-T-106 | 299-W10-196 | 53.7 | 53 | 0.182 | 0.018 | 0.005 | 1.5410 | 4.19E-05 | 2.19 |

ERDF = Environmental Restoration Disposal Facility

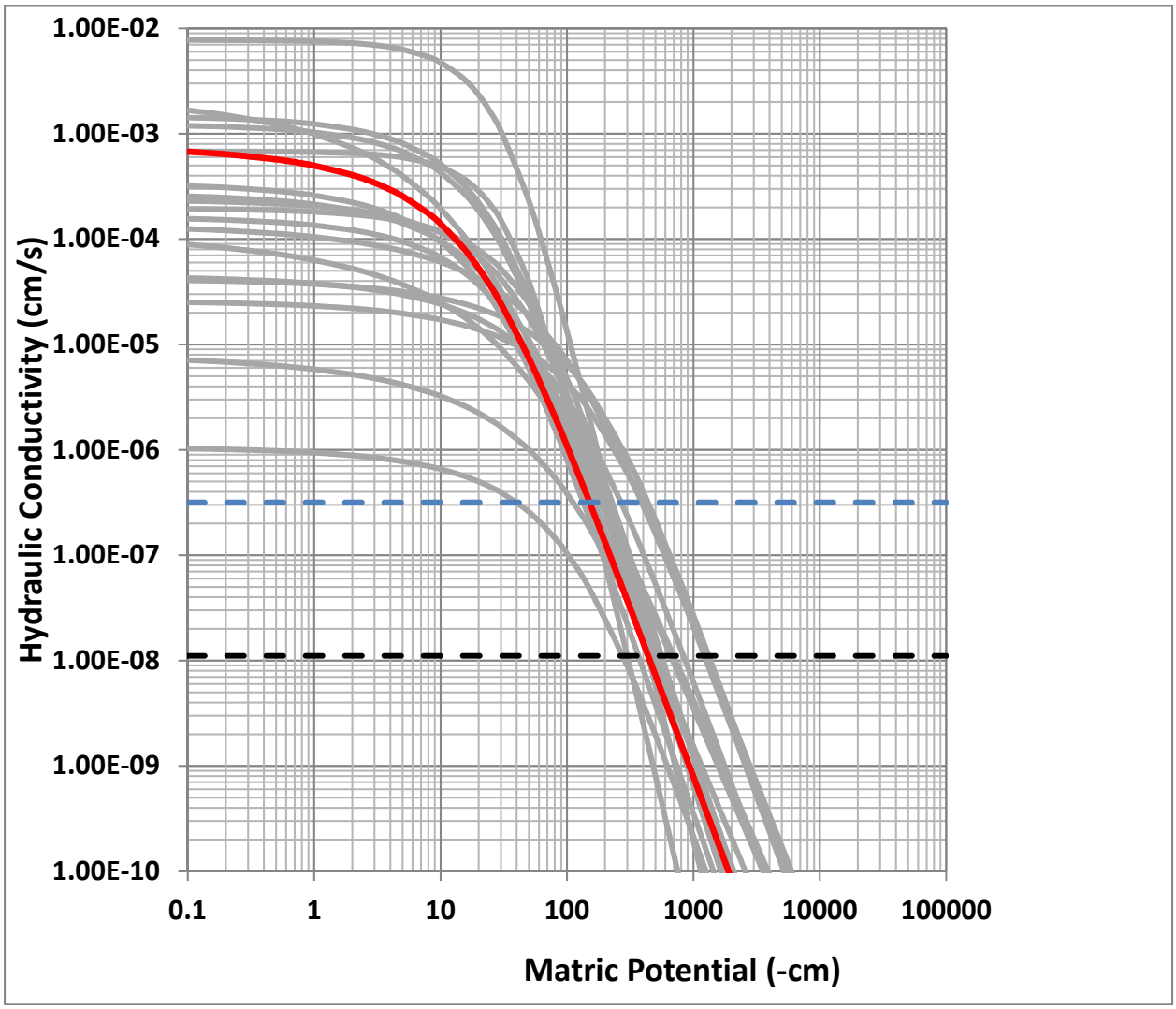
**Figure B-18. Moisture Retention Data for H1 and H3 Units (17 Samples). The composite curve is shown in red.**




## B.4 EFFECTIVE TRANSPORT PARAMETERS

Base case effective transport parameter (bulk density, diffusivity, and dispersivity) estimates are presented in this section. Because of natural variability, the transport parameters are all spatially variable. The purpose is again, similar to the flow parameters, to evaluate the effect of such variability on the large-scale transport process.

**Figure B-19. Unsaturated Hydraulic Conductivity Data for H1 and H3 Units (17 Samples). The composite curve is shown in red.**




### B.4.1 Bulk Density and $K_d$

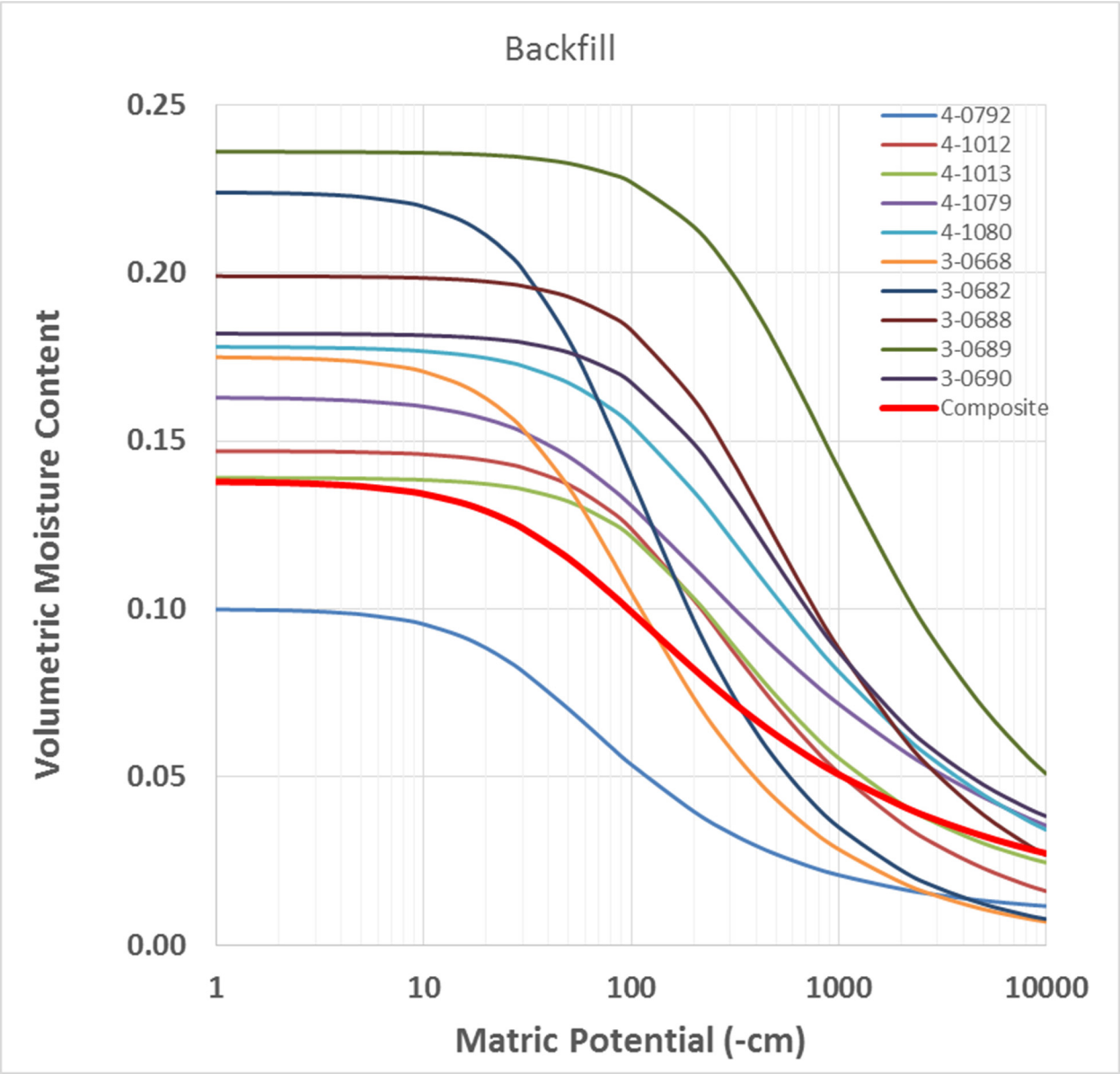
Both bulk density ($\rho_b$) and $K_d$ estimates are needed to calculate retardation factors for different species. The effective, large-scale estimate for bulk density is the average of the small-scale laboratory measurements for bulk density (Stochastic Subsurface Hydrology [Gelhar 1993]). Table B-10 provides the effective, large-scale bulk density estimates for WMA C HSUs. The $K_d$ values, presented in Section 7, were corrected for the gravel (>2-mm size) fraction, and are not repeated here. The correction procedure followed is described in PNNL-17154, "Geochemical Characterization Data Package for the Vadose Zone in the Single-Shell Tank Waste Management Areas at the Hanford Site." For materials that contain significant amounts of gravel (notably H1 and H3), $K_d$ values are typically lower than those determined with <2-mm size material because the surface area and the corresponding quantity of adsorption sites is lower (PNNL-17154).

**Table B-6. van Genuchten Parameters, Fitted Saturated Hydraulic Conductivity, and Measured Bulk Density Data for Backfill Unit (10 Samples).**

| Sample | Site | Borehole Number | Depth (m) | Percent Gravel | $\theta_s$ ($cm^3/cm^3$) | $\theta_r$ ($cm^3/cm^3$) | $\alpha$ (1/cm) | $n$ (-) | Fitted $K_s$ (cm/s) | Bulk Density ($g/cm^3$) |
|---|---|---|---|---|---|---|---|---|---|---|
| 4-0792 | ERDF | 699-35-65A | 75.4 | 71 | 0.100 | 0.0084 | 0.03 | 1.5858 | 3.42E-04 | 2.32 |
| 4-1012 | ERDF | 699-35-69A | 73.9 | 55 | 0.147 | 0 | 0.0076 | 1.5109 | 4.50E-05 | 2.19 |
| 4-1013 | ERDF | 699-35-69A | 77.9 | 65 | 0.139 | 0.0127 | 0.0065 | 1.5656 | 1.06E-06 | 2.20 |
| 4-1079 | ERDF | 699-35-61A | 90.9 | 61 | 0.163 | 0 | 0.014 | 1.3079 | 1.18E-04 | 2.06 |
| 4-1080 | ERDF | 699-35-61A | 93.5 | 43 | 0.178 | 0 | 0.0074 | 1.3819 | 8.11E-06 | 2.00 |
| 3-0668 | 241-T-106 | 299-W10-196 | 38.9 | 62 | 0.175 | 0 | 0.0192 | 1.6124 | 1.63E-04 | 2.13 |
| 3-0682 | 241-T-106 | 299-W10-196 | 46.1 | 51 | 0.224 | 0 | 0.0166 | 1.6577 | 2.37E-04 | 2.14 |
| 3-0688 | 241-T-106 | 299-W10-196 | 48.5 | 49 | 0.199 | 0 | 0.0043 | 1.5321 | 2.60E-05 | 2.17 |
| 3-0689 | 241-T-106 | 299-W10-196 | 52.2 | 28 | 0.236 | 0 | 0.0025 | 1.4747 | 4.58E-05 | 1.93 |
| 3-0690 | 241-T-106 | 299-W10-196 | 53.7 | 53 | 0.1819 | 0.0177 | 0.0046 | 1.541 | 4.19E-05 | 2.19 |

ERDF = Environmental Restoration Disposal Facility

**Figure B-20. Moisture Retention Data for Backfill Unit (10 Samples). The composite curve is shown in red.**



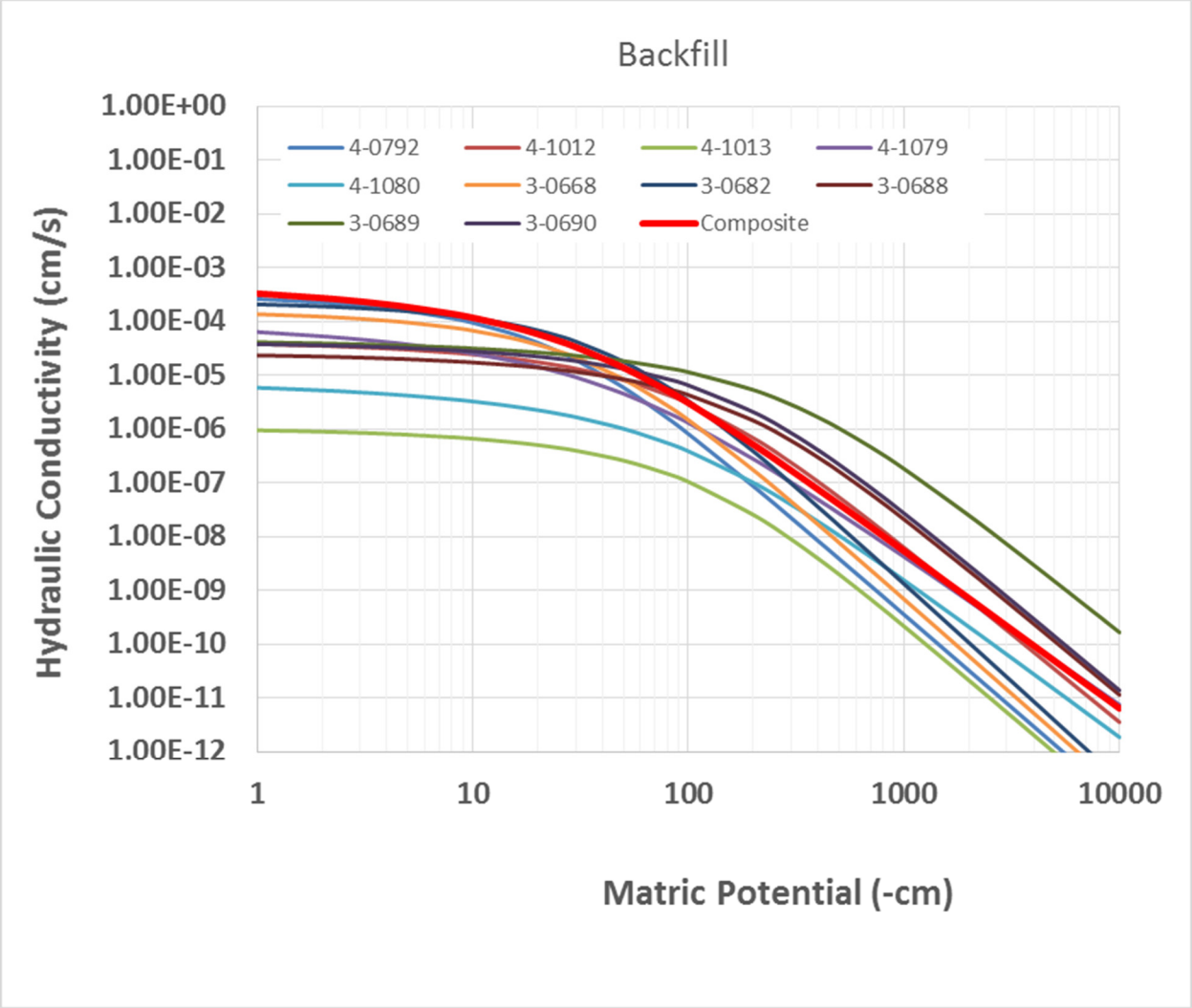

### B.4.2 Diffusivity

It is assumed that the effective, large-scale diffusion coefficients for all HSUs are a function of volumetric moisture content, θ, and can be estimated based on an empirical relation ("Permeability of Porous Solids" [Millington and Quirk 1961]):

$$D_e(\theta) = D_0 \frac{\theta^{10/3}}{\theta_s^2} \tag{B-4}$$

where $D_e(\theta)$ is the effective diffusion coefficient of an ionic species, and $D_0$ is the effective diffusion coefficient for the same species in free water. The molecular diffusion coefficient for all species in pore water is assumed to be $2.5 \times 10^{-5}$ $cm^2/sec$ (WHC-SD-WM-EE-004, "Performance Assessment of Grouted Double-Shell Tank Waste Disposal at Hanford").

**Figure B-21. Unsaturated Hydraulic Conductivity Data for Backfill Units (10 Samples). The composite curve is shown in red.**




### B.4.3 Vadose Zone Macrodispersivities

Field-scale dispersivities are referred to as macrodispersivities. The terms macrodispersivity and dispersivity are used interchangeably in this section. Readers can go directly to Section B.4.3.4 for the macrodispersivity values recommended for WMA C RCA calculations. Details on how the selections are made using different methods are provided in Section B.4.3.1 (Numerical Simulations), Section B.4.3.2 (Stochastic Theory), and Section B.4.3.3 (Experimental Observations).

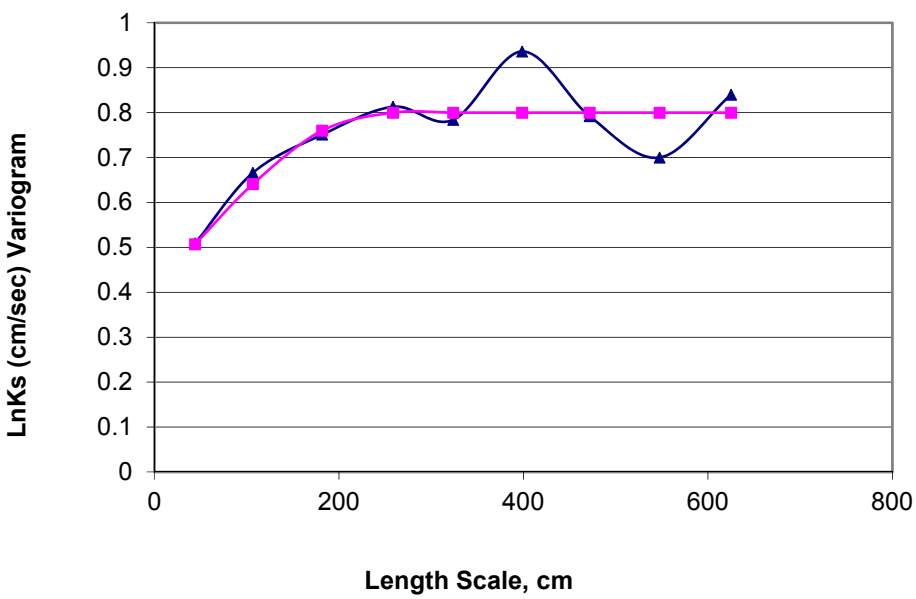
**Table B-7. Composite van Genuchten-Mualem Parameters for Waste Management Area C Hydrostratigraphic Units.**

| Hydrostratigraphic Unit | Number of Samples | $\theta_s$ | $\theta_r$ | $\alpha$ (1/cm) | n | $\ell$ | Fitted $K_s$ (cm/s) |
|---|---|---|---|---|---|---|---|
| Backfill Gravelly Unit | 10 | 0.138 | 0.010 | 0.021 | 1.374 | 0.5 | 5.60E-04 |
| H1 and H3 Gravelly Units | 15 | 0.171 | 0.011 | 0.036 | 1.491 | 0.5 | 7.70E-04 |
| H2 Sand-Dominated Unit | 44 | 0.315 | 0.0392 | 0.0631 | 2.047 | 0.5 | 4.15E-03 |

**Table B-8. Simulated Average Tension Ranges for Polmann Anisotropy Model.**

| Hydrostratigraphic Unit | Simulated Average Tension (cm) |
|---|---|
| Backfill Gravelly Unit | 400 – 750 |
| H1 and H3 Gravelly Units | 150 – 400 |
| H2 Sand-Dominated Unit | 80 – 300 |

**Figure B-22. Experimental (Triangles) and Fitted Theoretical (Squares) Variogram for Saturated Hydraulic Conductivity ($LnK_s$).**

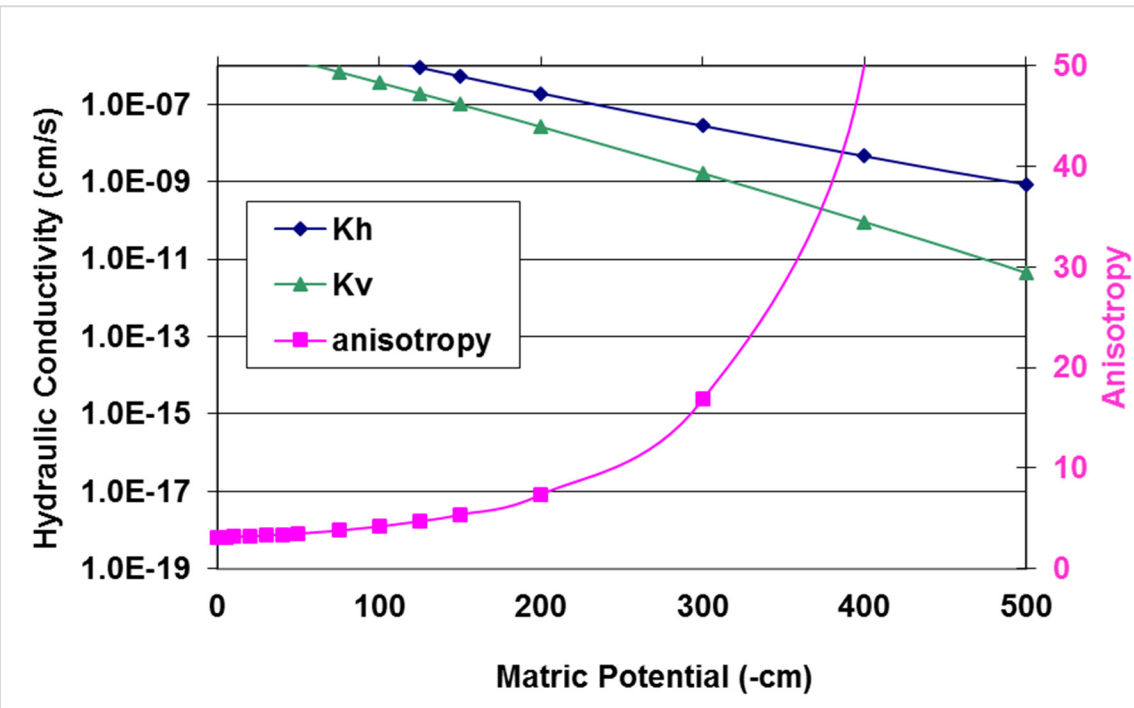



Reference: RPP-20621, "Far-Field Hydrology Data Package for the Integrated Disposal Facility Performance Assessment."

**Table B-9. Variable, Macroscopic Anisotropy Parameter Estimates for Various Waste Management Area C Units.**

| Hydrostratigraphic Unit | Number of Samples | <*LnKs*> | $\sigma^2_{LnK_s}$ | p | ζ | λ (cm) | A |
|---|---|---|---|---|---|---|---|
| Backfill Gravelly Unit | 10 | -14.60 | 2.98 | -2.28E-04 | 3.53E-04 | 30 | 0.00534 |
| H1 and H3 Gravelly Units | 17 | -12.34 | 1.41 | 1.04E-03 | 2.68E-03 | 30 | 0.01249 |
| H2 Sand-Dominated Unit | 44 | -11.79 | 2.50 | -7.45E-04 | 3.33E-03 | 50 | 0.02415 |

**Figure B-23. Calculated Macroscopic Anisotropy as a Function of Mean Matric Potential for the H2 Sand-Dominated Unit.**

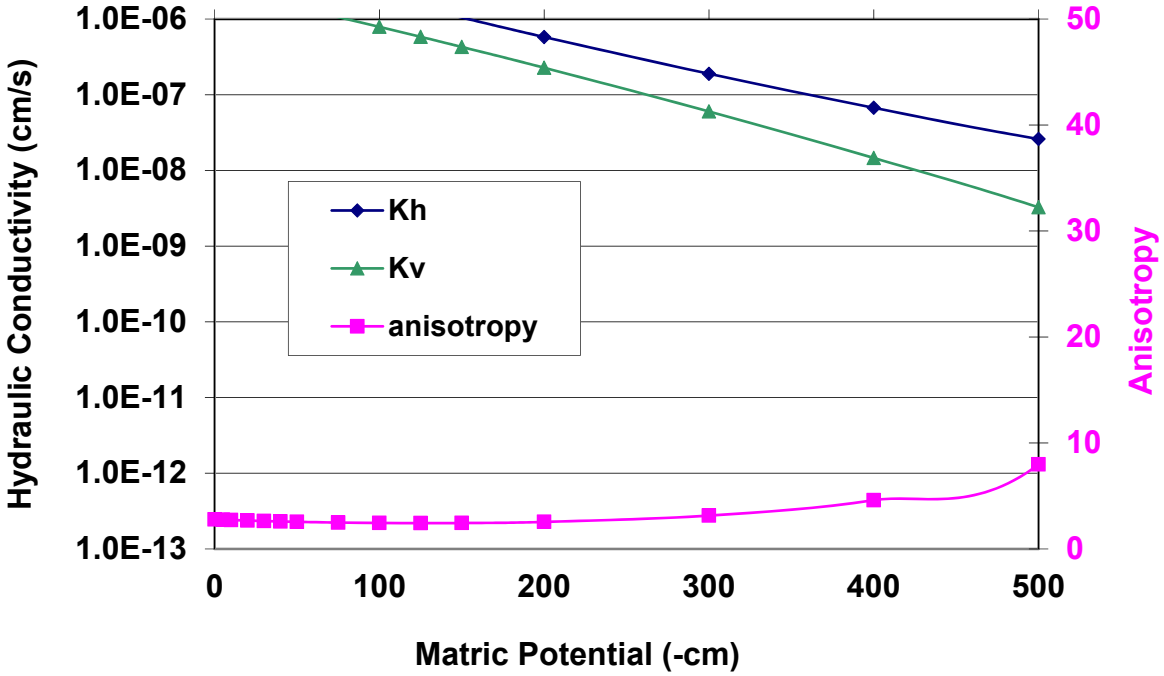



Field observations indicate that the dispersion coefficients required to describe the large-scale transport processes, at field scales of tens or hundreds of meters, are much different from those observed in small-scale laboratory experiments (Gelhar 1993). In fact, field-scale dispersivities (i.e., macrodispersivities) may often be orders of magnitude larger than those observed in the laboratory. Consequently, laboratory-scale dispersivities, which are typically ~1 cm or less, would be of little use in estimating field-scale dispersivities.

There is general agreement in hydrology literature that hydraulic conductivity variations induced by field-scale heterogeneities play an important role in field-scale transport processes. However, there does not appear to be a clear consensus about how best to describe such processes quantitatively (Gelhar 1993). While well-designed, large-scale tracer experiments would provide

useful information, limited field data are available at this time to quantify macrodispersivities in unsaturated media.

**Figure B-24. Calculated Macroscopic Anisotropy as a Function of Mean Matric Potential for the H1 and H3 Gravelly Units.**




Dispersivities are a function of matric potential (or soil moisture content) in unsaturated media (Mantoglou and Gelhar 1987). As with saturated media, heterogeneities that exist at various length scales result also in a scale dependence of macrodispersivities in unsaturated media ("A Critical Review of Data on Field-Scale Dispersion in Aquifers" [Gelhar et al. 1992]). Dispersivities increase with time, or equivalently with distance, until they tend to converge on their unique asymptotic (large-time) values. However, it can take a long time (e.g., years or decades) for the asymptotic Fickian approximation to take hold. Nonetheless, the second-moment evolution or the time-dependent, preasymptotic dispersivities are of marginal interest in simulations involving long-times or large-mean travel distances such as those in performance assessment modeling. The use of a constant (asymptotic) macrodispersivity is thus considered appropriate in performance assessment simulations (NUREG/CR-6114, Auxiliary Analyses in Support of Performance Assessment of a Hypothetical Low-Level Waste Facility: Groundwater Flow and Transport Simulation, Vol. 3; NUREG/CR-5965, Modeling Field Scale Unsaturated Flow and Transport Processes).

Note that, because of the relatively dry moisture regime, unsaturated media macrodispersivity estimates are expected to be smaller, compared to saturated media estimates. Below, a range of estimates on the basis of numerical simulations (Section B.4.3.1), stochastic theory (Section B.4.3.2), and experimental observations (Section B.4.3.3) is provided. To obtain macrodispersivity, the local pore-scale dispersivities, which are typically small (<1 cm), are not

included either in numerical simulations or stochastic solutions. This is consistent with the approach used by other investigators ("Stochastic analysis of adsorbing solute transport in three-dimensional, heterogeneous, unsaturated soils" [Yang et al. 1997]; Gelhar 1993; "Three-Dimensional Stochastic Analysis of Macrodispersion in Aquifers" [Gelhar and Axness 1983]).

**Figure B-25. Calculated Macroscopic Anisotropy as a Function of Mean Matric Potential for Backfill Gravelly Unit.**

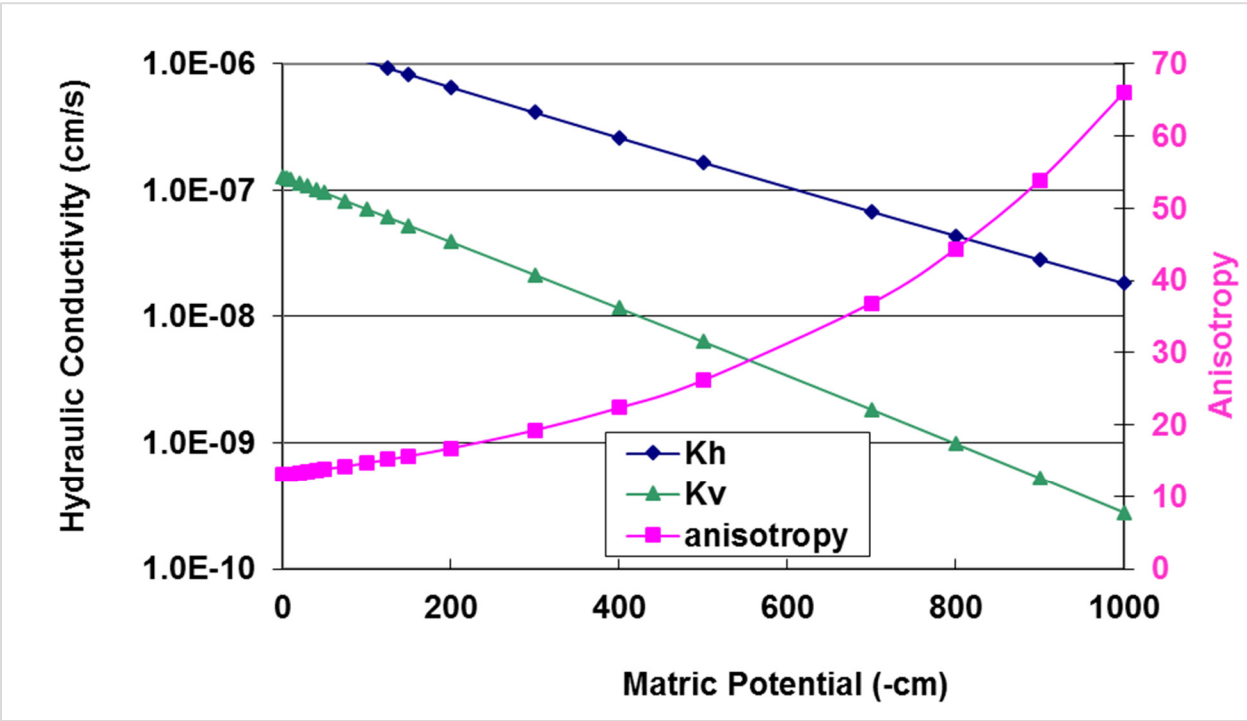



**Table B-10. Effective Bulk Density (g/cm$^3$) Estimates for Waste Management Area C Hydrostratigraphic Units.**

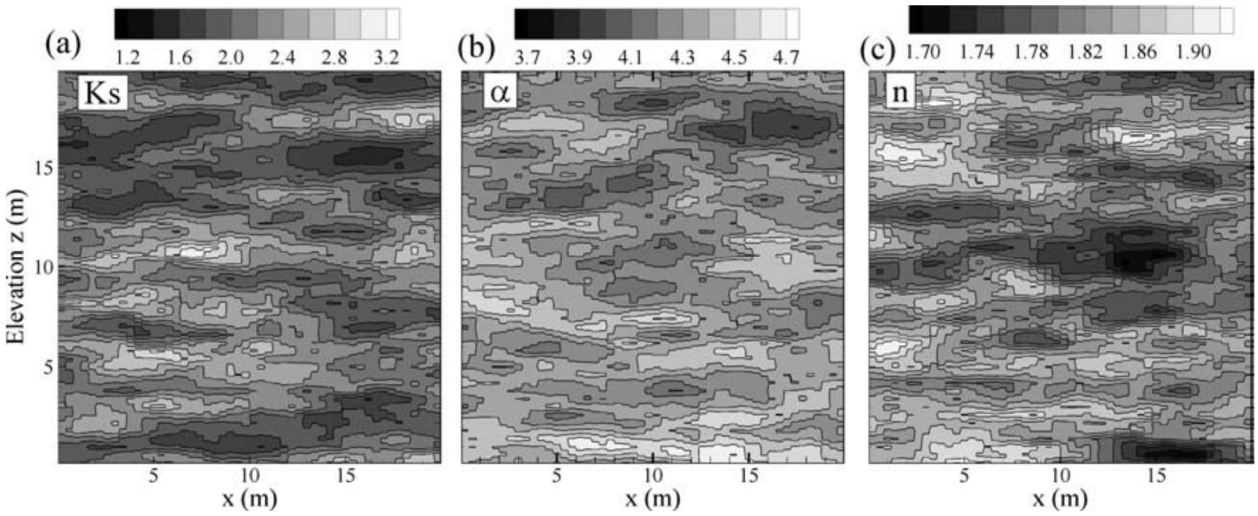
| Hydrostratigraphic Unit | E[$\rho_b$]* |
|---|---|
| Backfill Gravelly Unit | 2.13 |
| Hanford H2 Sand-dominated Unit | 1.71 |
| Hanford H1 and H3 Gravelly Units | 2.05 |

*E = Expectation.

**B.4.3.1 Numerical Simulations.** Details of the numerical simulation approach are described in Khaleel et al. (2002). Briefly, Monte Carlo (MC) simulations are used to obtain upscaled (effective) properties. The simulations mimic steady-state, gravity infiltration for 50 realizations in two-dimensional (20 m × 20 m) heterogeneous flow regions. Constitutive relations for unsaturated media at the mesh-size scale are based on the van Genuchten-Mualem relationships.

A realization of the flow field is shown in Figure B-26. The sediment properties are based on laboratory measurements of moisture retention and unsaturated *K* for coarse-textured sandy samples from the upper Hanford formation (HNF-4769, "Far-Field Hydrology Data Package for Immobilized Low-Activity Tank Waste Performance Assessment"); these data show somewhat less variability when compared to the 44 Hanford formation H2 samples discussed earlier. A unit-mean-gradient approach is used to derive upscaled properties for flow perpendicular to bedding. For a specified infiltration rate, the simulated pressure head distributions for 50 realizations are averaged to yield a mean pressure head, H. Because the simulated flow field is under a unit mean gradient condition, the infiltration rate is equal to the effective conductivity at the calculated H.

**Figure B-26. (a) Ks, (b) α, and (c) n Random Distribution for a Single Realization.**




Reference: "Upscaled Flow and Transport Properties for Heterogeneous Unsaturated Media" (Khaleel et al. 2002).

Following flow simulations, macrodispersivities are calculated on the basis of spatial moments of the ensemble-mean plume (Khaleel et al. 2002). For a given steady flow and a prescribed flux, the migration and spread of a slug of tracer is simulated. Snapshots are taken of the two-dimensional plume distribution at different times. The snapshot at each sampling time is then averaged over the length across the flow domain to obtain the solute concentration profiles as a function of depth. The concentration profiles for all realizations are averaged to obtain the ensemble mean profile; these profiles are then used to evaluate their spatial moments. The calculated second spatial moment of the plume about the center of mass (i.e., spatial variance) over time allows estimation of the longitudinal macrodispersivity.

Figures B-27a, B-27b and B-27c are snapshots, for a mean pressure head of -1.0 m, of the simulated plume for a single realization and for flow perpendicular to bedding at 400, 700, and 1,000 days after simulating the release of a conservative tracer across the top boundary of a mildly heterogeneous media (Figure B-26). The averaged concentration profiles for the flow regime and for the corresponding sampling times are illustrated in Figure B-27d. Bedding perpendicular to flow direction enhances lateral mixing and prevents growth of irregular flow paths. Consequently, the averaged concentration profiles for flow perpendicular to bedding (Figure B-27d) exhibit the typical bell-shaped distribution as described by the classical Fickian

advection-dispersion equation. The computed longitudinal macrodispersivity for a mean pressure head (H) of -2 m was ~25 cm, ranging from ~15 cm to ~40 cm for the 50 realizations. On the other hand, for a mean H of -20 m, the macrodispersivity was ~100 cm, ranging from ~70 cm to ~130 cm for the 50 realizations. As the MC simulations indicate, considerable variability in longitudinal macrodispersivity estimates is expected depending on the mean matric potential. Nonetheless, results show a clear dependence of longitudinal macrodispersivity on the moisture regime; longitudinal macrodispersivity estimates are higher for the drier moisture regime.

To evaluate directional dependence, simulations were also run for flow parallel to geologic bedding for the same flow domain. Figures B-28a, B-28b, and B-28c are snapshots of the plume at identical sampling times for flow parallel to bedding for the same single realization and for H=-1 m; Figure B-28d shows the averaged profile. A comparison of Figures B-27 and B-28 shows that the two-dimensional concentration distribution is more irregular in case of flow parallel to bedding than for flow perpendicular to bedding (Figures B-28a, B-28b, and B-28c versus Figures B-27a, B-27b, and B-27c). Compared with flow perpendicular to bedding, the concentration profiles for flow parallel to bedding are highly skewed and characterized by multiple peaks, and spread out over greater distances, characteristics of a non-Fickian behavior. Thus, while the averaged concentration profiles for flow perpendicular to bedding show "textbook like" Fickian behavior, the averaged profiles for flow parallel to bedding are highly skewed and non-Fickian. At H=-2 m, the computed longitudinal macrodispersivity for flow parallel to bedding is considerably higher (~120 cm) than for flow perpendicular to bedding (~25 cm). For a mean H of -20 m, the macrodispersivity is ~180 cm for flow parallel to bedding versus ~100 cm for flow perpendicular to bedding.

In summary, the numerical results for Hanford H2 sands having mild heterogeneity (HNF-4769) show that the longitudinal dispersivities for flow parallel to bedding are higher than those for flow perpendicular to bedding (Khaleel et al. 2002). For both perpendicular and parallel to bedding, macrodispersivities increase as the mean matric potential becomes more negative. However, the Fickian regime is reached much earlier for cases with flow perpendicular to bedding than for those with flow parallel to bedding (Khaleel et al. 2002). For WMA C RCA modeling, the flow is mostly perpendicular to geologic bedding; nonetheless, the preceding analysis provides estimates in situations where the flow is not necessarily perpendicular to bedding.

**B.4.3.2 Stochastic Models.** For unsaturated media, in addition to the size of flow domain and media heterogeneities, macrodispersivities are expected to be a function of soil moisture content (or matric potential). Furthermore, as demonstrated via preceding MC simulations, macrodispersivities are larger for flow parallel to bedding than for flow perpendicular to bedding. Below, we apply two stochastic models to estimate WMA C longitudinal macrodispersivities for flow perpendicular to geologic bedding.

**B.4.3.2.1 Mantoglou Model.** Using spectral perturbation techniques (Gelhar and Axness 1983; Gelhar 1993), an approximate equation was derived for macrodispersivities in unsaturated media for flow perpendicular to bedding ("Large-Scale Models of Transient Unsaturated Flow and Contaminant Transport Using Stochastic Methods" [Mantoglou 1984]). Mantoglou showed

that the asymptotic value of tension-dependent longitudinal macrodispersivity, $A_{\perp}$ under unit mean gradient condition, for flow perpendicular to bedding, is

$$A_{\perp}(H) = \frac{\sigma^2_{LnK_u}\lambda_u}{\gamma^2} \tag{B-5}$$

where $A_{\perp}$ depends on the mean pressure head *H*, $\sigma^2_{LnK_u}$ is the variance in log unsaturated *K*, $\lambda_u$ is the correlation length scale for unsaturated hydraulic conductivity, and $\gamma$ is a flow factor that depends on the direction of mean flow and the orientation of heterogeneity (Gelhar and Axness 1983).

Equation B-5 represents the asymptotic macrodispersivity estimate for steady-state uniform flow with uniform mean tension. Because macrodispersivity modeled by Equation B-5 is an asymptotic parameter, it applies only when the concentration plume has traveled a large distance in a geologic unit and has encountered numerous heterogeneities in the formation. Furthermore, it is important to note that similar to other stochastic perturbation approaches (Gelhar 1993), the validity of Equation B-5 relies on the variance of hydraulic properties being relatively small (i.e., $\sigma^2_{LnK_u} < 1$).

Mantoglou (1985; Figure 5.9) presents longitudinal macrodispersivity estimates, based on Equation B-5, for Maddock sandy loam ("Spatial Variability of in Situ Unsaturated Hydraulic Conductivity of Maddock Sandy Loam" [Carvallo et al. 1976]) and Panoche silty clay loam ("Spatial Variability of Field-Measured Soil-Water Properties" [Nielsen et al. 1973]) soil types. Mantoglou results show considerable variability even for mild tensions. Based on the Mantoglou model (Equation B-5), for Maddock soil type, the asymptotic longitudinal macrodispersivity was 2.4 m at a mean tension of 50 cm. For Panoche soil type, the estimate was 0.8 m at a mean tension of 300 cm.

**B.4.3.2.2 Russo Model.** Using the Lagrangian framework in conjunction with the Yeh et al. (1985) velocity covariance, theoretical expressions were developed for evolution of contaminant plume spatial moments in unsaturated heterogenous media under steady-state conditions ("Stochastic Analysis of Simulated Vadose Zone Solute Transport in a Vertical Cross Section of Heterogeneous Soil During Nonsteady Water Flow" [Russo 1991]). The spatial moments were then used to assess the preasymptotic evolution of macrodispersivity.

$$A_{zz}(t) = \sigma^2_{LnK_u}\lambda_u\left\{1 - 3(2\tau)^{-1} - 3(\tau)^{-2}\exp(-\tau) + 3(\tau)^{-3}[1-\exp(-\tau)]\right\} \tag{B-6}$$

where $A_{zz}$ is the longitudinal macrodispersivity (i.e., similar to $A_{\perp}$), *z* denotes vertical direction, *t* is time, $\lambda_u$ is vertical correlation length, and $\tau = z_c(t)/\lambda_u$. The unsaturated conductivity variance $\sigma^2_{LnK_u}$ was derived by Russo (1991) using the Gardner (1958) exponential model for

unsaturated conductivity. At large times, $\tau \rightarrow \infty$; the longitudinal asymptotic macrodispersivity is therefore

$$A_{zz}(\infty) = \sigma^2_{LnK_u} \lambda_u \,. \tag{B-7}$$

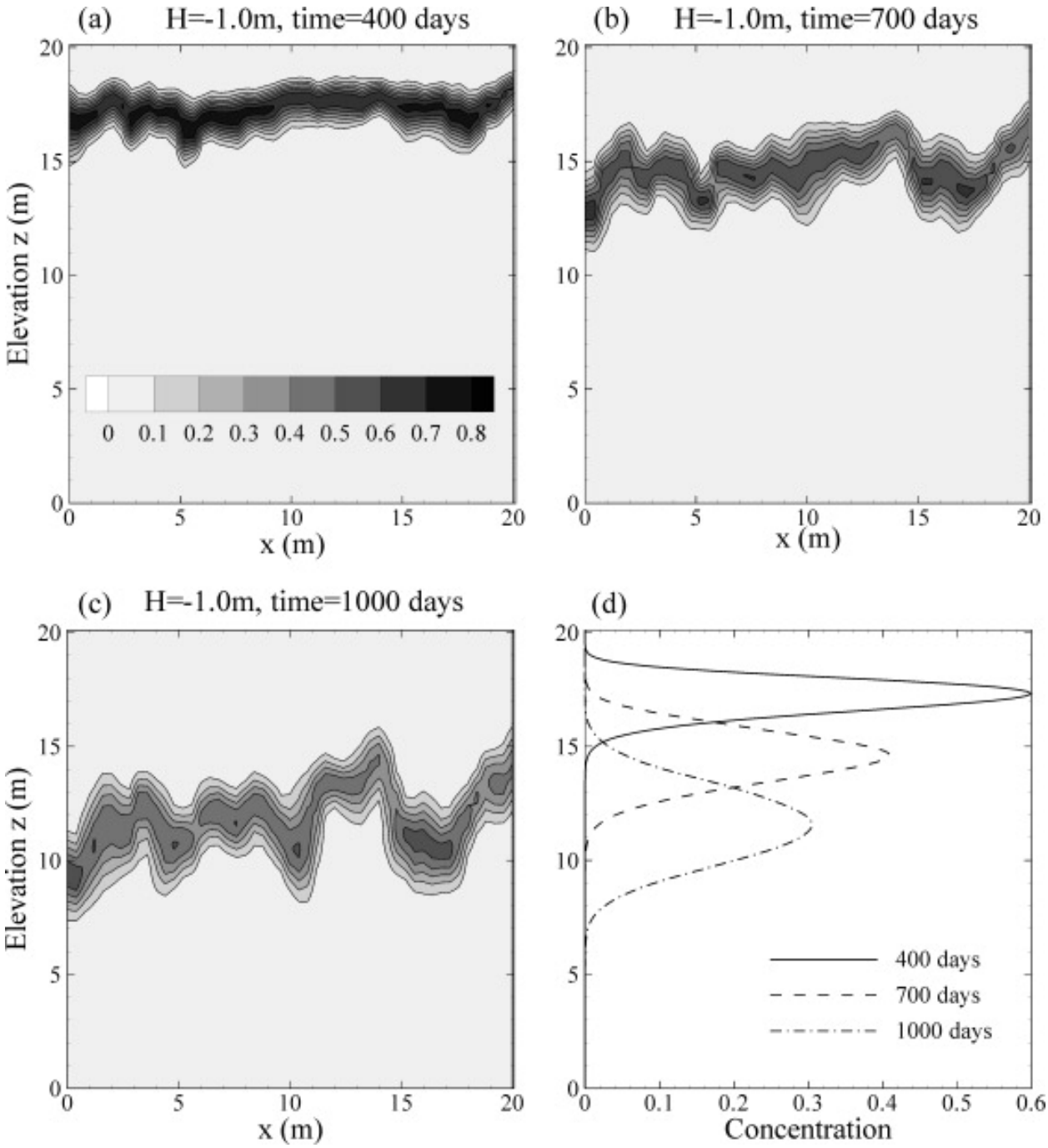
Note that this is the same as Mantoglou Equation B-5 without the flow factor $\gamma$ in the denominator. For hypothetical vadose zone flow domains having $\sigma^2_{LnK_u}$ = 0.29 and extending 15 m and 10 m in the horizontal and vertical directions, respectively, and a correlation length of 0.12 m in the vertical direction, Russo (1991) computed an asymptotic longitudinal macrodispersivity (Equation B-7) of 3.48 cm. As discussed later, the conductivity variance of 0.29 is, however, much smaller compared to variance for Hanford H2 unsaturated conductivity data.

**B.4.3.2.3 Stochastic Theory-Based Macrodispersivity Estimates for Waste Management Area C.** To apply stochastic Equations B-5 and B-7, an estimate of $\lambda_u$ for unsaturated K is needed. As discussed earlier, a correlation length of the order of 50 cm was used for saturated conductivity. However, as saturation decreases, an increase in the variance of log unsaturated conductivity is accompanied by a decrease in the correlation scale of log unsaturated K ("Stochastic Modeling of Macrodispersion for Solute Transport in a Heterogeneous Unsaturated Porous Formation" [Russo 1993]). Also, the Equation B-5 flow factor $\gamma$ (Mantoglou 1984) in a predominantly vertical unsaturated flow through a layered system would be less than 1; it is approximately the ratio of the harmonic and geometric means of unsaturated K (Gelhar 1993; Gelhar and Axness 1983). Assuming a correlation length of 10 cm (approximate measurement scale for small-scale unsaturated K measurements), and $\gamma$ estimates based on the ratio of the harmonic and geometric means (Khaleel et al. 2002), for H2 sands, Mantoglou's model yields asymptotic macrodispersivity estimates, for flow perpendicular to bedding, that are ~360 cm at relatively low tensions of ~2 m. For the Russo (1991) model (Equation B-7), at ~2 m tension, the asymptotic longitudinal macrodispersivity for H2 sands is ~32 cm. Note that the MC simulations (Khaleel et al. 2002) yielded a longitudinal macrodispersivity of ~25 cm for flow perpendicular to bedding and for H=-2m. However, the favorable comparison with Russo's model is coincidental since $\sigma^2_{LnK}$ and mean tension values are different.

Reported values have a relatively low tension of 2 m because of the limitation of low perturbation for stochastic models. The variance $\sigma^2_{LnKu}$ in Equation B-5 becomes rather large for H2 sands; at a mean tension of 1 m, $\sigma^2_{LnKu}$ is about 1.96, whereas at a tension of 2 m, $\sigma^2_{LnKu}$ is about 4.73. Compared to H2 sands, $\sigma^2_{LnKu}$ for the H1/H3/Backfill gravelly units is significantly lower; at a mean tension of 150 cm, $\sigma^2_{LnKu}$ is about 1.22, whereas at a mean tension of 400 cm, $\sigma^2_{LnK}$ is about 2.02. Such variance results are consistent with the unsaturated *K* data reported earlier for sandy and gravelly samples (Figure B-17). Unsaturated *K* for gravelly samples fall within a narrow range, and well within the range of measured *K* for sandy samples. At a matric potential of -1 m, the unsaturated *K* for sandy samples ranges over four orders of magnitude,

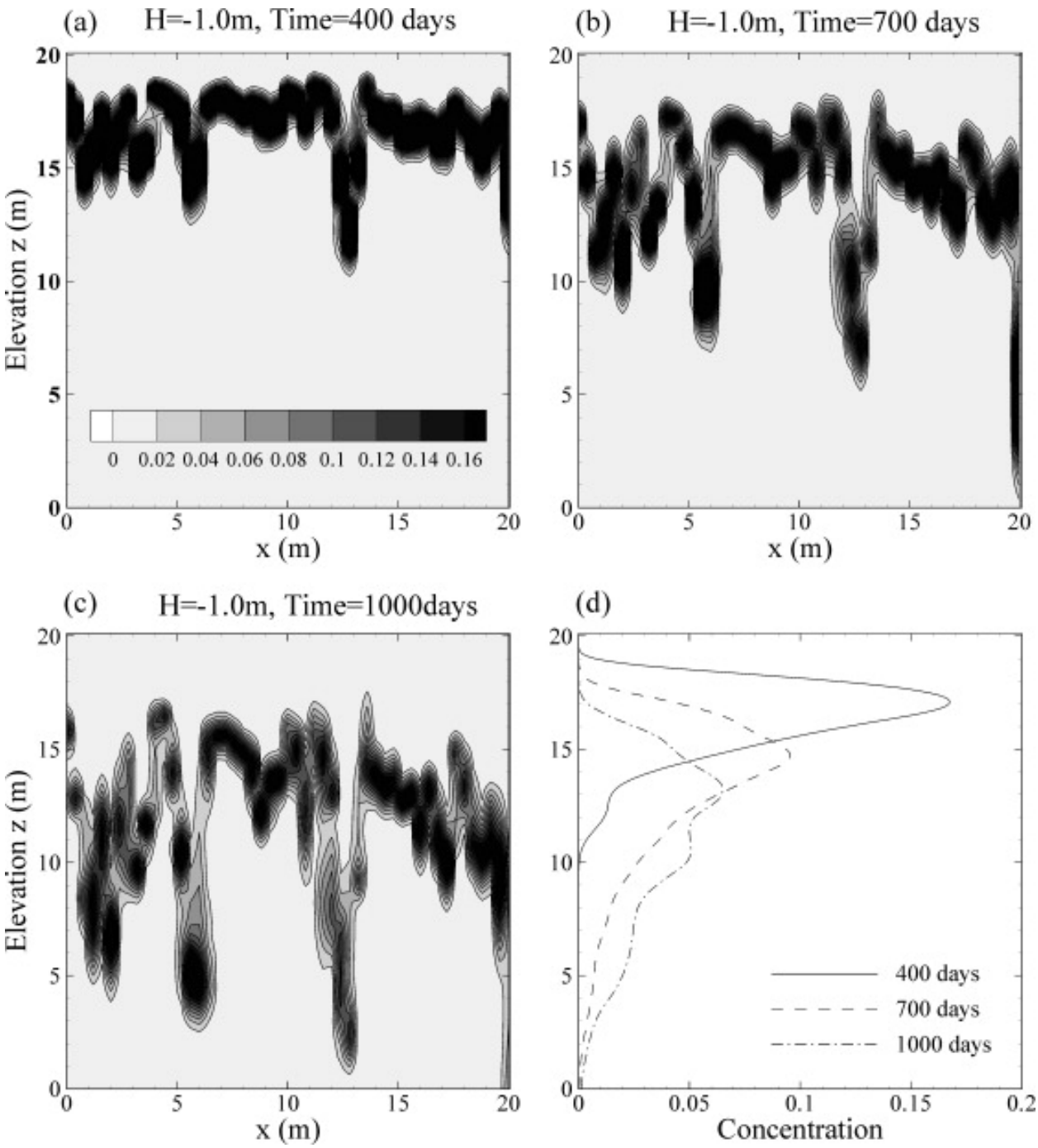
whereas the unsaturated *K* for gravelly samples ranges over two orders of magnitude (Figure B-17).

**Figure B-27. Simulated Concentration Distribution for a Single Realization at (a) 400 days, (b) 700 days, and (c) 1,000 days and (d) the Averaged Concentration Profile at Those Times for Flow Perpendicular to Bedding for a Mean Pressure Head (H) of -1 m.**




Reference: "Upscaled Flow and Transport Properties for Heterogeneous Unsaturated Media" (Khaleel et al. 2002).

**Figure B-28. Simulated Concentration Distribution for a Single Realization at (a) 400 days, (b) 700 days, and (c) 1,000 days and (d) the Averaged Concentration Profile at Those Times for Flow Parallel to Bedding for a Mean Pressure Head (H) of -1 m.**




Reference: "Upscaled Flow and Transport Properties for Heterogeneous Unsaturated Media" (after Khaleel et al. 2002).

**B.4.3.3 Experimental Data from 200 Areas and Other Sites.** Field experiments were conducted at a location in 200 East Area, using potassium chloride as a tracer (RPP-20621 Appendix E, "Hanford Low-Activity Tank Waste Performance Assessment Activity:

Determination of in Situ Hydraulic Parameters of the Upper Hanford Formation"). Analysis of the data, using moment analysis, provided dispersivities that ranged from 1.3 cm to 7.8 cm for travel distances ranging from 25 cm to 125 cm. Although these estimates are for the Hanford formation, the transport distance within the vadose zone is indeed of limited extent. Nonetheless, results based on the limited data are consistent with the concept of a scale-dependent dispersivity; it is expected that the asymptotic value will be larger than those based on the small-scale tracer experiment. In fact, extrapolation of the trend line for the data (RPP-20621 Appendix E) suggests that an asymptotic dispersivity estimate of ~1 m is not unlikely if the heterogeneity at the field site is similar to that of the sandy sediments underlying C Farm, and if the entire sandy sequence of the Hanford formation is treated as EHM.

In addition to the preceding data, results of artificial tracer experiments are available from several arid/semi-arid regions. Two massively instrumented solute transport experiments were performed in desert soils near Las Cruces, New Mexico ("The Las Cruces Trench Site: Characterization, Experimental Results, and One-Dimensional Flow Predictions" [Wierenga et al. 1991]; "The Second Las Cruces Trench Experiment: Experimental Results and Two-Dimensional Flow Predictions" [Hills et al. 1991]). Drip emitters were used to irrigate a plot adjoining a deep trench in heterogeneous media, with well in excess of one order of magnitude standard deviation in saturated hydraulic conductivity. Monitoring of the trench face showed a spatially uniform progression of the wetting front and did not reveal indications of preferential flow (Wierenga et al. 1991). Hills et al. (1991) found that a dispersivity of 5 cm provided reasonably realistic simulations of tritium and bromine tracer distributions.

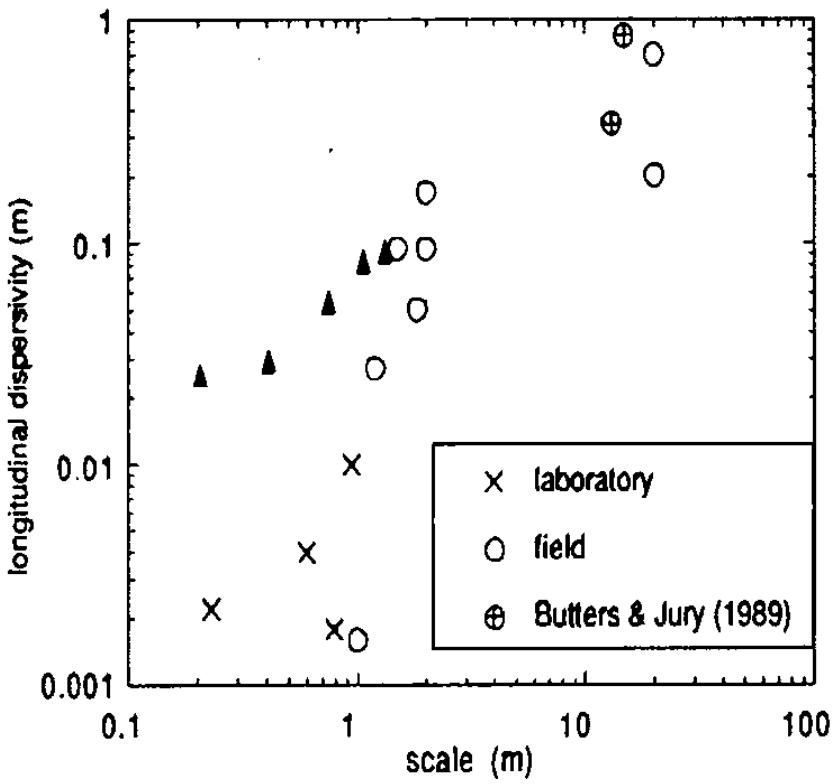
One additional study ("Chlorine 36 and Tritium From Nuclear Weapons Fallout as Tracers for Long-Term Liquid and Vapor Movement in Desert Soils" [Phillips et al. 1988]) assessed the degree of mixing in desert soils using the conventional advection-dispersion modeling, yielding a dispersion coefficient of 50 $cm^2$/yr. This compares with the calculated effective diffusion coefficient of 25 $cm^2$/yr. A similar study ("Evaluation of Liquid and Vapor Water Flow in Desert Soils Based on Chlorine 36 and Tritium Tracers and Nonisothermal Flow Simulations" [Scanlon 1992]) at another southwestern arid site obtained a dispersion coefficient of about 14 $cm^2$/yr. These, then, lead to effective dispersivities of about 7 cm and 4 cm at the two arid sites, and Peclet numbers (displacement divided by dispersivity) of 23 and 17. In summary, long-term environmental tracer studies at several arid southwestern sites indicate vadose zone dispersivities being less than 10 cm.

Based on a different survey of literature, Gelhar (1993) presented the longitudinal vadose zone dispersivities as a function of the scale of the experiment (Figure B-29). The figure shows sparse data for scales larger than 2 m. Nonetheless, similar to saturated flow (Gelhar et al. 1992), Figure B-29 shows an increase of dispersivity with an increase in scale. Also, shown in Figure B-29 are results of the 200 East Area field experiment (RPP-20621 Appendix E); the trend line dispersivity estimate at a field scale of ~10 m is in close agreement with "Field Scale Transport of Bromide in an Unsaturated Soil, 2. Dispersion Modeling" (Butters and Jury 1989) field data.

**B.4.3.4 Recommended Macrodispersivities for Waste Management Area C RCRA Closure Analysis.** Table B-11 summarizes the macrodispersivity estimates based on results of

numerical simulation, stochastic theory, and 200 Areas experimental data. Table B-11 shows that, for H2 sands, estimates are available by all three methods. For the H2 sand unit, for the RCA modeling, the recommendation is to use longitudinal macrodispersivity values ranging from 25 cm (based on numerical simulations) to 100 cm (based on field experiments). For H1/H3/Backfill sediments, the recommendation is to use, based on stochastic theory, longitudinal macrodispersivity values ranging from 20 cm to 100 cm. The transverse macrodispersivity is typically much lower; in saturated media, it may range from 1 to 10% of the longitudinal macrodispersivity (Gelhar and Axness 1983). In the absence of unsaturated media experimental data, the recommendation is to use a transverse macrodispersivity 1/10th of the longitudinal macrodispersivity.

**Figure B-29. Longitudinal Laboratory- and Field-Scale Dispersivities in Unsaturated Media as a Function of Overall Problem Scale.**




Note: The triangles are data from RPP-20621, "Far-Field Hydrology Data Package for the Integrated Disposal Facility Performance Assessment," Appendix E, "Hanford Low-Activity Tank Waste Performance Assessment Activity: Determination of In Situ Hydraulic Parameters of the Upper Hanford Formation."

References:
"Field Scale Transport of Bromide in an Unsaturated Soil, 2. Dispersion Modeling" (Butters and Jury 1989).
Stochastic Subsurface Hydrology (Gelhar 1993).

**Table B-11. Longitudinal Macrodispersivity Estimates (cm).**

| Hydrostratigraphic Unit | Numerical Simulation | Stochastic Theory (Russo and Mantoglou Equations 5 and 7) | 200 Area Field Experiments |
|---|---|---|---|
| H2 Sand-Dominated Unit | 25 | ~32[a] – 360[a] | ~100[c] |
| H1, H3, and Backfill Gravelly Units | NA | ~20[b] – 100[b] | NA |

[a]Evaluated at a mean tension of 2 m.

[b]Evaluated at a mean tension of 4 m.

[c]Extrapolated experimental data (RPP-20621, "Far-Field Hydrology Data Package for the Integrated Disposal Facility Performance Assessment," Appendix E, "Hanford Low-Activity Tank Waste Performance Assessment Activity: Determination of In Situ Hydraulic Parameters of the Upper Hanford Formation").

NA = Not Available

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"Stochastic Analysis of Simulated Vadose Zone Solute Transport in a Vertical Cross Section of Heterogeneous Soil During Nonsteady Water Flow" (Russo 1991).

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# APPENDIX C

# TECHNICAL BASIS FOR WASTE MANAGEMENT AREA C UNCONFINED AQUIFER CONCEPTUAL MODEL: FIELD DATA AND RELATED INVESTIGATIONS

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| | |
|---|---|
| CCU | Cold Creek unit |
| CPGWM | Central Plateau in the Central Plateau Groundwater Model |
| EHM | equivalent homogeneous medium |
| FY | fiscal year |
| HSU | hydrostratigraphic unit |
| LLWMA | Low-Level Waste Management Area |
| RCA | Resource Conservation and Recovery Act of 1976 (RCRA) Closure Analysis |
| STOMP | Subsurface Transport Over Multiple Phases |
| TC&WM EIS | Tank Closure and Waste Management Environmental Impact Statement |
| WMA | Waste Management Area |

# APPENDIX C

## TECHNICAL BASIS FOR WASTE MANAGEMENT AREA C UNCONFINED AQUIFER CONCEPTUAL MODEL: FIELD DATA AND RELATED INVESTIGATIONS

The groundwater pathway analysis is an important aspect of the Waste Management Area (WMA) C Resource Conservation and Recovery Act of 1976 (RCRA) Closure Analysis (RCA). As the contaminant mass flux arriving from the vadose zone enters the aquifer, it mixes with the groundwater and undergoes dilution, dispersion, and retardation while traveling along the flow path. The amount of dilution is strongly dependent on the ratio of volumetric groundwater flux to contaminant mass flux within the mixing zone. However, groundwater flux is not ordinarily a measurable quantity. Instead, it is inferred from hydraulic head measurements and from hydraulic properties of the aquifer (i.e., estimates of the hydraulic gradients and hydraulic conductivities), which are deduced from a variety of measurement methods, such as pump and slug tests, or derived from inverse modeling of the aquifer to estimate conductivity from measured head values.

Past and present measured field data (hydraulic heads) in observation boreholes in the vicinity of WMA C must be used carefully as the region is recovering from the effects of both surface (ponds, cribs, trenches, and ditches) and subsurface (leaking pipelines, leaking tanks, and injection wells) liquid discharges from Hanford operations for many years. Groundwater mounding continues to dissipate to an equilibrium condition that is likely to be similar to the pre-Hanford operations condition (see Section 3). As a result, the post-closure position of the water table, and its hydraulic gradient, can only be estimated through evaluating the current water table and forecasting the anticipated changes. Modeling is a critical tool in this evaluation, as it can be used to estimate both the hydraulic gradient and the recovery of hydraulic heads from the operational liquid discharges. Consequently, this analysis uses modeling tools to calculate the future groundwater flux, based on aquifer hydraulic properties, and the projected hydraulic gradient.

This appendix provides a detailed assessment and evaluation of saturated media field data used to estimate the aquifer hydraulic properties, including saturated hydraulic conductivity, groundwater fluxes, and hydraulic gradients, and specifies the technical basis for parameter selection and use in the WMA C RCA modeling. Included in this assessment/evaluation is the following:

- A brief review of scale dependence of saturated media parameters (Section C.1)
- A brief overview of the hydrogeologic conditions pertinent to WMA C (Section C.2)
- A summary of measured and theoretically-estimated aquifer hydraulic parameter estimates available for the areas near WMA C (Section C.3)

- A summary of how this information is used for the RCRA Closure Analysis (Section C.4).

## C.1 HIERARCHY OF LENGTH SCALES AND SCALE DEPENDENCE OF MEDIA PROPERTIES

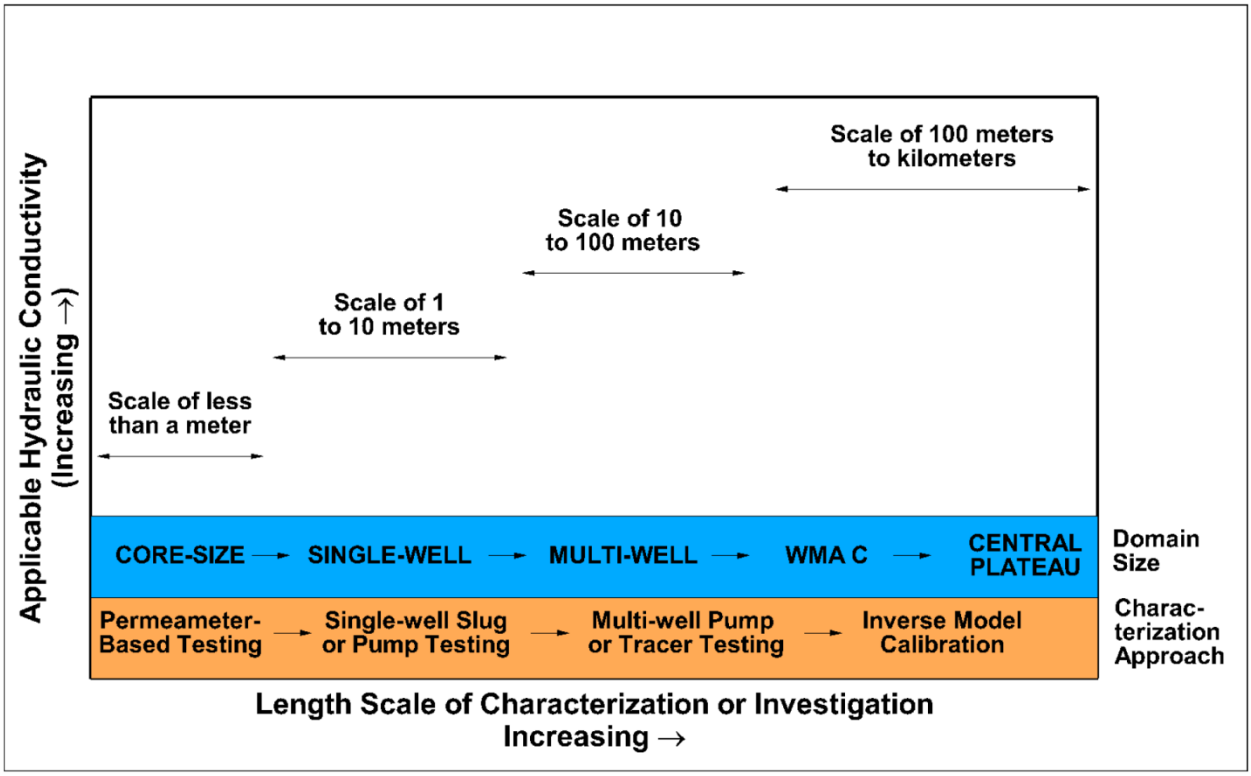
A variety of methods exist which can be used to estimate hydraulic conductivity, including permeameter cells, slug tests, pump tests, and model calibration. In general, estimates of saturated hydraulic conductivity, either inferred by aquifer testing or determined from calibrated models, tend to increase as the scale of the flow domain increases (e.g., U.S. Geological Survey Water-Supply Paper 2237, "Regional Flow in the Dakota Aquifer: A Study of the Role of Confining Layers"). The evolving heterogeneities at various length scales result in a scale dependence of effective parameters such as saturated hydraulic conductivity ("An Analysis Platform for Multiscale Hydrogeologic Modeling with Emphasis on Hybrid Multiscale Methods" [Scheibe et al. 2015]). For WMA C RCA saturated media modeling, the flow domain size of interest is shown on the right side of Figure C-1, with the characteristic length scale for flow and transport on the order of hundred meters. As the length scale of observation increases, the effective properties increase in discretely hierarchical stages or evolve continuously (Scheibe et al. 2015). The effects of large-scale heterogeneity on flow and determination of media properties can therefore be inferred most effectively by using regional-scale groundwater models.

Determining effective hydraulic conductivities applicable to the field scale appears to be best evaluated using inverse modeling conditioned by available data, using appropriate boundary conditions. Measurements of hydraulic conductivity appear to be dependent on the test scale, and increase as the scale increases, particularly in heterogeneous media ("Scale Dependency of Hydraulic Conductivity Measurements" [Rovey and Cherkauer 1995]; "Scale Dependency of Hydraulic Conductivity in Heterogeneous Media" [Schulze-Makuch et al. 1999]). In-situ measures of aquifer flow and hydraulic properties inferred from hydraulic testing represent relatively small areas (Figure C-1) compared to the overall scale and dimensions of the model domain, and therefore do not provide representative results appropriate for the field scale (MASSFLUX-1, "Use and Measurements of Mass Flux and Mass Discharge"). Similarly, individual well-based slug and pump tests provide information at a relatively small scale, albeit larger than core-scale permeameter tests. Permeameter, slug, and pump tests are also limited in their ability to quantify spatial averages or trends, and are less likely to produce central measures of flow magnitudes than a regional model (MASSFLUX-1). Field estimates for saturated hydraulic conductivity based on slug tests, for example, provide estimates of hydraulic representation at a scale of meters and are not considered generally appropriate to be used directly in the modeling, even though slug and pumping test data are important input for model calibration (MASSFLUX-1).

Consequently, in evaluating available information for the aquifer at WMA C, hydraulic conductivities derived from a calibrated model are regarded as more reliable than direct measurements by permeameter, slug, or pump tests. This distinction is important because, as

Section C.2 will show, substantially different values for hydraulic conductivity have been estimated by various investigators using different methods.

**Figure C-1. Schematic Illustrating Scale in a Heterogeneous Media and Scale Dependence of Saturated Hydraulic Conductivity.**




WMA = Waste Management Area

## C.2 HYDROGEOLOGIC CONDITIONS AND STRUCTURE

To understand the groundwater flow conditions in the vicinity of WMA C, and in particular the large-scale saturated hydraulic conductivity and hydraulic gradient, it is important to note the regional geology and the hydrogeologic conditions and geologic structure in the 200 Areas. Groundwater in the unconfined aquifer at Hanford generally flows from recharge areas in the elevated region near the western boundary of the Hanford Site, toward the Columbia River on the eastern and northern boundaries. The Columbia River is the primary discharge area for the unconfined aquifer.

The unconsolidated sediments of the present-day Central Plateau reflect deposits of the ancient Columbia River, and the Pleistocene cataclysmic flooding (Sections 3.1.4 and 3.1.9 provide a detailed discussion of the regional and local geology that is not repeated here). Briefly, WMA C lies on the northern flank of the Cold Creek bar, a large compound flood bar formed during Pleistocene cataclysmic flooding, which last occurred about 15,000 years ago (On the Trail of the Ice Age Floods: A Geological Field Guide to the Mid-Columbia Basin [Bjornstad 2006]). The cataclysmic floods caused repeated large erosional and depositional events, which have

significantly shaped the Central Plateau and the present WMA C geology. Erosion by Ice Age flooding and the ancestral Columbia River are believed to have removed much of the Ringold Formation from the area and created a highly transmissive paleochannel. The cataclysmic floods deposited into the channel the gravel-dominated facies of the Hanford formation that consists of coarse-grained basaltic sand and granule- to boulder-size gravel displaying an open framework. These large-scale features significantly influence groundwater flow and plume migration because the deposits in the channel are much more transmissive than those outside of the channel. The groundwater flow direction in the unconfined aquifer in the vicinity of WMA C trends toward the southeast. This conclusion is based on the following: 1) slightly higher hydraulic heads to the northwest, 2) the orientation of the southeast trending paleochannel in the area, and 3) the configuration of the major contamination plumes.

### C.2.1 Paleochannel Configuration and Flow Paths

As discussed above, the paleochannel has a significant influence on flow and contaminant transport under WMA C. The open-framework gravels of the paleochannel are highly conductive, and as such constitute a potential fast pathway for migration of contaminants. It is therefore important to characterize the spatial extent of the paleochannel in the vicinity of WMA C, and to appropriately estimate its permeability.

Based on current understanding of the ancestral Columbia River deposits, a large paleochannel is interpreted extending southeast through Gable Gap (Figure C-2) that bifurcates just south of the gap. One sub-channel trends easterly following along the direction of strike of the Gable Mountain anticline, while the other sub-channel trends in a more southerly direction through the eastern portion of the 200 Area Inner Boundary (the paleochannel identified in Figure C-2). The southerly-trending paleochannel configuration, flow path, and dimensions have been the subject of numerous studies, owing to their importance to site-wide contaminant transport.

Recent reports providing information supporting the current interpretation of the extent of the paleochannel include the following.

- PNNL-12261, “Revised Hydrogeology for the Suprabasalt Aquifer System, 200-East Area and Vicinity, Hanford Site, Washington.” The report includes detailed interpretations on the paleo and flood channels, and has several cross sections and figures displaying their configuration and flow paths.

- Aero-Metric LiDAR, “RCCC-Hanford Battelle/PNNL/DOE, Digital Orthophotography & LiDAR Surveys Photogrammetric Report,” prepared by Aero-Metric, Seattle, Washington. The report includes LiDAR data; surficial expression of paleochannel outlines are apparent from ground-proofed Aero-Metric LiDAR data collected in 2008.

- Fiscal year (FY) 2013 and 2014 Annual Groundwater Monitoring Reports, CH2M HILL Plateau Remediation Company. Interpretation of tritium and $^{129}$I plume extents follow the highly conductive flow paleochannel flow path.

- ECF-Hanford-13-0029, "Development of the Hanford South Geologic Framework Model, Hanford Site, Washington." The report shows areas where interpolated sediment volumes are not present, suggesting scouring along the paleochannel flow paths. All but two of the wells used in ECF-Hanford-13-0029 in the immediate vicinity of WMA C lie within the paleochannel. Geologic and geophysical logging data from the wells were also used in estimating paleochannel location.

Scouring of suprabasalt sediments in the paleochannels is evident in that, along much of its path, only the Hanford formation overlies the top of the basalt. Hanford formation material makes up almost entirely the material within the paleochannels in general, as well as all of the material within the paleochannel at the WMA C water table. Removal of pre-Hanford formation suprabasalt sediments, except for a thin layer of Cold Creek unit (CCU) beneath the eastern half of WMA C, is apparent suggesting a paleochannel width of over 500 m beneath WMA C. Wells 299-E27-14 and 299-E27-15 penetrate the Hanford formation within the paleochannel beneath WMA C. The Hanford formation is ~86 m thick and saturated thickness from the water table to the top of the basalt is ~13 m.

### C.2.2 Theoretical Basis for Hydraulic Conductivity Estimates of Paleochannel Sediments

As discussed above, the paleochannel comprises an open-framework gravelly medium below WMA C. Figure C-3 is a digital photo log for borehole 299-E27-4 showing its proximity to WMA C and the open-framework gravelly media below the water table (the broken blue line is the water table location). The importance of the paleochannel-to-groundwater transport in the central plateau has led to a number of efforts to characterize its permeability, which can be applied to the WMA C RCRA closure analysis.

Permeability measurements in open-framework gravelly media present special challenges, as the permeabilities are so high that they are above the measurement range of most laboratory constant-head permeameters—the head difference is too small to be measured. "Measuring the permeability of open-framework gravel" (Ferreira et al. 2010) addresses the challenge of measuring the high permeability by using a 3-m long permeameter. The head difference over this length was of the order of $10^{-2}$ to $10^{-3}$ m, which could be measured to the nearest $10^{-5}$ m. Measured permeability values varied between 3,456 m/day (for uniform pebbles) to 86,400 m/day (for open-framework gravels).

Figure C-4 illustrates an idealized unit cell model of an open-framework gravelly medium. "Scale Dependence of Continuum Models for Fractured Basalts" (Khaleel 1989) derived an expression (Equation C-1) for the isotropic saturated hydraulic conductivity ($K$) for such idealized media.

$$K_1 = K_2 = \frac{b^3 g}{12\sqrt{3}\ell\nu} \qquad \text{(C-1)}$$

where g is the acceleration ($LT^{-2}$) due to gravity, $b$ is the open space aperture (L), $\ell$ is the coordinate length (L) along the opening of the unit cell, and $\nu$ is the kinematic viscosity ($L^2T^{-1}$)

of the fluid. By inspection of Equation C-1 for equivalent isotropic *K*, the aperture size or width *b* is the most sensitive parameter in influencing conductivity estimates. For different aperture widths, and for a hexagon side length of 0.005 m (i.e., representative of 0.01-m [10-mm]-diameter pebbles), the calculated equivalent *K* estimates range from a low of 8 m/day to 65,000 m/day for aperture widths (*b*) ranging from a rather modest spacing of 0.1 mm to as high as 2 mm. In regard to WMA C, according to sieve results of sandy gravel samples collected from near the water table and below at well 299-E27-4, the grain size of approximately 35% to 40% of the material exceeds 10 mm (PNNL-14656, "Borehole Data Package for Four CY 2003 RCRA Wells 299-E27-4, 299-E27-21, 299-E27-22, and 299-E27-23 at Single-Shell Tank, Waste Management Area C, Hanford Site, Washington").

A theoretical estimate of the permeability of a uniform pebble network can also be obtained using the Kozeny-Carman equation (Dynamics of Fluids in Porous Media [Bear 1972]):

$$k = \frac{d}{180}\frac{\phi^3}{(1-\phi)^2} \tag{C-2}$$

The 10-mm diameter (*d*) uniform pebble model having a measured porosity $\phi$=40% yields a permeability of about 86,000 m/day. Therefore, the two theoretical approaches are the same order of magnitude, and both provide very high estimates of saturated conductivity that are comparable to those based on the large-scale permeameter experiments (Ferreira et al. 2010).

## C.3 ESTIMATES OF UNCONFINED AQUIFER FLOW AND TRANSPORT PROPERTIES

Estimation of aquifer flow and transport parameters at WMA C are necessary for evaluating the rate and extent of migration of contaminants arriving from the vadose zone and to assess the groundwater quality as required under RCRA. The RCRA groundwater quality assessment program requires determination of whether past releases from WMA C are affecting groundwater quality and estimation of the rate and extent of migration of dangerous waste or dangerous waste constituents in the groundwater (DOE/RL-2009-77, Groundwater Quality Assessment Plan for the Single-Shell Tank Waste Management Area C; SGW-54508, "WMA C September 2012 Quarterly Groundwater Monitoring Report").

### C.3.1 Groundwater Flow Velocities and Fluxes

Estimates of groundwater flow velocity or Darcy flux can provide valuable information about the hydraulic properties of the aquifer. These estimates can be made by measuring the flow within a borehole (using downhole flowmeters) or by interrogating the local or regional scale flow models.

Few direct measurements of groundwater flow exist in the 200 East Area, and none are particularly relevant to the groundwater flow conditions forecast for the unconfined aquifer in the immediate vicinity of WMA C. Measurements of groundwater flow velocity (groundwater

flux divided by porosity) in the vicinity of WMA B-BX-BY, collected using a colloidal borescope circa 2001, reflected the impact of the large mound caused by the discharges at 216-B-3 Pond diverting flow from the east or southeast. The results did indicate that the flow velocities appeared to be greater in magnitude in the southern half of WMA B-BX-BY than in the northern half ("Application of the Colloidal Borescope to Determine a Complex Groundwater Flow Pattern" [Narbutovskih et al. 2002]). WHC-SD-EN-WP-012, "Groundwater Screening Evaluation/Monitoring Plan -- 200 Area Treated Effluent Disposal Facility (Project W-049H)" documents the results of an evaluation conducted using a heat pulse flowmeter used to measure the magnitude and direction of groundwater flow velocity in three wells located east of the 216-B-3 Pond complex. However, during January and February 1994 when the evaluation occurred, the 216-B-3 Pond complex still received effluent and sustained the prominent groundwater mound, and the results of the testing were influenced by the mound created by the 216-B-3 pond discharges.

Groundwater flux information for particular subareas of regional models is often difficult to obtain from previous studies, and often must be inferred from whatever information is available. DOE/EIS-0391, "Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington" estimated the future steady-state flow velocity in the highly conductive Hanford formation sediments at the 216-BY Cribs to be approximately 2 to 3 m/day toward the southeast, according to figures in Appendix L (i.e., Figures L-55, L-56, and L-57). According to the range of specific yield values presented in Table L-12 of Appendix L of DOE/EIS-0391, the flux in the aquifer is between 0.3 and 0.9 m/day.

Groundwater flux in the aquifer is estimated using the Central Plateau Groundwater Model (CPGWM) CP-47631, "Model Package Report: Central Plateau Groundwater Model Version 6.3.3") by evaluating the water budget through a planar rectangular window (300 m × 200 m that encompasses most of WMA C flow domain) over the unconfined aquifer thickness (Figure C-5). The results of the CPGWM include two times of interest, present day and post-closure steady state:

- For Year 2014 (approximating present day conditions), the CPGWM-calculated flow through the window volume is 1,100 $m^3$/day, which divided by the cross-sectional area of 3,300 $m^2$ translates to a Darcy flux of 0.33 m/day

- For Year 2100 (approximating post-closure steady state conditions), the CPGWM-calculated flow through the window volume is 580 $m^3$/day, which divided by the cross-sectional area of 3,300 $m^2$ translates to a Darcy flux of 0.18 m/day.

### C.3.2 Hydraulic Conductivity of Unconfined Aquifer Sediments

The basis for the hydraulic conductivity of the unconfined aquifer used in the RCA takes account of the accumulated knowledge and experience of many years of study of the aquifer beneath the Central Plateau, undertaken for a variety of purposes by different investigators, using a variety of measurement and modeling approaches. The hydraulic conductivity estimates from various investigations, with focus on the aquifer within the 200 East Area, are presented in Figure C-6 in such a manner that the length scale of observation increases from left to right. The results

presented on the left-hand side are from slug tests (small spatial scale measurements), while the pumping test-based measurements are in the middle and the regional scale model-based estimates are on the right-hand side. Where multiple results are provided within a single report that cover slug and pump test data, the range of hydraulic conductivity is shown with a vertical line (Figure C-6). The generally increasing estimates of effective hydraulic conductivity moving from the left to the right are consistent with Figure C-1 and the description in Section C.1. The results of most hydrologic tests indicate the presence of highly permeable conditions in the unconfined aquifer within the Central Plateau, and measured hydraulic conductivity estimates range as high as 51,500 m/day.

SGW-54508 considers hydraulic conductivity of the Hanford gravel at WMA C to range from 100 to 2,100 m/day on the basis of the results of slug and pumping tests conducted in wells located in the immediate vicinity of WMA C. Excluded from this range are unpublished slug test results from well 299-E27-24 that produced hydraulic conductivity estimates ranging from 3,650 to 51,500 m/day, and slug test results from well 299-E27-22 that range from 1,888 to 6,888 m/day (shown in Figure C-6). SGW-54508 discounts the results from well 299-E27-24 because the open interval and well radius were not controlled and sloughing conditions existed before testing. SGW-54508 also discounts the results from well 299-E27-22 because the sediment borehole log description at well 299-E27-22 indicates a more dominant silt matrix with less gravel content than at well 299-E27-23, where slug test results indicated that the hydraulic conductivity measures 100 to 108 m/day. However, the borehole log of well 299-E27-22 (Figure C-7) does indicate the presence of the open-framework gravel in the aquifer, and SGW-54508 does not explain why sloughing would cause hydraulic conductivity estimates derived from a slug test to be overestimated. In addition, the slug test data presented in SGW-48722, “Borehole Summary Report for the ARRA Installation of Five RCRA Groundwater Monitoring Wells in the 200 Areas, FY 2010” collected from wells 299-E27-24 and 299-E27-25 exhibit the oscillatory response indicative of highly permeable conditions. While the summary of data presented in SGW-54508 is appropriate for the purposes of the RCRA groundwater quality assessment program, which include collecting and analyzing the available data, the data represent measurements made at a much smaller observation scale than is appropriate for developing an effective hydraulic conductivity estimate for WMA C (Figure C-1).

PNNL-14656 indicates that the high values measured at the wells are indicative of, and consistent with, the geologic interpretation of the open, highly permeable lower Hanford H3 gravels. The slug test and well screen development drawdown data also indicate comparable highly permeable conditions in the aquifer at wells 299-E27-21 and 299-E27-22 (PNNL-14656). Lastly, the results of an aquifer test with multiple observation wells conducted at well 699-55-50 indicate an aquifer hydraulic conductivity of 2,700 m/day (HW-60601, “Aquifer Characteristics and Ground-Water Movement at Hanford”). HW-60601 describes the aquifer as consisting of “Glaciofluviatile sands and gravels,” which are described as unconsolidated sands and gravels occurring chiefly as glacial outwash. This description matches that given to the highly-permeable gravel contained in the paleochannel.

Past calibration efforts (e.g., PNL-10886, “Development of a Three-Dimensional Ground-Water Model of the Hanford Site Unconfined Aquifer System: FY 1995 Status Report”; PNNL-11801,

"Three-Dimensional Analysis of Future Groundwater Flow Conditions and Contaminant Plume Transport in the Hanford Site Unconfined Aquifer System: FY 1996 and 1997 Status Report") estimated that an upper limit of hydraulic conductivity for coarse-gravel flood deposits found in the central part of the Hanford Site is on the order of several tens of thousands of meters per day (Figure C-8). Figure C-8 shows the influence of the high hydraulic conductivity paleochannel in the aquifer beneath WMA C, as denoted by the swath of red. This swath indicates hydraulic conductivity exceeding 7,000 m/day, extending from the Gable Gap through the southeast corner of the 200 East Area. In one calibration effort, the hydraulic conductivity ranged from 271 m/day to 8,840 m/day within the WMA C RCA model domain, and a value of 7,020 m/day in the immediate vicinity of WMA C (PNNL-14753, "Groundwater Data Package for Hanford Assessments"). In another effort, the hydraulic conductivity of the Hanford formation sediments ranged up to about 1,000,000 m/day for the Hanford flood deposits (PNNL-13641, "Uncertainty Analysis Framework – Hanford Site-Wide Groundwater Flow and Transport Model"). The Tank Closure and Waste Management Environmental Impact Statement (TC&WM EIS) model estimates the hydraulic conductivity of the highly conductive Hanford gravel present at WMA C to be ~4,000 m/day (DOE/EIS-0391). In a more recent modeling effort, CP-57037, "Model Package Report: Plateau to River Groundwater Transport Model Version 7.1" developed a calibrated estimate of 17,000 m/day for the Hanford formation associated with the paleochannel.

The CPGWM provides calibrated hydraulic conductivity estimates for the hydrostratigraphic units (HSUs) present within the aquifer. The CPGWM represents the most recent culmination of understanding of the unconfined aquifer under the Central Plateau and, given the rigorous nature of the development effort, is deemed to be the most suitable for predicting flow. The thicknesses and extent of the different HSUs within the selected model layers in the vicinity of WMA C for the saturated zone are shown in Figure C-9. The equivalent hydraulic conductivity for a given layer within the rectangular area (approximate extent of WMA C) ranges between 5,802 m/day and 17,000 m/day (Table C-1). Using a layer thickness weighted averaging scheme, the effective hydraulic conductivity for an equivalent homogeneous medium (EHM) is estimated to be 11,000 m/day for the entire aquifer (Table C-1). The EHM approach is used for representing the saturated zone in the three-dimensional WMA C PA model using Subsurface Transport Over Multiple Phases (STOMP)© [1], as discussed in Appendix D, and therefore the value of 11,000 m/day is used for the aquifer.

### C.3.3 Groundwater Flow Directions and Hydraulic Gradients

In the vicinity of WMA C, directions of groundwater flow and hydraulic gradients are inferred from water-level measurements in another part of the 200 East Area around Low-Level Waste Management Area (LLWMA)-1 (DOE/RL-2013-22, Hanford Site Groundwater Monitoring Report for 2012), which is located northwest of WMA C. According to DOE/RL-2014-32, Hanford Site Groundwater Monitoring Report for 2013, the hydraulic gradient ranges between $2.2 \times 10^{-5}$ m/m and $2.9 \times 10^{-5}$ m/m, with flow moving in a southeastern direction. The average hydraulic gradient estimated from July 2011 through September 2012 was $2.5 \times 10^{-5}$ ($\pm 0.4 \times 10^{-5}$) m/m toward the south (SGW-54165, "Evaluation of the Unconfined Aquifer Hydraulic Gradient Beneath the 200 East Area, Hanford Site"). SGW-54165 indicates that while

[1] Subsurface Transport Over Multiple Phases (STOMP)© is copyrighted by Battelle Memorial Institute, 1996.

the hydraulic gradient determination represents a spatial average across the entire Low-gradient Monitoring Network in the vicinity of LLWMA-1, mapping of water levels from August 2011 indicates that the flow direction directly beneath LLWMA-1 is more toward the southeast rather than toward the south.

Hydraulic gradient estimates in groundwater based on the CPGWM estimates of future conditions within the Central Plateau are summarized in Table C-1. Although water levels in the 200 East Area continue to decline, an evaluation of current groundwater flow directions and rates at WMA C is difficult due to the very low hydraulic gradient (on the order of $10^{-5}$ m/m). The hydraulic gradient according to the CPGWM is calculated from the volumetric flux through the window described in Section C.3.1.2 and the hydraulic conductivity value described in Section C.3.1.2. As indicated previously, the results of the CPGWM include two times of interest, present day and post-closure steady state (Table C-1), as follows.

- For Year 2014 (approximating present day conditions), the CPGWM-calculated flow through the window volume is 1,000 $m^3$/day, which divided by the cross-sectional area of 3,300 $m^2$ and equivalent hydraulic conductivity of 11,000 m/day translates to a hydraulic gradient of $3 \times 10^{-5}$. The direction of flow inferred from the modeling and consistent with plume movements is in a south-to-southeasterly direction.

- For Year 2100 (approximating post-closure steady state conditions), the CPGWM-calculated flow through the window volume is 730 $m^3$/day, which divided by the cross-sectional area of 3,300 $m^2$ and equivalent hydraulic conductivity of 11,000 m/day translates to a hydraulic gradient of $2 \times 10^{-5}$. The direction of flow inferred from the model is in a southeasterly direction.

The CPGWM model estimate of $3 \times 10^{-5}$ m/m for year 2014 is consistent with the average gradient measured during 2013 ($2.6 \times 10^{-5}$ m/m) (DOE/RL-2014-32), and within the range of what is reported in SGW-54508 and SGW-58561, "WMA C Quarterly October through December 2014 Quarterly Groundwater Monitoring Report" ($5.9 \times 10^{-6}$ to $4.5 \times 10^{-5}$ m/m).

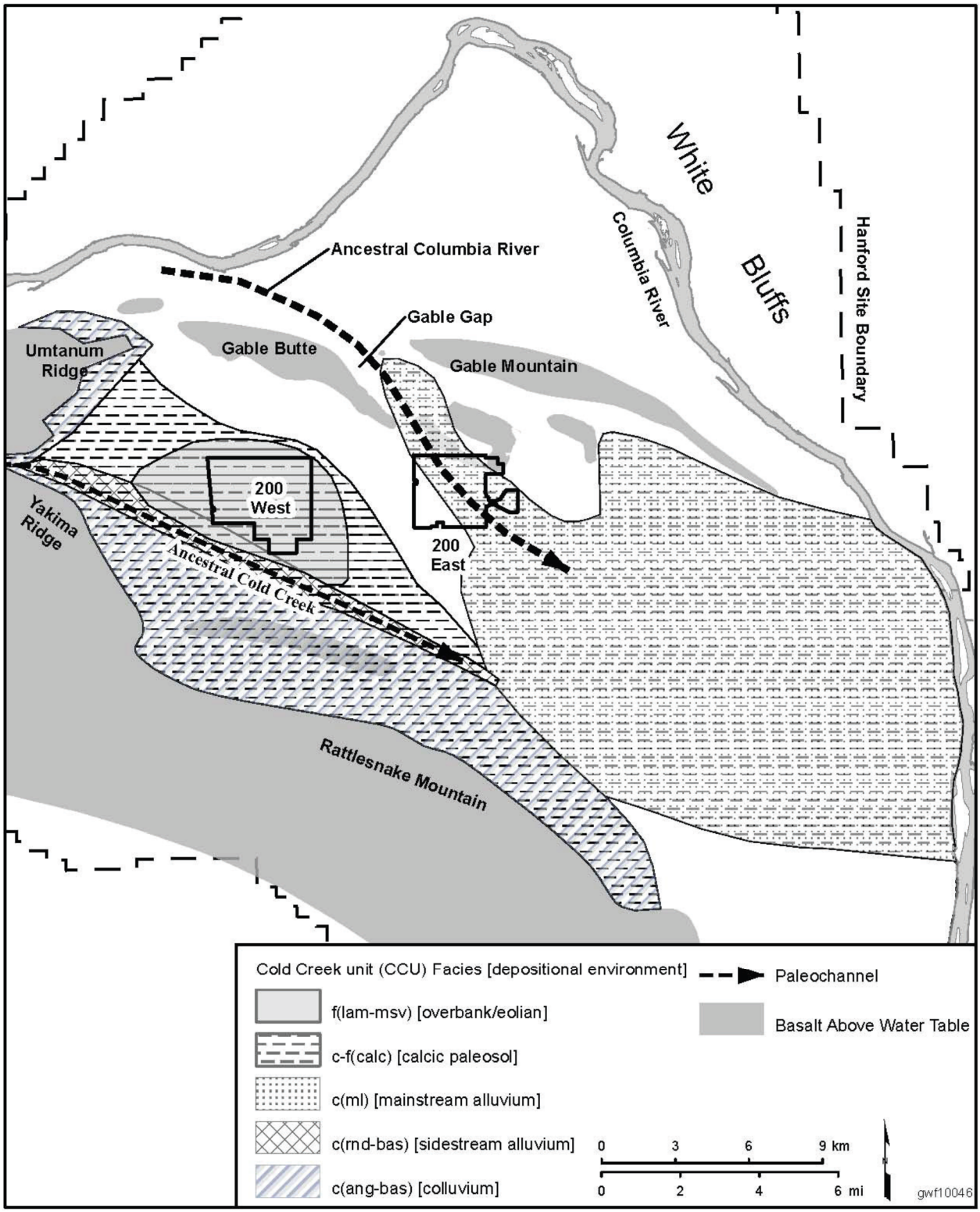
### C.3.4 Anisotropy

Anisotropy in saturated hydraulic conductivity for Hanford H3 gravels has been estimated from pumping tests, which indicate values ranging from 0.01 to 0.1 (PNL-10886) and 0.015 to 0.5 (DOE/RL-2007-28, Feasibility Study Report for the 200-ZP-1 Groundwater Operable Unit) for post-year 2000 testing. Previous modeling analyses (e.g., PNNL-14398, "Transient Inverse Calibration of the Site-Wide Groundwater Flow Model [ACM-2]: FY 2003 Progress Report"; PNNL-14753; DOE/EIS-0391; and CPGWM [CP-47631]) estimate anisotropy to be 0.1.

### C.3.5 Properties for Contaminant Transport

The transport of contaminants also requires estimates of the porosity, the volume of pore space in the aquifer, and the macrodispersivity, which accounts for the mixing that occurs because of variations in the flow and velocity caused by heterogeneities.

**Figure C-2. Interpreted Extent of a Paleochannel Associated with the Ancestral Columbia River in 200 East Area in the Vicinity of Waste Management Area C.**




Source: DOE/RL-2011-118, Hanford Site Groundwater Monitoring for 2011, Appendix E.

**Figure C-3. Digital Photo Log for Borehole 299-E27-4 Showing an Open Framework Gravel below the Water Table.**

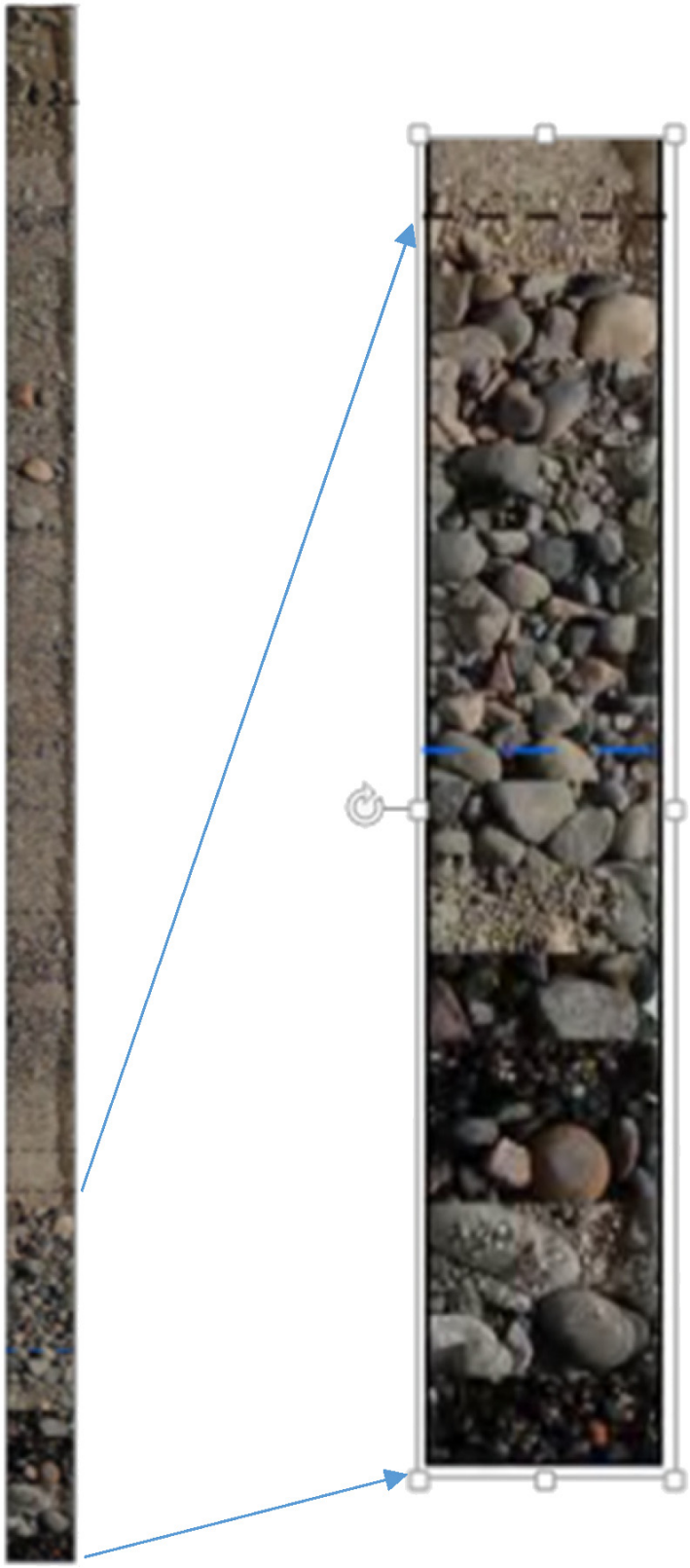
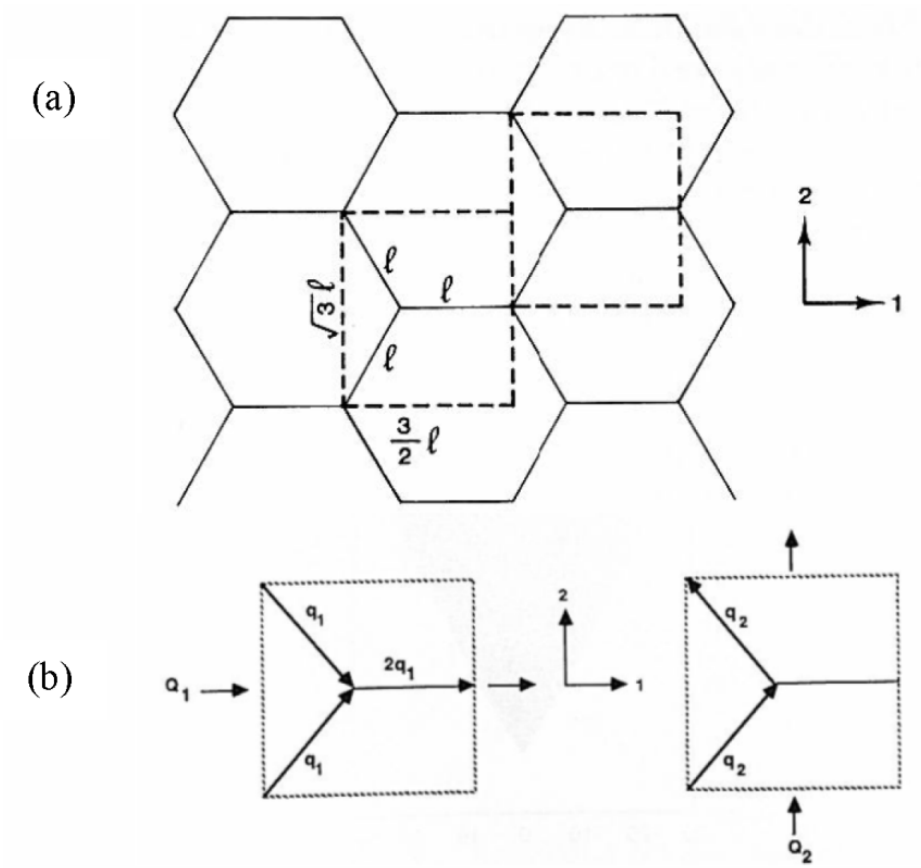


**Figure C-4. (a) An Idealized Hexagonal Model Approximation of Open-Framework Gravelly Media, and (b) Representative Flow Regions Used to Determine Equivalent Hydraulic Conductivity.**




**C.3.5.1 Porosity.** According to RPP-14430, "Subsurface Conditions Description of the C and A-AX Waste Management Area," porosity is generally estimated to be about 30% for unconsolidated coarse-grained sediments, but a value closer to 20% may be more appropriate where boulders and cobbles are present and mixed with sand and gravels, such as at WMA C. Other estimated values include 0.06 determined from an aquifer pumping test at a well (699-62-43) screened within the Hanford gravel sequence similar to that at WMA C (HW-60601); 0.1 derived from laboratory tests of Hanford gravels discussed in PNNL-19277, "Conceptual Models for Migration of Key Groundwater Contaminants Through the Vadose Zone and Into the Unconfined Aquifer Below the B-Complex"; and 0.25 in RPP-RPT-46088, "Flow and Transport in the Natural System at Waste Management Area C." DOE/EIS-0391 identified 0.15 to 0.30 as a reasonable range for the storage property value (expressed as specific yield values) of the highly conductive Hanford formation present in the paleochannel. CP-57037 estimated porosity of the Hanford formation associated with the paleochannel to be 0.2.

**Figure C-5. Plan View of the Central Plateau Groundwater Model Representing the Aquifer and the Volumetric Flux Calculation Window in the Vicinity of Waste Management Area C.**

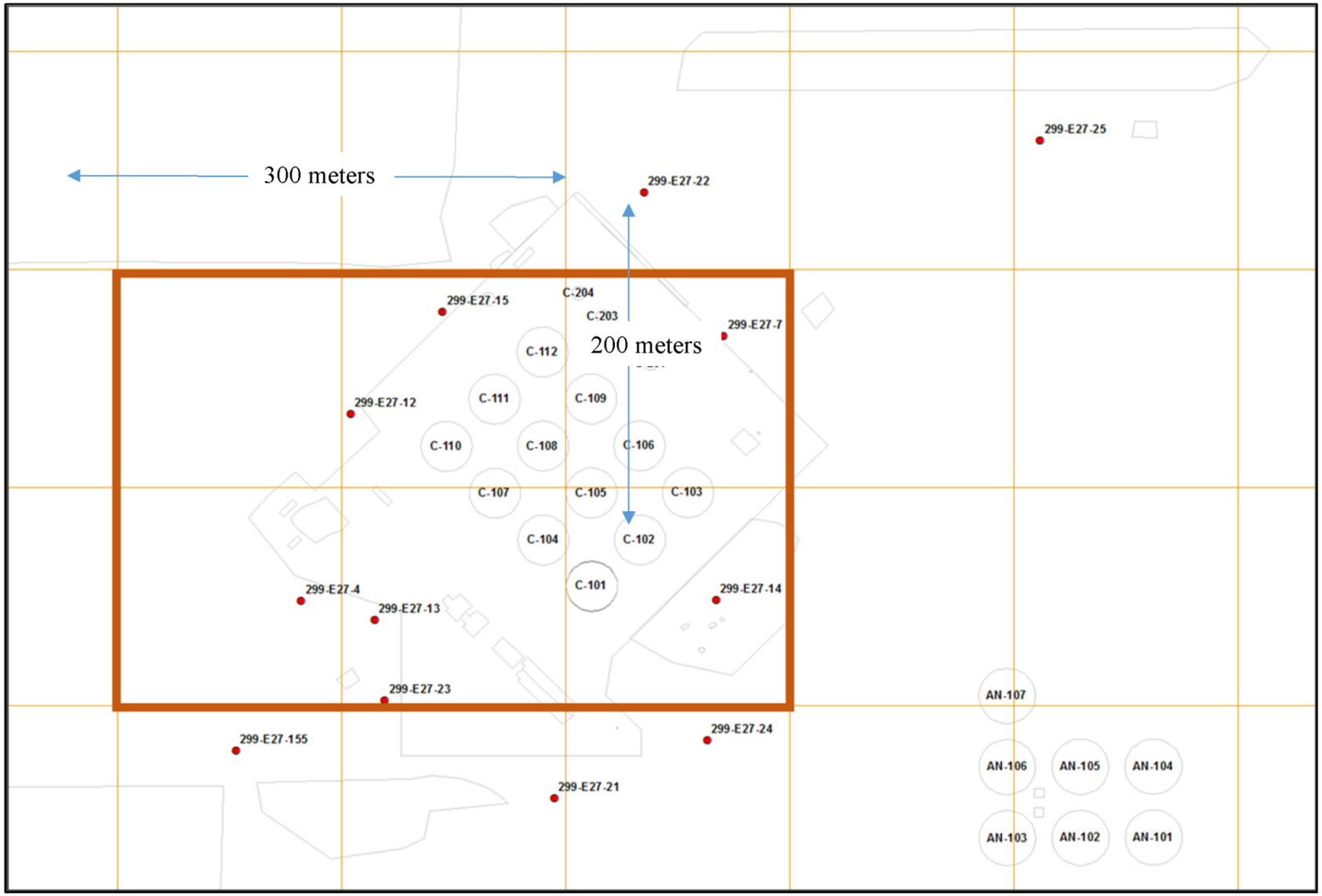
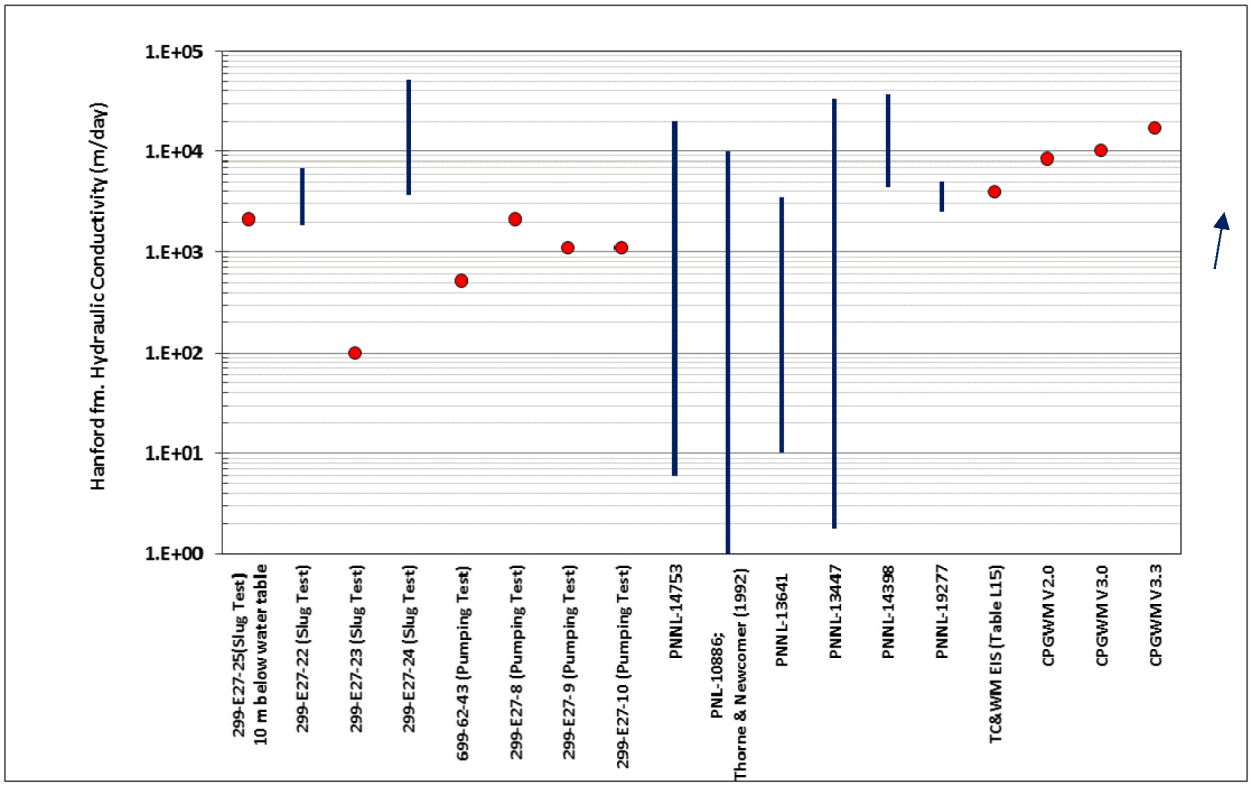


**Figure C-6. Hanford Formation Saturated Hydraulic Conductivity Estimates Based on Slug Tests, Pump Tests, and Model Calibration.**



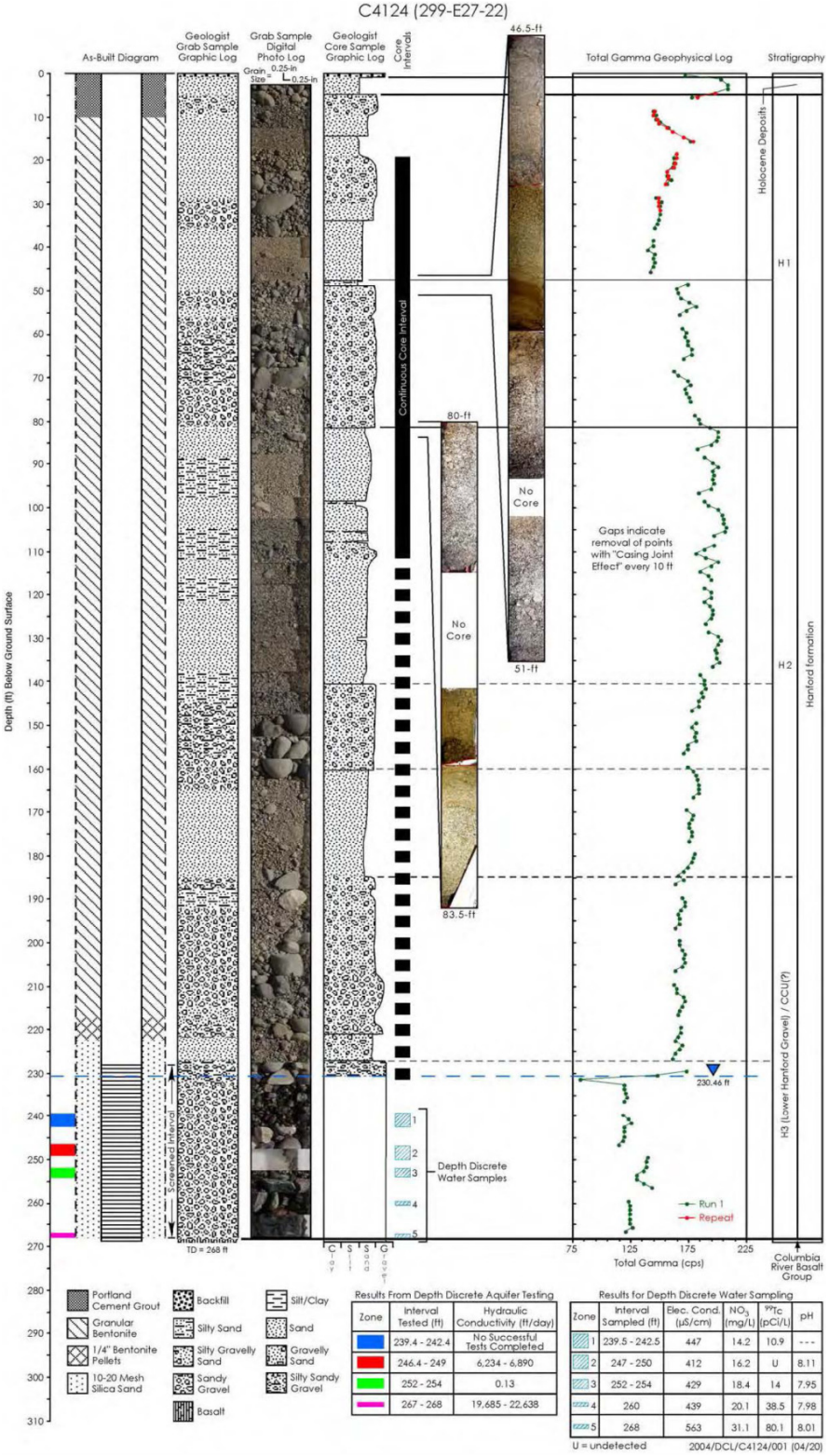

CPGWM = Central Plateau in the Central Plateau Groundwater Model
TC&WM EIS = Tank Closure and Waste Management Environmental Impact Statement

References:

DOE/EIS-0391, "Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington."
PNL-10886, "Development of a Three-Dimensional Ground-Water Model of the Hanford Site Unconfined Aquifer System: FY 1995 Status Report."
PNNL-13447, "Transient Inverse Calibration of Hanford Site-Wide Groundwater Model to Hanford Operational Impact – 1943 to 1996."
PNNL-13641, "Uncertainty Analysis Framework – Hanford Site-Wide Groundwater Flow and Transport Model."
PNNL-14398, "Transient Inverse Calibration of the Site-Wide Groundwater Flow Model (ACM-2): FY 2003 Progress Report."
PNNL-14753, "Groundwater Data Package for Hanford Assessments."
PNNL-19277, "Conceptual Models for Migration of Key Groundwater Contaminants Through the Vadose Zone and Into the Unconfined Aquifer Below the B-Complex."
"Thorne & Newcomer (1992)" = PNL-8337, "Summary and Evaluation of Available Hydraulic Property Data for the Hanford Site Unconfined Aquifer System."

**C.3.5.2 Macrodispersivity Estimates.** Field-scale dispersivities are referred to as macrodispersivities. Field observations indicate that the dispersion coefficients required to describe the large-scale transport processes, at field scales of tens or hundreds of meters, are much different from those observed in small-scale laboratory experiments (Stochastic Subsurface Hydrology [Gelhar 1993]). In fact, macrodispersivities may often be orders of magnitude larger than those observed in the laboratory. Consequently, laboratory-scale dispersivities, which are typically ~1 cm or less, are of little use in estimating field-scale dispersivities.

**Figure C-7. Borehole Log of Well 299-E27-22.**

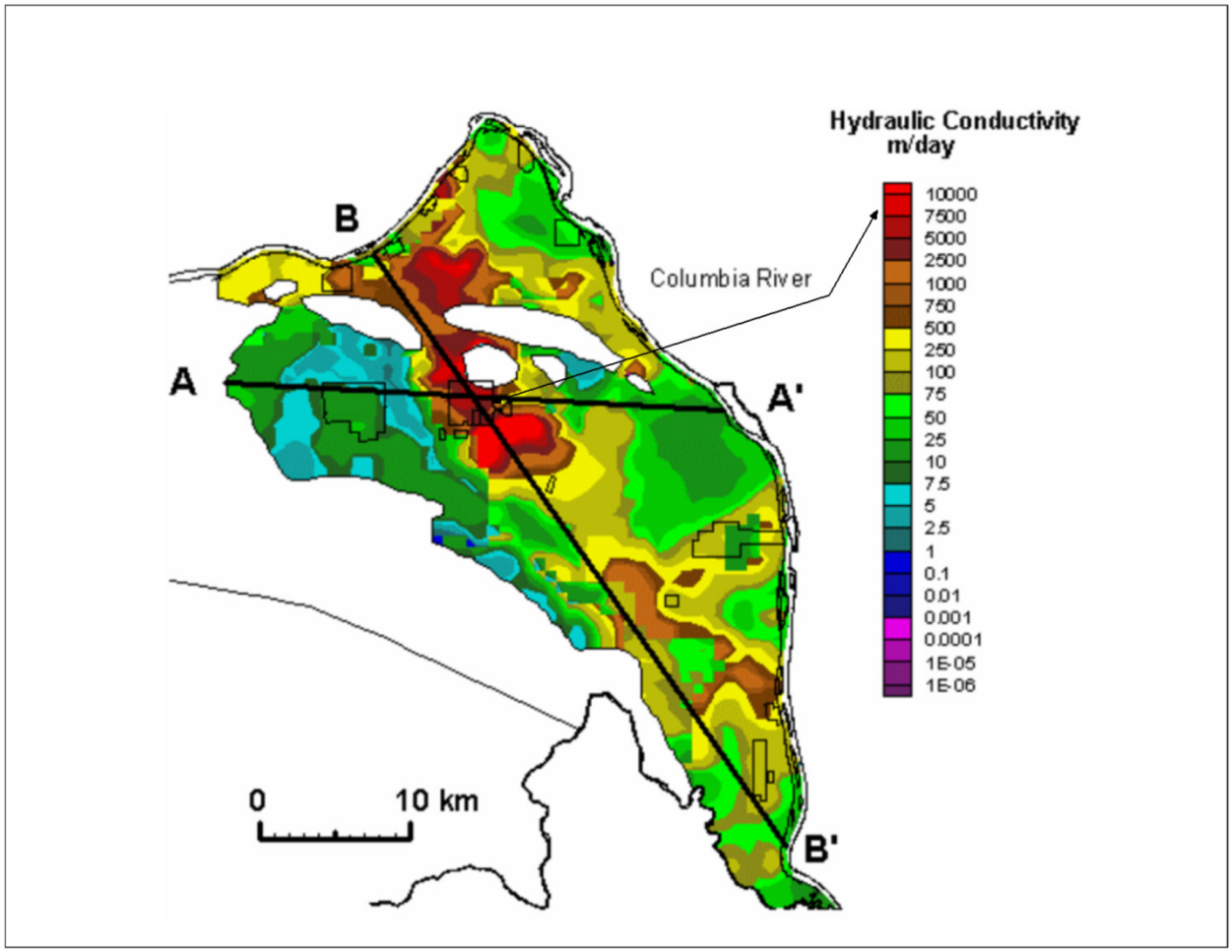



| Zone | Interval Tested (ft) | Hydraulic Conductivity (ft/day) |
|---|---|---|
| | 239.4 - 242.4 | No Successful Tests Completed |
| | 246.4 - 249 | 6,234 - 6,890 |
| | 252 - 254 | 0.13 |
| | 267 - 268 | 19,685 - 22,638 |

| Zone | Interval Sampled (ft) | Elec. Cond. (µS/cm) | $NO_3$ (mg/L) | $^{99}Tc$ (pCi/L) | pH |
|---|---|---|---|---|---|
| 1 | 239.5 - 242.5 | 447 | 14.2 | 10.9 | --- |
| 2 | 247 - 250 | 412 | 16.2 | U | 8.11 |
| 3 | 252 - 254 | 429 | 18.4 | 14 | 7.95 |
| 4 | 260 | 439 | 20.1 | 38.5 | 7.98 |
| 5 | 268 | 563 | 31.1 | 80.1 | 8.01 |

Source: PNNL-14656, "Borehole Data Package for Four CY 2003 RCRA Wells 299-E27-4, 299-E27-21, 299-E27-22, and 299-E27-23 at Single-Shell Tank, Waste Management Area C, Hanford Site, Washington."

**Figure C-8. Pacific Northwest National Laboratory Sitewide Model Calibration of Hydraulic Conductivity of the Unconfined Aquifer with the Location of Waste Management Area C and Magnitude of Hydraulic Conductivity Indicated.**




Excerpted and adapted from PNNL-13447, "Transient Inverse Calibration of Hanford Site-Wide Groundwater Model to Hanford Operational Impact – 1943 to 1996."

There is general agreement in hydrology literature that hydraulic conductivity variations induced by field-scale heterogeneities play an important role in field-scale transport processes. However, there does not appear to be a clear consensus about how best to describe such processes quantitatively (Gelhar 1993). While well-designed, large-scale tracer experiments would provide useful information, limited field data are available at this time to quantify macrodispersivities in unsaturated media.

Heterogeneities that exist at various length scales result in a scale dependence of macrodispersivities (Figure C-10; "A Critical Review of Data on Field-Scale Dispersion in Aquifers" [Gelhar et al. 1992]). Dispersivities increase with time, or equivalently with distance, until they tend to converge on their unique asymptotic (large-time) values. However, it can take a long time (e.g., years or decades) for the asymptotic Fickian approximation to take hold. Nonetheless, the second-moment evolution or the time-dependent, preasymptotic dispersivities are of marginal interest in simulations involving long-times or large-mean travel distances such

as those in RCA modeling. The use of a constant (asymptotic) macrodispersivity is thus considered appropriate in RCA simulations (NUREG/CR-6114, Auxiliary Analyses in Support of Performance Assessment of a Hypothetical Low-Level Waste Facility: Groundwater Flow and Transport Simulation).

The longitudinal and transverse macrodispersivity estimates in the saturated zone are based on a review of three general relationships ("Universal Scaling of Hydraulic Conductivities and Dispersivities in Geologic Media" [Neuman 1990]; "Longitudinal Dispersivity Data and Implications for Scaling Behavior" [Schulze-Makuch 2005]; and "Use of Weighted Least-Squares Method in Evaluation of the Relationship Between Dispersivity and Field Scale" [Xu and Eckstein 1995]) that quantify the dependence of this parameter on measurement scale ($L_s$). For the 100 m scale of transport calculations considered in the RCA effort, which is the approximate distance of transport from source areas to a compliance well located in the saturated zone, the calculated values fall within the range of 3.5 to 17 m (Table C-2).

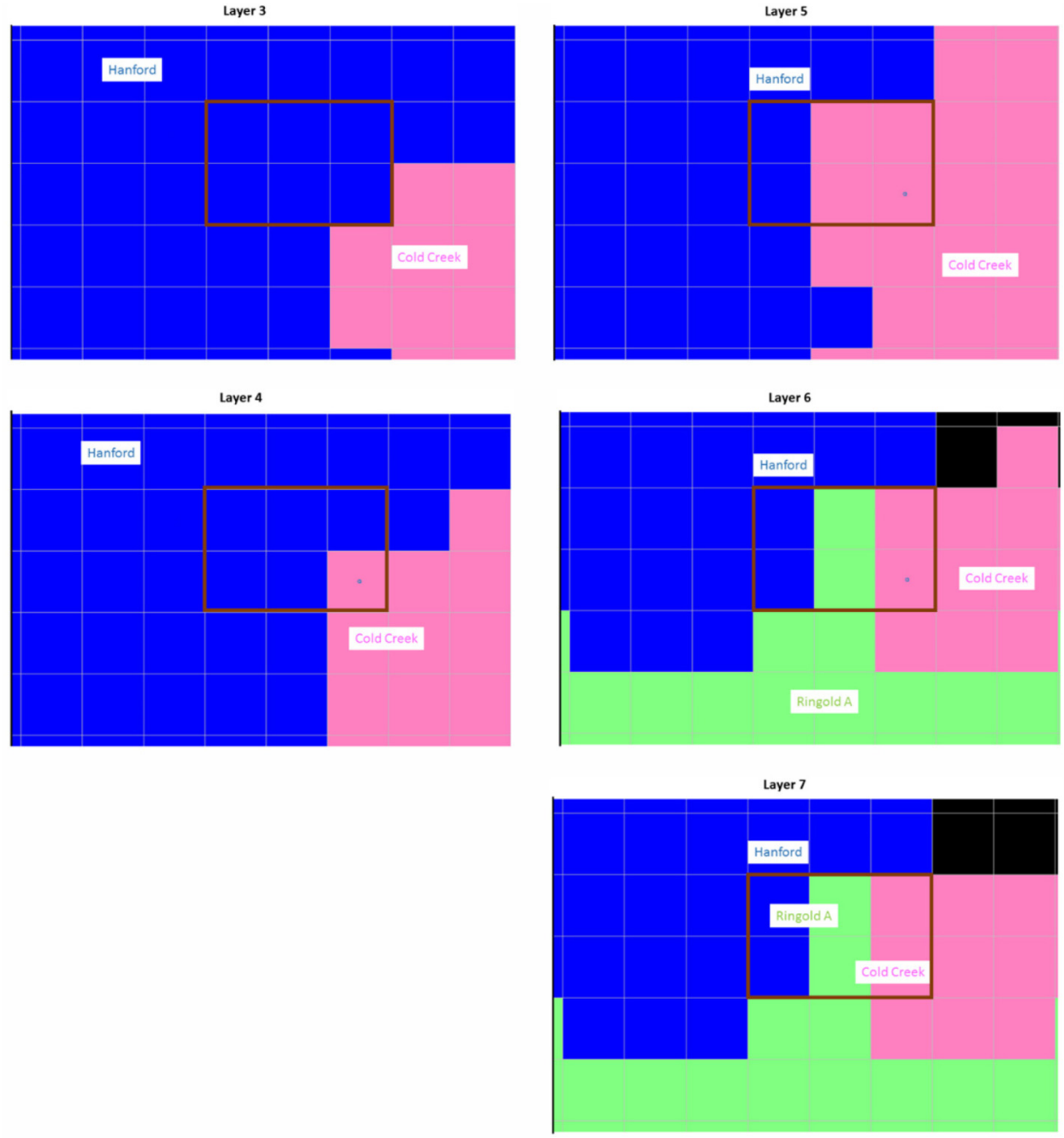
RPP-17209, "Modeling Data Package for an Initial Assessment of Closure of the S and SX Tank Farms," and "Field Study of a Long and Very Narrow Contaminant Plume" (van der Kamp et al. 1994) indicate that a value of 10 represents a reasonable estimate of the ratio of longitudinal to transverse macrodispersivity.

## C.4 UNCONFINED AQUIFER FLOW AND TRANSPORT PROPERTIES USED IN THE WASTE MANAGEMENT AREA C RCRA CLOSURE ANALYSIS

The WMA C RCA mostly adopted flow and transport properties derived from results developed from the calibrated CPGWM. The CPGWM takes into account the accumulated knowledge and experience of many years of study of the aquifer beneath the Central Plateau. One of the objectives for the CPGWM is to create a common modeling platform that can be used for investigations that support remedial activities and decisions in the four groundwater operable units that exist in the Central Plateau region (CP-47631). As discussed in Section C.1, the scale of the WMA C RCA requires aquifer flow property estimates consistent with large area model calibration studies that are on the appropriate spatial scale.

The CPGWM incorporates the large-scale geologic and hydrogeologic features, and provides estimates of water levels, hydraulic gradients, and groundwater flows throughout the 200 West and 200 East Areas for current and expected future groundwater conditions. The model domain includes six suprabasalt HSUs with hydraulic properties established primarily through a transient calibration of the model to historical water level measurements. The CPGWM calibration places emphasis on matching water level data from the 1940s, early 1950s, and first decade of the 21$^{st}$ century to estimate hydraulic properties using flow conditions relatively unperturbed by site operations. Simulated water levels are compared to observed values for wells located upgradient and downgradient of WMA C (Figure C-11). The observed heads and CPGWM-simulated heads, representing a time span of over 20 years, compare well as indicated in Figure C-11, providing confidence in the predictive capabilities of the CPGWM.

**Figure C-9. Central Plateau Groundwater Model Calibrated Hydraulic Conductivity Estimates for the Model Layers and Hydrostratigraphic Units Present within the Aquifer in the Vicinity of Waste Management Area C.**




The CPGWM is not a single-time-use tool, but represents the product of ongoing development and continued improvement that began in FY 2009 (CP-47631). The CPGWM represents the most recent culmination of understanding of the unconfined aquifer under the Central Plateau. CP-47631 provides information pertaining to the CPGWM objectives; conceptualization; model

implementation; sensitivity, calibration, and uncertainty analyses; configuration control; and limitations of the groundwater flow component of the CPGWM.

**Table C-1. Calculation of Weighted Average Hydraulic Conductivity Value and Volumetric Water Flux from the Central Plateau Groundwater Model.**

| Year | Model Layer | Predicted Volumetric Water Flux ($m^3$/day) | Length of Window (m) | Layer Thickness (m) | Hanford Unit Calibrated Horizontal Hydraulic Conductivity (m/day) | Calculated Gradient (m/m) |
|---|---|---|---|---|---|---|
| 2014 | 3 | 286.9 | 300 | 3 | 17,000 | 1.88E-05 |
| 2014 | 4 | 337.4 | 300 | 3 | 14,233 | 2.60E-05 |
| 2014 | 5 | 268.1 | 300 | 3 | 5,933 | 5.06E-05 |
| 2014 | 6 | 149.8 | 300 | 1 | 5,802 | 8.62E-05 |
| 2014 | 7 | 53.9 | 300 | 1 | 5,802 | 3.10E-05 |
| 2200 | 3 | 107.8 | 300 | 3 | 17,000 | 7.06E-06 |
| 2200 | 4 | 192.3 | 300 | 3 | 14,233 | 1.48E-05 |
| 2200 | 5 | 159.9 | 300 | 3 | 5,933 | 3.03E-05 |
| 2200 | 6 | 86.8 | 300 | 1 | 5,802 | 5.00E-05 |
| 2200 | 7 | 31.1 | 300 | 1 | 5,802 | 1.72E-05 |
| Layer Thickness Weighted Hydraulic Conductivity (m/day, rounded): | | | | | | 11,000 |
| Hydraulic Gradient 2014 (m/m, rounded): | | | | | | 3E-05 |
| Hydraulic Gradient 2200 (m/m, rounded): | | | | | | 2E-05 |

The CPGWM has undergone several revisions (currently at Revision 6.3.3) to improve its performance with respect to calibration. CPGWM 6.3.3 takes account of the historical development of understanding the unconfined aquifer, along with current interpretations of the geology (including the extent of the paleochannel), and up-to-date measurements of the recovery of the water table from operational discharges. Hence, it represents the best current understanding of flow under the Central Plateau.

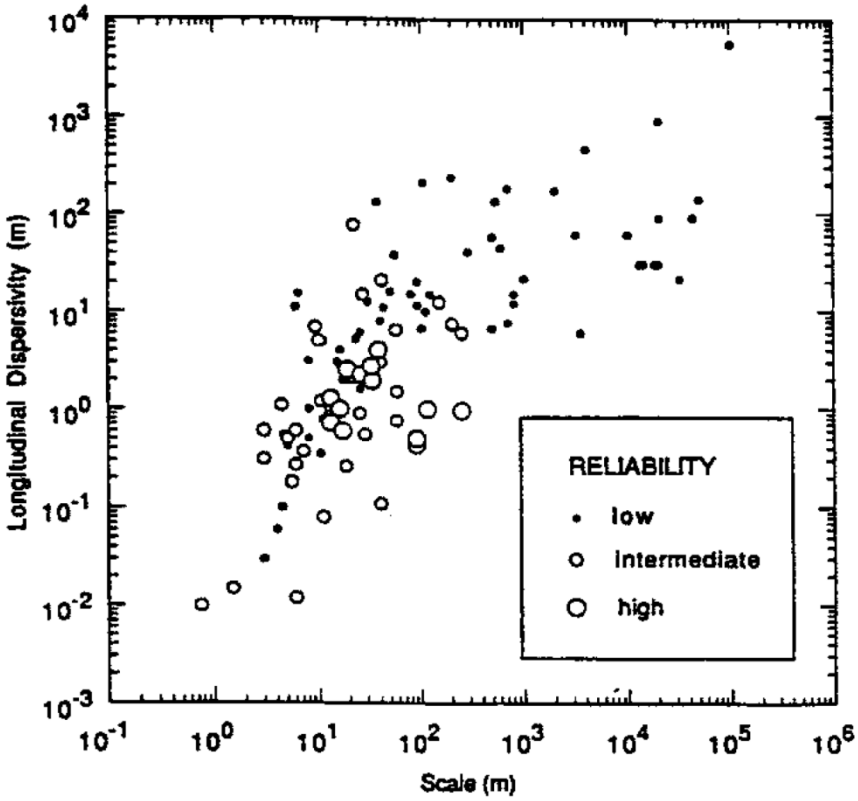
### C.4.1 Flow Properties

**C.4.1.1 Hydraulic Conductivity.** As discussed in Section C.3.2, the effective hydraulic conductivity for the entire aquifer at WMA C using an EHM approach is estimated to be 11,000 m/day (Table C-1). This is based on the layer thickness weighted averaging scheme of calibrated hydraulic conductivity of the HSUs in the CPGWM in the WMA C flow domain.

**C.4.1.2 Hydraulic Gradient.** The hydraulic gradient estimate ($2 \times 10^{-5}$ m/m, Table C-1) is based on the CPGWM estimates of future conditions within the Central Plateau. Water levels in the 200 East Area continue to decline, and evaluation of current flow direction and rate of groundwater flow at WMA C is difficult due to the very low hydraulic gradient. However, no

appreciable change in hydraulic gradient is expected to occur after about 100 years after closure of WMA C, once the remedial actions in the nearby operable units are completed and the water table is at or near steady state. It is expected that by the time the contaminants are released from WMA C and reach the water table, several hundred years would have passed and the water table would be at a steady-state condition. These conditions justify the use of a single value of hydraulic gradient for the water table, even though it is known to have changed substantially in the past owing to operational releases.

**Figure C-10. Longitudinal Macrodispersivity in Saturated Media as a Function of Overall Problem Scale with Data Classified by Reliability.**




Reference: "A Critical Review of Data on Field-Scale Dispersion in Aquifers" (Gelhar et al. 1992).

**C.4.1.3 Anisotropy.** The CPGWM estimate of 0.1 (CP-47631) for the anisotropy, which is defined here as the ratio of vertical to horizontal hydraulic conductivity, is consistent with previous modeling analyses (e.g., PNNL-14398, PNNL-14753, and DOE/EIS-0391).

### C.4.2 Contaminant Transport Properties

**C.4.2.1 Porosity.** The CPGWM value of 0.20 is consistent with the conclusion in RPP-14430, the vadose zone value of 0.17 for the Hanford H1 and H3 sediments discussed in Section 6.3.2.2, and with the aquifer test results presented in HW-60601. The porosity value is within the range of other estimated values (e.g., PNNL-19277 and RPP-RPT-46088).

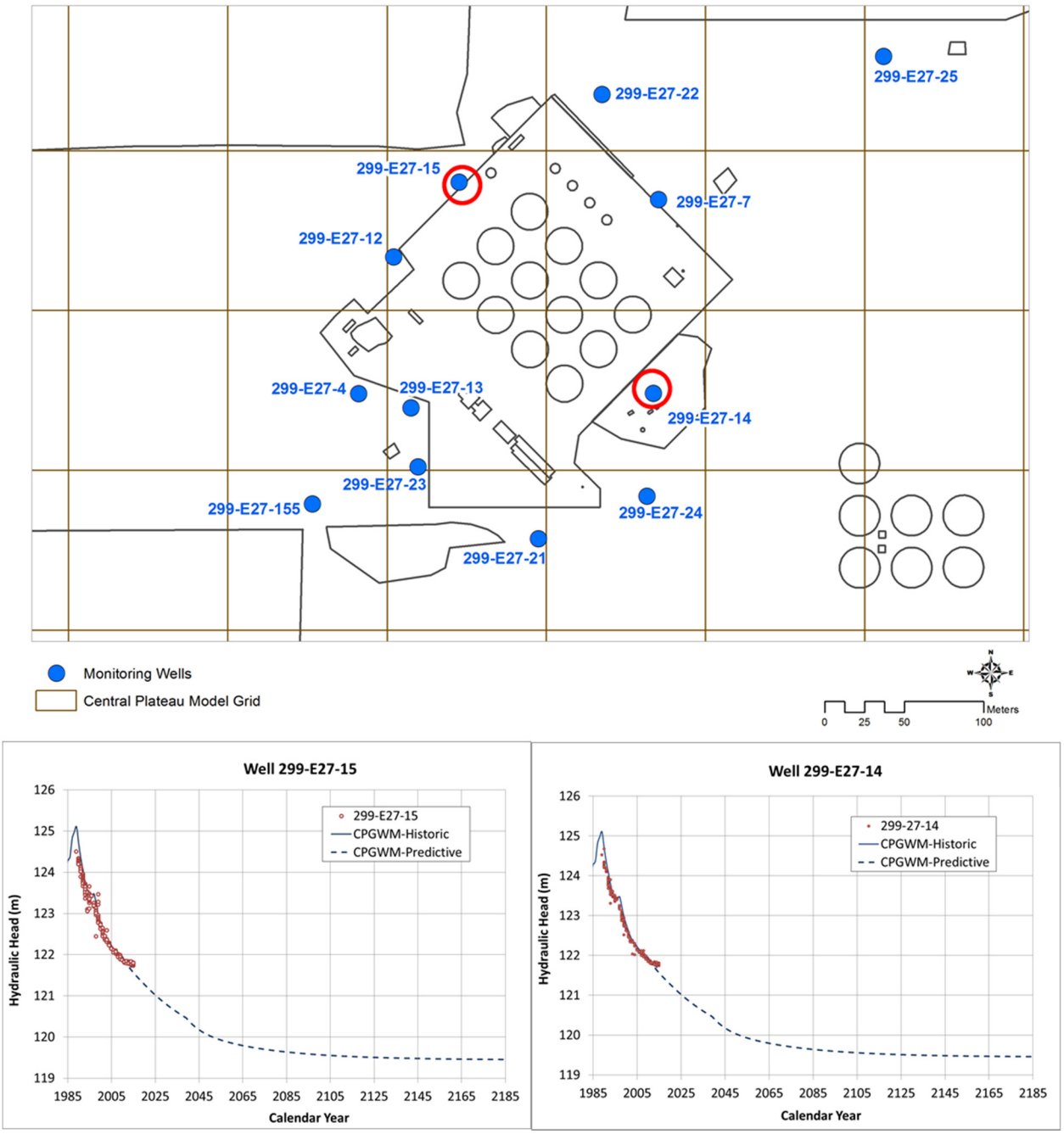
**Table C-2. Relationship Between Saturated Longitudinal Macrodispersivity ($\alpha_L$) and Scale of Measurement ($L_s$).**

| Reference | Relationship | Origin | Saturated Longitudinal Macrodispersivity Estimate (m) for a Scale ≈ 100 m |
|---|---|---|---|
| Neuman (1990) | $\alpha_L \approx 0.017 L_s^{1.5}$ | "Universal relationship" established considering both field and laboratory data (excluding modeling results) | 17 |
| Schulze-Makuch (2005) | $\alpha_L \approx 0.085 L_s^{0.81}$ | Established considering field and modeling results (all reliabilities) and excluding laboratory data | 3.5 |
| Xu and Eckstein (1995) | $\alpha_L \approx 0.94 (\log_{10} L_s)^{2.693}$ | Established considering the same data set as Neuman (1990) including numerical model results | 6 |

References:
"Universal Scaling of Hydraulic Conductivities and Dispersivities in Geologic Media" (Neuman 1990).
"Longitudinal Dispersivity Data and Implications for Scaling Behavior" (Schulze-Makuch 2005).
"Use of Weighted Least-Squares Method in Evaluation of the Relationship Between Dispersivity and Filed Scale" (Xu and Eckstein 1995).

**C.4.2.2 Macrodispersivity Estimates.** A value of 10.5 m is considered representative and the midpoint of the range of values presented in Section C.3.5.2. The ratio of longitudinal to transverse macrodispersivity is chosen to be 10. The reasonableness of these selected macrodispersivity values for the RCA effort is discussed in Section C.3.5.2.

**Figure C-11. Central Plateau Groundwater Model Calibration Results in the Vicinity of Waste Management Area C.**




CPGWM = Central Plateau Groundwater Model

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# APPENDIX D

# FLOW AND CONTAMINANT TRANSPORT NUMERICAL MODEL FOR THE WASTE MANAGEMENT AREA C PERFORMANCE ASSESSMENT AND RCRA CLOSURE ANALYSIS

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## LIST OF TERMS

| | |
|---|---|
| 3-D | three-dimensional |
| CERCLA | Comprehensive Environmental Response, Compensation, and Liability Act of 1982 |
| CHPRC | CH2M HILL Plateau Remediation Company |
| Ci | curie(s) |
| cm | centimeter(s) |
| cm/s | centimeters per second |
| CPGWM | Central Plateau Groundwater Model |
| Cr | chromium |
| DOE | U.S. Department of Energy |
| EHM | equivalent homogeneous medium |
| EMMA | Environmental Model Management Archive |
| EPA | U.S. Environmental Protection Agency |
| FEPs | Features, Events, and Processes |
| ft | feet |
| g | gram(s) |
| h | hour(s) |
| HSU | hydrostratigraphic unit |
| in. | inch |
| IPA | Hanford Federal Facility Agreement and Consent Order Appendix I Performance Assessment |
| kg | kilogram(s) |
| K-U-T | potassium, uranium, and thorium |
| m | meter(s) |

| | |
|---|---|
| µg/L | micrograms per liter |
| mg/kg | milligrams per kilogram |
| mi | mile(s) |
| mL/g | microliters per gram |
| mm/yr | millimeters per year |
| NAVD88 | North American Vertical Datum of 1988, National Geodetic Survey, U.S. Department of Commerce. |
| PA | Performance Assessment |
| PNNL | Pacific Northwest National Laboratory |
| RCA | RCRA Closure Analysis |
| RCRA | Resource Conservation and Recovery Act of 1976 |
| RETC | RETention Curve (software) |
| STOMP | Subsurface Transport Over Multiple Phases |
| UPR | unplanned release |
| WMA | Waste Management Area |
| WRPS | Washington River Protection Solutions |
| yr | year |

# D1.0 INTRODUCTION

This appendix documents the development of the vadose zone flow and transport model for the Waste Management Area (WMA) C Hanford Federal Facility Agreement and Consent Order (Ecology et al. 1989) Appendix I Performance Assessment (IPA), including support to this Resource Conservation and Recovery Act of 1976 (RCRA) Closure Analysis. The results of the flow and transport model are intended to assist in evaluating the potential long-term impact on groundwater of post-retrieval single-shell tank waste residuals, and waste left in ancillary equipment, including pipelines. Impacts related to historical unplanned releases (UPRs) are outside the scope of this modeling effort. The objectives are to address the requirements outlined in Appendix I of the Hanford Federal Facility Agreement and Consent Order (Ecology et al. 1989) for assessment of radiological impacts of waste residuals in a closed WMA C under U.S. Department of Energy (DOE) Order 435.1, Radioactive Waste Management, and evaluation of hazardous chemical impacts for the same wastes under RCRA. The modeling results are used to estimate the possible future concentration in groundwater of various radionuclides and non-radiological contaminants to support WMA C closure decisions associated with the PA. The overall objective of the modeling effort is to provide a basis for making informed closure decisions pertinent to WMA C.

This appendix discusses the development and translation of the conceptual model for flow and contaminant transport into the WMA C three-dimensional (3-D) numerical flow and transport model evaluated using the Subsurface Transport Over Multiple Phases (STOMP)©[1] simulator. The development of the geologic conceptual model is described, along with the implementation of waste release models used to represent contaminant releases from waste residuals remaining in tanks and ancillary equipment. The technical basis for specific model parameters and boundary conditions, along with description of modeling assumptions, is provided. The methodology used in estimating the peak concentrations in the groundwater from residual contamination in the tank residuals and ancillary equipment is described in detail. The modeling includes a screening process used to identify and narrow the list of contaminants of potential concern that require specific evaluation in the 3-D numerical flow and transport model of the post-retrieval closed WMA C. Control of all software used to implement the model is directed by the requirements of PRC-PRO-IRM-309, “Controlled Software Management.”

This appendix documents the 3-D numerical flow and transport model itself and its applicability, along with certain calculations that are necessary to demonstrate the soundness of the model. This appendix does not discuss base case results, or the uncertainty and sensitivity analyses. Those results are presented in Sections 8 and 9. Parameters, values, and ranges identified for evaluation in the uncertainty and sensitivity analyses are presented in Sections 6, 8, and 9.

[1] Subsurface Transport Over Multiple Phases (STOMP)© is copyrighted by Battelle Memorial Institute, 1996.

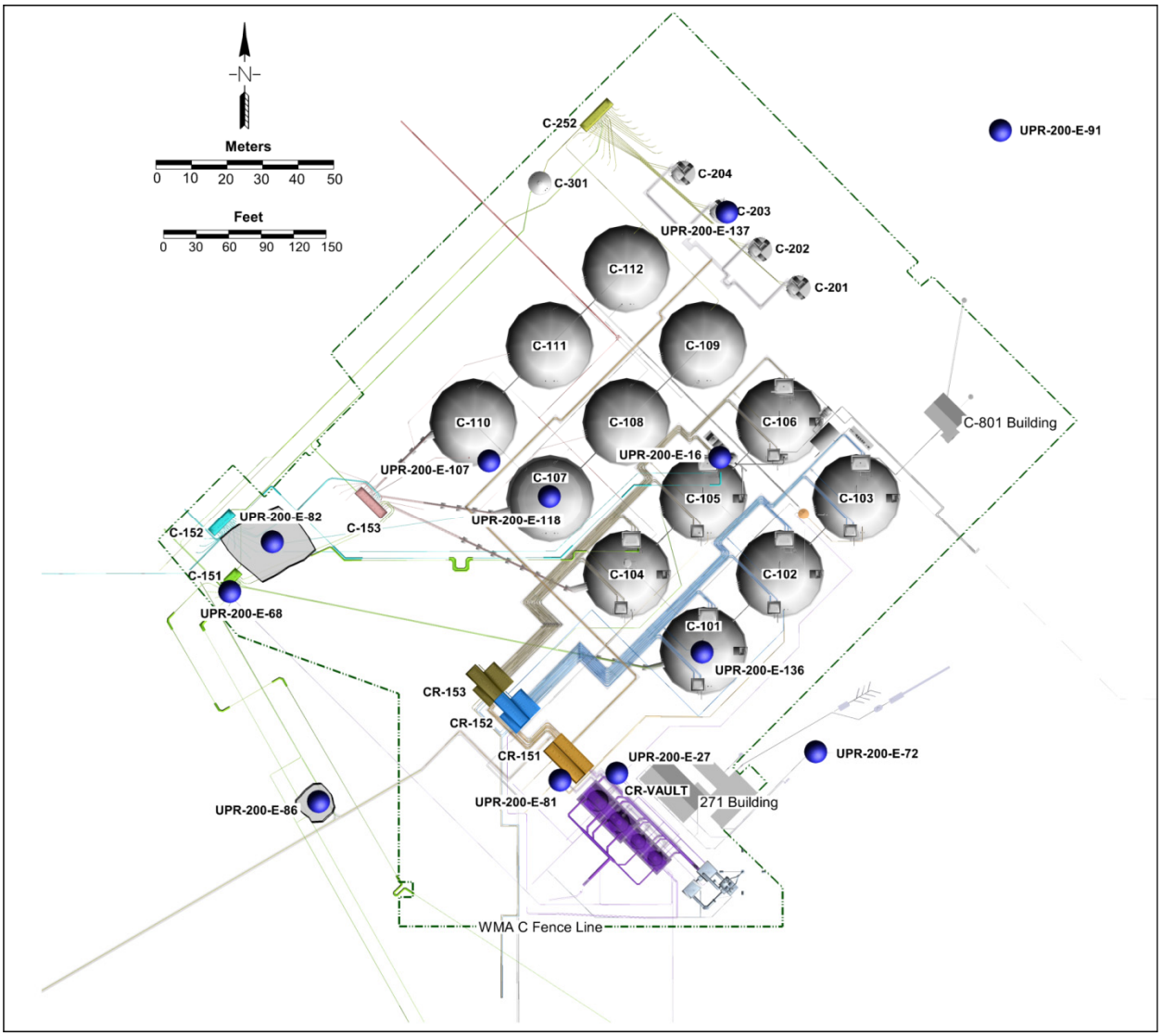
## D2.0 PURPOSE

The 3-D WMA C PA and RCA flow and transport model evaluates quantitatively foreseeable or plausible future radiological and non-radiological contaminant concentrations in groundwater to determine the extent of protection to human health and the environment that the planned WMA C retrieval and closure activities provide. The purpose of the WMA C PA and RCA flow and transport modeling is to evaluate the impacts to groundwater associated with waste remaining in tank residuals after closure of WMA C. While there are no Federal requirements for protection of water resources for a radioactive waste disposal facility, the impacts from the WMA C tank residuals must comply with any applicable State or local law, regulation, or other legally-applicable requirement for water resource protection (DOE M 435.1-1, Radioactive Waste Management Manual). Therefore, water resources protection impacts are assessed on the basis of comparison to Washington State (Washington Administrative Code [WAC] 173-340, "Model Toxics Control Act – Cleanup") or Federal Drinking Water Standards (Title 40, Code of Federal Regulations, Part 141, "National Primary Drinking Water Regulations"), whichever are more restrictive.

The modeling is conducted in accordance with the DOE G 435.1-1, Implementation Guide for Use with DOE M 435.1-1, Radioactive Waste Management Manual PA guidelines. The modeling includes both a screening phase and detailed evaluation of the groundwater concentrations and radionuclide arrival times during the 1,000-year compliance and 10,000-year sensitivity-uncertainty periods per DOE O 435.1, Radioactive Waste Management. This analysis does not consider contaminant release during WMA C operations, only the post-closure impacts of the radionuclides and non-radiological contaminants to the environment. The intent of the screening phase is to limit the model analysis to those radionuclides sufficiently mobile to impact groundwater within the compliance and sensitivity-uncertainty periods. The screening phase follows Federal soil screening guidance and DOE PA guidelines (EPA/540/F-95/041, Soil Screening Guidance: Fact Sheet; DOE G 435.1-1, Chapter 4) that approve of the use of simple site-specific models for risk assessment screening purposes. For the WMA C PA and RCA reference case evaluation, the flow and transport model is 3-D to account for the lateral movement of water and radionuclides and to maintain comparability with other vadose zone transport analyses conducted at the Hanford Site.

Details of the site and facilities (Figure D-1) are provided in Sections 2 and 3 that describe to date the conditions, geologic and hydrologic interpretations, subsurface contamination approximations, and source term estimates. During its operational history, a number of confirmed or suspected waste release events have occurred at WMA C. These included suspected tank leaks and known UPRs from waste transfer lines and systems. Although these suspected tank leaks and UPRs are believed to have impacted groundwater, the evaluation of their impacts to groundwater is outside the scope of this WMA C PA and RCA modeling effort for tank residual impacts.

**Figure D-1. Waste Management Area C Tanks and Associated Infrastructure and Unplanned Releases.**




WMA = Waste Management Area

## D3.0 MODELING OBJECTIVES

The objectives of the vadose zone fate and transport modeling include the capability to provide results that support the water resource impact evaluation and the estimation of dose at the point of assessment for the "all-pathways" exposure scenario described in DOE M 435.1-1. The analysis needs to include time history results of the transport of radionuclides and non-radiological contaminants individually and collectively, and be suitable for estimating the maximum concentration in the environment. DOE M 435.1-1 requires that the WMA C PA

includes calculations of potential doses to representative future members of the public and environmental impacts from potential releases from the tank residuals for a 1,000-year period after closure. The corresponding public protection performance measures for this RCA are outlined in Section 2.2 of this document. The point of compliance for this analysis is at the point of highest calculated concentration or impact, with an allowance for some volume averaging based on projected groundwater use, beyond a 100-m buffer zone around WMA C.

The modeling objectives of both the RCA and PA also include conducting sensitivity and uncertainty analyses with the goal of defining bounding estimates for modeling predictions. The sensitivity-uncertainty analyses extend to 10,000 years to calculate the maximum impacts and the time of those impacts. These analyses take account of parameter values, initial conditions, boundary conditions, and changes in properties with time that are appropriate for the longer time frame. These sensitivity-uncertainty analyses are used to evaluate the significance of the assumptions used in the development of the transport modeling and their relevance to the controlling pathways or scenarios analyzed in DOE M 435.1-1. Assumptions necessary to develop inputs to the transport models, or to address uncertainties, data gaps, or linkages to other models used in the analysis are identified, justified, and shown to be consistent with the conceptual model.

# D4.0 MODEL CONCEPTUALIZATION

This section describes the modeling methodology and approach for the determination of the WMA C residual waste impacts to groundwater. A synopsis of vadose zone conceptual model, conceptual model components, and the technical basis and rationale for the selection of parameters is provided here, along with supporting information and rationale. This section includes a description of the WMA C vadose zone geology and the pertinent vadose zone physical and chemical features, events, and processes (FEPs). A summary of the rationale and basis for selection of the Point of Calculation, a protectiveness metric, and the time frame for compliance is also presented.

## D4.1 FEATURES, EVENTS, AND PROCESSES

The development of conceptual models and exposure scenarios for the WMA C PA and RCA builds upon work that began in 1999 with the intent to promote consistency and completeness in the development of conceptual models to support ongoing long-term assessments at Hanford through implementation of the FEPs methodology developed by the Nuclear Energy Agency for the Organization for Economic Co-operation and Development (RPP-RPT-41918, “Assessment Context for Performance Assessment for Waste in C Tank Farm Facilities after Closure”). The FEPs methodology, as adopted by the Hanford Site, identifies a list of FEPs that are relevant to the assessment of long-term safety or risks associated with solid radioactive waste repositories and other waste disposal sites (RPP-RPT-41918). DOE/RL-2011-50, Regulatory Basis and Implementation of a Graded Approach to Evaluation of Groundwater Protection identifies and

describes the FEPs applicable to most vadose zone modeling applications in the 200 Areas, and concludes with the development of a "basic" Hanford Site-specific vadose zone conceptual model. This conceptual model provides a basis for identifying the model attributes and criteria that lead to the selection of the appropriate model type and computer code applicable for most Hanford Site vadose zone modeling needs (DOE/RL-2011-50).

The following list of key conceptual model components derives from the basic Hanford Site vadose zone conceptual model identified in DOE/RL-2011-50 and includes:

- Model domain and boundary conditions
- Geologic setting
- Source term
- Vadose zone hydrogeology and contaminant transport
- Infiltration and recharge
- Geochemistry and sorption
- Groundwater domain.

These conceptual model components are consistent with those identified in EPA guidelines for the evaluation of the protection of groundwater pathway [EPA 402-R-94-012, A Technical Guide to Ground-Water Model Selection at Sites Contaminated with Radioactive Substances; OSWER No. 9200.4-18, "Establishment of Cleanup Levels for CERCLA Sites with Radioactive Contamination"; and HNF-5294, "Computer Code Selection Criteria for Flow and Transport Code(s) To Be Used in Vadose Zone Calculations for Environmental Analyses in the Hanford Site's Central Plateau"]. The principal FEPs associated with these conceptual model components include the following:

- Relatively thick vadose zone composed of predominantly similar sediments (geologic setting conceptual model component)

- Semi-arid region (infiltration recharge conceptual model component)

- Underlying unconfined aquifer (groundwater domain conceptual model component)

- Relatively few contaminants of concern in the vadose zone soils (source term) that have potential impacts to groundwater.

To apply the general or basic FEPs to the WMA C PA, conceptual model components must account for the source release of radionuclides and non-radiological contaminants from the grouted tanks, contaminant transport through engineered barriers, and contaminant transport through the natural environment, while accounting for decay and ingrowth of daughter isotopes (RPP-RPT-48490, "Technical Approach and Scope for Flow and Contaminant Transport Analysis in the Initial Performance Assessment of Waste Management Area C"). Transport through engineered barriers must take into account the degradation of the tank structures, as well as flow of water through the waste in the tanks and contaminant releases into the vadose zone (RPP-RPT-41918). These processes include details of physical and chemical mechanisms on a refined local scale.

The key conceptual model components listed above and their associated FEPs are discussed in the following subsections. The discussion includes the rationale and basis for each of the conceptual model components, and describes the function each conceptual model component and corresponding FEPs serve in the model, the assumptions associated with them, a description of the FEPs included in each component, and a qualitative assessment of the impact the component has on the model results.

### D4.1.1 Model Domain and Boundary Conditions

The model domain and boundary conditions establish both a framework and limiting conditions for the numerical model. The model domain for flow and transport in the vadose zone is represented in 3-D space, with one of the horizontal axes aligned in the general direction of groundwater flow. Aligning an axis with the general direction of groundwater flow allows concentrations to be calculated more easily downgradient of the waste sites. The numerical model adapts the physical elements of the conceptual model to a Cartesian grid, and also assigns numerical values to the parameters used in algorithms to represent the physical and geochemical systems and processes.

The WMA C model domain is 737.9 m (2,421 ft) northwest to southeast by 795.3 m (2,609 ft) southwest to northeast by 116 m (381 ft) vertically, extending about 12 m (49 ft) below the water table. The southwestern and northwestern boundaries of the model are 574656.09 m, 136454.41 m, and 575218.45 m, 137016.78 m, respectively (Lambert Coordinate system easting, NOAA Manual NOS NGS 5, "State Plane Coordinate System of 1983"). The southeastern and northeastern boundaries are 575177.86 m, 135932.64 m, and 575740.22 m, 136495.00 m, respectively. The vertical base elevation of the model is nominally 95 m (North American Vertical Datum of 1988 [NAVD88]), although the bottom and top of the model domain vary spatially according to the top of basalt elevation and surface relief, respectively (RPP-RPT-56356, "Development of Alternative Digital Geologic Models of Waste Management Area C").

A specified-flux boundary condition is applied at the surface, and net infiltration rates representing recharge vary spatially and temporally along the upper boundary depending on site and surface conditions simulated, the location and physical dimensions of WMA C (recharge parameterization is discussed in Section 3.1.5), and the time of WMA C operations (RPP-RPT-44042, "Recharge and Waste Release within Engineered System in Waste Management Area C") (Figure D-2). The bottom boundary of the unsaturated (vadose) zone is the water table, and the bottom of the model (aquifer) is defined as a vertical no flow boundary condition. Boundary conditions at the sides of the model domain are assumed to be no flow in the vadose zone and prescribed flux and prescribed head in the aquifer on the upgradient and downgradient boundaries, respectively.

The boundary condition in the aquifer on the upgradient boundary applies a prescribed flux calculated on the basis of the aquifer hydraulic conductivity and gradient, independent of recharge. The prescribed flux boundary condition value includes a factor to account for the fact that the thickness of the unconfined aquifer varies because of the uneven surface of the underlying basalt. To account for the non-uniform aquifer thickness from the underlying basalt

boundary, the nominal flux rate calculated as the product of the hydraulic conductivity and gradient (base case values of 11,000 m/day and $2.0 \times 10^{-5}$ m/m, respectively; see Section D4.1.7) is proportioned according to the ratio of the average aquifer area throughout the model domain (9,440 $m^2$) and the aquifer area along the southwest-northwest boundary (6,151 $m^2$) where the prescribed flux is applied. The aquifer area refers to the area perpendicular to the direction of groundwater flow.

### D4.1.2 Geologic Setting

The geological setting information presented here is a summary of the information presented in RPP-RPT-46088, "Flow and Transport in the Natural System at Waste Management Area C" and RPP-RPT-56356. Waste Management Area C is located near the eastern edge of the 200 East Area on the Hanford Site on what is known as the Central Plateau. The vadose zone is ~80 to 100 m (262.4 to 328.1 ft) thick, and there are ~68 m between the base of WMA C and the present-day water table. Waste Management Area C lies within the gravel-dominated H1 unit in the vadose zone. The stratigraphic units recognized in the WMA C area include:

- Recent (Holocene) backfill material (Hdb) (~10 m thick)
- Hanford formation unit H1 – Gravel-dominated sequence (~10 m to 30 m thick)
- Hanford formation unit H2 –
    - Hanford H2 Sand-dominated sequence (~45 m to 70 m thick)
    - Hanford H2 Coarse subunit (gravel/coarse-grained facies that underlies the H2 sands)
    - Hanford H2 Silty sand subunit (silty sand lower permeability laminations/lenses)
- Hanford formation unit H3 – gravel-dominated sequence (~0 m to 20 m thick)
- Columbia River Basalt Group.

As part of the RCRA facility investigations (DOE/ORP-2008-01, RCRA Facility Investigation Report for Hanford Single-Shell Tank Waste Management Areas and RPP-PLAN-39114, "Phase 2 RCRA Facility Investigation/Corrective Measures Study Work Plan for Waste Management Area C"), the geologic strata underlying WMA C have been characterized in conjunction with soil sampling and borehole logging for radionuclides and hazardous waste constituents. The geophysical and geologic logging from the boreholes has been used to identify the elevations of tops of the geologic units in the vicinity of WMA C. Specifically, potassium, uranium, and thorium (K-U-T) data from geophysical logs were used to map the tops of the different geologic units at WMA C (RPP-RPT-56356).

In discussions associated with the 2009 to 2011 working sessions and additional discussions with regulators in 2013 and 2014, two alternative geological models were proposed and developed on

the basis of the data discussed in the preceding paragraph. Both of these models have been incorporated into the RCA and PA as a means to explore the performance implications of the alternative conceptualizations. This section provides a brief summary of important differences between these alternative models. Details on the basis for their development are provided in RPP-RPT-56356 and only briefly summarized here.

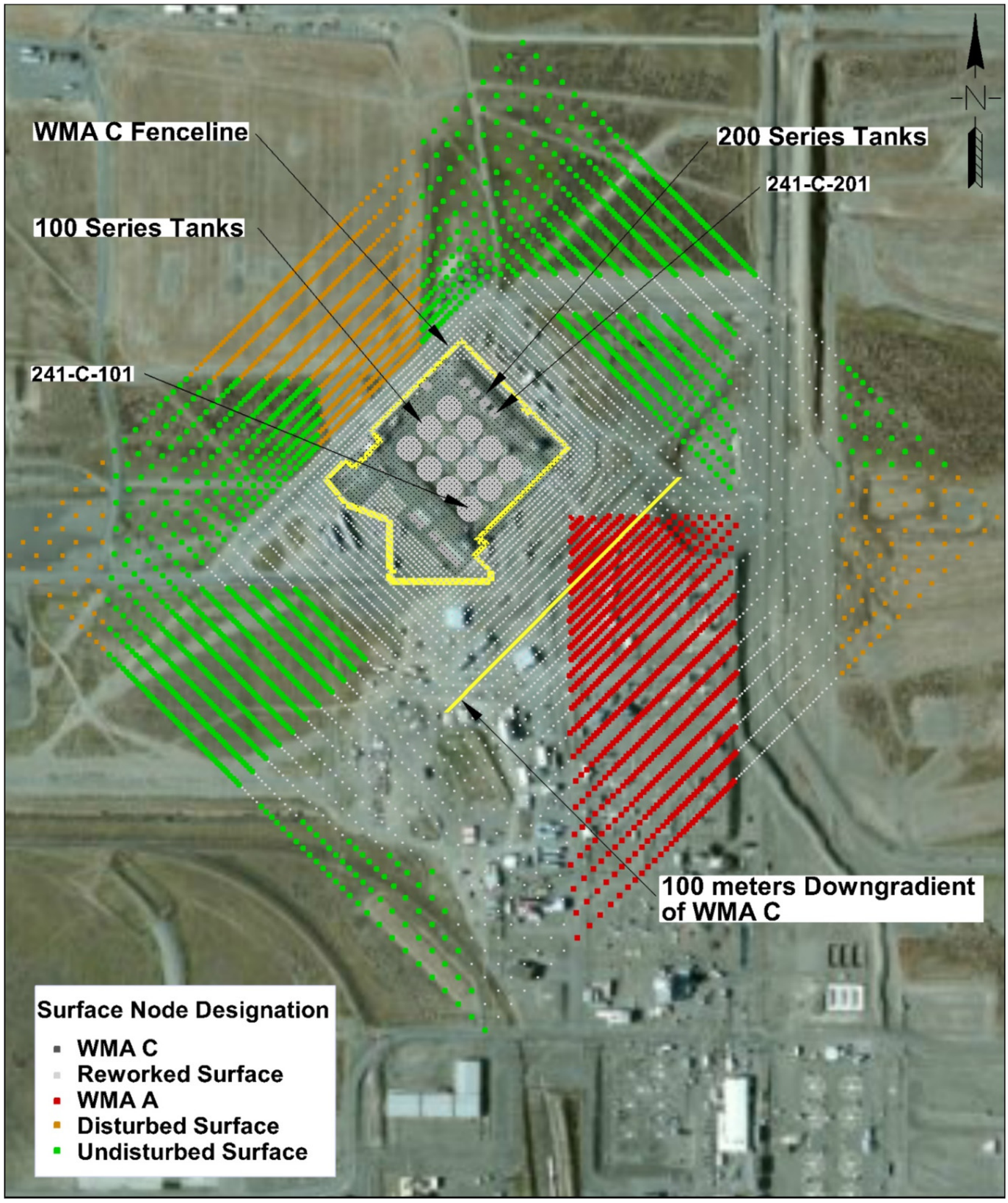
The primary difference between the two alternative models concerns whether or not a sandy gravel facies followed by a silty sand layer exist at the bottom of the H2 subunit in the vicinity of WMA C. The K-U-T data (i.e., a lower gross gamma and potassium count) indicates that there is a coarsening of the sand at the bottom of the H2 that turns more into a sandy gravel. Underlying this sandy gravel facies is a silty sand unit that presents a strong potassium peak and an occasional but strong natural uranium peak. The difficulty in making the determination between the two alternative models is that there are few direct pushes or drywells that go deep enough in which there are both good geophysical logs and geologic logs (with drill cuttings). For the most part, only the nearby groundwater wells extend to a sufficient depth. The drill cuttings from nearby ground wells indicate that there is a definite fining of the sands, along with some silty sands found at the vertical location as indicated by the K-U-T data in the geophysical logs, but a competent silt layer was not observed. Alternative Model I does not distinguish the sandy gravel and underlying silty sand unit distinctly from Hanford H2, while Alternative Model II does distinguish them. The significance of distinguishing these layers is that their differing characteristics, as expressed by different soil hydraulic property values, could cause increased lateral movement in the vadose zone. A series of fence diagrams showing the differences between the two models within WMA C is given in RPP-RPT-56356. The fence diagram for both these models running southwest to northeast through the center of WMA C is given in Figure D-3.

The WMA C RCA and PA include the evaluation of Alternative Model II in their sensitivity analyses. This appendix includes the discussion of Alternative Model II because Alternative Model II represents an alternative conceptualization of the entire geologic model, and not a parametric variation.

### D4.1.3 Source Term

The radionuclide inventory information presented here is a summary of the information presented in RPP-RPT-42323, “Hanford C-Farm Tank and Ancillary Equipment Residual Waste Inventory Estimates” and the WMA C PA. The source term conceptual model component defines the characteristics of the inventory and the release of residual waste from the tanks, ancillary equipment, and pipelines. RPP-RPT-42323 presents the basis for chemical and radiological inventory estimates for residual waste remaining in 241-C Tank Farm single-shell tanks and associated transfer equipment after tank waste is retrieved. As discussed in RPP-RPT-42323, a conservative or bounding bias is built into the inventory estimating process, generally resulting in larger than likely inventory estimates. Inventory estimates applicable to the vadose zone fate and transport evaluation presented in Table D-1 are derived from the values presented in RPP-RPT-42323 (Appendix B-1, C-3 and C-5), with the radionuclides decayed to January 1, 2020.

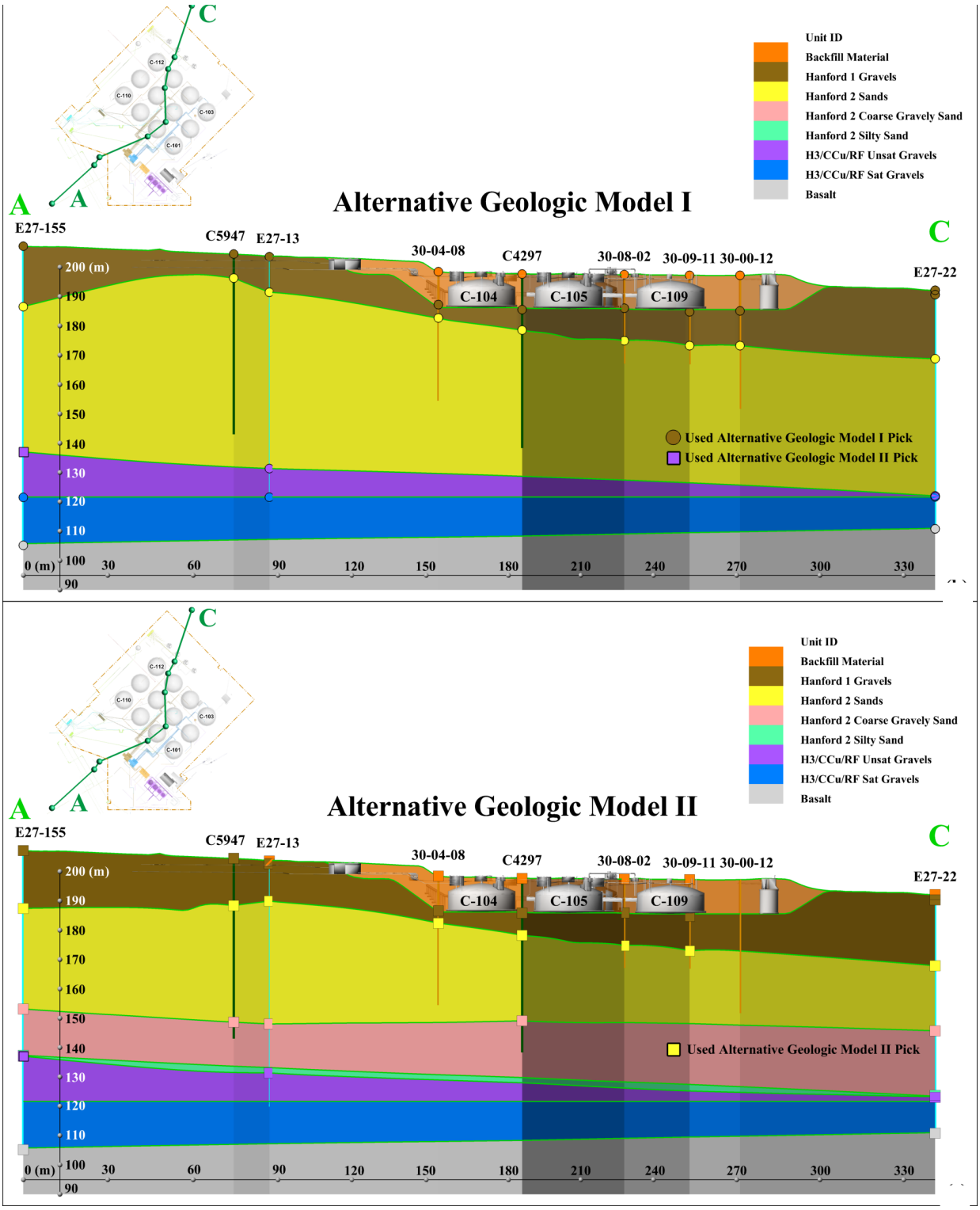
**Figure D-2. Plan View of Waste Management Area C Performance Assessment and RCRA Closure Analysis Model Domain Showing the Horizontal Distribution and Surface Type of the Irregularly-Spaced Calculation Nodes. The resolution increases in the area of Waste Management Area C.**




RCRA = Resource Conservation and Recovery Act of 1976

WMA = Waste Management Area

**Figure D-3. Fence Diagram of Alternative Geologic Models Used in the Performance Assessment and RCRA Closure Analysis for Waste Management Area C.**




H3/CCu/RF = undifferentiated H3, Cold Creek unit and Ringold Formation
RCRA = Resource Conservation and Recovery Act of 1976

Both mineral phase solubility-limited and matrix degradation rate-limited processes are considered for the key radionuclides and non-radiological contaminants $^{99}$Tc, chromium, and uranium. Release processes associated with these three contaminants have been studied in detail in the laboratory, and the laboratory results have been incorporated in the source term analysis. In particular, the following release models are used, which are based on empirical evidence (Section 6.3.1):

- Matrix-degradation-rate-based release of $^{99}$Tc that considers an initial 6% fraction of the $^{99}$Tc inventory to be instantaneously available for release while the remaining 94% fraction undergoes relatively slower release at the fractional rate of $6 \times 10^{-4}$ day$^{-1}$

- Solubility-controlled releases of uranium that impose a solubility limit of $1 \times 10^{-4}$ M for 1,000 years followed by solubility limit of $1 \times 10^{-6}$ M

- Dissolved concentration limited release for chromium that imposes a dissolved concentration upper limit of 2,000 µg/L.

For the other analytes evaluated in the WMA C PA, conservative source-term calculations are performed whereby all the analytes are assumed to be instantly and completely available in solution within the residual waste volume, and available for an immediate diffusive release.

While the tank (and ancillary equipment) infill material remains intact, it is assumed that releases occur by a diffusion process through the base of the tank base mat, consisting of grout and concrete layers. The diffusive thickness being considered is the 8-in. combined thickness of concrete and grout layer located at the base of the tank (ignoring the steel plate) because the shortest diffusive pathway for release to the near-field environment is through the base of the tank. The aqueous phase diffusive transport occurs along the thin water films within the pore spaces of the grout and concrete layer. The effective diffusion coefficient of contaminant (which includes effects of tortuosity), and sorption behavior within the grout and concrete layer, control the diffusive mass flux, in addition to the concentration gradient.

Section 7.3.1 of this WMA C RCA presents detailed discussion about the theoretical and empirical development and applicability of the equations and the parameters incorporated into the release functions for the individual radionuclides and non-radiological contaminants. That discussion and all of those equations are not repeated here. The discussion and equations presented here only intend to provide context for the relationship between the equations and parameters used to develop the release functions, and an indication of the magnitude of the parameter values associated with the different radionuclides and non-radiological contaminants.

Conceptually, the diffusive release occurs in response to the solute concentration gradient that develops through the interstitial fluid contained in the tank grout and the surrounding soil. Diffusive mass transport is proportional to the concentration gradient. Solute mass diffuses from fluid volumes containing the higher concentration to volumes containing the lower concentration in proportion to the diffusive conductance. Diffusive conductance is a function of the properties

of the contaminant, the fluid media, and the geometry of the diffusive process. For the diffusion release model, the diffusive conductance for a contaminant solute ($D_s$) is computed as:

$$D_s = \frac{(A\,d\,\tau)}{L} \tag{D-1}$$

Where:

$D_s$ = diffusive conductance of the solute in the fluid ($L^3/T$)
A = mean cross-sectional area of the connection ($L^2$)
d = free-water diffusivity of the contaminant solute ($L^2/T$)
τ = tortuosity of the porous medium that implicitly includes the effect of porosity and saturation (dimensionless)
L = diffusive length, i.e., the length through which diffusion occurs (L).

The diffusive flux $f_s$ (M/T) through the fluid is computed as follows:

$$f_s = D_s(C_{high} - C_{low}) \tag{D-2}$$

where $C_{high}$ and $C_{low}$ ($M/L^3$) are the high concentration to low concentration values of the dissolved solute. The parameters used to populate the diffusion equations in Section 7.3.1 of the WMA C RCA are presented in Table D-2.

As the solute mass diffuses through the fluid in the grout, it instantaneously partitions between the solid (grout and/or soil) and fluid (water and/or air) media. The partitioning is controlled by the partition coefficients defined for each solute in each media, and the quantities of fluid and solid media present. Thus, there becomes a concentration in each medium. In the absence of solubility limits, the concentration of the solute in a particular medium (referred to as medium "m" in Equation 3) is calculated as follows:

$$C_{ims} = \left(\frac{K_{dm}}{\sum_{g=1}^{NM} K_{grs}.VM_g}\right) m_s \tag{D-3}$$

Where:

$C_{ims}$ = concentration of solute in a particular medium (medium "m"), either fluid or solid ([$M/L^3$] for fluid media or [M/M] for solid media)
$m_s$ = total mass of solute present (M)
$K_{dm}$ = partition coefficient of the solute between medium "m" and a reference fluid ([$L^3/L^3$] for fluid media or [$L^3/M$] for solids)
$g$ = media identifying index
$K_{grs}$ = partition coefficient between the other media present, as identified by the index, and a reference fluid for the solute ([$L^3/L^3$] for fluid media or [$L^3/M$] for solids)
$VM_g$ = quantity (volume or mass) of a particular medium present ($L^3$ for fluids or M for solids)
$NM$ = the number of media present.

The partition coefficients for the radionuclides and non-radiological contaminants evaluated in the vadose zone flow and transport model are listed in Table D-3.

### D4.1.4 Vadose Zone Hydrogeology and Contaminant Transport

The vadose zone hydrogeology and transport information presented here is a summary of the information presented in Section 6.3.2.2. Detailed discussion and description of the data available and the methods used to develop the parameters, distributions, and percentile values are not repeated here.

The flow and transport pathway process used for the WMA C vadose zone modeling is porous media continuum flow. The porous media continuum assumption and the soil relative permeability/saturation/capillary pressure relations provide the basis for vadose zone flow and transport modeling (PNNL-11216, "STOMP Subsurface Transport Over Multiple Phases Application Guide"; PNNL-12030, "STOMP Subsurface Transport Over Multiple Phases Version 2.0 Theory Guide"). The vadose zone at the Hanford Site is composed of sediments ranging in particle size associated with gravels to silts or clays. In the model domain, the hydraulic properties describing fluid transport characteristics associated with each geologic layer are approximated by average upscaled values, with each unit having different flow and transport parameter values (hydraulic conductivity, bulk density, and dispersivity). The model describes bulk (or mean) flow and radionuclide transport behavior in the vadose zone, limiting the applicability of the evaluation to estimating overall and eventual radionuclide impacts to groundwater. Porous media continuum transport in unsaturated media of this type is regarded as the fundamental process and feature for modeling contaminant fate and transport behavior in the vadose zone at the Hanford Site (DOE/RL-2011-50).

Table D-4 lists the upscaled composite-fitted van Genuchten-Mualem parameters for the various strata at the WMA C site ("A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils" [van Genuchten 1980]; "A New Model for Predicting the Hydraulic Conductivity of Unsaturated Porous Media" [Mualem 1976]; EPA/600/2-91/065, The RETC Code for Quantifying the Hydraulic Functions of Unsaturated Soils). A simultaneous fit of both laboratory-measured moisture retention and unsaturated conductivity data was used in this work, and all five unknown parameters $\theta_r$, $\theta_s$, $\alpha$, n, and $K_s$, with m=1-1/n (van Genuchten 1980) were fitted to the data via a code named RETention Curve (RETC) (EPA/600/2-91/065). $K_s$ is treated as a fitted parameter during the curve fitting process in order to obtain a better agreement with experimental data for the region of interest (i.e., relatively dry moisture regime). Estimated unsaturated conductivities, based on saturated conductivity ($K_s$) and the van Genuchten retention model parameters, have been shown to differ by up to several orders of magnitude with measured conductivities at the dry end (e.g., "Evaluation of van Genuchten-Mualem Relationships to Estimate Unsaturated Hydraulic Conductivity at Low Water Contents" [Khaleel et al. 1995]). The pore size distribution factor $\ell$ (Mualem 1976) was kept fixed at 0.5 during the simultaneous fitting.

**Table D-1. Post-Retrieval Residual Waste Inventory for Waste Management Area C Tanks, Ancillary Equipment, and Pipelines.**

| Source | 241-C-101 | 241-C-102 | 241-C-103 | 241-C-104 | 241-C-105 | 241-C-106 | 241-C-107 | 241-C-108 | 241-C-109 | 241-C-110 | 241-C-111 | 241-C-112 | 241-C-201 | 241-C-202 | 241-C-203 | 241-C-204 | 241-C-301 | 244-CR-Vault | Pipelines |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Carbon-14 (Ci) | 0.003 | 0.001 | 0.007 | 0.003 | 0.05 | 0.008 | 0.02 | 0.008 | 0.0008 | 0.002 | 0.1 | 0.02 | 0.0008 | 0.0002 | 0.0002 | 0.0002 | 0.002 | 0.002 | 0.003 |
| Cobalt-60 (Ci) | 0.0002 | 0.21 | 0.02 | 0.47 | 0.68 | 2.2 | 0.0009 | 0.0007 | 0.0005 | 0.0001 | 0.1 | 0.0007 | 0.002 | 0.002 | 0.002 | 0.002 | 0.12 | 0.12 | 0.19 |
| Tritium (Ci) | 0.02 | 2E-5 | 0.004 | 0.009 | 4.1 | 0.004 | 0.01 | 0.02 | 0.004 | 0.002 | 2.6 | 0.01 | 0.0002 | 0.0002 | 0.0001 | 0.0001 | 0.002 | 0.002 | 0.003 |
| Iodine-129 (Ci) | 6E-5 | 0.003 | 0.003 | 0.0005 | 0.009 | 0.0006 | 0.04 | 4E-5 | 3E-5 | 0.0003 | 0.01 | 4E-5 | 5E-7 | 7E-6 | 1E-5 | 4E-7 | 0.0002 | 0.0002 | 0.0003 |
| Niobium-93m (Ci) | 2E-5 | 0.01 | 0.0004 | 0.03 | 0.001 | 5.9 | 0.08 | 0.05 | 0.05 | 0.01 | 0.1 | 0.06 | 0.0007 | 0.0008 | 0.0006 | 0.0006 | 0.23 | 0.24 | 0.38 |
| Radium-226 + Daughters (Ci) | 6E-7 | 3E-7 | 2E-8 | 3E-7 | 2E-7 | 0.0005 | 6E-7 | 5E-7 | 3E-7 | 9E-8 | 5E-6 | 4E-7 | 1E-9 | 1E-9 | 8E-10 | 8E-10 | 2E-5 | 2E-5 | 3E-5 |
| Selenium-79 (Ci) | 0.0003 | 2E-6 | 3E-5 | 0.009 | 0.0002 | 0.01 | 0.0003 | 0.002 | 0.0001 | 4E-5 | 0.004 | 0.0002 | 5E-5 | 6E-5 | 5E-5 | 4E-5 | 0.001 | 0.001 | 0.002 |
| Tin-126 + Daughters (Ci) | 0.0005 | 0.0002 | 5E-5 | 0.009 | 0.0003 | 1.8 | 0.0005 | 0.0004 | 0.0003 | 0.02 | 0.007 | 0.0004 | 0.0001 | 0.0001 | 9E-5 | 9E-5 | 0.07 | 0.07 | 0.11 |
| Technetium-99 (Ci) | 0.04 | 0.004 | 0.04 | 0.3 | 7.8 | 0.16 | 2.1 | 0.05 | 0.009 | 0.04 | 2.2 | 1.7 | 0.003 | 0.002 | 0.002 | 0.003 | 0.04 | 0.04 | 0.06 |
| Uranium-232* (Ci) | 2E-6 | 0.03 | 4E-6 | 0.04 | 9E-6 | 0.0005 | 2E-6 | 5E-7 | 1E-7 | 2E-8 | 2E-5 | 5E-7 | 2E-6 | 2E-6 | 7E-6 | 5E-6 | 0.002 | 0.002 | 0.003 |
| Uranium-233* (Ci) | 2E-7 | 2.2 | 0.006 | 2.2 | 5E-7 | 0.002 | 2E-7 | 4E-8 | 1E-8 | 2E-9 | 5E-5 | 4E-8 | 1E-5 | 1E-5 | 3E-5 | 3E-5 | 0.12 | 0.12 | 0.19 |
| Uranium-234* (Ci) | 0.17 | 0.11 | 0.01 | 0.42 | 0.24 | 0.0009 | 0.21 | 0.03 | 0.009 | 0.003 | 0.77 | 0.04 | 0.04 | 0.04 | 0.11 | 0.08 | 0.23 | 0.24 | 0.37 |
| Uranium-235* (Ci) | 0.008 | 0.004 | 0.0007 | 0.02 | 0.01 | 4E-5 | 0.009 | 0.002 | 0.0004 | 0.0001 | 0.03 | 0.002 | 0.001 | 0.001 | 0.005 | 0.003 | 0.01 | 0.01 | 0.02 |
| Uranium-236* (Ci) | 0.002 | 0.001 | 0.0004 | 0.005 | 0.005 | 2E-5 | 0.002 | 0.0003 | 1E-4 | 3E-5 | 0.01 | 0.0005 | 0.0005 | 0.0004 | 0.0008 | 0.0005 | 0.002 | 0.002 | 0.003 |
| Uranium-238 +Daughters (Ci) | 0.17 | 0.1 | 0.02 | 0.44 | 0.24 | 0.0009 | 0.21 | 0.04 | 0.01 | 0.003 | 0.79 | 0.04 | 0.04 | 0.03 | 0.11 | 0.08 | 0.23 | 0.23 | 0.36 |
| Chromium (VI) (dissolved) (Kg) | 7.2 | 11.3 | 2.4 | 3.1 | 37 | 3.8 | 55.4 | 0.63 | 0.18 | 1.1 | 73.3 | 57.8 | 12.2 | 9.1 | 2.6 | 1.4 | 17.9 | 18.3 | 28.6 |
| Fluoride (Kg) | 34.6 | 0.006 | 0.16 | 15.4 | 79.2 | 0.54 | 605 | 121 | 96.8 | 138 | 807 | 709 | 2.7 | 2.3 | 1.6 | 0.008 | 21.2 | 21.8 | 34.1 |
| Nitrite (Kg) | 564 | 0.03 | 0.48 | 5.1 | 647 | 41.4 | 2,148 | 5.8 | 3.8 | 2.7 | 5,500 | 675 | 0.53 | 0.45 | 0.99 | 0.03 | 3.9 | 4 | 6.2 |
| Nitrate (Kg) | 8,200 | 0.1 | 0.87 | 9.4 | 783 | 34.8 | 3,588 | 9.2 | 4.5 | 6.7 | 14,700 | 8,760 | 1.4 | 1.3 | 3.8 | 0.02 | 7.5 | 7.7 | 12 |
| Total Uranium (soluble salts) (Kg) | 516 | 293 | 49.1 | 1320 | 734 | 2.7 | 632 | 121 | 28.6 | 5.5 | 2,360 | 129 | 111 | 98.8 | 326 | 243 | 676 | 693 | 1,084 |
| Cobalt (Kg) | 0 | 0 | 0.09 | 0.04 | 0 | 0.38 | 0 | 0.05 | 0.01 | 0.02 | 0 | 0 | 0.08 | 0.08 | 0.02 | 0.04 | 0 | 0 | 0 |
| Cyanide (Kg) | 0 | 0 | 0.01 | 0.02 | 0 | 0.08 | 0 | 0.16 | 0.39 | 0.008 | 0 | 0 | 0.002 | 0.004 | 0.004 | 0.0007 | 0 | 0 | 0 |
| Selenium and compounds (Kg) | 0 | 0 | 0.69 | 0.14 | 0 | 2.9 | 0 | 0.31 | 0.08 | 0.04 | 0 | 0 | 0.11 | 0.09 | 0.18 | 0.4 | 0 | 0 | 0 |
| Tin (Kg) | 0 | 0 | 1.1 | 0.37 | 0 | 2.4 | 0 | 0.15 | 0.04 | 0.85 | 0 | 0 | 0.13 | 0.38 | 0.15 | 0.2 | 0 | 0 | 0 |
| Tributyl Phosphate (Kg) | 0 | 0 | 1 | 0.02 | 0 | 0 | 0 | 0.05 | 0.009 | 0.1 | 0 | 0 | 19.9 | 5.3 | 8.7 | 65.5 | 0 | 0 | 0 |

*The base case analysis also includes Uranium-232, Uranium-233, Uranium-234, Uranium-235, and Uranium-236, but these isotopes were not evaluated directly using the STOMP© model.

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**Table D-2. Summary Explanation and List of Parameters Used to Develop the Source-Term Release Calculations and Functions. (2 sheets)**

| Parameter | Value | Reference |
|---|---|---|
| Release Type | Diffusive release from the tanks and CR-Vaults under intact conditions;<br>Both advective and diffusive release for the Pipelines;<br>Both advective and diffusive release for tanks and CR-Vaults under degraded conditions. | |
| Technetium-99 release | 6% of the waste inventory available for release instantaneously; remaining 94% waste form inventory made available based on first order fractional release rate of 6E-4 $day^{-1}$. | Waste Management Area (WMA) C RCRA Closure Analysis (RCA) Section 7.3.1 |
| Chromium dissolved concentration limit | 2,000 µg/L dissolved concentration limit imposed | WMA C RCA Section 7.3.1 |
| Uranium solubility for intact tank conditions | 1E-4 M for 1,000 years;<br>1E-6 M for time >1,000 years | WMA C RCA Section 7.3.1 |
| Uranium solubility for degraded tank conditions | 1E-4 M for 1,000 years;<br>2E-5 M for time >1,000 years | WMA C RCA Section 7.3.1 |
| Contaminant $K_d$ values for transport through the grout and concrete layer | Variable; see Table D-3 | WMA C RCA Table 7-4 |
| Porosity of Residual Waste Layer | 0.4 | Assumed |
| Saturation of Residual Waste Layer | 1 | Assumed fully saturated to maximize diffusive release |
| Residual Waste Volume | Variable by source | WMA C RCA Section 3.1 |
| Porosity of Concrete and Grout layer below the waste layer | 0.11 | SRNL-STI-2008-00421, Table 39 |
| Saturation of Concrete and Grout layer below the waste layer | 1 | Assumed to maximize diffusive release |
| Bulk Density of Concrete and Grout layer below the waste layer | 2.41 $g/cm^3$ | RPP-RPT-50934, pp. C-3 (C-107 dome core density of 151 $lb/ft^3$) |
| Diffusive Length of Waste form layer | 0 m | Assumed to maximize diffusive release |
| Diffusive Length of Concrete and Grout layer below the waste layer | 0.203 m (8 in.) | Minimum diffusive thickness based on tank bottom geometry |

**Table D-2. Summary Explanation and List of Parameters Used to Develop the Source-Term Release Calculations and Functions. (2 sheets)**

| Parameter | Value | Reference |
|---|---|---|
| Diffusive Area for source term release | 410.4 $m^2$ for 100-Series Tanks;<br>29.2 $m^2$ for 200-Series Tanks and C-301 catch tank;<br>162.4 $m^2$ for CR-Vaults;<br>22,500 $m^2$ for Pipelines | Base area for tanks based on circular geometry; area of CR-Vault is based on rectangular area with length of 92 ft and average width of 19 ft; area of Pipeline assumed to be 150 m × 150 m. |
| Effective Diffusion Coefficient through grout and concrete layer (incorporates effects of tortuosity) | 3E-8 $cm^2/s$ | WMA C RCA Section 7.3.1 |

RCRA = Resource Conservation and Recovery Act of 1976

References:
RPP-RPT-50934, "Inspection and Test Report for the Removed 241-C-107 Dome Concrete."
SRNL-STI-2008-00421, "Hydraulic and Physical Properties of Saltstone Grouts and Vault Concretes."

A stochastic model of variable moisture or tension-dependent anisotropy provides the framework for upscaling small-scale measurements to the effective (upscaled) properties for the large-scale vadose zone ("Application of Stochastic Methods to Transient Flow and Transport in Heterogeneous Unsaturated Soils" [Polmann 1990]). The upscaling processes factor the inherent spatial variability that occurs on different scales in heterogeneous media into the field scale parameter estimates ("Stochastic analysis of moisture plume dynamics of a field injection experiment" [Ye et al. 2005]; "Estimation of effective unsaturated hydraulic conductivity tensor using spatial moments of observed moisture plume" [Yeh et al. 2005]). Specific upscaled flow parameters include moisture retention, and saturated and unsaturated hydraulic conductivity. Upscaled transport parameters include bulk density, diffusivity, sorption coefficients, and macrodispersivity. Detailed discussion of the Polmann (1990) model and the derivation of the upscaled parameters are presented in Section 6.3.2.2.

For the Alternative Geologic Model II evaluation, the Hanford H2 gravel/coarse sand subunit was assumed to be more transmissive, and the Hanford H2 silty sand less transmissive, than the Hanford H2 sand. Therefore, as an initial estimate of these properties, the hydraulic properties associated with the $5^{th}$ and $95^{th}$ percentile realizations of unsaturated hydraulic conductivity curves developed for the Hanford H2 sand unit were considered representative of the Hanford H2 gravel/coarse sand and the Hanford H2 silty sand subunits, respectively.

The effective transport parameter (i.e., macrodispersivity, bulk density, and diffusivity) estimates used in the base case and sensitivity cases are presented. Because of natural variability, the transport parameters are all spatially variable. The purpose is similar to the upscaled flow parameters, to evaluate the effect of such variability on the large-scale transport process. Effective bulk density ($\rho_b$) estimates are needed to calculate retardation factors for different species. The average $\rho_b$ ($E[\rho_b]$) estimates for various strata at WMA C are presented in

Table D-5. These estimates are derived from bulk density values listed in Section 7.2.2. According to "Solute transport in heterogeneous porous formations" (Dagan 1984), macrodispersivity reaches a constant, asymptotic value after the solute travels a few tens of correlation scales (~50 cm) of the hydraulic conductivity field; therefore, the use of a constant (asymptotic) macrodispersivity value is considered appropriate in PA simulations (Section 7.2.2). On the basis of results of numerical simulation, stochastic theory, and 200 Areas experimental data, the recommendation is to use a longitudinal macrodispersivity value of 25 cm for the H2 sand unit in the WMA C PA base case. For H1/H3/Backfill sediments, the recommendation is to use a longitudinal macrodispersivity value of 20 cm. The transverse macrodispersivity is typically much lower; in saturated media, it may range from 1 to 10% of the longitudinal macrodispersivity ("Three-dimensional stochastic analysis of macrodispersion in aquifers" [Gelhar and Axness 1983]). In the absence of unsaturated media experimental data, the recommendation is to use a transverse macrodispersivity 1/10th of the longitudinal macrodispersivity. The estimated values of macrodispersivity applicable to the scale of the WMA C PA model for the base case are shown in Table D-6. It is assumed that the effective, large-scale diffusion coefficients for all strata in the vadose zone at the WMA C site are a function of volumetric moisture content, θ, and can be expressed using the Millington-Quirk ("Permeability of Porous Solids" [Millington and Quirk 1961]) empirical relation:

$$D_e(\theta) = D_0 \frac{\theta^{10/3}}{\theta_s^2} \tag{4-1}$$

Where:

$D_e(\theta)$ = the effective diffusion coefficient of an ionic species
$D_0$ = the effective diffusion coefficient for the same species in free water
θ = the localized volumetric moisture content.

The tortuosity formulation in the Millington-Quirk model is based on theoretical considerations absent from other empirical models, and accounts for the ranges of moisture contents present in the vadose zone around WMA C. The molecular diffusion coefficient for all species in pore water is assumed to be $2.5 \times 10^{-5}$ $cm^2/sec$ (WHC-SD-WM-EE-004, "Performance Assessment of Grouted Double-Shell Tank Waste Disposal at Hanford") which is consistent with, and representative of, values used in other Hanford PAs.

### D4.1.5 Infiltration and Recharge

The magnitude of recharge for soils at the Hanford Site varies as a function of the soil type, condition of the vegetation cover, and soil integrity (e.g., disturbed versus undisturbed). The range of recharge values reported in RPP-RPT-44042 represents distinct populations of data based on lysimetry and isotopic measurements, and based on interpretation and, in some instances, extrapolation by Hanford Site subject matter experts. The natural background recharge rates represent a population for natural vegetated conditions. The range of values for operational conditions represents a population of recharge rates for vegetation-free disturbed soil. Table D-7 presents a summary of the base case recharge rates applied to the different surface types.

**Table D-3. Partition Coefficient Values for Grout/Concrete Used for Waste Management Area C Performance Assessment and RCRA Closure Analysis Source Release Functions.**

| Radionuclide or Non-radiological Contaminant | Best Estimate $K_d$ Value (mL/g) | Reference |
|---|---|---|
| C | 2.53E+03 | PSI Bericht Nr. 95-06 |
| CN | 0.00E+00 | No relevant information |
| Co | 4.00E+01 | SKB R-05-75 |
| Cr | 0.00E+00 | No relevant information |
| F | 0.00E+00 | No relevant information |
| H | 1.00E-01 | NAGRA NTB 02-20 |
| I | 3.00E+00 | SKB R-05-75 |
| Nb | 5.00E+02 | SKB R-05-75 |
| $NO_2$ | 0.00E+00 | No relevant information |
| $NO_3$ | 0.00E+00 | No relevant information |
| Ra | 5.00E+01 | SKB R-05-75 |
| Rn | 0.00E+00 | No relevant information |
| Se | 6.00E+00 | SKB R-05-75 |
| Sn | 5.00E+02 | SKB R-05-75 |
| Tri-butyl Phosphate | 0.00E+00 | No relevant information |
| Tc | 1.00E+00 | NAGRA NTB 02-20 |
| U isotopes | 2.00E+03 | NAGRA NTB 02-20 |
| U_total | 2.00E+03 | NAGRA NTB 02-20 |

RCRA = Resource Conservation and Recovery Act of 1976

References:
NAGRA NTB 02-20, "Cementitious Near-Field Sorption Data Base for Performance Assessment of an ILW Repository in Opalinus Clay."
PSI Bericht Nr. 95-06, "Sorption Databases for the Cementitious Near-Field of a L/ILW Repository for Performance Assessment."
SKB Rapport R-05-75, "Assessment of uncertainty intervals for sorption coefficients, SFR-1 uppföljning av SAFE."

The design for the WMA C surface barrier at closure has not been finalized, but it is expected to function comparably to a Modified RCRA Subtitle C Barrier. Summary of data collected over 13 years at the Prototype Hanford Barrier (PNNL-17176, "200-BP-1 Prototype Hanford Barrier Annual Monitoring Report for Fiscal Years 2005 Through 2007"; DOE/RL-93-33, Focused Feasibility Study of Engineered Barriers for Waste Management Units in the 200 Areas) indicates that infiltration through the prototype is much less than 0.1 mm/yr, and evaluations of the design using lysimeter data indicate that the barrier is capable of limiting recharge to this

amount even with a complete lack of vegetation ("Multiple-Year Water Balance of Soil Covers in a Semiarid Setting" [Fayer and Gee 2006]). However, for RCA and PA simulations involving WMA C with a functioning surface barrier, a base case recharge rate of 0.5 mm/yr is assumed, which is consistent with the drainage design specification in DOE/RL-93-33.

**Table D-4. Composite van Genuchten-Mualem Parameters for Various Strata at the Waste Management Area C Site Used in the Base Case Evaluations of Alternative Geologic Models I and II.**

| Strata | Number of Samples | $\theta_s$ | $\theta_r$ | α (1/cm) | n | $\ell^c$ | Fitted $K_s$ (cm/s) |
|---|---|---|---|---|---|---|---|
| Backfill (Gravelly) | 10 | 0.138 | 1.11E-02 | 0.021 | 1.374 | 0.5 | 5.60E-04 |
| Hanford H1/H3 (Gravel-dominated) | 15 | 0.171 | 1.11E-02 | 0.036 | 1.491 | 0.5 | 7.70E-04 |
| Hanford H2 (Sand-dominated) | 44 | 0.315 | 3.92E-02 | 0.063 | 2.047 | 0.5 | 4.15E-03 |
| **Hydrostratigraphic Units only applicable to Alternative Geologic Model II** | | | | | | | |
| Hanford H2 – Gravel/coarse sand subunit* | not applicable (75th Percentile) | 0.265 | 2.11E-03 | 0.108 | 1.724 | 0.5 | 1.68E-02 |
| Hanford H2 – Silty sand subunit* | not applicable (5th Percentile) | 0.354 | 2.89E-02 | 0.040 | 1.633 | 0.5 | 1.79E-03 |

* Hydraulic properties of these units are only used in numerical model simulation of Alternative Geologic Model II. As an initial estimate of these properties, the hydraulic properties associated with the 5th and 95th percentile realizations of unsaturated hydraulic conductivity curves developed in the Uncertainty and Sensitivity Analysis for the Hanford H2 sand unit were considered to be representative of the Hanford H2 gravel/coarse sand and the Hanford H2 silty sand subunits.

**Table D-5. Effective Bulk Density (E[ρb], g/cm$^3$) Estimates for Various Strata at Waste Management Area C Used in the Base Case Evaluations of Alternative Geologic Models I and II.**

| Strata | $E[\rho_b]$ |
|---|---|
| Backfill (Gravelly) | 2.13 |
| Hanford H1/H3 (Gravel-dominated) | 2.05 |
| Hanford H2 (Sand-dominated) | 1.71 |
| **Hydrostratigraphic Units only applicable to Alternative Geologic Model II** | |
| Hanford H2 – Gravel/coarse sand subunit* | 1.83 |
| Hanford H2 – Silty sand subunit* | 1.61 |

* Effective bulk densities of these units are only used in numerical model simulation of Alternative Geologic Model II.

At the end of 500 years, the surface barrier performance is assumed to degrade to permit an infiltration rate of 3.5 mm/yr and maintain that infiltration rate for the remainder of the

sensitivity and uncertainty analysis time frame. No quantifying data are available for specifying the performance of the barrier top after its design life. According to PNNL-13033, "Recharge Data Package for the Immobilized Low-Activity Waste 2001 Performance Assessment," the erosion of the silt loam layer and deposition of dune sand on the barrier is not likely to alter the barrier performance significantly. The value of 3.5 mm/yr (0.14 in./yr) corresponds to the recharge in an undisturbed area, which indicates that native vegetation is assumed to reclaim the land.

**Table D-6. Macrodispersivity Estimates for Various Strata at Waste Management Area C Used in the Base Case Evaluations of Alternative Geologic Models I and II.**

| Strata | $A_L$ (cm) | $A_T$ (cm) |
|---|---|---|
| Backfill (Gravelly) | ~20 | 2 |
| Hanford H1/H3 (Gravel-dominated) | ~20 | 2 |
| Hanford H2 (Sand-dominated) | ~25 | 2.5 |
| **Hydrostratigraphic Units only applicable to Alternative Geologic Model II** | | |
| Hanford H2 –Gravel/coarse sand subunit* | ~25 | 2.5 |
| Hanford H2 – Silty sand subunit* | ~25 | 2.5 |

* Macrodispersivities of these units are only used in numerical model simulation of Alternative Geologic Model II.

Although the side slopes and berm are likely to function and perform differently than the surface of the barrier, they are included as part of the barrier surface. The impact of the side slopes on the overall recharge rate is expected to be relatively minor. The sandy gravel/gravelly sand barrier side slope and berm are assumed eventually to resemble a Burbank loamy sand, and PNNL-16688, "Recharge Data Package for Hanford Single-Shell Tank Waste Management Areas" indicates that the long-term recharge rate for that soil type is 1.9 mm/yr, which is less than the value of 3.5 mm/yr used in the analysis for the degraded barrier surface.

### D4.1.6 Geochemistry and Sorption

The geochemistry conceptual model component involves the partitioning behavior or sorption characteristics regarding release, retardation, and attenuation mechanisms, and any simplifying assumptions for specific radionuclides and non-radiological contaminants. The key aspects of this geochemistry conceptual model and its applicability to the Hanford Site 200 Areas include the following, and are discussed in detail in DOE/RL-2011-50:

- The use of a linear $K_d$ isotherm is a reasonable description for the release and attenuation of radionuclides in the context of providing an upper-bounding condition
- The source(s) of the data used in the selection of radionuclide $K_d$ values
- The use of a single $K_d$ in the individual vadose zone hydrostratigraphic units (HSUs).

**Table D-7. Base Case Recharge Rate (Net Infiltration) Estimates for Surface Conditions during the Pre-Construction, Operational, and Post-Closure Periods.**

| Period | Waste Management Area (WMA) C Region and Surface Condition | Base Case Value of Recharge Rate (mm/yr) |
|---|---|---|
| Pre-construction (before 1944) | Undisturbed region (Rupert sand with vegetation) | 3.5 |
| Operational period (1945 to 2020) | Undisturbed region (Rupert sand with vegetation) | 3.5 |
| | WMA C Surface region (Gravel without vegetation) | 100 |
| | WMA A Surface region (Gravel without vegetation) | 100 |
| | Disturbed revegetated region (Rupert sand with vegetation) | 22 |
| | Disturbed unrevegetated region (Rupert sand with no vegetation) | 63 |
| Early post-closure (2020 to 2520) | Undisturbed region (Rupert sand with vegetation) | 3.5 |
| | WMA C Surface region (Surface barrier with vegetation) | 0.5 |
| | WMA A Surface region (Surface barrier with vegetation beginning in 2050) | 0.5 |
| | Disturbed revegetated region (Rupert sand with vegetation beginning in 2050 with vegetation recovery completed in 2080) | 3.5 |
| | Disturbed unrevegetated region (Rupert sand with no vegetation until vegetation recovery begins in 2050 and completes in 2080) | 3.5 |
| Late post-closure (2520 to 3020 and beyond) | Undisturbed region (Rupert sand with vegetation) | 3.5 |
| | WMA C Surface region (Surface barrier with vegetation) | 3.5 |
| | WMA A Surface region (Degraded surface barrier with vegetation begins in 2550) | 3.5 |
| | Disturbed revegetated region (Rupert sand with vegetation recovery completed in 2080) | 3.5 |
| | Disturbed unrevegetated region (Rupert sand with vegetation recovery completed in 2080) | 3.5 |

The geochemistry conceptual models for the Hanford Site are based on extensive laboratory studies, testing, and measurements of adsorption and desorption coefficients under saturated and unsaturated conditions involving Hanford Site-specific sediments, contaminants, and conditions (DOE/RL-2011-50; RPP-RPT-46088; PNNL-13895, "Hanford Contaminant Distribution Coefficient Database and Users Guide"). The basis and rationale for the $K_d$ values used to approximate the transport of the radionuclides is presented in RPP-RPT-46088, and the base case values are presented in Table D-8. The differing values for the different geologic units represent the adjustment of values resulting from the approximate gravel content of each unit.

The radionuclides and non-radiological contaminants listed in Table D-8 are limited to those with $K_d$ values less than 2 mL/g (prior to any adjustments because of gravel content) because the

results of the screening analysis indicated that radionuclides with $K_d$ values greater than 2 mL/g did not impact groundwater within the 10,000-year sensitivity-uncertainty time frame (see Section 8.2.1 Result of Screening Analysis for Groundwater Pathway regarding this determination).

**Table D-8. Summary of the Waste Management Area C Performance Assessment and RCRA Closure Analysis Base Case $K_d$ (mL/g) Values.**

| Radionuclide or Non-radiological Contaminant | $K_d$ (mL/g) | | | |
|---|---|---|---|---|
| | Backfill | H1 | H2 | H3 |
| Carbon-14 (C-14) | 0.46 | 0.58 | 0.8 | 0.58 |
| Cobalt/Cobalt-60 (Co/Co-60) | 0 | 0 | 0 | 0 |
| Chromium (Cr) | 0 | 0 | 0 | 0 |
| Fluoride (F) | 0 | 0 | 0 | 0 |
| Tritium (H-3) | 0 | 0 | 0 | 0 |
| Iodine-129 (I-129) | 0.09 | 0.12 | 0.16 | 0.12 |
| Niobium-93m (Nb-93m) | 0 | 0 | 0 | 0 |
| Nitrite ($NO_2$) | 0 | 0 | 0 | 0 |
| Nitrate ($NO_3$) | 0 | 0 | 0 | 0 |
| Radon-222 (Rn-222) | 0 | 0 | 0 | 0 |
| Selenium/Selenium-79 (Se/Se-79) | 0.05 | 0.06 | 0.08 | 0.06 |
| Tin/Tin-126 (Sn/Sn-126) | 0.23 | 0.29 | 0.4 | 0.29 |
| Technetium-99 (Tc-99) | 0 | 0 | 0 | 0 |
| Total Uranium/Uranium-238 (U Total/U-238*) | 0.28 | 0.35 | 0.48 | 0.35 |
| Tri-butyl Phosphate (TBP) | 1.89 | 0.87 | 1.1 | 1.5 |

* The base case analysis also includes Uranium-232, Uranium-233, Uranium-234, Uranium-235, Uranium-236, and the Uranium-238 daughter products, but these isotopes were not evaluated directly using the STOMP© model.

RCRA = Resource Conservation and Recovery Act of 1976

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### D4.1.7 Groundwater Domain

The integrated, saturated-unsaturated, 3-D WMA C model calculates groundwater concentrations of contaminants approximately 100 m downgradient of the WMA C fenceline that are estimated to occur several hundred to several thousand years into the future. The unconfined aquifer flow and transport parameters play a critical role in WMA C PA modeling because of the dilution that occurs as recharge containing contaminants enters the aquifer. Additional dilution and concentration attenuating dispersion occurs as the contaminants travel through the aquifer. The dilution and dispersion are strongly dependent on the groundwater flux, which is a rate measure

defined as the flow through a defined area. Groundwater flow beneath WMA C has been difficult to measure historically because the hydraulic gradient is very small and the hydraulic conductivity is very large in this region of the Hanford Site.

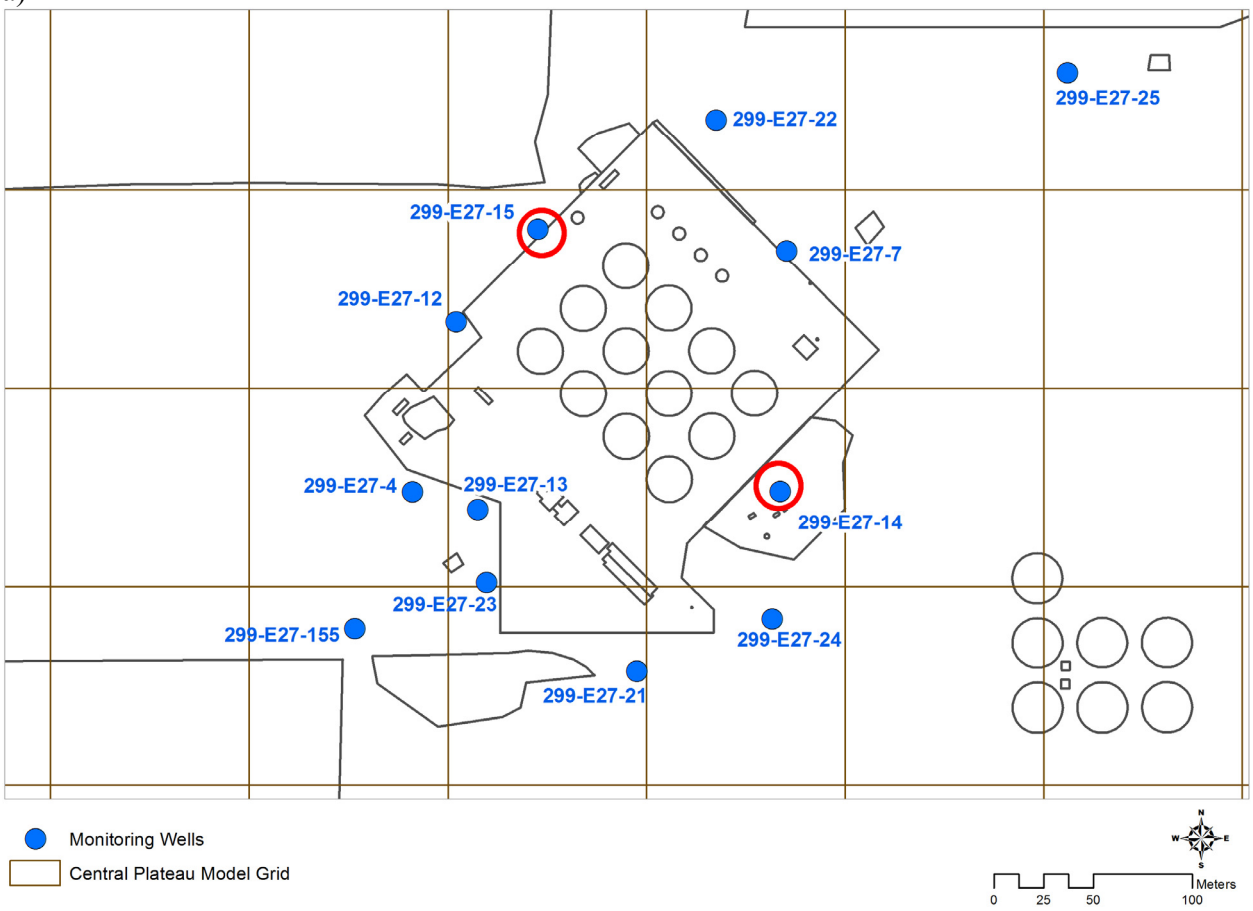
The groundwater in the aquifer system in the vicinity of WMA C has been studied extensively as part of the site characterization as discussed in RPP-RPT-46088 and Appendix C. The groundwater conceptual model for WMA C includes the uppermost unconfined aquifer system that exists within a channel eroded by the cataclysmic floods of the Pleistocene. The base of the aquifer is the underlying basalt surface. The undifferentiated lower sands and gravels associated with the Hanford formation, Cold Creek unit, and the Ringold Formation (Unit A) that comprise the aquifer sediments are simply categorized as saturated Hanford H3 sediments in the model. The thickness of the uppermost aquifer beneath WMA C is approximately 12 m (39 ft). The model results provided represent concentrations in the upper 5 m (16.4 ft) of the aquifer. The 5-m vertical interval corresponds to the well screen length of a conceptual groundwater monitoring well, and the basis for that delimiter to the groundwater concentrations calculation is presented in Section D4.1.8 Point of Calculation, Protectiveness Metric, and Time Frame Considerations. The aquifer, identified as Hanford H3 – aquifer, is separated from that portion of the Hanford H3 above the water table, reflecting the distinctly different saturation conditions.

For the WMA C RCA and PA modeling, the unconfined aquifer is treated as an equivalent homogeneous medium (EHM) that requires parameterization for the appropriate scale. Effective parameterization for WMA C saturated media hydraulic conductivity appears to be best achieved via a field-scale calibrated regional groundwater model that accounts for appropriate local-scale boundary conditions, flow configuration, and history matching of well head data (WMA C RCA Appendix C). The Central Plateau Groundwater Model (CPGWM) provides calibrated hydraulic conductivity estimates for the model layers and HSUs present within the aquifer in the vicinity of WMA C. The thicknesses of the different aquifer HSUs are mapped from the CPGWM onto the WMA C RCA and PA STOMP© model flow domain, and an averaging scheme weighted according to HSU thickness provides estimates of the EHM effective saturated hydraulic conductivity and the hydraulic gradient.

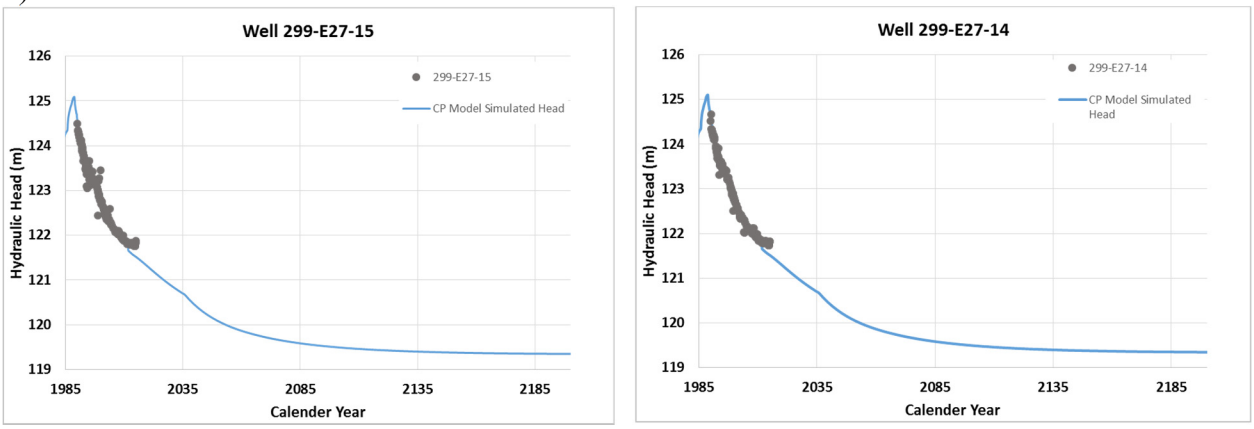
The weighted average of hydraulic conductivity of the CPGWM HSUs mapped onto the WMA C flow domain indicates that the effective STOMP© EHM saturated hydraulic conductivity is approximately 11,000 m/day. As discussed previously, field-scale calibrated groundwater models provide an effective parameterization for WMA C saturated media hydraulic conductivity for the overall dimensions of the WMA C RCA and PA model domain. The hydraulic gradient is calculated from a planar rectangular window (300 m × 200 m) in the CPGWM having an unconfined aquifer depth that encompasses most of the WMA C flow domain (Figure D-4, adapted from CP-47631, “Model Package Report: Central Plateau Groundwater Model Version 3.4”) by taking into account the net volumetric flux through the domain. Volumetric flux through the window is divided by the vertical cross-sectional area of the aquifer and the STOMP© EHM hydraulic conductivity to calculate the hydraulic gradient.

**Figure D-4. Central Plateau Groundwater Model Calibration Results in the Vicinity of Waste Management Area C.**

a)




b)




In the future, the gradient is generally expected to be from northwest to southeast. The water table in the unconfined aquifer is expected to continue declining because the large discharges of operational liquid to the ground at 216-B-3 Pond system and other large discharge sites in 200 East Area have ceased. The hydraulic heads around WMA C are expected to continue

declining slowly until they stabilize around year 2030 at 119.5 m (392 ft) (Figure D-4). For Year 2100 (approximating post-closure steady state conditions), the CPGWM-calculated flow through the window volume is 580 $m^3$/day, which divided by the cross-sectional area of 3,300 $m^2$ translates to a Darcy flux of 0.18 m/day with a hydraulic gradient of $2 \times 10^{-5}$, which is close to the one observed prior to start of Hanford operations, as estimated from Figure 7-31 (adapted from Figure 2-8 in WHC-EP-0645, "Performance Assessment for the Disposal of Low-Level Waste in the 200 West Area Burial Grounds"). Changes in hydraulic gradient are only expected to occur within the first 10 to 50 years of the post-closure simulation period, which, according to the screening analysis (see Sections 7.3.2.3 Groundwater Pathway Screening Analysis Methodology and 8.2.1 Result of Screening Analysis for Groundwater Pathway), is before the mobile radionuclides reach the water table. Thus, the hydraulic gradient is assumed to be stable for this analysis.

According to RPP-14430, "Subsurface Conditions Description for C and A-AX Waste Management Area," porosity is generally estimated to be about 30% for unconsolidated coarse-grained sediments, but a value closer to 20% may be more appropriate where boulders and cobbles are present and mixed with sand and gravels, such as at WMA C. The STOMP© EHM porosity value of 0.20 is consistent with the vadose zone value of 0.17 for the Hanford H1 and H3 sediments, and with the aquifer test results from well 699-55-50 presented in HW-60601, "Aquifer Characteristics and Ground-Water Movement at Hanford." The STOMP© EHM includes the CPGWM estimate of 0.1 (CP-47631) for the anisotropy, which is defined here as the ratio of vertical to horizontal hydraulic conductivity. The longitudinal and transverse macrodispersivity estimates in the saturated zone are based on a review of three general relationships ("Universal Scaling of Hydraulic Conductivities and Dispersivities in Geologic Media" [Neuman 1990]; "Longitudinal Dispersivity Data and Implications for Scaling Behavior" [Schulze-Makuch 2005]; and "Use of Weighted Least-Squares Method in Evaluation of the Relationship Between Dispersivity and Field Scale" [Xu and Eckstein 1995]) that quantify the dependence of this parameter on measurement scale ($L_s$). For 100 m, which is the approximate distance of travel to the compliance well located in the saturated zone, the calculated values fall within the range of 1 to 20 m (Table D-9). Thus, a value of 10.5 m is chosen for the base calculation. The ratio of longitudinal to transverse macrodispersivity is chosen to be 10 based on RPP-17209, "Modeling Data Package for an Initial Assessment of Closure of the S and SX Tank Farms" and "Field Study of a Long and Very Narrow Contaminant Plume" (van der Kamp et al. 1994). Table D-10 presents a summary of the aquifer hydraulic parameters for the Hanford H3 – aquifer used for the base case.

### D4.1.8 Point of Calculation, Protectiveness Metric, and Time Frame Considerations

In accordance with risk and performance assessment guidelines, the determination of soil contamination impacts to groundwater also requires the definition and rationale for (1) the point of calculation, i.e., the place and points in the groundwater domain where modeled groundwater concentrations are to be assessed for potential impacts and protectiveness; (2) the protectiveness metric, i.e., the groundwater metric(s) to be used in the assessment of protectiveness at the point of calculation; and (3) the time frame considered applicable for the calculation of impacts to groundwater. The point of calculation is intended to effectively serve as the point where exposure point groundwater concentrations are evaluated in the model for the purpose of

evaluating the achievement of the groundwater protection performance objectives. The point of calculation for the protection of groundwater is related to "Point of Compliance" in Federal PA requirements (DOE M 435.1-1; DOE G 435.1-1, Chapter 4) and described as follows:

> "The point of compliance shall correspond to the point of highest projected dose or concentration beyond a 100 meter buffer zone surrounding the disposed waste. A larger or smaller buffer zone may be used if adequate justification is provided."

Thus, the point of calculation for the groundwater impact analysis is 100 m downgradient from the WMA C fenceline. While the DOE manual and guide state that point of compliance is the point of highest calculated dose (groundwater concentration), neither indicates how that groundwater concentration should be calculated—i.e., within what volume the concentration is to be calculated, apart from indicating that the aquifer mixing must be consistent with State or local laws, regulations, or agreements.

**Table D-9. Relationship Between Saturated Longitudinal Macrodispersivity (αL) and Scale of Measurement ($L_s$).**

| Reference | Relationship | Origin | Saturated Longitudinal Macrodispersivity Estimate (m) for a Scale ≈ 100 m |
|---|---|---|---|
| Neuman (1990) | $\alpha_L \approx 0.017\ L_s^{1.5}$ | "Universal relationship" established considering both field and laboratory data (excluding modeling results) | 17 |
| Schulze-Makuch (2005) | $\alpha_L \approx 0.085\ L_s^{0.81}$ | Established considering field and modeling results (all reliabilities) and excluding laboratory data | 3.5 |
| Xu and Eckstein (1995) | $\alpha_L \approx 0.94(\log_{10} L_s)^{2.693}$ | Established considering the same data set as Neuman (1990) including numerical model results | 6 |

References:
"Longitudinal Dispersivity Data and Implications for Scaling Behavior" (Schulze-Makuch 2005).
"Universal Scaling of Hydraulic Conductivities and Dispersivities in Geologic Media" (Neuman 1990).
"Use of Weighted Least-Squares Method in Evaluation of the Relationship Between Dispersivity and Field Scale" (Xu and Eckstein 1995).

The approach identified in EPA/540/R-95/128, Soil Screening Guidance: Technical Background Document and WAC 173-340-747, "Deriving Soil Concentrations for Groundwater Protection" indicates that the cross section of the aquifer volume is usually prescribed to be a unit width of 1 m (3.3 ft), because the equations are developed on the basis of a unit width. This implies that the cross section width is equal to the width of contamination entering the aquifer. Consistent with this reasoning, other performance assessments conducted at Hanford and other DOE facilities have used an aquifer mixing width equal to the width of the facility (e.g., WCH-520, "Performance Assessment for the Environmental Restoration Disposal Facility, Hanford Site, Washington"; WSRC-MS-2003-00582, "Performance Assessment/Composite Analysis

Modeling to Support a Holistic Strategy for the Closure of F Area, a Large Nuclear Complex at The Savannah River Site").

**Table D-10. Waste Management Area C Performance Assessment and RCRA Closure Analysis Unconfined Aquifer Flow and Transport Properties.**

| Property | Waste Management Area C |
|---|---|
| Horizontal saturated hydraulic conductivity (m/day)[a] | 11,000 |
| Ratio of vertical to horizontal saturated hydraulic conductivity | 0.1 |
| Specific storage (1/m)[b] | 1.1E-3 |
| Effective porosity (dimensionless) | 0.20 (Hanford Gravel) |
| Hydraulic gradient (m/m)[c] | 2.0E-5 |
| Depth to water table (m) | 80 |
| Longitudinal macrodispersivity (m) | 10.5 |
| Longitudinal to transverse macrodispersivity ratio | 10 |

[a] Thickness weighted average conductivity estimate derived from Central Plateau Groundwater Model based on Equivalent Homogeneous Media approach adopted for representing the aquifer in the model.

[b] Using the assumed values of an aquifer compressibility of 1.0E-7 1/Pa (STOMP© default), a water compressibility of 0.0046 1/atm (CRC Handbook of Chemistry and Physics [Haynes and Lide 2011]), and a water density of 1,000 kg/m$^3$ (Haynes and Lide 2011).

[c] Thickness weighted gradient estimate derived from Central Plateau Groundwater Model based on Equivalent Homogeneous Media approach adopted for representing the aquifer in the model.

RCRA = Resource Conservation and Recovery Act of 1976

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To calculate the highest groundwater concentration, the base case evaluated the average concentration in the aquifer within nine segments along the line perpendicular to, and 100 m beyond, the southeast edge of WMA C (Figure D-5). Concentrations calculated in the nine segments of the aquifer are assumed to be comparable to concentrations that would be measured by sampling a monitoring well at that location. The nine segments are approximately 30 m long (Table D-11), and aligned such that the centerlines of the plumes in the groundwater resulting from the residuals released from a single line of 100-series tanks parallel to the direction of groundwater flow (e.g., the centerline of the plumes resulting from the tank residuals in 241-C-102, 241-C-105, 241-C-108, and 241-C-111) intersect the perpendicular line within the same segment.

The WAC specifies a 5-m mixing zone in groundwater that is consistent with a 5-m vertical interval corresponding to a conceptual groundwater monitoring well with the 15-ft well screen length (and mixing zone dimension) associated with State monitoring well descriptions (e.g., see Equation 747-4 in WAC 173-340-747). The aquifer mixing zone extends into the upper 5 m of the aquifer for the purpose of the evaluations. DOE M 435.1-1 does not specify the level of

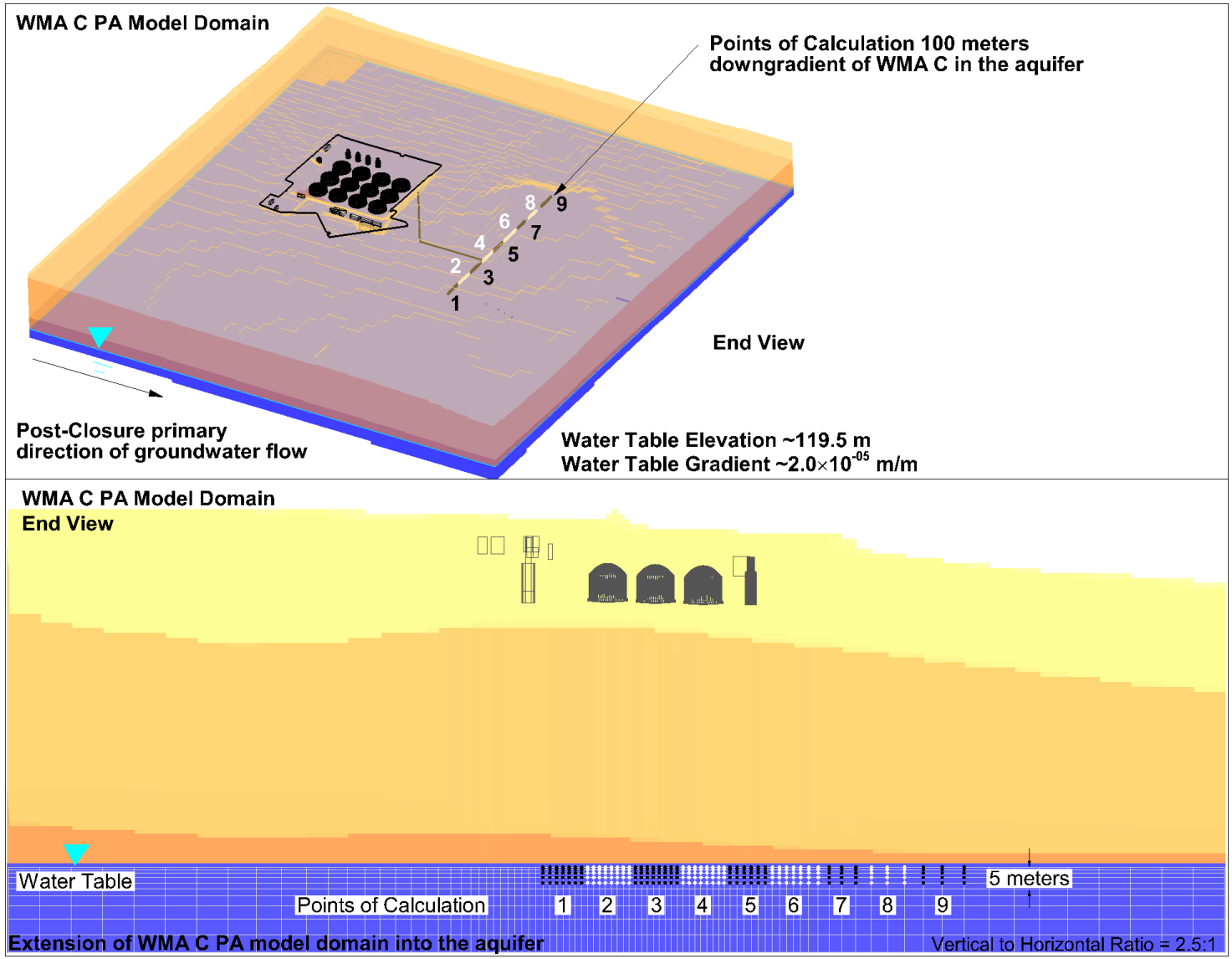
protection required for water resources, and there are no applicable parameterization requirements or guidelines indicated in DOE G 435.1-1, Chapter 4.

The compliance time frame is defined as 1,000 years following closure of the facility (DOE M 435.1-1; DOE G 435.1-1, Chapter 4). The sensitivity-uncertainty analysis along with the U.S. Nuclear Regulatory Commission's guidance (NUREG-1854, NRC Staff Guidance for Activities Related to U.S. Department of Energy Waste Determinations – Draft Final Report for Interim Use) extends the evaluation to 10,000 years, which is sufficient to evaluate the peak dose from all of the radionuclides that the screening analysis indicates may not impact groundwater within the compliance period. DOE M 435.1-1 and DOE G 435.1-1, Chapter 4 state that the sensitivity-uncertainty analysis time frame should include calculation of the maximum dose regardless of the time at which the maximum occurs, as a means of increasing confidence in the outcome of the modeling and increasing the understanding of the models used. However, EPA-SAB-RAC-ADV-99-006, An SAB Advisory: Modeling of Radionuclide Releases from Disposal of Low Activity Mixed Waste warns that extending the modeling time frame beyond 10,000 years could make the results irrelevant, and hinder public acceptance of the results because of the inherent scientific and social uncertainties associated with such an extended time frame. The 10,000-year time frame is sufficient to address uncertainty associated with radionuclides that impact groundwater during the compliance period (NUREG-1573, A Performance Assessment Methodology for Low-Level Radioactive Waste Disposal Facilities: Recommendations of NRC's Performance Assessment Working Group).

DOE G 435.1-1, Chapter 4 states that DOE low-level waste disposal facilities must comply with legally applicable requirements for water resource protection. The protectiveness metrics determined to be most appropriate for the evaluation of impacts to groundwater during the compliance period from the radionuclide and contaminant inventory in WMA C are the maximum concentration limits. Maximum concentration limits represent the "allowable concentrations" and/or "acceptable limits" of a radionuclide for minimizing further degradation of groundwater in accordance with the conditions identified in State and Federal anti-degradation goals (e.g., EPA/540/R-92/003, Guidance for Data Useability in Risk Assessment (Part A) Final; EPA/530-SW-87-017, Alternate Concentration Limit Guidance; DOE/RL-2002-59, Hanford Site Groundwater Strategy Protection, Monitoring, and Remediation).

Defining the protection of groundwater in the context of vadose zone fate and transport requires consideration of the soil and groundwater media as a hybrid or coupled pathway. This pathway involves the determination of future concentrations in the groundwater medium that result from the transport of the radionuclide and contaminant inventory existing in the WMA C tank residuals. The working definition of protectiveness for the protection of groundwater pathway is considered achieved if the radionuclide and contaminant levels in the WMA C tank residuals do not cause groundwater concentrations to exceed maximum concentration limits at the point of calculation within 1,000 years after closure, which is assumed to begin in 2020.

**Figure D-5. Points of Calculation 100 Meters Downgradient of Waste Management Area C.**




PA = Performance Assessment WMA = Waste Management Area

**Table D-11. Width of Point of Calculation Segments 100 Meters Downgradient of Waste Management Area C.**

| Point of Calculation Segment | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| Width (m) | 28.8 | 30.5 | 30.4 | 29.6 | 27 | 34.5 | 36 | 34 | 28 |

## D4.2 NATURE AND EXTENT OF CONTAMINATION

The WMA C PA addresses the radionuclide and non-radiological contaminant inventory contained in waste residuals in tanks and ancillary equipment in WMA C at the assumed time of closure. Tank waste can be grouped into three types based on physical properties: supernate, salt, and sludge (RPP-RPT-42323). The 241-C Tank Farm contains little salt types, and with the supernate having been pumped out as part of interim stabilization, the tanks now mainly contain sludge (RPP-RPT-42323). As of the summer of 2015, all retrieval has been completed in all but three tanks.

The residual waste volume for tanks not yet retrieved is unknown; therefore, assumptions about the inventory have been made based on current threshold requirements. Most constituents' inventory uncertainties vary by a factor of 5 or less, but may vary by as much as a factor of 10 for certain constituents in tanks not yet retrieved. For tanks already retrieved, uncertainty in residual waste estimates is on the order of 20 to 30% for most constituents, assuming no additional retrieval is required.

Specific information about the residual inventory and the release of the radionuclide and non-radiological contaminant inventory from the tanks, ancillary equipment, and pipelines is presented in Section D4.1.3.

# D5.0 STOMP© SOFTWARE

STOMP© is used to solve the Richards equation (the water mass conservation equation in PNNL-12030) and the Advection-Dispersion equation (the solute mass conservation equation in PNNL-12030) that govern water flow and solute transport, respectively, under variably-saturated conditions in the vadose zone and groundwater in and around WMA C. STOMP© (PNNL-11216; PNNL-12030; PNNL-15782, "STOMP Subsurface Transport Over Multiple Phases Version 4.0 User's Guide") was selected to simulate the transport of contaminants in the vadose zone of the 100 Area because it fulfills the following specifications.

- The STOMP© simulator operational modes needed for implementation of this model are available free for government use under a limited government-use agreement.

- The STOMP© simulator solves the necessary governing equations, e.g., the Richards equation, the van Genuchten soil water retention equation, the Mualem unsaturated hydraulic conductivity equation, and the Advection-Dispersion equation.

- It is capable of directly simulating the principal FEPs that are relevant (see Section D4.1).

- The STOMP© simulator is well documented (PNNL-11216; PNNL-12030; PNNL-15782).

- The STOMP© simulator development is compliant with DOE O 414.1C, Quality Assurance requirements [PNNL-SA-54024, "Project Management Plan for Subsurface Transport Over Multiple Phases (STOMP) Software Maintenance and Development"; PNNL-SA-54022, "STOMP Software Test Plan Rev. 1.0"; PNNL-SA-54023, "STOMP Software Configuration Management Plan Rev. 1.3"; PNNL-SA-54079, "Requirements for STOMP Subsurface Transport Over Multiple Phases"].

- The STOMP© simulator is distributed with source code, enhancing transparency.

- The modeling team implementing this model has expertise in use of this simulator.

- There is an extensive history of application of STOMP© at Hanford and elsewhere including verification, validation, and benchmarking (DOE/RL-2011-50).

- Use of STOMP© is in keeping with DOE direction for simulation of vadose zone flow and transport at the Hanford Site (Letter 06-AMCP-0133, "Hanford Groundwater Modeling Integration").

The software used to implement this model and perform calculations was approved under the requirements of, and use was compliant with, PRC-PRO-IRM-309. This software is managed under the following software quality assurance documents consistent with PRC-PRO-IRM-309 that address all aspects of STOMP© usage and management: functional requirements, software management, software installation and acceptance testing and reporting, and the preparation of a requirements traceability matrix.

## D5.1 STOMP© CONTROLLED CALCULATION SOFTWARE

The following describes the STOMP© controlled calculation software.

- Software Title: STOMP-W (a scientific tool for analyzing single- and multiple-phase subsurface flow and transport using the integrated finite volume discretization technique with Newton-Raphson iteration).

- Software Version: STOMP-W was provided by Pacific Northwest National Laboratory on January 30, 2013, and was tested and approved for use by CH2M HILL Plateau Remediation Company (CHPRC) as "CHPRC Build 4."

- Hanford Information System Inventory Identification Number: 2471 (Safety Software S3, graded Level C).

## D5.2 SOFTWARE INSTALLATION AND CHECKOUT

Safety Software (CHPRC Build 4 of STOMP©) is checked out in accordance with procedures specified in the software management plan. Source or executable files are obtained from the CHPRC software owner, who maintains the configuration-managed copies in MKS Integrity™[2]. Installation tests identified in the test plan are performed. Upon confirmation of successful installation, software installation and checkout forms are required and must be approved for installations used to perform model runs. Approved users are registered in the Hanford Information System Inventory for safety software.

## D5.3 STATEMENT OF VALID SOFTWARE APPLICATION

Use of the STOMP© software for implementing the model described in this report is consistent with its intended use for CHPRC (DOE/RL-2011-50), as identified in the functional requirements document.

# D6.0 MODEL IMPLEMENTATION

The 3-D model incorporates spatial heterogeneity and temporal changes of geologic and recharge conditions, with the ability to include lateral spreading, commingling of plumes, and preferential flow. The gridding scheme and extent of the domain intend to minimize the numerical error and impact that the boundary conditions have on the model calculations in the areas of interest, i.e., the points of calculation. The discretization scheme allows the distinct representation of the different sources within WMA C such that no sources, with the exception of the pipelines, overlap one another.

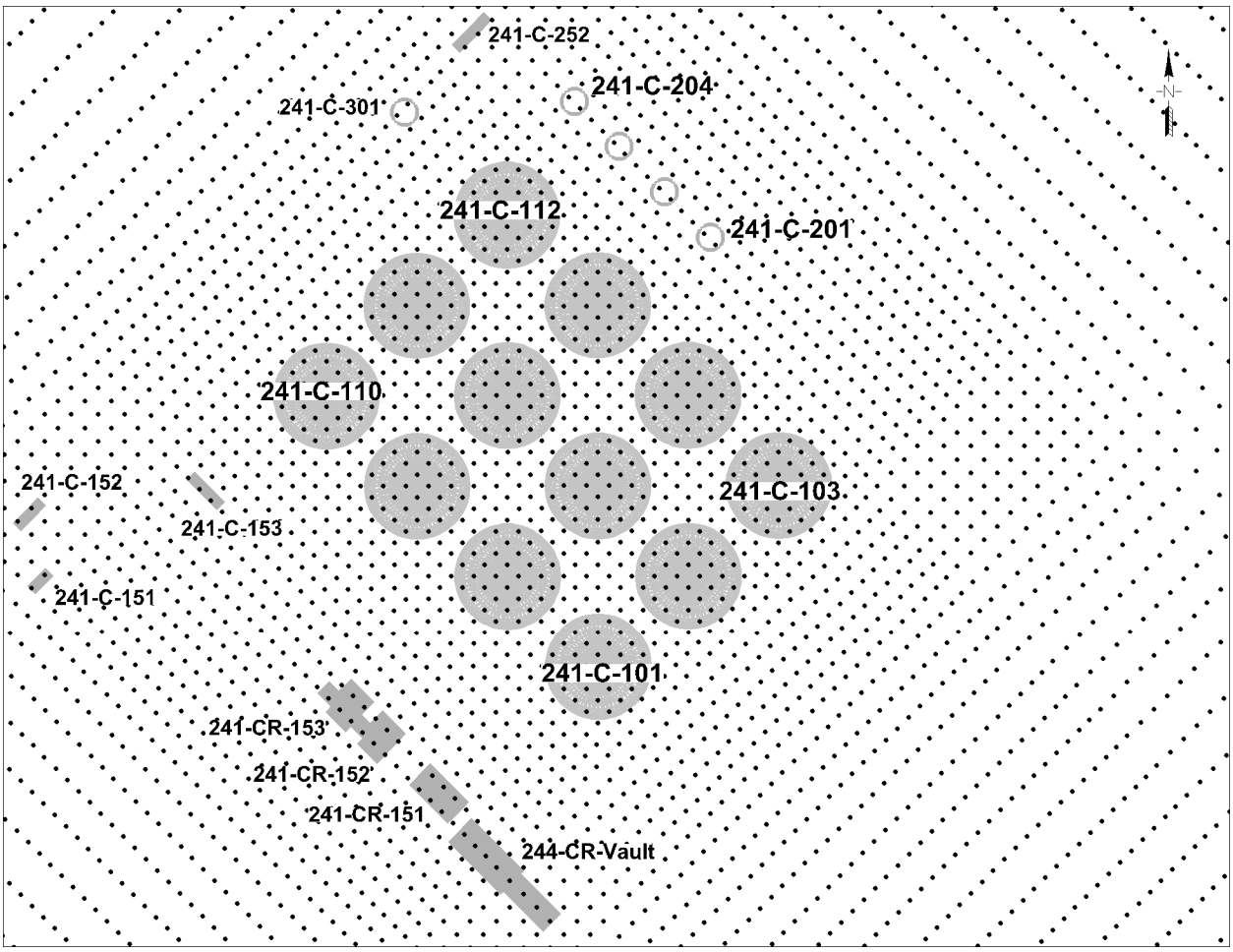
## D6.1 DISCRETIZATION

The horizontal node spacing varies between 3.0 and 20 m to optimize the discretization in the areas attempting to approximate the slopes associated with construction of WMA C and the 100-series tanks without overwhelming the available computational resources. Within the confines of WMA C, the horizontal grid cell dimensions ranged between 3 and 4 m to align the nodes with the tanks, vault, and other ancillary equipment (Figure D-6). Outside of WMA C, the grid cells expanded in size such that no adjoining grids differed in length by more than a factor of 1.5. Table D-12 presents the pattern of the spacing of the finite difference cells. Vertical spacing in the vadose zone ranged between 1 and 1.25 m, except around the water table where

[2] MKS Integrity is a trademark of MKS, Incorporated.

the spacing decreased to 0.5 m to capture the impact of the capillary fringe above the water table (Figure D-7).

**Figure D-6. Horizontal Alignment of Three-Dimensional Model Computational Nodes with Waste Management Area C Single-Shell Tanks, 241-C-301 Catch Tank, 244-CR-Vault, and Other Waste Management Area C Ancillary Equipment.**




The total number of nodes in the modeled rectangular prism equaled 736,653. During the pre-operational phase, the engineered structures were non-existent. Hence, the number of active nodes equaled 640,565 with 96,088 inactive. During the operational and post-closure phases, WMA C backfill replaced Hanford H1 Gravel, and the number of active nodes equaled 637,543 with 99,110 inactive. The increase in inactive nodes is attributed to the inactivation of the tank and ancillary equipment nodes within the WMA C excavation. Figure D-8 shows the relative change in moisture content from the pre-Hanford steady-state condition at the four vertical boundaries of the model at three times of interest: at Year 2020, at the end of the WMA C operational period; at Year 2520, at the end of the design life of the WMA C surface barrier; and at Year 3020, which is the end of the compliance time frame and when the system has reacquired or nearly reacquired steady-state conditions. In general, the effects are contained within a relatively small segment along the boundaries near the water table and appear to be minor (less

than $1.0 \times 10^{-5}$). The changes in moisture content are negligibly small in magnitude, which indicates that the boundaries are far enough removed from the area of interest to avoid unintentional impacts to the model solution. Consequently, they are not considered to affect adversely the evaluation of radionuclide transport and groundwater impacts associated with the radionuclide and non-radiological contaminant inventory in WMA C.

**Table D-12. Horizontal and Vertical Spacing of the Finite Difference Cells in the Three-Dimensional Waste Management Area C Flow and Transport Model Domain.**

| | | | | | | |
|---|---|---|---|---|---|---|
| West to East Spacing; Southeastern Boundary Coordinate = 574656 m (Lambert Coordinate System[1] Easting) | | | | | | |
| 4@ 20.00 m | 2@ 16.00 m | 2@ 12.00 m | 2@ 10.00 m | 2@ 8.00 m | 2@ 6.00 m | 7@ 4.50 m |
| 1@ 3.70 m | 6@ 3.80 m | 2@ 3.85 m | 14@ 3.80 m | 2@ 3.85 m | 6@ 3.80 m | 1@ 3.00 m |
| 7@ 4.50 m | 3@ 6.00 m | 4@ 8.00 m | 10@ 10.00 m | 2@ 12.00 m | 1@ 16.00 m | 9@ 20.00 m |
| South to North Spacing; Southwestern Boundary Coordinate = 136454 m (Lambert Coordinate System[1] Northing) | | | | | | |
| 8@ 20.00 m | 3@ 16.00 m | 2@ 12.00 m | 4@ 10.00 m | 3@ 8.00 m | 2@ 6.00 m | 11@ 4.50 m |
| 4@ 4.00 m | 8@ 3.80 m | 1@ 3.90 m | 15@ 3.80 m | 1@ 3.00 m | 11@ 4.50 m | 2@ 6.00 m |
| 2@ 8.00 m | 3@ 10.00 m | 3@ 12.00 m | 4@ 16.00 m | 6@ 20.00 m | | |
| Vertical Spacing; Bottom Elevation = 95 m (NAVD88[2]) | | | | | | |
| 1@ 5.00 m | 2@ 4.00 m | 1@ 3.00 m | 1@ 2.00 m | 2@ 1.50 m | 1@ 1.25 m | 1@ 1.00 m |
| 1@ 0.75 m | 3@ 0.50 m | 1@ 0.75 m | 12@ 1.00 m | 40@ 1.25 m | 4@ 1.00 m | 19@ 1.25 m |

[1] NOAA Manual NOS NGS 5, State Plane Coordinate System of 1983.

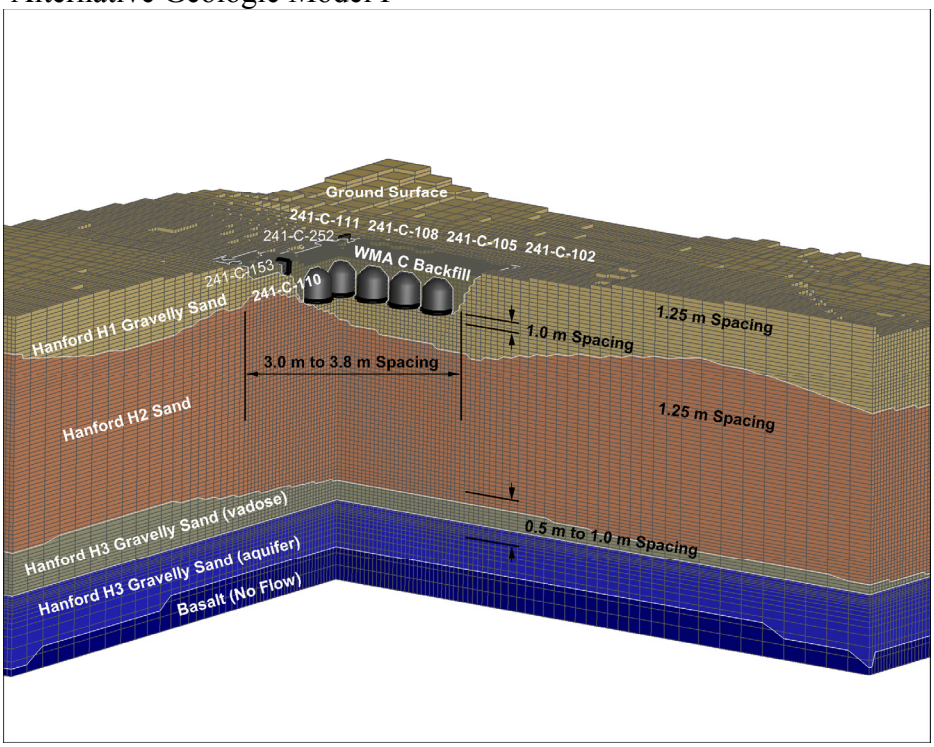
[2] North American Vertical Datum of 1988, National Geodetic Survey, U.S. Department of Commerce.

Note: The sequences read left to right. The number preceding the "@" symbol indicates the number of columns (west to east), rows (south to north), or vertical layers (bottom to top) that have the length indicated by the distance following it.

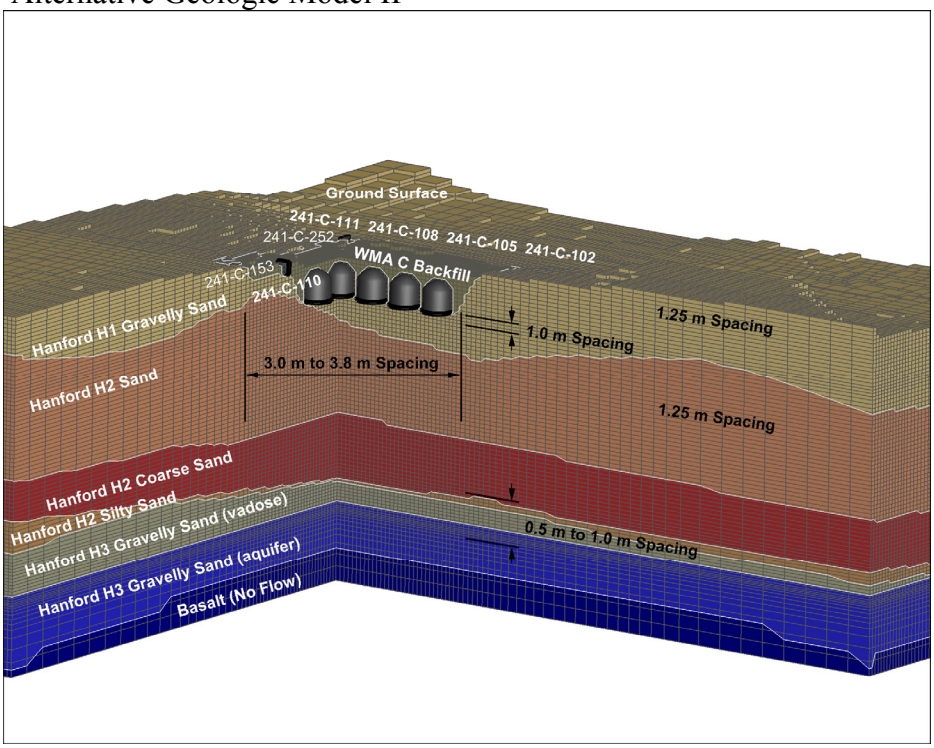
For the base case, the vadose Peclet number equaled approximately 6 (1.25 m / 0.20 m), with an imposed Courant (number) restriction of 10. While the value of 1 for these numbers is often considered ideal, it has been demonstrated that acceptably small numerical oscillations may be obtained with local Peclet numbers as high as 10 (Computational Methods in Subsurface Flow [Huyakorn and Pinder 1983]). It is difficult to assess numerical impacts on the solution caused by the grid spacing, apart from consideration of the Peclet criteria. The total number of nodes in the model is close to the maximum that the computer hardware and solver can accommodate, so evaluating solution stability through grid refinement is not feasible. Other comparably-scaled models indicate that the WMA C RCA and PA grid size and spacing is sufficient. DOE/EIS-0391, "Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington," Appendix N indicates that the horizontal grid size and spacing of 5 m within WMA C, and vertical spacing of 2 m, are small enough in that 3-D model to provide accurate simulation of flow and transport.

**Figure D-7. Horizontal and Vertical Alignment and Distribution of Waste Management Area C Performance Assessment and RCRA Closure Analysis Three-Dimensional Model Computational Nodes.**

a) Alternative Geologic Model I

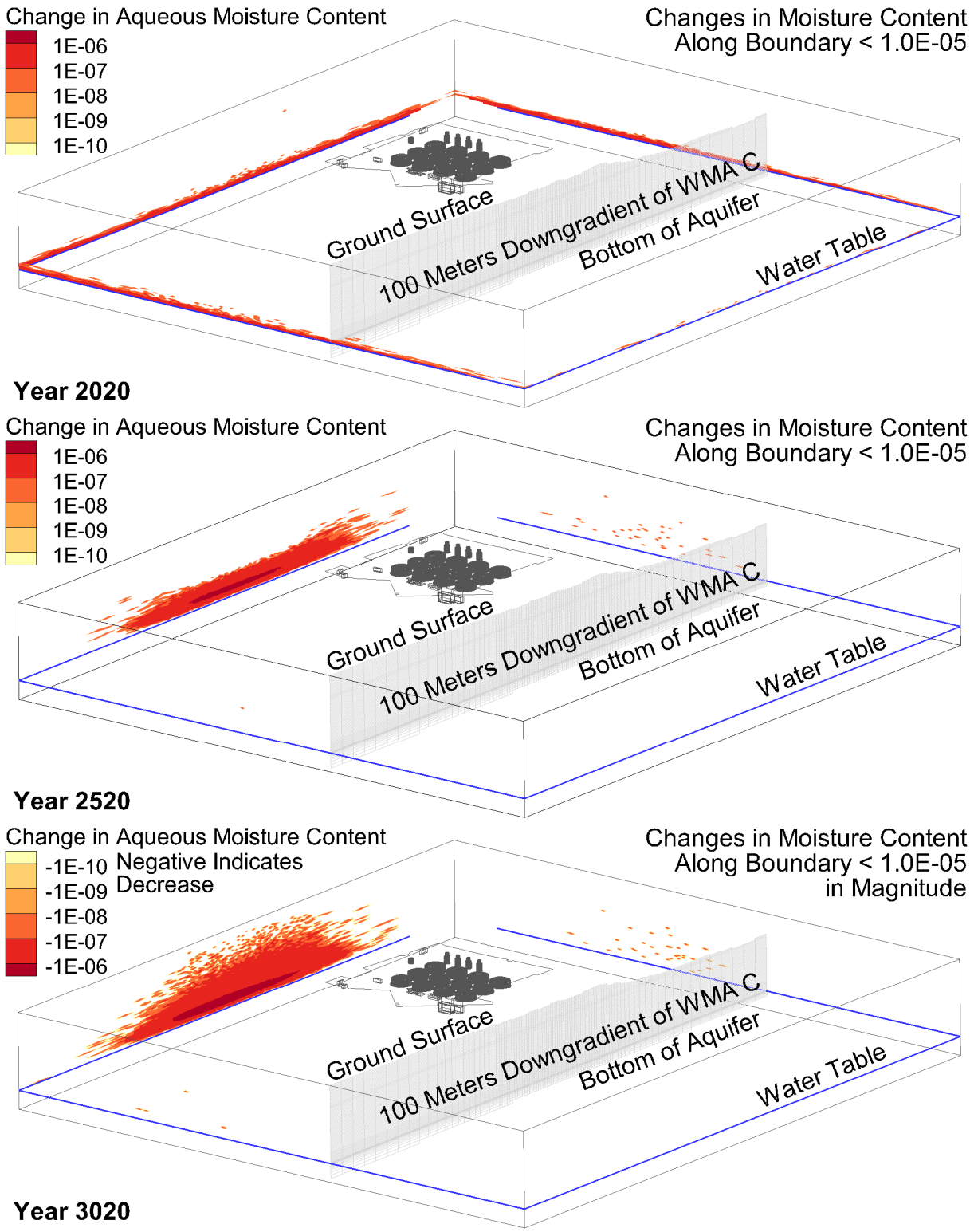



b) Alternative Geologic Model II




RCRA = Resource Conservation and Recovery Act of 1976 WMA = Waste Management Area

**Figure D-8. Relative Change in Moisture Content from the Pre-Hanford Steady State Condition at the Four Vertical Boundaries of the Model at Three Times of Interest: Year 2020, Year 2520, and Year 3020.**




WMA = Waste Management Area

Figure D-9 shows a comparison of the $^{99}$Tc concentration at the nine points of calculation located 100 m downgradient between the base case dispersivity values and dispersivity values intended to test numerical dispersion (Table D-13). These values represent the approximate maximum values associated with the different HSUs. The perceptible increase in maximum concentration observed in the base case results, compared to the numerical dispersion test case results, indicates that the grid is sized adequately such that numerical dispersion is not unduly affecting or obscuring the model computations.

The vertical Courant numbers in the vadose zone tend to be small (e.g., 10 yr × 0.0035 m/yr recharge / 0.05 moisture content / 1 m grid spacing = 0.7), but the horizontal Courant numbers become large near the water table and capillary fringe where the velocity approaches 400 m/yr. These few places impose an impractical limit on the time step while the Courant number remains small elsewhere. Table D-14 presents the results of a Courant criteria evaluation, which evaluated the maximum concentration of $^{99}$Tc at the points of calculation associated with a subset of the WMA C sources: tank 241-C-105, tank 241-C-203, and the pipelines contained in a single STOMP© input file. The negligible differences in the results indicate that an overly strict Courant restriction does not affect the solution and appears to be unwarranted, especially considering the improved efficiency in solution time when the Courant restriction is relaxed to 10. These evaluations indicate that the grid is adequately discretized.

## D6.2 PARAMETERIZATION

Table D-15 presents a summary of the model parameters and values assigned, including boundary and initial conditions, and identifies the section where the data sources and data quality are discussed. Parameters and values that are already tabularized in the subsections of Section D4.1 are simply referenced by the applicable table number.

## D6.3 MODELING STAGES

The WMA C tank residual simulations using STOMP© require running three separate stages of the model in sequence. The first stage is a long-term transient simulation of only water flow resulting from historic recharge conditions. This stage is needed to obtain near steady-state soil moisture conditions throughout the model domain at the start time for the second stage. The second stage begins with the initial moisture distribution provided from the first stage, and simulates only water flow during the operational period of WMA C, which is the time between the construction of WMA C in 1945 and its assumed closure in 2020. The use of a previously simulated condition as a starting point for another simulation is referred to as a “restart” condition in STOMP©. The contaminant transport stage (stage 3) begins with the moisture distribution provided from the second stage, and simulates flow and transport for 10,000 years, from 2020 to 12020. Each tank, ancillary equipment, and pipeline residual source is simulated individually. The groundwater concentrations resulting from each source are summed according to the principle of superposition to produce time series concentration breakthrough curves at the points of calculation identified in Section D4.1.8. The principle of superposition also applies to the spatial distribution of the pore water concentrations in the vadose zone resulting from each

source. The superposition and summing of the concentration results occurs outside of STOMP©, and is not addressed in this appendix.

## D6.4 CALIBRATION

DOE G 435.1-1 and Federal risk assessment guidelines [e.g., EPA/540/1-89/002, Risk Assessment Guidance for Superfund Volume I Human Health Evaluation Manual (Part A) Interim Final] acknowledge that the assessment of uncertainties associated with how well models approximate actual relationships and conditions in the field (i.e., field validation) is desirable, but that field data for model calibration is generally not available and/or attainable for vadose zone models. No specific effort to calibrate the WMA C RCA and PA flow and transport model has been made; however, a comparison of measured and simulated water contents was carried out for this analysis, and parameters were adjusted accordingly (Appendix B).

## D6.5 SCREENING

The screening analysis uses the 3-D model to determine the maximum $K_d$ value of contaminants in the WMA C tank residuals that reach the water table in 1,000 and 10,000 years. The purpose of this screening phase was to streamline the RCA and PA modeling by identifying those contaminants sufficiently mobile to impact groundwater during the compliance, sensitivity and uncertainty analysis time frames. This analysis was performed to considerably reduce the computation time required to conduct the RCA and PA modeling by limiting the number of radionuclides evaluated in the model. According to the facility performance requirements in DOE O 435.1, performance objectives must be met for 1,000 years, and post-closure evaluations must extend out to 10,000 years to clarify long-term impacts. Given the combination of low infiltration rates and a deep vadose zone below the facility, it is evident that contaminants that are highly sorptive on the soils may not reach the water table within 10,000 years,[3] even for combinations of input parameters that are highly conservative. If the travel time exceeds 10,000 years, even for conservative combinations of input parameters, the contaminant will not affect any of the calculated results in the RCA and PA, and can reasonably be screened from the analysis.

[3] In this analysis, the travel time to the aquifer is defined as the time to first arrival of the contaminant at the aquifer, taking into account advection, diffusion, and dispersion. This metric will tend to screen fewer contaminants than using the arrival of the peak concentration.

**Figure D-9. Comparison of the Technetium-99 Concentration at the Nine Points of Calculation Located 100 Meters Downgradient between the Base Case Dispersivity Values and the Numerical Dispersion Test Case Dispersivity Values.**

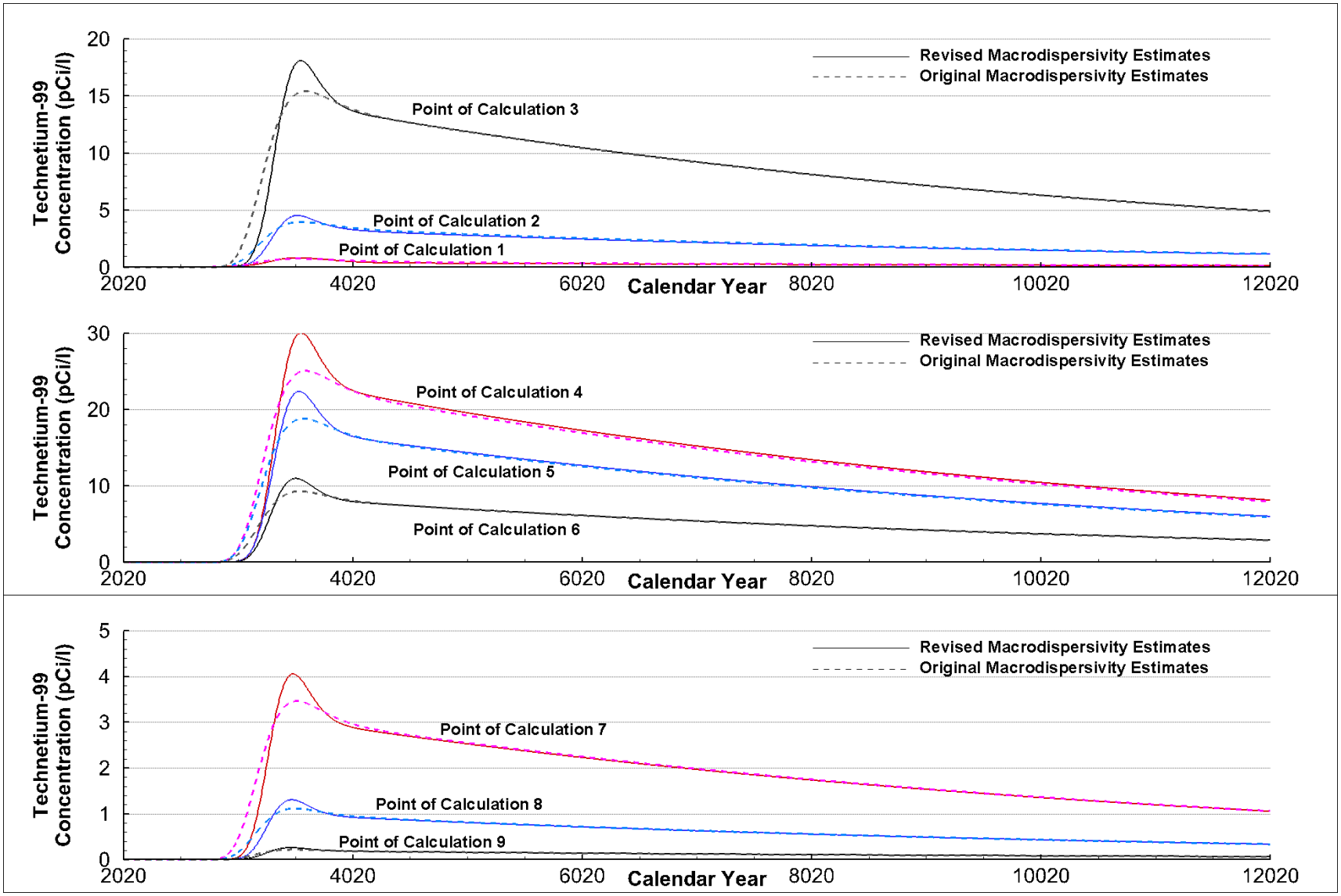


**Table D-13. Waste Management Area C RCRA Closure Analysis and Performance Assessment Vadose Zone Dispersivity Values and Numerical Dispersion Evaluation.**

| Hydrostratigraphic Unit | Numerical Dispersion Test Case Longitudinal Macrodispersivity (cm) | Base Case Longitudinal Macrodispersivity (cm) |
|---|---|---|
| Backfill | 150 | 20 |
| Hanford H1 | 100 | 20 |
| Hanford H2 | 200 | 25 |
| Hanford H3 | 100 | 20 |
| **Point of Calculation 100 meters downgradient of Waste Management Area C** | **Maximum Concentration (pCi/L)** | **Maximum Concentration (pCi/L)** |
| 1 | 0.80 | 0.83 |
| 2 | 4.0 | 4.5 |
| 3 | 15 | 18 |
| 4 | 25 | 30 |
| 5 | 19 | 22 |
| 6 | 9.2 | 11 |
| 7 | 3.4 | 4.1 |
| 8 | 1.1 | 1.3 |
| 9 | 0.22 | 0.26 |

RCRA = Resource Conservation and Recovery Act of 1976

The specific methodology, basis for the parameters selected, and key assumptions used in the screening phase analysis are described in detail in Section 7.3.2.3 Groundwater Pathway Screening Analysis Methodology. The screening analysis includes vadose zone hydraulic property values and recharge rates developed for the uncertainty analysis detailed in Section 8.1.4 of RPP-ENV-58782, "Performance Assessment of Waste Management Area C, Hanford Site, Washington." In particular, the screening analysis applies the maximum recharge rates associated with each period for each surface type (Table D-16), assigns the vadose zone hydraulic properties that produce the fastest pore water velocity for each HSU as determined for the uncertainty analysis (Table D-17), and implements an advection release function for the radionuclides. Other parameters (e.g., dispersivity, distribution coefficient gravel correction, and aquifer hydraulic properties) remain the same as the base case parameters. The use of these parameter values prevents the occurrence of a false negative, i.e., that a radionuclide or non-radioactive contaminant that could impact groundwater within the 1,000- or 10,000-year simulation time frames is screened from the fate and transport evaluations. Model results indicating the time of first arrival at the water table for contaminants with distribution coefficients ranging between 0.1 and 2.0 mL/g are summarized in Table D-18.

**Table D-14. Waste Management Area C RCRA Closure Analysis and Performance Assessment Vadose Zone Courant Criteria and Numerical Dispersion Evaluation.**

| | Numerical Dispersion Test Case Courant Number = 1 (pCi/L) | | | Base Case Courant Number = 10 (pCi/L) | | |
|---|---|---|---|---|---|---|
| Simulation Duration and Time to Complete | 4,000 years completed in 112.51 hours | | | 10,000 years completed in 32.08 hours | | |
| Point of Calculation 100 meters downgradient of Waste Management Area C | Maximum Concentration (pCi/L) | | | Maximum Concentration (pCi/L) | | |
| | **Source** | | | **Source** | | |
| | **241-C-105** | **241-C-203** | **Pipelines** | **241-C-105** | **241-C-203** | **Pipelines** |
| 1 | 0.02 | 0 | 0.36 | 0.02 | 0 | 0.36 |
| 2 | 0.86 | 0 | 0.53 | 0.86 | 0 | 0.53 |
| 3 | 10 | 0.000003 | 0.74 | 10 | 0.000003 | 0.73 |
| 4 | 21 | 0.0001 | 0.94 | 21 | 0.0001 | 0.92 |
| 5 | 13 | 0.002 | 1.0 | 13 | 0.002 | 1.0 |
| 6 | 4.1 | 0.006 | 0.74 | 4.1 | 0.006 | 0.73 |
| 7 | 0.92 | 0.007 | 0.34 | 0.91 | 0.007 | 0.34 |
| 8 | 0.22 | 0.004 | 0.12 | 0.22 | 0.004 | 0.12 |
| 9 | 0.03 | 0.001 | 0.03 | 0.03 | 0.001 | 0.03 |

RCRA = Resource Conservation and Recovery Act of 1976

The results of the screening analysis indicate that, even when using parameter estimates biased to produce the greatest pore water velocity in the vadose zone, contaminants with a $K_d$ in the fine fraction > 0.15 mL/g do not reach groundwater within the 1,000-year compliance time frame, and radionuclides with a $K_d$ > 1.5 mL/g do not reach groundwater within the 10,000-year post-compliance period (Table D-18). The screening evaluation helps in reducing the number of radionuclides to be evaluated using 3-D modeling analysis.

Of the list of radionuclides in the WMA C residuals inventory and on the basis of the results of the screening phase, only 12 (Table D-19) appear to be sufficiently mobile to arrive at groundwater during the compliance period, with 6 others sufficiently mobile to arrive at groundwater during the sensitivity and uncertainty analysis time frame. During the sensitivity and uncertainty analysis time frame, even some contaminants that undergo appreciable retardation in the vadose zone, e.g., $^{129}I$, $^{14}C$, and $^{238}U$, are sufficiently mobile to arrive at groundwater within the sensitivity and uncertainty analysis time frame. The other contaminants in the WMA C residual inventory are not included in further groundwater impact analysis because they do not reach the water table within the evaluation time frames.

**Table D-15. Summary of Key Elements and Base Case Parameters Associated with Site-Specific Model Components for Waste Management Area C (The basis for the elements and parameter selection provided in the individual model components sections). (2 sheets)**

| | |
|---|---|
| Model Domain and Boundary Conditions | Rectangular Prism: 737. 9 m (2,421 ft) × 795. 3 m (2,609 ft) × 116 m (381 ft)<br><br>Prescribed flux across the top (Recharge); no-flow along vertical side boundaries in the vadose zone; prescribed flux and head along the upgradient and downgradient vertical side boundaries in the aquifer, respectively; no-flow along the bottom of the model (aquifer).<br><br>The prescribed volumetric water flux boundary condition is calculated to maintain mass conservation in the aquifer independent of recharge. |
| Geologic Setting | The Waste Management Area (WMA) C cross section includes the following anthropogenic or natural units that occur from surface to groundwater (RPP-RPT-56356, "Development of Alternative Digital Geologic Models of Waste Management Area C," Rev. 0):<br>• WMA C Backfill<br>• Hanford H1 (gravel-dominated, generally identified as gravel or very coarse sand)<br>• Hanford H2 Sand (sand-dominated facies generally identified as fining upward sequences of gravel, sandy/gravel to sand to very fine sand)<br>• Hanford H3 (coarse-grained open framework gravel to sandy gravel; in the vicinity of WMA C is often referred to as undifferentiated H3 gravels, Cold Creek, and Ringold)<br>• In Alternative Geologic Model II, the Hanford H2 Sand includes following two additional subunits<br>  o Hanford H2 Coarse (gravel/coarse-grained facies that underlies the H2 fines)<br>  o Hanford H2 Silty Sand – (a silty sand unit that is only observed in deep groundwater wells and a mappable unit may not be readily identified) |
| Groundwater Domain and Characteristics | WMA C post-closure water table elevation ~119.5 m NAVD88 and average hydraulic gradient ~0.00001 m/m<br>Aquifer area along northwest cross section boundary = 6,151.04 $m^2$<br>Aquifer area along southeast cross section boundary = 13,997.55 $m^2$<br>Average aquifer area along all aquifer cross sections = 9,439.56 $m^2$<br>Prescribed flux along northwest cross section boundary (saturated K = 11,000 m/d);<br>11,000 m/d × 0.2000E-04 × 365.25 d/yr = 0.80355E+02 m/yr; 0.0.80355E+02 m/yr × 9,439.56 $m^2$ / 6,151.04 $m^2$ = 0.12331E+03 m/yr<br>Prescribed head along southeast cross section boundary = 119.49 m<br>Groundwater thickness is ~12 m (39 ft) in the aquifer; Groundwater concentrations evaluated for upper 5 m (16 ft) of the aquifer (rationale for aquifer depth presented in section D4.1.8 Point of Calculation, Protectiveness Metric, and Time Frame Considerations) |
| Source Term/ Inventory | WMA C Base Case inventory presented in Table D-3.<br><br>Diffusion controlled release from the grouted tanks and advection controlled release from the pipelines along with equilibrium sorption-desorption processes (i.e., $K_d$ control). |

**Table D-15. Summary of Key Elements and Base Case Parameters Associated with Site-Specific Model Components for Waste Management Area C (The basis for the elements and parameter selection provided in the individual model components sections). (2 sheets)**

| | | | | | |
|---|---|---|---|---|---|
| Vadose Zone Hydrogeology and Fluid Transport | WMA C Base Case hydrogeologic properties presented in Table D-4.<br><br>Aquifer Hydraulic Conductivity Horizontal to Vertical Anisotropy **10:1**; Vadose Zone Hydraulic Conductivity Anisotropy allowed to vary as a function of the moisture content in accordance with the Polmann model ("Application of Stochastic Methods to Transient Flow and Transport in Heterogeneous Unsaturated Soils" [Polmann 1990]).<br><br>Aquifer and Vadose Zone Dispersion Horizontal to Vertical Anisotropy **10:1**.<br><br>$K_d$-control for radionuclide transport in the vadose zone and groundwater. | | | | |
| Recharge | Phase | Recharge on Surface (mm/yr [in./yr]) | | | |
| | | Natural Vegetation | Tank Farm Disturbed Surface | Non-Tank Farm Disturbed Surface* | Surface Barrier |
| | Pre-operations | 3.5 [0.14] | NP | NP | NP |
| | Operations | 3.5 [0.14] | 100 [3.9] | 22 [0.87]/63 [2.5] | NP |
| | First 100 years Post-Closure | 3.5 [0.14] | NP | 3.5 [0.14] | 0.5 [0.02] |
| | Early Post-Closure (100 to 500 years) | 3.5 [0.14] | NP | 3.5 [0.14] | 0.5 [0.02] |
| | Late Post-Closure (after 500 years) | 3.5 [0.14] | NP | 3.5 [0.14] | 3.5 [0.14] |
| | * Disturbed areas that allow vegetation are assigned 22 mm/yr [0.87 in./yr]. Disturbed areas that are reworked such that vegetation does not grow are assigned 63 mm/yr [2.5 in./yr]. | | | | |
| Sorption Characteristics | WMA C Base Case $K_d$ values (partition coefficients) presented in Table 7-10. | | | | |

*Applies to all subfacies of this unit.

NAVD88 = North American Vertical Datum of 1988, National Geodetic Survey, U.S. Department of Commerce.

NP = Not present

**Table D-16. van Genuchten-Mualem Parameters Associated with the Maximum Pore Water Velocity at Specific Tension Ranges Based on Cumulative Distribution Functions.**

| Strata | $\theta_s$ | $\theta_r$ | α (1/cm) | n | Fitted $K_s$ (cm/s) |
|---|---|---|---|---|---|
| Hanford H1 (gravelly sand) | 0.100 | 0.0006 | 0.0190 | 1.789 | 5.07E-04 |
| Hanford H2 (sand-dominated) | 0.239 | 0.0006 | 0.0743 | 2.042 | 8.84E-04 |
| Hanford H3 (gravelly sand) | 0.100 | 0.0006 | 0.0190 | 1.789 | 5.07E-04 |
| Backfill | 0.100 | 0.0003 | 0.0116 | 1.601 | 9.42E-05 |
| Aquifer | 0.20 | 0.016 | 0.0190 | 1.789 | 3.49E-03* |

* The vertical aquifer hydraulic conductivity value is determined from the horizontal hydraulic conductivity value and the aquifer anisotropy.

**Table D-17. Maximum Net Infiltration (Recharge) Estimates Used in the Screening Analysis for Pre-Construction Period, Operational Period, and Post-Closure of Waste Management Area C (See Section 8.2.4).**

| Surface Status | Pre-Construction (mm/yr) | Operational Period (mm/yr) | Post-Closure | |
|---|---|---|---|---|
| | | | Until End of Barrier Design Life (500 yr after closure) (mm/yr) | After End of Barrier Design Life (mm/yr) |
| Waste Management Area C | 5.2 | 140 | 1.0 | 5.2 |
| Undisturbed | 5.2 | 5.2 | 5.2 | 5.2 |
| Disturbed | 5.2 | 22 | 5.2 | 5.2 |
| Reworked | 5.2 | 63 | 5.2 | 5.2 |
| Waste Management Area A | 5.2 | 140 | 1.0 | 5.2 |

## D7.0 MODEL LIMITATIONS

The evaluation of WMA C RCA and PA tank residuals model limitations must consider two types of limitations: (1) the limitations associated with the model that affect the results, and (2) the limitations associated with the applicability of the model results outside the model's intended purpose. Model limitations primarily depend on the inherent capabilities of the model; the scale and boundary conditions of the model domain; assumptions used in the model design; the extent to which the model input parameters represent actual, bounding, or limiting conditions; and the ability of the model and code to represent individual and combinations of dynamic FEPs. Limitations associated with the applicability of the model results concern the

extent to which the model results are relevant and applicable to model conditions, parameters, or assumptions that differ from those of the specific modeling purpose and objectives (e.g., attempting to apply the tank residuals model to the evaluation of past UPRs).

**Table D-18. First-Arrival Time (in Calendar Year) of Radionuclides for Various $K_d$ Values Based on Screening Analysis Using Subsurface Transport Over Multiple Phases.**

| Contaminant $K_d$ (mL/g) | | | | Calendar Year of First Arrival at the Water Table | Time of Arrival, Post-Closure (Closure occurring in 2020) Years |
|---|---|---|---|---|---|
| Fine Fraction | Backfill | Hanford H1 and H3 | Hanford H2 | | |
| 0.10 | 0.05 | 0.06 | 0.08 | 2517.5 | 497.5 |
| 0.15 | 0.07 | 0.09 | 0.12 | 3022.5 | 1,002.5 |
| 0.20 | 0.09 | 0.12 | 0.16 | 3505 | 1,485 |
| 0.25 | 0.12 | 0.15 | 0.20 | 3900 | 1,880 |
| 0.30 | 0.14 | 0.17 | 0.24 | 4210 | 2,190 |
| 0.40 | 0.18 | 0.23 | 0.32 | 4840 | 2,820 |
| 0.60 | 0.28 | 0.35 | 0.48 | 6110 | 4,090 |
| 0.80 | 0.37 | 0.46 | 0.64 | 7390 | 5,370 |
| 1.0 | 0.46 | 0.58 | 0.80 | 8680 | 6,660 |
| 1.5 | 0.69 | 0.87 | 1.2 | 11900 | 9,880 |
| 2.0 | 0.92 | 1.2 | 1.6 | >12020 | >10,000 |

DOE/RL-2011-50 identifies generalized model and code limitations associated with the relevant FEPs for the 200 Areas vadose zone. Other limitations specific to WMA C were considered during FEPs process working sessions conducted from 2009 to 2011, and additional discussions with regulators in 2013 and 2014. The description of the limitations involves a summary of those FEPs considered and not considered in the model, along with possible consequences of their omission on the model results. The limitations also address or involve uncertainties in the model results. Some specific examples of limitations in the applicability of the WMA C RCA and PA tank residuals vadose zone model results include the following.

- Domain and scale limitations:
  - Results represent incremental groundwater contamination from WMA C residuals and do not include interaction with earlier WMA C waste releases or contamination from other sources
  - Applicability of model results limited to releases containing no accompanying water discharges within the model domain.

- Geologic setting limitations:
  - Applicability of model results limited to evaluations with a comparable stratigraphy to WMA C.
- Source-term limitations:
  - Applicability of model results limited to source-term components of finite or estimable volume within the model domain
  - Applicability of model results limited to contaminant release and retardation mechanisms based on the assumption of diffusion control or reversible equilibrium conditions.
- Groundwater domain limitations:
  - Applicability of model results limited to sites with dilution effects comparable to WMA C aquifer hydrologic properties.
- Hydrogeologic parameter limitations:
  - Applicability of WMA C model results limited to evaluations where flow and transport are dominated by unsaturated porous media continuum flow, with comparable or acceptably bounding moisture content profiles
  - Applicability of WMA C model results limited to evaluations where hydrogeologic parameter values remain constant (unchanging) over time
  - Applicability of model results limited to sites where preferential pathways (e.g., discordant voids such as well seals/casing, clastic dikes, and sills) are not considered important.
- Recharge limitations:
  - Applicability of model results limited to conditions similar to or bounded by the values of recharge rates evaluated in the WMA C PA.
- Geochemical limitations:
  - Applicability of model results limited to radionuclides and non-radiological contaminants exhibiting linear isotherm behavior for contaminant release and attenuation, which neglect surface complexation and precipitation
  - Applicability of model results limited to the radionuclides and non-radiological contaminants for which the assumption applies that the adsorption $K_d$ and desorption $K_d$ values are equivalent

– Applicability of model results limited to radionuclides and non-radiological contaminants with transport characteristics similar to, or within the range of, evaluated $K_d$ values.

**Table D-19. Radionuclides that Arrive at the Water Table within the 1,000-Year Compliance and 10,000-Year Sensitivity and Uncertainty Time Frame Based on the Screening Analysis Conducted Using Subsurface Transport Over Multiple Phases.**

| Contaminant | $K_d$ [Fine Fraction] (mL/g) | $K_d$ [Backfill] (mL/g) | $K_d$ [Hanford H1 and H3] (mL/g) | $K_d$ [Hanford H2] (mL/g) |
|---|---|---|---|---|
| Radionuclides and non-radiological contaminants that may arrive at the water table within 1,000 years | | | | |
| CN | 0 | 0 | 0 | 0 |
| Co/Co-60 | 0 | 0 | 0 | 0 |
| Cr | 0 | 0 | 0 | 0 |
| F | 0 | 0 | 0 | 0 |
| H-3 | 0 | 0 | 0 | 0 |
| Hg | 0 | 0 | 0 | 0 |
| Nb-93m | 0 | 0 | 0 | 0 |
| $NO_2$ | 0 | 0 | 0 | 0 |
| $NO_3$ | 0 | 0 | 0 | 0 |
| Rn-222 | 0 | 0 | 0 | 0 |
| Tc-99 | 0 | 0 | 0 | 0 |
| Se/Se-79 | 0.1 | 0.05 | 0.06 | 0.08 |
| Radionuclides and non-radiological contaminants that may arrive at the water table within 10,000 years | | | | |
| I-129 | 0.2 | 0.09 | 0.12 | 0.16 |
| Sn/Sn-126 | 0.5 | 0.23 | 0.29 | 0.40 |
| U-238 | 0.6 | 0.28 | 0.35 | 0.48 |
| U Total | 0.6 | 0.28 | 0.35 | 0.48 |
| C-14 | 1.0 | 0.46 | 0.58 | 0.80 |
| Tri-butyl Phosphate | 1.89 | 0.87 | 1.1 | 1.5 |

For the purposes of establishing that the requirements of DOE O 435.1 to protect the public and environment from exposure to radiation from radioactive materials are being met, these limitations appear to be acceptable because the results represent reasonable (upper) bounding or limiting conditions, or the risk implications of the results are not sensitive to the limitations apart from those identified through the sensitivity analysis (DOE/RL-2011-50; Section 9).

## D8.0 MODEL CONFIGURATION MANAGEMENT

Consistent with the requirements of CHPRC-00189, "CH2M Hill Plateau Remediation Company Environmental Quality Assurance Program Plan," Revision 9, all inputs and outputs for the development of WMA C RCA and PA models are committed to the Environmental Model Management Archive (EMMA) to maintain and preserve configuration managed models. Basis information (that information collected to form the basis for model input parameterization) is also stored in the EMMA for traceability purposes.

The STOMP© software is used to implement the models collectively described in this report. These models are managed as discussed in Section 11.2.1. Safety Software (CHPRC Build 4 of STOMP©) is checked out in accordance with procedures specified in CHPRC-00176, "STOMP Software Management Plan." Source or executable files are obtained from the CHPRC software owner, who maintains the configuration-managed copies in MKS Integrity™. Installation tests identified in CHPRC-00211, "STOMP Software Test Plan" are performed and successful installation confirmed, and software installation and checkout forms (see Appendix A) are required and must be approved for installations used to perform model runs. Approved users are registered in the Hanford Information System Inventory for Safety Software.

Use of the STOMP© software for implementing the model described in this report is consistent with its intended use for CHPRC, as identified in CHPRC-00222, "STOMP Functional Requirement Document."

## D9.0 MODEL APPLICATION

The STOMP© simulation results developed from this modeling effort are recommended for use in the WMA C RCA and PA residual waste evaluation. These results provide adequate confidence that the radioactive waste management requirements of DOE O 435.1 are being met. The activities associated with the disposition of the tank, ancillary equipment, and pipeline residual waste of WMA C are being systematically planned, documented, executed, and evaluated. These activities appear sufficient to protect the environment and the public from exposure to radiation from radioactive materials per the requirements contained in DOE O 5400.1, General Environmental Protection Program and DOE O 5400.5, Radiation Protection of the Public and the Environment. The results also indicate that any eventual groundwater impacts will comply with applicable Federal, State, and local laws and regulations.

The WMA C RCA and PA tank residuals model represents a closure condition, and would therefore need to be evaluated for applying this model to other conditions, such as in the evaluation of past releases. In addition, the effects of preferential pathways or other phenomena that direct or deflect transport may become important considerations because of the enhanced net infiltration of precipitation through the gravel surface and the planned and unplanned anthropogenic releases of water.

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# OTHER SUPPORTING RISK INFORMATION

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# APPENDIX E

## OTHER SUPPORTING RISK INFORMATION

Tables E-1 through E-11 provide additional risk management information related to residual concentrations of non-radiological contaminants for tanks with post-retrieval samples (241-C-103, 241-C-104, 241-C-106, 241-C-108, 241-C-109, 241-C-110, 241-C-201, 241-C-202, 241-C-203, and 241-C-204) and ancillary equipment. Non-radiological contaminants identified in this comparison are from the Best-Basis Inventory (BBI) and RPP-23403, "Single-Shell Tank Component Closure Data Quality Objectives"; primary analytes and required organics are evaluated. Residual concentrations for each tank, and an average of retrieved tank concentrations for ancillary equipment, were compared against the Washington Administrative Code 173-340, "Model Toxics Control Act – Cleanup" cleanup levels.

Tables E-12 through E-17 provide additional risk management information related to residual concentrations for non-radiological contaminants for tanks without post-retrieval samples (unretrieved tanks 241-C-101, 241-C-102, 241-C-105, 241-C-107, 241-C-111, and 241-C-112). Non-radiological contaminants identified in this comparison are from the BBI. Residual concentration for each tank was compared against Washington Administrative Code 173-340 cleanup levels.

Table E-18 provides information on background concentrations at the Hanford Site that have been developed for selected constituents. This is provided to bring additional perspective in the concentration levels of constituents remaining in residual wastes.

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**Table E-1. Comparison of Tank 241-C-103 Residual Waste Concentrations to Model Toxics Control Act Cleanup Levels. (1 of 2 sheets)**

| Analyte | Residual Concentration[a] (mg/kg) | 90th Percentile Background (mg/kg) | Soil Method B Unrestricted Land Use[b] (mg/kg) | Soil Method C Industrial Land Use[c] (mg/kg) | Soil Concentration Protective of Groundwater[d] (mg/kg) | Ratio of Residual Concentration in Tank 241-C-103 Residual Waste to Soil Cleanup Levels | | | Above 90th Percentile Background? |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Method B | Method C | 3-Phase | |
| 1, 1, 2-Trichloroethylene (Trichloroethene) | 0.011 | — | 22 | 1,750 | 0.0036 | 5.06E-04 | 6.29E-06 | ***3.06E+00*** | — |
| 2-Butanone | 0.099 | — | 48,000 | 2.10E+06 | 20 | 2.06E-06 | 4.71E-08 | 5.04E-03 | — |
| 2-Propanone (Acetone) | 0.11 | — | 72,000 | 3.15E+06 | 29 | 1.53E-06 | 3.49E-08 | 3.81E-03 | — |
| 4-Methyl-2-pentanone | 0.012 | — | — | — | — | 1.88E-06 | 4.29E-08 | 4.44E-03 | — |
| Acetate | 5.6 | — | 6,400 | 280,000 | 2.7 | — | — | — | — |
| Aluminum | 261,000 | 11,800 | 80,000 | 3.50E+06 | 480,064 | ***3.26E+00*** | 7.46E-02 | 5.44E-01 | Yes |
| Ammonium | 17 | — | — | — | — | — | — | — | — |
| Antimony | 22 | 0.13 | 32 | 1,400 | 5.4 | 6.88E-01 | 1.57E-02 | ***4.06E+00*** | Yes |
| Aroclor-1016 | 4.29E-02 | — | 5.6 | 245 | 1.1 | 7.66E-03 | 1.75E-04 | 4.00E-02 | — |
| Aroclor-1221 | 1.36E-02 | — | 0.50 | 66 | 0.0038 | 2.72E-02 | 2.07E-04 | ***3.61E+00*** | — |
| Aroclor-1232 | 2.41E-01 | — | 0.50 | 66 | 0.0038 | 4.82E-01 | 3.67E-03 | ***6.41E+01*** | — |
| Aroclor-1242 | 4.38E-02 | — | 0.50 | 66 | 0.069 | 8.76E-02 | 6.67E-04 | 6.39E-01 | — |
| Aroclor-1248 | 1.39E-02 | — | 0.50 | 66 | 0.067 | 2.78E-02 | 2.12E-04 | 2.07E-01 | — |
| Aroclor-1254 | 8.15E-03 | — | 0.50 | 66 | 0.11 | 1.63E-02 | 1.24E-04 | 7.13E-02 | — |
| Aroclor-1260 | 5.91E-02 | — | 0.50 | 66 | 0.72 | 1.18E-01 | 9.01E-04 | 8.21E-02 | — |
| Arsenic | 46 | 6.5 | 0.67 | 88 | 0.034 | ***6.90E+01*** | 5.26E-01 | ***1.35E+03*** | Yes |
| Barium | 199 | 132 | 16,000 | 700,000 | 1,648 | 1.24E-02 | 2.84E-04 | 1.21E-01 | Yes |
| Beryllium | 4.7 | 1.5 | 160 | 7,000 | 63 | 2.94E-02 | 6.71E-04 | 7.43E-02 | Yes |
| Bismuth | 79 | — | — | — | — | — | — | — | — |
| Cadmium | 70 | 0.56 | 80 | 3,500 | 0.69 | 8.75E-01 | 2.00E-02 | ***1.01E+02*** | Yes |
| Calcium | 1,560 | 17,200 | — | — | — | — | — | — | No |
| Chlorine | — | — | — | — | 1,000 | — | — | — | — |
| Chromium (total) | 171 | 19 | 120,000 | 5.25E+06 | 2,000 | 1.43E-03 | 3.26E-05 | 8.55E-02 | Yes |
| Cobalt | 6.2 | 16 | 24 | 1,050 | 4.3 | 2.58E-01 | 5.90E-03 | ***1.43E+00*** | No |
| Copper | 59 | 22 | 3,200 | 140,000 | 284 | 1.84E-02 | 4.21E-04 | 2.08E-01 | Yes |
| Cyanide | 0.78 | — | 48 | 2,100 | 0.97 | 1.63E-02 | 3.71E-04 | 8.04E-01 | — |
| Fluoride | 12 | 2.8 | 4,800 | 210,000 | 2,884 | 2.50E-03 | 5.71E-05 | 4.16E-03 | Yes |
| Formate+$A_2$ | 5.8 | — | — | — | — | — | — | — | — |
| Glycolate | 3.8 | — | — | — | — | — | — | — | — |
| Iron | 8,590 | 32,600 | 56,000 | 2.45E+06 | 5,645 | 1.53E-01 | 3.51E-03 | ***1.52E+00*** | No |
| Lanthanum | 13 | — | — | — | — | — | — | — | — |
| Lead | 611 | 10 | — | 1,000[e] | 3,000 | — | 6.11E-01 | 2.04E-01 | Yes |
| Manganese | 318 | 512 | 11,200 | 490,000 | 501 | 2.84E-02 | 6.49E-04 | 6.35E-01 | No |
| Mercury | 76 | 0.013 | 24 | 1,050 | 2.1 | ***3.17E+00*** | 7.24E-02 | ***3.64E+01*** | Yes |

**Table E-1. Comparison of Tank 241-C-103 Residual Waste Concentrations to Model Toxics Control Act Cleanup Levels. (2 of 2 sheets)**

| Analyte | Residual Concentration[a] (mg/kg) | 90th Percentile Background (mg/kg) | Soil Method B Unrestricted Land Use[b] (mg/kg) | Soil Method C Industrial Land Use[c] (mg/kg) | Soil Concentration Protective of Groundwater[d] (mg/kg) | Ratio of Residual Concentration in Tank 241-C-103 Residual Waste to Soil Cleanup Levels | | | Above 90th Percentile Background? |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Method B | Method C | 3-Phase | |
| m-Xylene | 0.015 | — | 16,000 | 700,000 | 14 | 9.38E-07 | 2.14E-08 | 1.11E-03 | — |
| Nickel | 329 | 19 | 1,600 | 70,000 | 130 | 2.06E-01 | 4.70E-03 | ***2.52E+00*** | Yes |
| Nitrate | 59 | 52 | 568,000 | 2.49E+07 | 180 | 1.04E-04 | 2.37E-06 | 3.28E-01 | Yes |
| Nitrite | 32 | — | 24,000 | 1.05E+06 | 13 | 1.33E-03 | 3.05E-05 | ***2.42E+00*** | — |
| Oxalate | 6.9 | — | — | — | — | — | — | — | — |
| o-Xylene | 0.0048 | — | 16,000 | 700,000 | 15 | 3.00E-07 | 6.86E-09 | 3.26E-04 | — |
| Phosphate | 27 | 0.79 | — | — | — | — | — | — | Yes |
| Polychlorinated Biphenyls (high risk) | — | — | 0.50 | 66 | — | — | — | — | — |
| Potassium | 258 | 2,150 | — | — | — | — | — | — | No |
| Selenium | 50 | 0.78 | 400 | 17,500 | 5.2 | 1.25E-01 | 2.86E-03 | ***9.62E+00*** | Yes |
| Silicon | 9,100 | 44 | — | — | — | — | — | — | Yes |
| Silver | 534 | 0.17 | 400 | 17,500 | 14 | ***1.34E+00*** | 3.05E-02 | ***3.93E+01*** | Yes |
| Sodium | 6,900 | 690 | — | — | — | — | — | — | Yes |
| Strontium | 173 | — | 48,000 | 2.10E+06 | 6,758 | 3.60E-03 | 8.24E-05 | 2.56E-02 | — |
| Sulfate | 13 | 237 | — | — | 1,000 | — | — | 1.30E-02 | No |
| Thallium | 43 | 0.19 | — | — | 0.71 | — | — | ***6.04E+01*** | Yes |
| Total inorganic carbon as $CO_3$ | — | — | — | — | — | — | — | — | — |
| Total organic carbon | — | — | — | — | — | — | — | — | — |
| Tributyl phosphate | 74 | — | 111 | 14,583 | 0.50 | 6.66E-01 | 5.07E-03 | ***1.49E+02*** | — |
| Uranium | 3,530 | 3.2 | 240 | 10,500 | 270 | ***1.47E+01*** | 3.36E-01 | ***1.31E+01*** | Yes |
| Vanadium | 4.7 | 85 | 400 | 17,500 | 1,600 | 1.18E-02 | 2.69E-04 | 2.94E-03 | No |
| Xylene (m & p) | 0.015 | — | 16,000[f] | 700,000[f] | 14[f] | 9.38E-07 | 2.14E-08 | 1.07E-03 | — |
| Xylenes | 0.020 | — | 16,000 | 700,000 | 15 | 1.25E-06 | 2.86E-08 | 1.37E-03 | — |
| Zinc | 192 | 68 | 24,000 | 1.05E+06 | 5,971 | 8.00E-03 | 1.83E-04 | 3.22E-02 | Yes |
| Zirconium | 959 | 39.8 | — | — | — | — | — | — | Yes |

Note: **Bolded** ratios indicate exceedances.

[a] RPP-RPT-42323, Rev. 3, "Hanford C-Farm Tank and Ancillary Equipment Residual Waste Inventory Estimates," Appendix D-1.3, "Mean Concentration of C-Farm Sludge Residual Waste (for post retrieval tank samples)."
[b] ECF-Hanford-10-0444, Rev. 3, "Documentation of Standard Method B Soil Cleanup Levels for Unrestricted Land Use."
[c] ECF-HANFORD-10-0453, Rev. 1, "Calculation of Standard Method C Direct Contact Soil Cleanup Levels for Industrial Land Use for the 100 Areas and 300 Area Remedial Investigation/Feasibility Study Reports."
[d] ECF-HANFORD-10-0442, Rev. 2, "Calculation of Nonradiological Soil Concentrations Protective of Groundwater Using the Fixed Parameter 3-Phase Equilibrium Partitioning Equation for the 100 Areas and 300 Area."
[e] The lead cleanup value is the Method A industrial soil cleanup level from Table 745-1 of Washington Administrative Code 173-340-745, "Soil Cleanup Standards for Industrial Properties," subsection (3) Method A industrial soil cleanup levels.
[f] The Xylene (m & p) cleanup values are represented using the calculated cleanup level for m-Xylene.

**Table E-2. Comparison of Tank 241-C-104 Residual Waste Concentrations to Model Toxics Control Act Cleanup Levels. (1 of 2 sheets)**

| Analyte | Residual Concentration[a] (mg/kg) | 90th Percentile Background (mg/kg) | Soil Method B Unrestricted Land Use[b] (mg/kg) | Soil Method C Industrial Land Use[c] (mg/kg) | Soil Concentration Protective of Groundwater[d] (mg/kg) | Ratio of Residual Concentration in Tank 241-C-104 Residual Waste to Soil Cleanup Levels | | | Above 90th Percentile Background? |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Method B | Method C | 3-Phase | |
| 1, 1, 2-Trichloroethylene (Trichloroethene) | 0.0011 | — | 22 | 1,750 | 0.0036 | 5.06E-05 | 6.29E-07 | 3.06E-01 | — |
| 2-Butanone | 0.028 | — | 48,000 | 2.10E+06 | 20 | 5.83E-07 | 1.33E-08 | 1.42E-03 | — |
| 2-Propanone (Acetone) | 0.039 | — | 72,000 | 3.15E+06 | 29 | 5.42E-07 | 1.24E-08 | 1.35E-03 | — |
| 4-Methyl-2-pentanone | 0.015 | — | 6,400 | 280,000 | 2.7 | 2.34E-06 | 5.36E-08 | 5.56E-03 | — |
| Acetate | 64 | — | — | — | — | — | — | — | — |
| Aluminum | 100,000 | 11,800 | 80,000 | 3.50E+06 | 480,064 | ***1.25E+00*** | 2.86E-02 | 2.08E-01 | Yes |
| Ammonium | — | — | — | — | — | — | — | — | — |
| Antimony | 12 | 0.13 | 32 | 1,400 | 5.4 | 3.75E-01 | 8.57E-03 | ***2.21E+00*** | Yes |
| Aroclor-1016 | — | — | 5.6 | 245 | 1.1 | — | — | — | — |
| Aroclor-1221 | — | — | 0.50 | 66 | 0.0038 | — | — | — | — |
| Aroclor-1232 | — | — | 0.50 | 66 | 0.0038 | — | — | — | — |
| Aroclor-1242 | — | — | 0.50 | 66 | 0.069 | — | — | — | — |
| Aroclor-1248 | — | — | 0.50 | 66 | 0.067 | — | — | — | — |
| Aroclor-1254 | — | — | 0.50 | 66 | 0.11 | — | — | — | — |
| Aroclor-1260 | — | — | 0.50 | 66 | 0.72 | — | — | — | — |
| Arsenic | 9.9 | 6.5 | 0.67 | 88 | 0.034 | ***1.49E+01*** | 1.13E-01 | ***2.91E+02*** | Yes |
| Barium | 58 | 132 | 16,000 | 700,000 | 1,648 | 3.63E-03 | 8.29E-05 | 3.52E-02 | No |
| Beryllium | 3.3 | 1.5 | 160 | 7,000 | 63 | 2.06E-02 | 4.71E-04 | 5.22E-02 | Yes |
| Bismuth | 256 | — | — | — | — | — | — | — | — |
| Cadmium | 172 | 0.56 | 80 | 3,500 | 0.69 | ***2.15E+00*** | 4.91E-02 | ***2.49E+02*** | Yes |
| Calcium | 1,190 | 17,200 | — | — | — | — | — | — | No |
| Chlorine | — | — | — | — | 1,000 | — | — | — | — |
| Chromium (total) | 269 | 19 | 120,000 | 5.25E+06 | 2,000 | 2.24E-03 | 5.12E-05 | 1.34E-01 | Yes |
| Cobalt | 3.2 | 16 | 24 | 1,050 | 4.3 | 1.33E-01 | 3.05E-03 | 7.37E-01 | No |
| Copper | 161 | 22 | 3,200 | 140,000 | 284 | 5.03E-02 | 1.15E-03 | 5.67E-01 | Yes |
| Cyanide | 1.6 | — | 48 | 2,100 | 0.97 | 3.33E-02 | 7.62E-04 | ***1.65E+00*** | — |
| Fluoride | 1,350 | 2.8 | 4,800 | 210,000 | 2,884 | 2.81E-01 | 6.43E-03 | 4.68E-01 | Yes |
| Formate+$A_2$ | 119 | — | — | — | — | — | — | — | — |
| Glycolate | 19 | — | — | — | — | — | — | — | — |
| Iron | 28,400 | 32,600 | 56,000 | 2.45E+06 | 5,645 | 5.07E-01 | 1.16E-02 | ***5.03E+00*** | No |
| Lanthanum | 2.1 | — | — | — | — | — | — | — | — |
| Lead | 569 | 10 | — | 1,000[e] | 3,000 | — | 5.69E-01 | 1.90E-01 | Yes |
| Manganese | 3,770 | 512 | 11,200 | 490,000 | 501 | 3.37E-01 | 7.69E-03 | ***7.53E+00*** | Yes |
| Mercury | 118 | 0.013 | 24 | 1,050 | 2.1 | ***4.92E+00*** | 1.12E-01 | ***5.65E+01*** | Yes |

**Table E-2. Comparison of Tank 241-C-104 Residual Waste Concentrations to Model Toxics Control Act Cleanup Levels. (2 of 2 sheets)**

| Analyte | Residual Concentration[a] (mg/kg) | 90th Percentile Background (mg/kg) | Soil Method B Unrestricted Land Use[b] (mg/kg) | Soil Method C Industrial Land Use[c] (mg/kg) | Soil Concentration Protective of Groundwater[d] (mg/kg) | Ratio of Residual Concentration in Tank 241-C-104 Residual Waste to Soil Cleanup Levels | | | Above 90th Percentile Background? |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Method B | Method C | 3-Phase | |
| m-Xylene | 0.0017 | — | 16,000 | 700,000 | 14 | 1.06E-07 | 2.43E-09 | 1.26E-04 | — |
| Nickel | 528 | 19 | 1,600 | 70,000 | 130 | 3.30E-01 | 7.54E-03 | ***4.05E+00*** | Yes |
| Nitrate | 825 | 52 | 568,000 | 2.49E+07 | 180 | 1.45E-03 | 3.32E-05 | ***4.58E+00*** | Yes |
| Nitrite | 445 | — | 24,000 | 1.05E+06 | 13 | 1.85E-02 | 4.24E-04 | ***3.37E+01*** | — |
| Oxalate | 20,800 | — | — | — | — | — | — | — | — |
| o-Xylene | 8.42E-04 | — | 16,000 | 700,000 | 15 | 5.26E-08 | 1.20E-09 | 5.73E-05 | — |
| Phosphate | 3,760 | 0.79 | — | — | — | — | — | — | Yes |
| Polychlorinated Biphenyls (high risk) | 0.51 | — | 0.50 | 66 | — | ***1.02E+00*** | 7.77E-03 | — | — |
| Potassium | 115 | 2,150 | — | — | — | — | — | — | No |
| Selenium | 12 | 0.78 | 400 | 17,500 | 5.2 | 3.00E-02 | 6.86E-04 | ***2.31E+00*** | Yes |
| Silicon | 11,500 | 44 | — | — | — | — | — | — | Yes |
| Silver | 1,440 | 0.17 | 400 | 17,500 | 14 | ***3.60E+00*** | 8.23E-02 | ***1.06E+02*** | Yes |
| Sodium | 101,000 | 690 | — | — | — | — | — | — | Yes |
| Strontium | 82 | — | 48,000 | 2.10E+06 | 6,758 | 1.71E-03 | 3.90E-05 | 1.21E-02 | — |
| Sulfate | 101 | 237 | — | — | 1,000 | — | — | 1.01E-01 | No |
| Thallium | 12 | 0.19 | — | — | 0.71 | — | — | ***1.69E+01*** | Yes |
| Total inorganic carbon as $CO_3$ | — | — | — | — | — | — | — | — | — |
| Total organic carbon | — | — | — | — | — | — | — | — | — |
| Tributyl phosphate | 1.6 | — | 111 | 14,583 | 0.50 | 1.44E-02 | 1.10E-04 | ***3.23E+00*** | — |
| Uranium | 116,000 | 3.2 | 240 | 10,500 | 270 | ***4.83E+02*** | ***1.10E+01*** | ***4.29E+02*** | Yes |
| Vanadium | 36 | 85 | 400 | 17,500 | 1,600 | 9.00E-02 | 2.06E-03 | 2.25E-02 | No |
| Xylene (m & p) | 0.0017 | — | 16,000[f] | 700,000[f] | 14[f] | 1.06E-07 | 2.43E-09 | 1.21E-04 | — |
| Xylenes | 0.0022 | — | 16,000 | 700,000 | 15 | 1.38E-07 | 3.14E-09 | 1.50E-04 | — |
| Zinc | 126 | 68 | 24,000 | 1.05E+06 | 5,971 | 5.25E-03 | 1.20E-04 | 2.11E-02 | Yes |
| Zirconium | 2,190 | 39.8 | — | — | — | — | — | — | Yes |

Note: **Bolded** ratios indicate exceedances.

[a] RPP-RPT-42323, Rev. 3, "Hanford C-Farm Tank and Ancillary Equipment Residual Waste Inventory Estimates," Appendix D-1.3, "Mean Concentration of C-Farm Sludge Residual Waste (for post retrieval tank samples)."
[b] ECF-Hanford-10-0444, Rev. 3, "Documentation of Standard Method B Soil Cleanup Levels for Unrestricted Land Use."
[c] ECF-HANFORD-10-0453, Rev. 1, "Calculation of Standard Method C Direct Contact Soil Cleanup Levels for Industrial Land Use for the 100 Areas and 300 Area Remedial Investigation/Feasibility Study Reports."
[d] ECF-HANFORD-10-0442, Rev. 2, "Calculation of Nonradiological Soil Concentrations Protective of Groundwater Using the Fixed Parameter 3-Phase Equilibrium Partitioning Equation for the 100 Areas and 300 Area."
[e] The lead cleanup value is the Method A industrial soil cleanup level from Table 745-1 of Washington Administrative Code 173-340-745, "Soil Cleanup Standards for Industrial Properties," subsection (3) Method A industrial soil cleanup levels.
[f] The Xylene (m & p) cleanup values are represented using the calculated cleanup level for m-Xylene.

**Table E-3. Comparison of Tank 241-C-106 Residual Waste Concentrations to Model Toxics Control Act Cleanup Levels. (1 of 2 sheets)**

| Analyte | Residual Concentration[a] (mg/kg) | 90th Percentile Background (mg/kg) | Soil Method B Unrestricted Land Use[b] (mg/kg) | Soil Method C Industrial Land Use[c] (mg/kg) | Soil Concentration Protective of Groundwater[d] (mg/kg) | Ratio of Residual Concentration in Tank 241-C-106 Residual Waste to Soil Cleanup Levels | | | Above 90th Percentile Background? |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Method B | Method C | 3-Phase | |
| 1, 1, 2-Trichloroethylene (Trichloroethene) | 0.010 | — | 22 | 1,750 | 0.0036 | 4.60E-04 | 5.71E-06 | ***2.78E+00*** | — |
| 2-Butanone | 0.028 | — | 48,000 | 2.10E+06 | 20 | 5.83E-07 | 1.33E-08 | 1.42E-03 | — |
| 2-Propanone (Acetone) | 0.081 | — | 72,000 | 3.15E+06 | 29 | 1.13E-06 | 2.57E-08 | 2.80E-03 | — |
| 4-Methyl-2-pentanone | 0.011 | — | 6,4000 | 280,000 | 2.7 | 1.72E-06 | 3.93E-08 | 4.07E-03 | — |
| Acetate | 2,220 | — | — | — | — | — | — | — | — |
| Aluminum | 24,100 | 11,800 | 80,000 | 3.50E+06 | 480,064 | 3.01E-01 | 6.89E-03 | 5.02E-02 | Yes |
| Ammonium | 61 | — | — | — | — | — | — | — | — |
| Antimony | 75 | 0.13 | 32 | 1,400 | 5.4 | ***2.34E+00*** | 5.36E-02 | ***1.38E+01*** | Yes |
| Aroclor-1016 | 7.47E-02 | — | 5.6 | 245 | 1.1 | 1.33E-02 | 3.05E-04 | 6.97E-02 | — |
| Aroclor-1221 | 2.35E-02 | — | 0.50 | 66 | 0.0038 | 4.70E-02 | 3.58E-04 | ***6.25E+00*** | — |
| Aroclor-1232 | 4.20E-01 | — | 0.50 | 66 | 0.0038 | 8.40E-01 | 6.40E-03 | ***1.12E+02*** | — |
| Aroclor-1242 | 7.62E-02 | — | 0.50 | 66 | 0.069 | 1.52E-01 | 1.16E-03 | ***1.11E+00*** | — |
| Aroclor-1248 | 2.42E-02 | — | 0.50 | 66 | 0.067 | 4.84E-02 | 3.69E-04 | 3.60E-01 | — |
| Aroclor-1254 | 1.47E-01 | — | 0.50 | 66 | 0.11 | 2.94E-01 | 2.24E-03 | ***1.29E+00*** | — |
| Aroclor-1260 | 1.05E-01 | — | 0.50 | 66 | 0.72 | 2.10E-01 | 1.60E-03 | 1.46E-01 | — |
| Arsenic | 182 | 6.5 | 0.67 | 88 | 0.034 | ***2.73E+02*** | ***2.08E+00*** | ***5.34E+03*** | Yes |
| Barium | 103 | 132 | 16,000 | 700,000 | 1,648 | 6.44E-03 | 1.47E-04 | 6.25E-02 | No |
| Beryllium | 3.6 | 1.5 | 160 | 7,000 | 63 | 2.25E-02 | 5.14E-04 | 5.69E-02 | Yes |
| Bismuth | 185 | — | — | — | — | — | — | — | — |
| Cadmium | 90.9 | 0.56 | 80 | 3,500 | 0.69 | ***1.14E+00*** | 2.60E-02 | ***1.32E+02*** | Yes |
| Calcium | 7,410 | 17,200 | — | — | — | — | — | — | No |
| Chlorine | — | — | — | — | 1,000 | — | — | — | — |
| Chromium (total) | 238 | 19 | 120,000 | 5.25E+06 | 2,000 | 1.98E-03 | 4.53E-05 | 1.19E-01 | Yes |
| Cobalt | 24 | 16 | 24 | 1,050 | 4.3 | 1.00E+00 | 2.29E-02 | ***5.53E+00*** | Yes |
| Copper | 145 | 22 | 3,200 | 140,000 | 284 | 4.53E-02 | 1.04E-03 | 5.10E-01 | Yes |
| Cyanide | 4.9 | — | 48 | 2,100 | 0.97 | 1.02E-01 | 2.33E-03 | ***5.05E+00*** | — |
| Fluoride | 34 | 2.8 | 4,800 | 210,000 | 2,884 | 7.08E-03 | 1.62E-04 | 1.18E-02 | Yes |
| Formate+$A_2$ | 2,220 | — | — | — | — | — | — | — | — |
| Glycolate | 1,840 | — | — | — | — | — | — | — | — |
| Iron | 13,000 | 32,600 | 56,000 | 2.45E+06 | 5,645 | 2.32E-01 | 5.31E-03 | ***2.30E+00*** | No |
| Lanthanum | 154 | — | — | — | — | — | — | — | — |
| Lead | 1,620 | 10 | — | 1,000[e] | 3,000 | — | ***1.62E+00*** | 5.40E-01 | Yes |
| Manganese | 34,600 | 512 | 11,200 | 490,000 | 501 | ***3.09E+00*** | 7.06E-02 | ***6.91E+01*** | Yes |
| Mercury | 122 | 0.013 | 24 | 1,050 | 2.1 | ***5.08E+00*** | 1.16E-01 | ***5.84E+01*** | Yes |

**Table E-3. Comparison of Tank 241-C-106 Residual Waste Concentrations to Model Toxics Control Act Cleanup Levels. (2 of 2 sheets)**

| Analyte | Residual Concentration[a] (mg/kg) | 90th Percentile Background (mg/kg) | Soil Method B Unrestricted Land Use[b] (mg/kg) | Soil Method C Industrial Land Use[c] (mg/kg) | Soil Concentration Protective of Groundwater[d] (mg/kg) | Ratio of Residual Concentration in Tank 241-C-106 Residual Waste to Soil Cleanup Levels | | | Above 90th Percentile Background? |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Method B | Method C | 3-Phase | |
| m-Xylene | — | — | 16,000 | 700,000 | 14 | — | — | — | — |
| Nickel | 1,900 | 19 | 1,600 | 70,000 | 130 | ***1.19E+00*** | 2.71E-02 | ***1.46E+01*** | Yes |
| Nitrate | 2,900 | 52 | 568,000 | 2.49E+07 | 180 | 5.11E-03 | 1.17E-04 | ***1.61E+01*** | Yes |
| Nitrite | 2,610 | — | 24,000 | 1.05E+06 | 13 | 1.09E-01 | 2.49E-03 | ***1.98E+02*** | — |
| Oxalate | 20,900 | — | — | — | — | — | — | — | — |
| o-Xylene | 0.0045 | — | 16,000 | 700,000 | 15 | 2.81E-07 | 6.43E-09 | 3.06E-04 | — |
| Phosphate | 2,610 | 0.79 | — | — | — | — | — | — | Yes |
| Polychlorinated Biphenyls (high risk) | — | — | 0.50 | 66 | — | — | — | — | — |
| Potassium | 1,110 | 2,150 | — | — | — | — | — | — | No |
| Selenium | 185 | 0.78 | 400 | 17,500 | 5.2 | 4.63E-01 | 1.06E-02 | ***3.56E+01*** | Yes |
| Silicon | 1,010 | 44 | — | — | — | — | — | — | Yes |
| Silver | 494 | 0.17 | 400 | 17,500 | 14 | ***1.24E+00*** | 2.82E-02 | ***3.63E+01*** | Yes |
| Sodium | 11,700 | 690 | — | — | — | — | — | — | Yes |
| Strontium | 115 | — | 48,000 | 2.10E+06 | 6,758 | 2.40E-03 | 5.48E-05 | 1.70E-02 | — |
| Sulfate | 3,090 | 237 | — | — | 1,000 | — | — | ***3.09E+00*** | Yes |
| Thallium | 445 | 0.19 | — | — | 0.71 | — | — | ***6.25E+02*** | Yes |
| Total inorganic carbon as $CO_3$ | — | — | — | — | — | — | — | — | — |
| Total organic carbon | — | — | — | — | — | — | — | — | — |
| Tributyl phosphate | — | — | 111 | 14,583 | 0.50 | — | — | — | — |
| Uranium | 185 | 3.2 | 240 | 10,500 | 270 | 7.71E-01 | 1.76E-02 | 6.85E-01 | Yes |
| Vanadium | 19 | 85 | 400 | 17,500 | 1,600 | 4.75E-02 | 1.09E-03 | 1.19E-02 | No |
| Xylene (m & p) | 0.014 | — | 16,000[f] | 700,000[f] | 14[f] | 8.75E-07 | 2.00E-08 | 1.00E-03 | — |
| Xylenes | 0.019 | — | 16,000 | 700,000 | 15 | 1.19E-06 | 2.71E-08 | 1.30E-03 | — |
| Zinc | 134 | 68 | 24,000 | 1.05E+06 | 5,971 | 5.58E-03 | 1.28E-04 | 2.24E-02 | Yes |
| Zirconium | 176 | 39.8 | — | — | — | — | — | — | Yes |

Note: **Bolded** ratios indicate exceedances.

[a] RPP-RPT-42323, Rev. 3, "Hanford C-Farm Tank and Ancillary Equipment Residual Waste Inventory Estimates," Appendix D-1.3, "Mean Concentration of C-Farm Sludge Residual Waste (for post retrieval tank samples)."

[b] ECF-Hanford-10-0444, Rev. 3, "Documentation of Standard Method B Soil Cleanup Levels for Unrestricted Land Use."

[c] ECF-HANFORD-10-0453, Rev. 1, "Calculation of Standard Method C Direct Contact Soil Cleanup Levels for Industrial Land Use for the 100 Areas and 300 Area Remedial Investigation/Feasibility Study Reports."

[d] ECF-HANFORD-10-0442, Rev. 2, "Calculation of Nonradiological Soil Concentrations Protective of Groundwater Using the Fixed Parameter 3-Phase Equilibrium Partitioning Equation for the 100 Areas and 300 Area."

[e] The lead cleanup value is the Method A industrial soil cleanup level from Table 745-1 of Washington Administrative Code 173-340-745, "Soil Cleanup Standards for Industrial Properties," subsection (3) Method A industrial soil cleanup levels.

[f] The Xylene (m & p) cleanup values are represented using the calculated cleanup level for m-Xylene.

**Table E-4. Comparison of Tank 241-C-108 Residual Waste Concentrations to Model Toxics Control Act Cleanup Levels. (1 of 2 sheets)**

| Analyte | Residual Concentration[a] (mg/kg) | 90th Percentile Background (mg/kg) | Soil Method B Unrestricted Land Use[b] (mg/kg) | Soil Method C Industrial Land Use[c] (mg/kg) | Soil Concentration Protective of Groundwater[d] (mg/kg) | Ratio of Residual Concentration in Tank 241-C-108 Residual Waste to Soil Cleanup Levels | | | Above 90th Percentile Background? |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Method B | Method C | 3-Phase | |
| 1, 1, 2-Trichloroethylene (Trichloroethene) | 0.0054 | — | 22 | 1,750 | 0.0036 | 2.48E-04 | 3.09E-06 | ***1.50E+00*** | — |
| 2-Butanone | 0.048 | — | 48,000 | 2.10E+06 | 20 | 1.00E-06 | 2.29E-08 | 2.44E-03 | — |
| 2-Propanone (Acetone) | 0.079 | — | 72,000 | 3.15E+06 | 29 | 1.10E-06 | 2.51E-08 | 2.73E-03 | — |
| 4-Methyl-2-pentanone | 0.032 | — | 64,000 | 280,000 | 2.7 | 5.00E-06 | 1.14E-07 | 1.19E-02 | — |
| Acetate | 57 | — | — | — | — | — | — | — | — |
| Aluminum | 129,000 | 11,800 | 80,000 | 3.50E+06 | 480,064 | ***1.61E+00*** | 3.69E-02 | 2.69E-01 | Yes |
| Ammonium | — | — | — | — | — | — | — | — | — |
| Antimony | 12 | 0.13 | 32 | 1,400 | 5.4 | 3.75E-01 | 8.57E-03 | ***2.21E+00*** | Yes |
| Aroclor-1016 | — | — | 5.6 | 245 | 1.1 | — | — | — | — |
| Aroclor-1221 | — | — | 0.50 | 66 | 0.0038 | — | — | — | — |
| Aroclor-1232 | — | — | 0.50 | 66 | 0.0038 | — | — | — | — |
| Aroclor-1242 | — | — | 0.50 | 66 | 0.069 | — | — | — | — |
| Aroclor-1248 | — | — | 0.50 | 66 | 0.067 | — | — | — | — |
| Aroclor-1254 | — | — | 0.50 | 66 | 0.11 | — | — | — | — |
| Aroclor-1260 | — | — | 0.50 | 66 | 0.72 | — | — | — | — |
| Arsenic | 9.6 | 6.5 | 0.67 | 88 | 0.034 | ***1.44E+01*** | 1.10E-01 | ***2.82E+02*** | Yes |
| Barium | 16 | 132 | 16,000 | 700,000 | 1,648 | 1.00E-03 | 2.29E-05 | 9.71E-03 | No |
| Beryllium | 46 | 1.5 | 160 | 7,000 | 63 | 2.88E-01 | 6.57E-03 | 7.28E-01 | Yes |
| Bismuth | 3,970 | — | — | — | — | — | — | — | — |
| Cadmium | 2 | 0.56 | 80 | 3,500 | 0.69 | 2.39E-02 | 5.46E-04 | ***2.77E+00*** | Yes |
| Calcium | 892 | 17,200 | — | — | — | — | — | — | No |
| Chlorine | — | — | — | — | 1,000 | — | — | — | — |
| Chromium (total) | 23 | 19 | 120,000 | 5.25E+06 | 2,000 | 1.92E-04 | 4.38E-06 | 1.15E-02 | Yes |
| Cobalt | 1.9 | 16 | 24 | 1,050 | 4.3 | 7.92E-02 | 1.81E-03 | 4.38E-01 | No |
| Copper | 20 | 22 | 3,200 | 140,000 | 284 | 6.25E-03 | 1.43E-04 | 7.04E-02 | No |
| Cyanide | 6.1 | — | 48 | 2,100 | 0.97 | 1.27E-01 | 2.90E-03 | ***6.29E+00*** | — |
| Fluoride | 4,480 | 2.8 | 4,800 | 210,000 | 2,884 | 9.33E-01 | 2.13E-02 | ***1.55E+00*** | Yes |
| Formate+$A_2$ | 86 | — | — | — | — | — | — | — | — |
| Glycolate | 33 | — | — | — | — | — | — | — | — |
| Iron | 10,400 | 32,600 | 56,000 | 2.45E+06 | 5,645 | 1.86E-01 | 4.24E-03 | ***1.84E+00*** | No |
| Lanthanum | 46 | — | — | — | — | — | — | — | — |
| Lead | 634 | 10 | — | 1,000[e] | 3,000 | — | 6.34E-01 | 2.11E-01 | Yes |
| Manganese | 151 | 512 | 11,200 | 490,000 | 501 | 1.35E-02 | 3.08E-04 | 3.02E-01 | No |
| Mercury | 0.76 | 0.013 | 24 | 1,050 | 2.1 | ***3.17E-02*** | 7.24E-04 | ***3.64E-01*** | Yes |

**Table E-4. Comparison of Tank 241-C-108 Residual Waste Concentrations to Model Toxics Control Act Cleanup Levels. (2 of 2 sheets)**

| Analyte | Residual Concentration[a] (mg/kg) | 90th Percentile Background (mg/kg) | Soil Method B Unrestricted Land Use[b] (mg/kg) | Soil Method C Industrial Land Use[c] (mg/kg) | Soil Concentration Protective of Groundwater[d] (mg/kg) | Ratio of Residual Concentration in Tank 241-C-108 Residual Waste to Soil Cleanup Levels | | | Above 90th Percentile Background? |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Method B | Method C | 3-Phase | |
| m-Xylene | 0.0076 | — | 16,000 | 700,000 | 14 | 4.75E-07 | 1.09E-08 | 5.63E-04 | — |
| Nickel | 2,760 | 19 | 1,600 | 70,000 | 130 | ***1.73E+00*** | 3.94E-02 | ***2.12E+01*** | Yes |
| Nitrate | 340 | 52 | 568,000 | 2.49E+07 | 180 | 5.99E-04 | 1.37E-05 | ***1.89E+00*** | Yes |
| Nitrite | 214 | — | 24,000 | 1.05E+06 | 13 | 8.92E-03 | 2.04E-04 | ***1.62E+01*** | — |
| Oxalate | 55 | — | — | — | — | — | — | — | — |
| o-Xylene | 0.0036 | — | 16,000 | 700,000 | 15 | 2.25E-07 | 5.14E-09 | 2.45E-04 | — |
| Phosphate | 43,600 | 0.79 | — | — | — | — | — | — | Yes |
| Polychlorinated Biphenyls (high risk) | 0.17 | — | 0.50 | 66 | — | 3.40E-01 | 2.59E-03 | — | — |
| Potassium | — | 2,150 | — | — | — | — | — | — | — |
| Selenium | 12 | 0.78 | 400 | 17,500 | 5.2 | 3.00E-02 | 6.86E-04 | ***2.31E+00*** | Yes |
| Silicon | 3,260 | 44 | — | — | — | — | — | — | Yes |
| Silver | 1.9 | 0.17 | 400 | 17,500 | 14 | 4.75E-03 | 1.09E-04 | 1.40E-01 | Yes |
| Sodium | 121,000 | 690 | — | — | — | — | — | — | Yes |
| Strontium | 730 | — | 48,000 | 2.10E+06 | 6,758 | 1.52E-02 | 3.48E-04 | 1.08E-01 | — |
| Sulfate | 109 | 237 | — | — | 1,000 | — | — | 1.09E-01 | No |
| Thallium | 3,970 | 0.19 | — | — | 0.71 | — | — | ***5.58E+03*** | Yes |
| Total inorganic carbon as $CO_3$ | — | — | — | — | — | — | — | — | — |
| Total organic carbon | — | — | — | — | — | — | — | — | — |
| Tributyl phosphate | 2.0 | — | 111 | 14,583 | 0.50 | 1.80E-02 | 1.37E-04 | ***4.03E+00*** | — |
| Uranium | 4,480 | 3.2 | 240 | 10,500 | 270 | ***1.87E+01*** | 4.27E-01 | ***1.66E+01*** | Yes |
| Vanadium | 199 | 85 | 400 | 17,500 | 1,600 | 4.98E-01 | 1.14E-02 | 1.24E-01 | Yes |
| Xylene (m & p) | — | — | 16,000[f] | 700,000[f] | 14[f] | — | — | — | — |
| Xylenes | 0.011 | — | 16,000 | 700,000 | 15 | 6.88E-07 | 1.57E-08 | 7.52E-04 | — |
| Zinc | 71 | 68 | 24,000 | 1.05E+06 | 5,971 | 2.96E-03 | 6.76E-05 | 1.19E-02 | Yes |
| Zirconium | 22 | 39.8 | — | — | — | — | — | — | Yes |

Note: **Bolded** ratios indicate exceedances.

[a] RPP-RPT-42323, Rev. 3, "Hanford C-Farm Tank and Ancillary Equipment Residual Waste Inventory Estimates," Appendix D-1.3, "Mean Concentration of C-Farm Sludge Residual Waste (for post retrieval tank samples)."
[b] ECF-Hanford-10-0444, Rev. 3, "Documentation of Standard Method B Soil Cleanup Levels for Unrestricted Land Use."
[c] ECF-HANFORD-10-0453, Rev. 1, "Calculation of Standard Method C Direct Contact Soil Cleanup Levels for Industrial Land Use for the 100 Areas and 300 Area Remedial Investigation/Feasibility Study Reports."
[d] ECF-HANFORD-10-0442, Rev. 2, "Calculation of Nonradiological Soil Concentrations Protective of Groundwater Using the Fixed Parameter 3-Phase Equilibrium Partitioning Equation for the 100 Areas and 300 Area."
[e] The lead cleanup value is the Method A industrial soil cleanup level from Table 745-1 of Washington Administrative Code 173-340-745, "Soil Cleanup Standards for Industrial Properties," subsection (3) Method A industrial soil cleanup levels.
[f] The Xylene (m & p) cleanup values are represented using the calculated cleanup level for m-Xylene.

**Table E-5. Comparison of Tank 241-C-109 Residual Waste Concentrations to Model Toxics Control Act Cleanup Levels. (1 of 2 sheets)**

| Analyte | Residual Concentration[a] (mg/kg) | 90th Percentile Background (mg/kg) | Soil Method B Unrestricted Land Use[b] (mg/kg) | Soil Method C Industrial Land Use[c] (mg/kg) | Soil Concentration Protective of Groundwater[d] (mg/kg) | Ratio of Residual Concentration in Tank 241-C-109 Residual Waste to Soil Cleanup Levels | | | Above 90th Percentile Background? |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Method B | Method C | 3-Phase | |
| 1, 1, 2-Trichloroethylene (Trichloroethene) | 0.0012 | — | 22 | 1,750 | 0.0036 | 5.52E-05 | 6.86E-07 | 3.33E-01 | — |
| 2-Butanone | 0.019 | — | 48,000 | 2.10E+06 | 20 | 3.96E-07 | 9.05E-09 | 9.67E-04 | — |
| 2-Propanone (Acetone) | 0.10 | — | 72,000 | 3.15E+06 | 29 | 1.39E-06 | 3.17E-08 | 3.46E-03 | — |
| 4-Methyl-2-pentanone | 0.016 | — | 6,400 | 280,000 | 2.7 | 2.50E-06 | 5.71E-08 | 5.93E-03 | — |
| Acetate | 113 | — | — | — | — | — | — | — | — |
| Aluminum | 162,000 | 11,800 | 80,000 | 3.50E+06 | 480,064 | ***2.03E+00*** | 4.63E-02 | 3.37E-01 | Yes |
| Ammonium | — | — | — | — | — | — | — | — | — |
| Aroclor-1016 | — | — | 5.6 | 245 | 1.1 | — | — | — | — |
| Aroclor-1221 | — | — | 0.50 | 66 | 0.0038 | — | — | — | — |
| Aroclor-1232 | — | — | 0.50 | 66 | 0.0038 | — | — | — | — |
| Aroclor-1242 | — | — | 0.50 | 66 | 0.069 | — | — | — | — |
| Aroclor-1248 | — | — | 0.50 | 66 | 0.067 | — | — | — | — |
| Aroclor-1254 | — | — | 0.50 | 66 | 0.11 | — | — | — | — |
| Aroclor-1260 | — | — | 0.50 | 66 | 0.72 | — | — | — | — |
| Antimony | 5.9 | 0.13 | 32 | 1,400 | 5.4 | 1.84E-01 | 4.21E-03 | ***1.09E+00*** | Yes |
| Arsenic | 7.7 | 6.5 | 0.67 | 88 | 0.034 | ***1.16E+01*** | 8.80E-02 | ***2.26E+02*** | Yes |
| Barium | 9.9 | 132 | 16,000 | 700,000 | 1,648 | 6.19E-04 | 1.41E-05 | 6.01E-03 | No |
| Beryllium | 0.99 | 1.5 | 160 | 7,000 | 63 | 6.19E-03 | 1.41E-04 | 1.57E-02 | No |
| Bismuth | 149 | — | — | — | — | — | — | — | — |
| Cadmium | 1 | 0.56 | 80 | 3,500 | 0.69 | 1.24E-02 | 2.83E-04 | ***1.43E+00*** | Yes |
| Calcium | 1,180 | 17,200 | — | — | — | — | — | — | No |
| Chlorine | — | — | — | — | 1,000 | — | — | — | — |
| Chromium (total) | 13 | 19 | 120,000 | 5.25E+06 | 2,000 | 1.08E-04 | 2.48E-06 | 6.50E-03 | No |
| Cobalt | 0.99 | 16 | 24 | 1,050 | 4.3 | 4.13E-02 | 9.43E-04 | 2.28E-01 | No |
| Copper | 55 | 22 | 3,200 | 140,000 | 284 | 1.72E-02 | 3.93E-04 | 1.94E-01 | Yes |
| Cyanide | 30 | — | 48 | 2,100 | 0.97 | 6.25E-01 | 1.43E-02 | ***3.09E+01*** | — |
| Fluoride | 7,320 | 2.8 | 4,800 | 210,000 | 2,884 | ***1.53E+00*** | 3.49E-02 | ***2.54E+00*** | Yes |
| Formate+$A_2$ | 169 | — | — | — | — | — | — | — | — |
| Glycolate | 64 | — | — | — | — | — | — | — | — |
| Iron | 7,020 | 32,600 | 56,000 | 2.45E+06 | 5,645 | 1.25E-01 | 2.87E-03 | ***1.24E+00*** | No |
| Lanthanum | 9.1 | — | — | — | — | — | — | — | — |
| Lead | 408 | 10 | — | 1,000[e] | 3,000 | — | 4.08E-01 | 1.36E-01 | Yes |
| Manganese | 43 | 512 | 11,200 | 490,000 | 501 | 3.84E-03 | 8.78E-05 | 8.59E-02 | No |
| Mercury | 1.4 | 0.013 | 24 | 1,050 | 2.1 | 5.83E-02 | 1.33E-03 | 6.70E-01 | Yes |
| m-Xylene | 0.0016 | — | 16,000 | 700,000 | 14 | 1.00E-07 | 2.29E-09 | 1.18E-04 | — |

**Table E-5. Comparison of Tank 241-C-109 Residual Waste Concentrations to Model Toxics Control Act Cleanup Levels. (2 of 2 sheets)**

| Analyte | Residual Concentration[a] (mg/kg) | 90th Percentile Background (mg/kg) | Soil Method B Unrestricted Land Use[b] (mg/kg) | Soil Method C Industrial Land Use[c] (mg/kg) | Soil Concentration Protective of Groundwater[d] (mg/kg) | Ratio of Residual Concentration in Tank 241-C-109 Residual Waste to Soil Cleanup Levels | | | Above 90th Percentile Background? |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Method B | Method C | 3-Phase | |
| Nickel | 1,010 | 19 | 1,600 | 70,000 | 130 | 6.31E-01 | 1.44E-02 | ***7.75E+00*** | Yes |
| Nitrate | 342 | 52 | 568,000 | 2.49E+07 | 180 | 6.02E-04 | 1.38E-05 | ***1.90E+00*** | Yes |
| Nitrite | 289 | — | 24,000 | 1.05E+06 | 13 | 1.20E-02 | 2.75E-04 | ***2.19E+01*** | — |
| Oxalate | 105 | — | — | — | — | — | — | — | — |
| o-Xylene | 8.74E-04 | — | 16,000 | 700,000 | 15 | 5.46E-08 | 1.25E-09 | 5.94E-05 | — |
| Phosphate | 74,300 | 0.79 | — | — | — | — | — | — | Yes |
| Polychlorinated Biphenyls (high risk) | 0.014 | — | 0.50 | 66 | — | 2.80E-02 | 2.13E-04 | — | — |
| Potassium | 20 | 2,150 | — | — | — | — | — | — | No |
| Selenium | 5.9 | 0.78 | 400 | 17,500 | 5.2 | 1.48E-02 | 3.37E-04 | ***1.13E+00*** | Yes |
| Silicon | 2,110 | 44 | — | — | — | — | — | — | Yes |
| Silver | 6.3 | 0.17 | 400 | 17,500 | 14 | 1.58E-02 | 3.60E-04 | 4.63E-01 | Yes |
| Sodium | 98,500 | 690 | — | — | — | — | — | — | Yes |
| Strontium | 37 | — | 48,000 | 2.10E+06 | 6,758 | 7.71E-04 | 1.76E-05 | 5.47E-03 | — |
| Sulfate | 216 | 237 | — | — | 1,000 | — | — | 2.16E-01 | No |
| Thallium | 6.7 | 0.19 | — | — | 0.71 | — | — | ***9.41E+00*** | Yes |
| Total inorganic carbon as $CO_3$ | — | — | — | — | — | — | — | — | — |
| Total organic carbon | — | — | — | — | — | — | — | — | — |
| Tributyl phosphate | 0.66 | — | 111 | 14,583 | 0.50 | 5.94E-03 | 4.53E-05 | ***1.33E+00*** | — |
| Uranium | 2,160 | 3.2 | 240 | 10,500 | 270 | ***9.00E+00*** | 2.06E-01 | ***8.00E+00*** | Yes |
| Vanadium | 0.99 | 85 | 400 | 17,500 | 1,600 | 2.48E-03 | 5.66E-05 | 6.19E-04 | No |
| Xylene (m & p) | — | — | 16,000[f] | 700,000[f] | 14[f] | — | — | — | — |
| Xylenes | 0.0019 | — | 16,000 | 700,000 | 15 | 1.19E-07 | 2.71E-09 | 1.30E-04 | — |
| Zinc | 53 | 68 | 24,000 | 1.05E+06 | 5,971 | 2.21E-03 | 5.05E-05 | 8.88E-03 | No |
| Zirconium | — | 39.8 | — | — | — | — | — | — | — |

Note: **Bolded** ratios indicate exceedances.

[a] RPP-RPT-42323, Rev. 3, "Hanford C-Farm Tank and Ancillary Equipment Residual Waste Inventory Estimates," Appendix D-1.3, "Mean Concentration of C-Farm Sludge Residual Waste (for post retrieval tank samples)."
[b] ECF-Hanford-10-0444, Rev. 3, "Documentation of Standard Method B Soil Cleanup Levels for Unrestricted Land Use."
[c] ECF-HANFORD-10-0453, Rev. 1, "Calculation of Standard Method C Direct Contact Soil Cleanup Levels for Industrial Land Use for the 100 Areas and 300 Area Remedial Investigation/Feasibility Study Reports."
[d] ECF-HANFORD-10-0442, Rev. 2, "Calculation of Nonradiological Soil Concentrations Protective of Groundwater Using the Fixed Parameter 3-Phase Equilibrium Partitioning Equation for the 100 Areas and 300 Area."
[e] The lead cleanup value is the Method A industrial soil cleanup level from Table 745-1 of Washington Administrative Code 173-340-745, "Soil Cleanup Standards for Industrial Properties," subsection (3) Method A industrial soil cleanup levels.
[f] The Xylene (m & p) cleanup values are represented using the calculated cleanup level for m-Xylene.

**Table E-6. Comparison of Tank 241-C-110 Residual Waste Concentrations to Model Toxics Control Act Cleanup Levels. (1 of 2 sheets)**

| Analyte | Residual Concentration[a] (mg/kg) | 90th Percentile Background (mg/kg) | Soil Method B Unrestricted Land Use[b] (mg/kg) | Soil Method C Industrial Land Use[c] (mg/kg) | Soil Concentration Protective of Groundwater[d] (mg/kg) | Ratio of Residual Concentration in Tank 241-C-110 Residual Waste to Soil Cleanup Levels | | | Above 90th Percentile Background? |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Method B | Method C | 3-Phase | |
| 1, 1, 2-Trichloroethylene (Trichloroethene) | 9.54E-04 | — | 22 | 1,750 | 0.0036 | 4.39E-05 | 5.45E-07 | 2.65E-01 | — |
| 2-Butanone | 0.016 | — | 48,000 | 2.10E+06 | 20 | 3.33E-07 | 7.62E-09 | 8.14E-04 | — |
| 2-Propanone (Acetone) | 0.020 | — | 72,000 | 3.15E+06 | 29 | 2.78E-07 | 6.35E-09 | 6.92E-04 | — |
| 4-Methyl-2-pentanone | 0.014 | — | 6,400 | 280,000 | 2.7 | 2.19E-06 | 5.00E-08 | 5.19E-03 | — |
| Acetate | 111 | — | — | — | — | — | — | — | — |
| Aluminum | 131,000 | 11,800 | 80,000 | 3.50E+06 | 480,064 | ***1.64E+00*** | 3.74E-02 | 2.73E-01 | Yes |
| Ammonium | — | — | — | — | — | — | — | — | — |
| Aroclor-1016 | — | — | 5.6 | 245 | 1.1 | — | — | — | — |
| Aroclor-1221 | — | — | 0.50 | 66 | 0.0038 | — | — | — | — |
| Aroclor-1232 | — | — | 0.50 | 66 | 0.0038 | — | — | — | — |
| Aroclor-1242 | — | — | 0.50 | 66 | 0.069 | — | — | — | — |
| Aroclor-1248 | — | — | 0.50 | 66 | 0.067 | — | — | — | — |
| Aroclor-1254 | — | — | 0.50 | 66 | 0.11 | — | — | — | — |
| Aroclor-1260 | — | — | 0.50 | 66 | 0.72 | — | — | — | — |
| Antimony | 6.1 | 0.13 | 32 | 1,400 | 5.4 | 1.91E-01 | 4.36E-03 | ***1.12E+00*** | Yes |
| Arsenic | 6.0 | 6.5 | 0.67 | 88 | 0.034 | ***9.00E+00*** | 6.86E-02 | ***1.76E+02*** | No |
| Barium | 51 | 132 | 16,000 | 700,000 | 1,648 | 3.19E-03 | 7.29E-05 | 3.09E-02 | No |
| Beryllium | 1.0 | 1.5 | 160 | 7,000 | 63 | 6.25E-03 | 1.43E-04 | 1.58E-02 | No |
| Bismuth | 3,680 | — | — | — | — | — | — | — | — |
| Cadmium | 1 | 0.56 | 80 | 3,500 | 0.69 | 1.26E-02 | 2.89E-04 | ***1.46E+00*** | Yes |
| Calcium | 591 | 17,200 | — | — | — | — | — | — | No |
| Chlorine | — | — | — | — | 1,000 | — | — | — | — |
| Chromium (total) | 113 | 19 | 120,000 | 5.25E+06 | 2,000 | 9.42E-04 | 2.15E-05 | 5.65E-02 | Yes |
| Cobalt | 2.4 | 16 | 24 | 1,050 | 4.3 | 1.00E-01 | 2.29E-03 | 5.53E-01 | No |
| Copper | 318 | 22 | 3,200 | 140,000 | 284 | 9.94E-02 | 2.27E-03 | ***1.12E+00*** | Yes |
| Cyanide | 0.82 | — | 48 | 2,100 | 0.97 | 1.71E-02 | 3.90E-04 | 8.46E-01 | — |
| Fluoride | 14,000 | 2.8 | 4,800 | 210,000 | 2,884 | ***2.92E+00*** | 6.67E-02 | ***4.85E+00*** | Yes |
| Formate+$A_2$ | 166 | — | — | — | — | — | — | — | — |
| Glycolate | 63 | — | — | — | — | — | — | — | — |
| Iron | 19,200 | 32,600 | 56,000 | 2.45E+06 | 5,645 | 3.43E-01 | 7.84E-03 | ***3.40E+00*** | No |
| Lanthanum | 1.0 | — | — | — | — | — | — | — | — |
| Lead | 569 | 10 | — | 1,000[e] | 3,000 | — | 5.69E-01 | 1.90E-01 | Yes |
| Manganese | 77 | 512 | 11,200 | 490,000 | 501 | 6.88E-03 | 1.57E-04 | 1.54E-01 | No |
| Mercury | 11 | 0.013 | 24 | 1,050 | 2.1 | 4.58E-01 | 1.05E-02 | ***5.27E+00*** | Yes |
| m-Xylene | 0.0034 | — | 16,000 | 700,000 | 14 | 2.13E-07 | 4.86E-09 | 2.52E-04 | — |

**Table E-6. Comparison of Tank 241-C-110 Residual Waste Concentrations to Model Toxics Control Act Cleanup Levels. (2 of 2 sheets)**

| Analyte | Residual Concentration[a] (mg/kg) | 90th Percentile Background (mg/kg) | Soil Method B Unrestricted Land Use[b] (mg/kg) | Soil Method C Industrial Land Use[c] (mg/kg) | Soil Concentration Protective of Groundwater[d] (mg/kg) | Ratio of Residual Concentration in Tank 241-C-110 Residual Waste to Soil Cleanup Levels | | | Above 90th Percentile Background? |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Method B | Method C | 3-Phase | |
| Nickel | 42 | 19 | 1,600 | 70,000 | 130 | 2.63E-02 | 6.00E-04 | 3.22E-01 | Yes |
| Nitrate | 682 | 52 | 568,000 | 2.49E+07 | 180 | 1.20E-03 | 2.74E-05 | ***3.79E+00*** | Yes |
| Nitrite | 277 | — | 24,000 | 1.05E+06 | 13 | 1.15E-02 | 2.64E-04 | ***2.10E+01*** | — |
| Oxalate | 103 | — | — | — | — | — | — | — | — |
| o-Xylene | 0.0017 | — | 16,000 | 700,000 | 15 | 1.06E-07 | 2.43E-09 | 1.16E-04 | — |
| Phosphate | 141,000 | 0.79 | — | — | — | — | — | — | Yes |
| Polychlorinated Biphenyls (high risk) | 0.016 | — | 0.50 | 66 | — | 3.20E-02 | 2.44E-04 | — | — |
| Potassium | 45 | 2,150 | — | — | — | — | — | — | No |
| Selenium | 4.0 | 0.78 | 400 | 17,500 | 5.2 | 1.00E-02 | 2.29E-04 | 7.69E-01 | Yes |
| Silicon | 2,070 | 44 | — | — | — | — | — | — | Yes |
| Silver | 25 | 0.17 | 400 | 17,500 | 14 | 6.25E-02 | 1.43E-03 | ***1.84E+00*** | Yes |
| Sodium | 121,000 | 690 | — | — | — | — | — | — | Yes |
| Strontium | 5,700 | — | 48,000 | 2.10E+06 | 6,758 | 1.19E-01 | 2.71E-03 | 8.43E-01 | — |
| Sulfate | 755 | 237 | — | — | 1,000 | — | — | 7.55E-01 | Yes |
| Thallium | 4.3 | 0.19 | — | — | 0.71 | — | — | ***6.04E+00*** | Yes |
| Total inorganic carbon as $CO_3$ | — | — | — | — | — | — | — | — | — |
| Total organic carbon | — | — | — | — | — | — | — | — | — |
| Tributyl phosphate | 10 | — | 111 | 14,583 | 0.50 | 9.00E-02 | 6.86E-04 | ***2.02E+01*** | — |
| Uranium | 556 | 3.2 | 240 | 10,500 | 270 | ***2.32E+00*** | 5.30E-02 | ***2.06E+00*** | Yes |
| Vanadium | 1.2 | 85 | 400 | 17,500 | 1,600 | 3.00E-03 | 6.86E-05 | 7.50E-04 | No |
| Xylene (m & p) | — | — | 16,000[f] | 700,000[f] | 14[f] | — | — | — | — |
| Xylenes | 0.0050 | — | 16,000 | 700,000 | 15 | 3.13E-07 | 7.14E-09 | 3.42E-04 | — |
| Zinc | 215 | 68 | 24,000 | 1.05E+06 | 5,971 | 8.96E-03 | 2.05E-04 | 3.60E-02 | Yes |
| Zirconium | 37 | 39.8 | — | — | — | — | — | — | No |

Note: **Bolded** ratios indicate exceedances.

[a] RPP-RPT-42323, Rev. 3, "Hanford C-Farm Tank and Ancillary Equipment Residual Waste Inventory Estimates," Appendix D-1.3, "Mean Concentration of C-Farm Sludge Residual Waste (for post retrieval tank samples)."
[b] ECF-Hanford-10-0444, Rev. 3, "Documentation of Standard Method B Soil Cleanup Levels for Unrestricted Land Use."
[c] ECF-HANFORD-10-0453, Rev. 1, "Calculation of Standard Method C Direct Contact Soil Cleanup Levels for Industrial Land Use for the 100 Areas and 300 Area Remedial Investigation/Feasibility Study Reports."
[d] ECF-HANFORD-10-0442, Rev. 2, "Calculation of Nonradiological Soil Concentrations Protective of Groundwater Using the Fixed Parameter 3-Phase Equilibrium Partitioning Equation for the 100 Areas and 300 Area."
[e] The lead cleanup value is the Method A industrial soil cleanup level from Table 745-1 of Washington Administrative Code 173-340-745, "Soil Cleanup Standards for Industrial Properties," subsection (3) Method A industrial soil cleanup levels.
[f] The Xylene (m & p) cleanup values are represented using the calculated cleanup level for m-Xylene.

**Table E-7. Comparison of Tank 241-C-201 Residual Waste Concentrations to Model Toxics Control Act Cleanup Levels. (1 of 2 sheets)**

| Analyte | Residual Concentration[a] (mg/kg) | 90th Percentile Background (mg/kg) | Soil Method B Unrestricted Land Use[b] (mg/kg) | Soil Method C Industrial Land Use[c] (mg/kg) | Soil Concentration Protective of Groundwater[d] (mg/kg) | Ratio of Residual Concentration in Tank 241-C-201 Residual Waste to Soil Cleanup Levels | | | Above 90th Percentile Background? |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Method B | Method C | 3-Phase | |
| 1, 1, 2-Trichloroethylene (Trichloroethene) | 0.012 | — | 22 | 1,750 | 0.0036 | 5.52E-04 | 6.86E-06 | ***3.33E+00*** | — |
| 2-Butanone | 0.0042 | — | 48,000 | 2.10E+06 | 20 | 8.75E-08 | 2.00E-09 | 2.14E-04 | — |
| 2-Propanone (Acetone) | 0.015 | — | 72,000 | 3.15E+06 | 29 | 2.08E-07 | 4.76E-09 | 5.19E-04 | — |
| 4-Methyl-2-pentanone | 0.0024 | — | 6,400 | 280,000 | 2.7 | 3.75E-07 | 8.57E-09 | 8.89E-04 | — |
| Acetate | 2,240 | — | — | — | — | — | — | — | — |
| Aluminum | 4,370 | 11,800 | 80,000 | 3.50E+06 | 480,064 | 5.46E-02 | 1.25E-03 | 9.10E-03 | No |
| Ammonium | 37 | — | — | — | — | — | — | — | — |
| Aroclor-1016 | 2.07E-01 | — | 5.6 | 245 | 1.1 | 3.70E-02 | 8.45E-04 | 1.93E-01 | — |
| Aroclor-1221 | 6.48E-02 | — | 0.50 | 66 | 0.0038 | 1.30E-01 | 9.87E-04 | ***1.72E+01*** | — |
| Aroclor-1232 | 1.17E+00 | — | 0.50 | 66 | 0.0038 | ***2.34E+00*** | 1.78E-02 | ***3.11E+02*** | — |
| Aroclor-1242 | 2.07E-01 | — | 0.50 | 66 | 0.069 | 4.14E-01 | 3.15E-03 | ***3.02E+00*** | — |
| Aroclor-1248 | 6.68E-02 | — | 0.50 | 66 | 0.067 | 1.34E-01 | 1.02E-03 | 9.95E-01 | — |
| Aroclor-1254 | 9.60E-02 | — | 0.50 | 66 | 0.11 | 1.92E-01 | 1.46E-03 | 8.39E-01 | — |
| Aroclor-1260 | 2.85E-01 | — | 0.50 | 66 | 0.72 | 5.70E-01 | 4.34E-03 | 3.96E-01 | — |
| Antimony | 95 | 0.13 | 32 | 1,400 | 5.4 | ***2.97E+00*** | 6.79E-02 | ***1.75E+01*** | Yes |
| Arsenic | 119 | 6.5 | 0.67 | 88 | 0.034 | ***1.79E+02*** | ***1.36E+00*** | ***3.49E+03*** | Yes |
| Barium | 168 | 132 | 16,000 | 700,000 | 1,648 | 1.05E-02 | 2.40E-04 | 1.02E-01 | Yes |
| Beryllium | 15 | 1.5 | 160 | 7,000 | 63 | 9.38E-02 | 2.14E-03 | 2.37E-01 | Yes |
| Bismuth | 649 | — | — | — | — | — | — | — | — |
| Cadmium | 10 | 0.56 | 80 | 3,500 | 0.69 | 1.22E-01 | 2.78E-03 | ***1.41E+01*** | Yes |
| Calcium | 7,200 | 17,200 | — | — | — | — | — | — | No |
| Chlorine | — | — | — | — | 1,000 | — | — | — | — |
| Chromium (total) | 12,900 | 19 | 120,000 | 5.25E+06 | 2,000 | 1.08E-01 | 2.46E-03 | ***6.45E+00*** | Yes |
| Cobalt | 90 | 16 | 24 | 1,050 | 4.3 | ***3.75E+00*** | 8.57E-02 | ***2.07E+01*** | Yes |
| Copper | 643 | 22 | 3,200 | 140,000 | 284 | 2.01E-01 | 4.59E-03 | ***2.26E+00*** | Yes |
| Cyanide | 2.2 | — | 48 | 2,100 | 0.97 | 4.58E-02 | 1.05E-03 | ***2.27E+00*** | — |
| Fluoride | 2,860 | 2.8 | 4,800 | 210,000 | 2,884 | ***5.96E-01*** | 1.36E-02 | ***9.92E-01*** | Yes |
| Formate+$A_2$ | 2,240 | — | — | — | — | — | — | — | — |
| Glycolate | 1,850 | — | — | — | — | — | — | — | — |
| Iron | 117,000 | 32,600 | 56,000 | 2.45E+06 | 5,645 | **2.09E+00** | 4.78E-02 | **2.07E+01** | Yes |
| Lanthanum | 13 | — | — | — | — | — | — | — | — |
| Lead | 6,650 | 10 | — | 1,000[e] | 3,000 | — | **6.65E+00** | ***2.22E+00*** | Yes |
| Manganese | 20,200 | 512 | 11,200 | 490,000 | 501 | **1.80E+00** | 4.12E-02 | ***4.03E+01*** | Yes |
| Mercury | 114 | 0.013 | 24 | 1,050 | 2.1 | ***4.75E+00*** | 1.09E-01 | ***5.46E+01*** | Yes |
| m-Xylene | 0.017 | — | 16,000 | 700,000 | 14 | 1.06E-06 | 2.43E-08 | 1.26E-03 | — |

**Table E-7. Comparison of Tank 241-C-201 Residual Waste Concentrations to Model Toxics Control Act Cleanup Levels. (2 of 2 sheets)**

| Analyte | Residual Concentration[a] (mg/kg) | 90th Percentile Background (mg/kg) | Soil Method B Unrestricted Land Use[b] (mg/kg) | Soil Method C Industrial Land Use[c] (mg/kg) | Soil Concentration Protective of Groundwater[d] (mg/kg) | Ratio of Residual Concentration in Tank 241-C-201 Residual Waste to Soil Cleanup Levels | | | Above 90th Percentile Background? |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Method B | Method C | 3-Phase | |
| Nickel | 6,540 | 19 | 1,600 | 70,000 | 130 | ***4.09E+00*** | 9.34E-02 | ***5.02E+01*** | Yes |
| Nitrate | 1,440 | 52 | 568,000 | 2.49E+07 | 180 | 2.54E-03 | 5.79E-05 | ***8.00E+00*** | Yes |
| Nitrite | 560 | — | 24,000 | 1.05E+06 | 13 | 2.33E-02 | 5.33E-04 | ***4.24E+01*** | — |
| Oxalate | 54,200 | — | — | — | — | — | — | — | — |
| o-Xylene | 0.0053 | — | 16,000 | 700,000 | 15 | 3.31E-07 | 7.57E-09 | 3.60E-04 | — |
| Phosphate | — | 0.79 | — | — | — | — | — | — | — |
| Polychlorinated Biphenyls (high risk) | — | — | 0.50 | 66 | — | — | — | — | — |
| Potassium | 948 | 2,150 | — | — | — | — | — | — | No |
| Selenium | 122 | 0.78 | 400 | 17,500 | 5.2 | 3.05E-01 | 6.97E-03 | ***2.35E+01*** | Yes |
| Silicon | 7,430 | 44 | — | — | — | — | — | — | Yes |
| Silver | 13 | 0.17 | 400 | 17,500 | 14 | 3.25E-02 | 7.43E-04 | 9.56E-01 | Yes |
| Sodium | 52,300 | 690 | — | — | — | — | — | — | Yes |
| Strontium | 968 | — | 48,000 | 2.10E+06 | 6,758 | 2.02E-02 | 4.61E-04 | 1.43E-01 | — |
| Sulfate | — | 237 | — | — | 1,000 | — | — | — | — |
| Thallium | 351 | 0.19 | — | — | 0.71 | — | — | ***4.93E+02*** | Yes |
| Total inorganic carbon as $CO_3$ | — | — | — | — | — | — | — | — | — |
| Total organic carbon | — | — | — | — | — | — | — | — | — |
| Tributyl phosphate | 21,200 | — | 111 | 14,583 | 0.50 | **1.91E+02** | ***1.45E+00*** | ***4.28E+04*** | — |
| Uranium | 143,000 | 3.2 | 240 | 10,500 | 270 | ***5.96E+02*** | ***1.36E+01*** | ***5.29E+02*** | Yes |
| Vanadium | 12 | 85 | 400 | 17,500 | 1,600 | 3.00E-02 | 6.86E-04 | 7.50E-03 | No |
| Xylene (m & p) | — | — | 16,000[f] | 700,000[f] | 14[f] | — | — | — | — |
| Xylenes | 0.022 | — | 16,000 | 700,000 | 15 | 1.38E-06 | 3.14E-08 | 1.50E-03 | — |
| Zinc | 443 | 68 | 24,000 | 1.05E+06 | 5,971 | 1.85E-02 | 4.22E-04 | 7.42E-02 | Yes |
| Zirconium | 11 | 39.8 | — | — | — | — | — | — | No |

Note: **Bolded** ratios indicate exceedances.

[a] RPP-RPT-42323, Rev. 3, "Hanford C-Farm Tank and Ancillary Equipment Residual Waste Inventory Estimates," Appendix D-1.3, "Mean Concentration of C-Farm Sludge Residual Waste (for post retrieval tank samples)."
[b] ECF-Hanford-10-0444, Rev. 3, "Documentation of Standard Method B Soil Cleanup Levels for Unrestricted Land Use."
[c] ECF-HANFORD-10-0453, Rev. 1, "Calculation of Standard Method C Direct Contact Soil Cleanup Levels for Industrial Land Use for the 100 Areas and 300 Area Remedial Investigation/Feasibility Study Reports."
[d] ECF-HANFORD-10-0442, Rev. 2, "Calculation of Nonradiological Soil Concentrations Protective of Groundwater Using the Fixed Parameter 3-Phase Equilibrium Partitioning Equation for the 100 Areas and 300 Area."
[e] The lead cleanup value is the Method A industrial soil cleanup level from Table 745-1 of Washington Administrative Code 173-340-745, "Soil Cleanup Standards for Industrial Properties," subsection (3) Method A industrial soil cleanup levels.
[f] The Xylene (m & p) cleanup values are represented using the calculated cleanup level for m-Xylene.

**Table E-8. Comparison of Tank 241-C-202 Residual Waste Concentrations to Model Toxics Control Act Cleanup Levels. (1 of 2 sheets)**

| Analyte | Residual Concentration[a] (mg/kg) | 90th Percentile Background (mg/kg) | Soil Method B Unrestricted Land Use[b] (mg/kg) | Soil Method C Industrial Land Use[c] (mg/kg) | Soil Concentration Protective of Groundwater[d] (mg/kg) | Ratio of Residual Concentration in Tank 241-C-202 Residual Waste to Soil Cleanup Levels | | | Above 90th Percentile Background? |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Method B | Method C | 3-Phase | |
| 1, 1, 2-Trichloroethylene (Trichloroethene) | 0.012 | — | 22 | 1,750 | 0.0036 | 5.52E-04 | 6.86E-06 | ***3.33E+00*** | — |
| 2-Butanone | 0.064 | — | 48,000 | 2.10E+06 | 20 | 1.33E-06 | 3.05E-08 | 3.26E-03 | — |
| 2-Propanone (Acetone) | 0.22 | — | 72,000 | 3.15E+06 | 29 | 3.06E-06 | 6.98E-08 | 7.61E-03 | — |
| 4-Methyl-2-pentanone | 0.023 | — | 6,400 | 280,000 | 2.7 | 3.59E-06 | 8.21E-08 | 8.52E-03 | — |
| Acetate | 95 | — | — | — | — | — | — | — | — |
| Aluminum | 8,850 | 11,800 | 80,000 | 3.50E+06 | 480,064 | 1.11E-01 | 2.53E-03 | 1.84E-02 | No |
| Ammonium | 57 | — | — | — | — | — | — | — | — |
| Aroclor-1016 | — | — | 5.6 | 245 | 1.1 | — | — | — | — |
| Aroclor-1221 | — | — | 0.50 | 66 | 0.0038 | — | — | — | — |
| Aroclor-1232 | — | — | 0.50 | 66 | 0.0038 | — | — | — | — |
| Aroclor-1242 | — | — | 0.50 | 66 | 0.069 | — | — | — | — |
| Aroclor-1248 | — | — | 0.50 | 66 | 0.067 | — | — | — | — |
| Aroclor-1254 | — | — | 0.50 | 66 | 0.11 | — | — | — | — |
| Aroclor-1260 | — | — | 0.50 | 66 | 0.72 | — | — | — | — |
| Antimony | 95 | 0.13 | 32 | 1,400 | 5.4 | ***2.97E+00*** | 6.79E-02 | ***1.75E+01*** | Yes |
| Arsenic | 95 | 6.5 | 0.67 | 88 | 0.034 | ***1.43E+02*** | ***1.09E+00*** | ***2.79E+03*** | Yes |
| Barium | 176 | 132 | 16,000 | 700,000 | 1,648 | 1.10E-02 | 2.51E-04 | 1.07E-01 | Yes |
| Beryllium | 15 | 1.5 | 160 | 7,000 | 63 | 9.38E-02 | 2.14E-03 | 2.37E-01 | Yes |
| Bismuth | 661 | — | — | — | — | — | — | — | — |
| Cadmium | 18 | 0.56 | 80 | 3,500 | 0.69 | 2.29E-01 | 5.23E-03 | ***2.65E+01*** | Yes |
| Calcium | 7,420 | 17,200 | — | — | — | — | — | — | No |
| Chlorine | — | — | — | — | 1,000 | — | — | — | — |
| Chromium (total) | 9,480 | 19 | 120,000 | 5.25E+06 | 2,000 | 7.90E-02 | 1.81E-03 | ***4.74E+00*** | Yes |
| Cobalt | 80 | 16 | 24 | 1,050 | 4.3 | ***3.33E+00*** | 7.62E-02 | ***1.84E+01*** | Yes |
| Copper | 320 | 22 | 3,200 | 140,000 | 284 | 1.00E-01 | 2.29E-03 | ***1.13E+00*** | Yes |
| Cyanide | 4.1 | — | 48 | 2,100 | 0.97 | 8.54E-02 | 1.95E-03 | ***4.23E+00*** | — |
| Fluoride | 2,360 | 2.8 | 4,800 | 210,000 | 2,884 | ***4.92E-01*** | 1.12E-02 | ***8.18E-01*** | Yes |
| Formate+$A_2$ | 67 | — | — | — | — | — | — | — | — |
| Glycolate | — | — | — | — | — | — | — | — | — |
| Iron | 90,800 | 32,600 | 56,000 | 2.45E+06 | 5,645 | ***1.62E+00*** | 3.71E-02 | ***1.61E+01*** | Yes |
| Lanthanum | 11 | — | — | — | — | — | — | — | — |
| Lead | 6,090 | 10 | — | 1,000[e] | 3,000 | — | ***6.09E+00*** | ***2.03E+00*** | Yes |
| Manganese | 17,600 | 512 | 11,200 | 490,000 | 501 | ***1.57E+00*** | 3.59E-02 | ***3.51E+01*** | Yes |
| Mercury | 299 | 0.013 | 24 | 1,050 | 2.1 | ***1.25E+01*** | 2.85E-01 | ***1.43E+02*** | Yes |
| m-Xylene | 0.017 | — | 16,000 | 700,000 | 14 | 1.06E-06 | 2.43E-08 | 1.26E-03 | — |

**Table E-8. Comparison of Tank 241-C-202 Residual Waste Concentrations to Model Toxics Control Act Cleanup Levels. (2 of 2 sheets)**

| Analyte | Residual Concentration[a] (mg/kg) | 90th Percentile Background (mg/kg) | Soil Method B Unrestricted Land Use[b] (mg/kg) | Soil Method C Industrial Land Use[c] (mg/kg) | Soil Concentration Protective of Groundwater[d] (mg/kg) | Ratio of Residual Concentration in Tank 241-C-202 Residual Waste to Soil Cleanup Levels | | | Above 90th Percentile Background? |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Method B | Method C | 3-Phase | |
| Nickel | 7,600 | 19 | 1,600 | 70,000 | 130 | ***4.75E+00*** | 1.09E-01 | ***5.83E+01*** | Yes |
| Nitrate | 1,300 | 52 | 568,000 | 2.49E+07 | 180 | 2.29E-03 | 5.23E-05 | ***7.22E+00*** | Yes |
| Nitrite | 471 | — | 24,000 | 1.05E+06 | 13 | 1.96E-02 | 4.49E-04 | ***3.57E+01*** | — |
| Oxalate | 39,200 | — | — | — | — | — | — | — | — |
| o-Xylene | 0.017 | — | 16,000 | 700,000 | 15 | 1.06E-06 | 2.43E-08 | 1.16E-03 | — |
| Phosphate | — | 0.79 | — | — | — | — | — | — | — |
| Polychlorinated Biphenyls (high risk) | 0.03 | — | 0.50 | 66 | — | 6.00E-02 | 4.57E-04 | — | — |
| Potassium | 948 | 2,150 | — | — | — | — | — | — | No |
| Selenium | 95 | 0.78 | 400 | 17,500 | 5.2 | 2.38E-01 | 5.43E-03 | ***1.83E+01*** | Yes |
| Silicon | 8,970 | 44 | — | — | — | — | — | — | Yes |
| Silver | 13 | 0.17 | 400 | 17,500 | 14 | 3.25E-02 | 7.43E-04 | 9.56E-01 | Yes |
| Sodium | 47,800 | 690 | — | — | — | — | — | — | Yes |
| Strontium | 1,270 | — | 48,000 | 2.10E+06 | 6,758 | 2.65E-02 | 6.05E-04 | 1.88E-01 | — |
| Sulfate | — | 237 | — | — | 1,000 | — | — | — | — |
| Thallium | 256 | 0.19 | — | — | 0.71 | — | — | ***3.60E+02*** | Yes |
| Total inorganic carbon as $CO_3$ | — | — | — | — | — | — | — | — | — |
| Total organic carbon | — | — | — | — | — | — | — | — | — |
| Tributyl phosphate | 5,530 | — | 111 | 14,583 | 0.50 | ***4.98E+01*** | 3.79E-01 | ***1.12E+04*** | — |
| Uranium | 121,000 | 3.2 | 240 | 10,500 | 270 | ***5.04E+02*** | ***1.15E+01*** | ***4.48E+02*** | Yes |
| Vanadium | 11 | 85 | 400 | 17,500 | 1,600 | 2.75E-02 | 6.29E-04 | 6.87E-03 | No |
| Xylene (m & p) | — | — | 16,000[f] | 700,000[f] | 14[f] | — | — | — | — |
| Xylenes | 0.022 | — | 16,000 | 700,000 | 15 | 1.38E-06 | 3.14E-08 | 1.50E-03 | — |
| Zinc | 514 | 68 | 24,000 | 1.05E+06 | 5,971 | 2.14E-02 | 4.90E-04 | 8.61E-02 | Yes |
| Zirconium | 99 | 39.8 | — | — | — | — | — | — | Yes |

Note: **Bolded** ratios indicate exceedances.

[a] RPP-RPT-42323, Rev. 3, "Hanford C-Farm Tank and Ancillary Equipment Residual Waste Inventory Estimates," Appendix D-1.3, "Mean Concentration of C-Farm Sludge Residual Waste (for post retrieval tank samples)."
[b] ECF-Hanford-10-0444, Rev. 3, "Documentation of Standard Method B Soil Cleanup Levels for Unrestricted Land Use."
[c] ECF-HANFORD-10-0453, Rev. 1, "Calculation of Standard Method C Direct Contact Soil Cleanup Levels for Industrial Land Use for the 100 Areas and 300 Area Remedial Investigation/Feasibility Study Reports."
[d] ECF-HANFORD-10-0442, Rev. 2, "Calculation of Nonradiological Soil Concentrations Protective of Groundwater Using the Fixed Parameter 3-Phase Equilibrium Partitioning Equation for the 100 Areas and 300 Area."
[e] The lead cleanup value is the Method A industrial soil cleanup level from Table 745-1 of Washington Administrative Code 173-340-745, "Soil Cleanup Standards for Industrial Properties," subsection (3) Method A industrial soil cleanup levels.
[f] The Xylene (m & p) cleanup values are represented using the calculated cleanup level for m-Xylene.

**Table E-9. Comparison of Tank 241-C-203 Residual Waste Concentrations to Model Toxics Control Act Cleanup Levels. (1 of 2 sheets)**

| Analyte | Residual Concentration[a] (mg/kg) | 90th Percentile Background (mg/kg) | Soil Method B Unrestricted Land Use[b] (mg/kg) | Soil Method C Industrial Land Use[c] (mg/kg) | Soil Concentration Protective of Groundwater[d] (mg/kg) | Ratio of Residual Concentration in Tank 241-C-203 Residual Waste to Soil Cleanup Levels | | | Above 90th Percentile Background? |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Method B | Method C | 3-Phase | |
| 1, 1, 2-Trichloroethylene (Trichloroethene) | 0.0097 | — | 22 | 1,750 | 0.0036 | 4.46E-04 | 5.54E-06 | ***2.69E+00*** | — |
| 2-Butanone | 0.079 | — | 48,000 | 2.10E+06 | 20 | 1.65E-06 | 3.76E-08 | 4.02E-03 | — |
| 2-Propanone (Acetone) | 0.22 | — | 72,000 | 3.15E+06 | 29 | 3.06E-06 | 6.98E-08 | 7.61E-03 | — |
| 4-Methyl-2-pentanone | 0.01 | — | 6,400 | 280,000 | 2.7 | 1.56E-06 | 3.57E-08 | 3.70E-03 | — |
| Acetate | 139 | — | — | — | — | — | — | — | — |
| Aluminum | 398 | 11,800 | 80,000 | 3.50E+06 | 480,064 | 4.98E-03 | 1.14E-04 | 8.29E-04 | No |
| Ammonium | 98 | — | — | — | — | — | — | — | — |
| Aroclor-1016 | 9.75E-02 | — | 5.6 | 245 | 1.1 | 1.74E-02 | 3.98E-04 | 9.10E-02 | — |
| Aroclor-1221 | 1.33E-02 | — | 0.50 | 66 | 0.0038 | 2.66E-02 | 2.03E-04 | ***3.54E+00*** | — |
| Aroclor-1232 | 2.28E-02 | — | 0.50 | 66 | 0.0038 | 4.56E-02 | 3.47E-04 | ***6.06E+00*** | — |
| Aroclor-1242 | 5.43E-02 | — | 0.50 | 66 | 0.069 | 1.09E-01 | 8.27E-04 | 7.93E-01 | — |
| Aroclor-1248 | 3.08E-02 | — | 0.50 | 66 | 0.067 | 6.16E-02 | 4.69E-04 | 4.59E-01 | — |
| Aroclor-1254 | 1.94E-01 | — | 0.50 | 66 | 0.11 | 3.88E-01 | 2.96E-03 | ***1.70E+00*** | — |
| Aroclor-1260 | 3.18E-02 | — | 0.50 | 66 | 0.72 | 6.36E-02 | 4.85E-04 | 4.42E-02 | — |
| Antimony | 199 | 0.13 | 32 | 1,400 | 5.4 | ***6.22E+00*** | 1.42E-01 | ***3.67E+01*** | Yes |
| Arsenic | 199 | 6.5 | 0.67 | 88 | 0.034 | ***2.99E+02*** | ***2.27E+00*** | ***5.84E+03*** | Yes |
| Barium | 51 | 132 | 16,000 | 700,000 | 1,648 | 3.19E-03 | 7.29E-05 | 3.09E-02 | No |
| Beryllium | 32 | 1.5 | 160 | 7,000 | 63 | 2.00E-01 | 4.57E-03 | 5.06E-01 | Yes |
| Bismuth | 1,400 | — | — | — | — | — | — | — | — |
| Cadmium | 21 | 0.56 | 80 | 3,500 | 0.69 | 2.63E-01 | 6.00E-03 | ***3.04E+01*** | Yes |
| Calcium | 2,200 | 17,200 | — | — | — | — | — | — | No |
| Chlorine | — | — | — | — | 1,000 | — | — | — | — |
| Chromium (total) | 2,830 | 19 | 120,000 | 5.25E+06 | 2,000 | 2.36E-02 | 5.39E-04 | ***1.41E+00*** | Yes |
| Cobalt | 26 | 16 | 24 | 1,050 | 4.3 | ***1.08E+00*** | 2.48E-02 | ***5.99E+00*** | Yes |
| Copper | 52 | 22 | 3,200 | 140,000 | 284 | 1.63E-02 | 3.71E-04 | 1.83E-01 | Yes |
| Cyanide | 4.5 | — | 48 | 2,100 | 0.97 | 9.38E-02 | 2.14E-03 | ***4.64E+00*** | — |
| Fluoride | 1,790 | 2.8 | 4,800 | 210,000 | 2,884 | 3.73E-01 | 8.52E-03 | 6.21E-01 | Yes |
| Formate+$A_2$ | 79 | — | — | — | — | — | — | — | — |
| Glycolate | 3,660 | — | — | — | — | — | — | — | — |
| Iron | 14,000 | 32,600 | 56,000 | 2.45E+06 | 5,645 | 2.50E-01 | 5.71E-03 | ***2.48E+00*** | No |
| Lanthanum | 24 | — | — | — | — | — | — | — | — |
| Lead | 3,340 | 10 | — | 1,000[e] | 3,000 | — | ***3.34E+00*** | ***1.11E+00*** | Yes |
| Manganese | 558 | 512 | 11,200 | 490,000 | 501 | 4.98E-02 | 1.14E-03 | ***1.11E+00*** | Yes |
| Mercury | 2.4 | 0.013 | 24 | 1,050 | 2.1 | 1.00E-01 | 2.29E-03 | ***1.15E+00*** | Yes |
| m-Xylene | 0.014 | — | 16,000 | 700,000 | 14 | 8.75E-07 | 2.00E-08 | 1.04E-03 | — |

**Table E-9. Comparison of Tank 241-C-203 Residual Waste Concentrations to Model Toxics Control Act Cleanup Levels. (2 of 2 sheets)**

| Analyte | Residual Concentration[a] (mg/kg) | 90th Percentile Background (mg/kg) | Soil Method B Unrestricted Land Use[b] (mg/kg) | Soil Method C Industrial Land Use[c] (mg/kg) | Soil Concentration Protective of Groundwater[d] (mg/kg) | Ratio of Residual Concentration in Tank 241-C-203 Residual Waste to Soil Cleanup Levels | | | Above 90th Percentile Background? |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Method B | Method C | 3-Phase | |
| Nickel | 222 | 19 | 1,600 | 70,000 | 130 | 1.39E-01 | 3.17E-03 | ***1.70E+00*** | Yes |
| Nitrate | 4,090 | 52 | 568,000 | 2.49E+07 | 180 | 7.20E-03 | 1.65E-04 | ***2.27E+01*** | Yes |
| Nitrite | 1,080 | — | 24,000 | 1.05E+06 | 13 | 4.50E-02 | 1.03E-03 | ***8.18E+01*** | — |
| Oxalate | 1,080 | — | — | — | — | — | — | — | — |
| o-Xylene | 0.0082 | — | 16,000 | 700,000 | 15 | 5.13E-07 | 1.17E-08 | 5.58E-04 | — |
| Phosphate | — | 0.79 | — | — | — | — | — | — | — |
| Polychlorinated Biphenyls (high risk) | — | — | 0.50 | 66 | — | — | — | — | — |
| Potassium | 1,990 | 2,150 | — | — | — | — | — | — | No |
| Selenium | 199 | 0.78 | 400 | 17,500 | 5.2 | 4.98E-01 | 1.14E-02 | ***3.83E+01*** | Yes |
| Silicon | 2,190 | 44 | — | — | — | — | — | — | Yes |
| Silver | 24 | 0.17 | 400 | 17,500 | 14 | 6.00E-02 | 1.37E-03 | ***1.76E+00*** | Yes |
| Sodium | 60,800 | 690 | — | — | — | — | — | — | Yes |
| Strontium | 250 | — | 48,000 | 2.10E+06 | 6,758 | 5.21E-03 | 1.19E-04 | 3.70E-02 | — |
| Sulfate | — | 237 | — | — | 1,000 | — | — | — | — |
| Thallium | 398 | 0.19 | — | — | 0.71 | — | — | ***5.59E+02*** | Yes |
| Total inorganic carbon as $CO_3$ | — | — | — | — | — | — | — | — | — |
| Total organic carbon | — | — | — | — | — | — | — | — | — |
| Tributyl phosphate | 9,440 | — | 111 | 14,583 | 0.50 | ***8.50E+01*** | 6.47E-01 | ***1.90E+04*** | — |
| Uranium | 339,000 | 3.2 | 240 | 10,500 | 270 | ***1.41E+03*** | ***3.23E+01*** | ***1.25E+03*** | Yes |
| Vanadium | 182 | 85 | 400 | 17,500 | 1,600 | 4.55E-01 | 1.04E-02 | 1.14E-01 | Yes |
| Xylene (m & p) | — | — | 16,000[f] | 700,000[f] | 14[f] | — | — | — | — |
| Xylenes | 0.02 | — | 16,000 | 700,000 | 15 | 1.25E-06 | 2.86E-08 | 1.37E-03 | — |
| Zinc | 446 | 68 | 24,000 | 1.05E+06 | 5,971 | 1.86E-02 | 4.25E-04 | 7.47E-02 | Yes |
| Zirconium | 114 | 39.8 | — | — | — | — | — | — | Yes |

Note: **Bolded** ratios indicate exceedances.

[a] RPP-RPT-42323, Rev. 3, "Hanford C-Farm Tank and Ancillary Equipment Residual Waste Inventory Estimates," Appendix D-1.3, "Mean Concentration of C-Farm Sludge Residual Waste (for post retrieval tank samples)."
[b] ECF-Hanford-10-0444, Rev. 3, "Documentation of Standard Method B Soil Cleanup Levels for Unrestricted Land Use."
[c] ECF-HANFORD-10-0453, Rev. 1, "Calculation of Standard Method C Direct Contact Soil Cleanup Levels for Industrial Land Use for the 100 Areas and 300 Area Remedial Investigation/Feasibility Study Reports."
[d] ECF-HANFORD-10-0442, Rev. 2, "Calculation of Nonradiological Soil Concentrations Protective of Groundwater Using the Fixed Parameter 3-Phase Equilibrium Partitioning Equation for the 100 Areas and 300 Area."
[e] The lead cleanup value is the Method A industrial soil cleanup level from Table 745-1 of Washington Administrative Code 173-340-745, "Soil Cleanup Standards for Industrial Properties," subsection (3) Method A industrial soil cleanup levels.
[f] The Xylene (m & p) cleanup values are represented using the calculated cleanup level for m-Xylene.

**Table E-10. Comparison of Tank 241-C-204 Residual Waste Concentrations to Model Toxics Control Act Cleanup Levels. (1 of 2 sheets)**

| Analyte | Residual Concentration[a] (mg/kg) | 90th Percentile Background (mg/kg) | Soil Method B Unrestricted Land Use[b] (mg/kg) | Soil Method C Industrial Land Use[c] (mg/kg) | Soil Concentration Protective of Groundwater[d] (mg/kg) | Ratio of Residual Concentration in Tank 241-C-204 Residual Waste to Soil Cleanup Levels | | | Above 90th Percentile Background? |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Method B | Method C | 3-Phase | |
| 1, 1, 2-Trichloroethylene (Trichloroethene) | 0.012 | — | 22 | 1,750 | 0.0036 | 5.52E-04 | 6.86E-06 | ***3.33E+00*** | — |
| 2-Butanone | 0.084 | — | 48,000 | 2.10E+06 | 20 | 1.75E-06 | 4.00E-08 | 4.27E-03 | — |
| 2-Propanone (Acetone) | 0.11 | — | 72,000 | 3.15E+06 | 29 | 1.53E-06 | 3.49E-08 | 3.81E-03 | — |
| 4-Methyl-2-pentanone | 0.013 | — | 6,400 | 280,000 | 2.7 | 2.03E-06 | 4.64E-08 | 4.81E-03 | — |
| Acetate | 18 | — | — | — | — | — | — | — | — |
| Aluminum | 6,550 | 11,800 | 80,000 | 3.50E+06 | 480,064 | 8.19E-02 | 1.87E-03 | 1.36E-02 | No |
| Ammonium | 19 | — | — | — | — | — | — | — | — |
| Aroclor-1016 | 1.02E-01 | — | 5.6 | 245 | 1.1 | 1.82E-02 | 4.16E-04 | 9.51E-02 | — |
| Aroclor-1221 | 1.42E-02 | — | 0.50 | 66 | 0.0038 | 2.84E-02 | 2.16E-04 | ***3.77E+00*** | — |
| Aroclor-1232 | 2.39E-02 | — | 0.50 | 66 | 0.0038 | 4.78E-02 | 3.64E-04 | ***6.35E+00*** | — |
| Aroclor-1242 | 5.69E-02 | — | 0.50 | 66 | 0.069 | 1.14E-01 | 8.67E-04 | 8.30E-01 | — |
| Aroclor-1248 | 3.22E-02 | — | 0.50 | 66 | 0.067 | 6.44E-02 | 4.91E-04 | 4.80E-01 | — |
| Aroclor-1254 | 2.03E-01 | — | 0.50 | 66 | 0.11 | 4.06E-01 | 3.09E-03 | ***1.78E+00*** | — |
| Aroclor-1260 | 3.34E-02 | — | 0.50 | 66 | 0.72 | 6.68E-02 | 5.09E-04 | 4.64E-02 | — |
| Antimony | 446 | 0.13 | 32 | 1,400 | 5.4 | ***1.39E+01*** | 3.19E-01 | ***8.22E+01*** | Yes |
| Arsenic | 271 | 6.5 | 0.67 | 88 | 0.034 | ***4.07E+02*** | ***3.10E+00*** | ***7.95E+03*** | Yes |
| Barium | 52 | 132 | 16,000 | 700,000 | 1,648 | 3.25E-03 | 7.43E-05 | 3.16E-02 | No |
| Beryllium | 7.9 | 1.5 | 160 | 7,000 | 63 | 4.94E-02 | 1.13E-03 | 1.25E-01 | Yes |
| Bismuth | 902 | — | — | — | — | — | — | — | — |
| Cadmium | 23 | 0.56 | 80 | 3,500 | 0.69 | 2.81E-01 | 6.43E-03 | 3.26E+01 | Yes |
| Calcium | 657 | 17,200 | — | — | — | — | — | — | No |
| Chlorine | — | — | — | — | 1,000 | — | — | — | — |
| Chromium (total) | 1,520 | 19 | 120,000 | 5.25E+06 | 2,000 | 1.27E-02 | 2.90E-04 | 7.60E-01 | Yes |
| Cobalt | 45 | 16 | 24 | 1,050 | 4.3 | ***1.88E+00*** | 4.29E-02 | ***1.04E+01*** | Yes |
| Copper | 24 | 22 | 3,200 | 140,000 | 284 | 7.50E-03 | 1.71E-04 | 8.45E-02 | Yes |
| Cyanide | 0.77 | — | 48 | 2,100 | 0.97 | 1.60E-02 | 3.67E-04 | 7.94E-01 | — |
| Fluoride | 9 | 2.8 | 4,800 | 210,000 | 2,884 | 1.88E-03 | 4.29E-05 | 3.12E-03 | Yes |
| Formate+$A_2$ | 18 | — | — | — | — | — | — | — | — |
| Glycolate | 15 | — | — | — | — | — | — | — | — |
| Iron | 35,800 | 32,600 | 56,000 | 2.45E+06 | 5,645 | 6.39E-01 | 1.46E-02 | ***6.34E+00*** | Yes |
| Lanthanum | 45 | — | — | — | — | — | — | — | — |
| Lead | 1,140 | 10 | — | 1,000[e] | 3,000 | — | ***1.14E+00*** | 3.80E-01 | Yes |
| Manganese | 266 | 512 | 11,200 | 490,000 | 501 | 2.38E-02 | 5.43E-04 | 5.31E-01 | No |
| Mercury | 164 | 0.013 | 24 | 1,050 | 2.1 | ***6.83E+00*** | 1.56E-01 | ***7.85E+01*** | Yes |
| m-Xylene | — | — | 16,000 | 700,000 | 14 | — | — | — | — |

**Table E-10. Comparison of Tank 241-C-204 Residual Waste Concentrations to Model Toxics Control Act Cleanup Levels. (2 of 2 sheets)**

| Analyte | Residual Concentration[a] (mg/kg) | 90th Percentile Background (mg/kg) | Soil Method B Unrestricted Land Use[b] (mg/kg) | Soil Method C Industrial Land Use[c] (mg/kg) | Soil Concentration Protective of Groundwater[d] (mg/kg) | Ratio of Residual Concentration in Tank 241-C-204 Residual Waste to Soil Cleanup Levels | | | Above 90th Percentile Background? |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Method B | Method C | 3-Phase | |
| Nickel | 893 | 19 | 1,600 | 70,000 | 130 | 5.58E-01 | 1.28E-02 | ***6.85E+00*** | Yes |
| Nitrate | 25 | 52 | 568,000 | 2.49E+07 | 180 | 4.40E-05 | 1.01E-06 | 1.39E-01 | No |
| Nitrite | 35 | — | 24,000 | 1.05E+06 | 13 | 1.46E-03 | 3.33E-05 | ***2.65E+00*** | — |
| Oxalate | 9.5 | — | — | — | — | — | — | — | — |
| o-Xylene | 0.0053 | — | 16,000 | 700,000 | 15 | 3.31E-07 | 7.57E-09 | 3.60E-04 | — |
| Phosphate | 88,700 | 0.79 | — | — | — | — | — | — | Yes |
| Polychlorinated Biphenyls (high risk) | — | — | 0.50 | 66 | — | — | — | — | — |
| Potassium | 2,250 | 2,150 | — | — | — | — | — | — | Yes |
| Selenium | 451 | 0.78 | 400 | 17,500 | 5.2 | ***1.13E+00*** | 2.58E-02 | ***8.67E+01*** | Yes |
| Silicon | 8,170 | 44 | — | — | — | — | — | — | Yes |
| Silver | 23 | 0.17 | 400 | 17,500 | 14 | 5.75E-02 | 1.31E-03 | ***1.69E+00*** | Yes |
| Sodium | 37,100 | 690 | — | — | — | — | — | — | Yes |
| Strontium | 409 | — | 48,000 | 2.10E+06 | 6,758 | 8.52E-03 | 1.95E-04 | ***6.05E-02*** | — |
| Sulfate | 14 | 237 | — | — | 1,000 | — | — | 1.40E-02 | No |
| Thallium | 451 | 0.19 | — | — | 0.71 | — | — | ***6.33E+02*** | Yes |
| Total inorganic carbon as $CO_3$ | — | — | — | — | — | — | — | — | — |
| Total organic carbon | — | — | — | — | — | — | — | — | — |
| Tributyl phosphate | 73,000 | — | 111 | 14,583 | 0.50 | ***6.57E+02*** | ***5.01E+00*** | ***1.47E+05*** | — |
| Uranium | 271,000 | 3.2 | 240 | 10,500 | 270 | ***1.13E+03*** | ***2.58E+01*** | ***1.00E+03*** | Yes |
| Vanadium | 45 | 85 | 400 | 17,500 | 1,600 | 1.13E-01 | 2.57E-03 | 2.81E-02 | No |
| Xylene (m & p) | 0.017 | — | 16,000[f] | 700,000[f] | 14[f] | 1.06E-06 | 2.43E-08 | 1.21E-03 | — |
| Xylenes | 0.022 | — | 16,000 | 700,000 | 15 | 1.38E-06 | 3.14E-08 | 1.50E-03 | — |
| Zinc | 269 | 68 | 24,000 | 1.05E+06 | 5,971 | 1.12E-02 | 2.56E-04 | 4.50E-02 | Yes |
| Zirconium | 23 | 39.8 | — | — | — | — | — | — | No |

Note: **Bolded** ratios indicate exceedances.

[a] RPP-RPT-42323, Rev. 3, "Hanford C-Farm Tank and Ancillary Equipment Residual Waste Inventory Estimates," Appendix D-1.3, "Mean Concentration of C-Farm Sludge Residual Waste (for post retrieval tank samples)."
[b] ECF-Hanford-10-0444, Rev. 3, "Documentation of Standard Method B Soil Cleanup Levels for Unrestricted Land Use."
[c] ECF-HANFORD-10-0453, Rev. 1, "Calculation of Standard Method C Direct Contact Soil Cleanup Levels for Industrial Land Use for the 100 Areas and 300 Area Remedial Investigation/Feasibility Study Reports."
[d] ECF-HANFORD-10-0442, Rev. 2, "Calculation of Nonradiological Soil Concentrations Protective of Groundwater Using the Fixed Parameter 3-Phase Equilibrium Partitioning Equation for the 100 Areas and 300 Area."
[e] The lead cleanup value is the Method A industrial soil cleanup level from Table 745-1 of Washington Administrative Code 173-340-745, "Soil Cleanup Standards for Industrial Properties," subsection (3) Method A industrial soil cleanup levels.
[f] The Xylene (m & p) cleanup values are represented using the calculated cleanup level for m-Xylene.

**Table E-11. Comparison of Average Residual Waste Concentrations for Retrieved Tanks (Ancillary Equipment) to Model Toxics Control Act Cleanup Levels. (1 of 2 sheets)**

| Analyte | Residual Concentration[a] (mg/kg) | 90th Percentile Background (mg/kg) | Soil Method B Unrestricted Land Use[b] (mg/kg) | Soil Method C Industrial Land Use[c] (mg/kg) | Soil Concentration Protective of Groundwater[d] (mg/kg) | Ratio of Residual Concentration in Ancillary Equipment Residual Waste to Soil Cleanup Levels | | | Above 90th Percentile Background? |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Method B | Method C | 3-Phase | |
| 1, 1, 2-Trichloroethylene (Trichloroethene) | 0.0075 | — | 22 | 1,750 | 0.0036 | 3.45E-04 | 4.29E-06 | ***2.08E+00*** | — |
| 2-Butanone | 0.047 | — | 48,000 | 2.10E+06 | 20 | 9.79E-07 | 2.24E-08 | 2.39E-03 | — |
| 2-Propanone (Acetone) | 0.098 | — | 72,000 | 3.15E+06 | 29 | 1.36E-06 | 3.11E-08 | 3.39E-03 | — |
| 4-Methyl-2-pentanone | 0.015 | — | 6,400 | 280,000 | 2.7 | 2.34E-06 | 5.36E-08 | 5.56E-03 | — |
| Acetate | 506 | — | — | — | — | — | — | — | — |
| Aluminum | 82,727 | 11,800 | 80,000 | 3.50E+06 | 480,064 | ***1.03E+00*** | 2.36E-02 | 1.72E-01 | Yes |
| Ammonium | 48 | — | — | — | — | — | — | — | — |
| Aroclor-1016 | 1.05E-01 | — | 5.6 | 245 | 1.1 | 1.87E-02 | 4.28E-04 | 9.78E-02 | — |
| Aroclor-1221 | 2.59E-02 | — | 0.50 | 66 | 0.0038 | 5.18E-02 | 3.94E-04 | ***6.88E+00*** | — |
| Aroclor-1232 | 3.76E-01 | — | 0.50 | 66 | 0.0038 | 7.51E-01 | 5.72E-03 | ***9.98E+01*** | — |
| Aroclor-1242 | 8.76E-02 | — | 0.50 | 66 | 0.069 | 1.75E-01 | 1.34E-03 | ***1.28E+00*** | — |
| Aroclor-1248 | 3.36E-02 | — | 0.50 | 66 | 0.067 | 6.72E-02 | 5.12E-04 | 5.00E-01 | — |
| Aroclor-1254 | 1.30E-01 | — | 0.50 | 66 | 0.11 | 2.59E-01 | 1.98E-03 | ***1.13E+00*** | — |
| Aroclor-1260 | 1.03E-01 | — | 0.50 | 66 | 0.72 | 2.06E-01 | 1.57E-03 | 1.43E-01 | — |
| Antimony | 97 | 0.13 | 32 | 1,400 | 5.4 | ***3.03E+00*** | 6.93E-02 | ***1.79E+01*** | Yes |
| Arsenic | 94 | 6.5 | 0.67 | 88 | 0.034 | ***1.41E+02*** | ***1.07E+00*** | ***2.76E+03*** | Yes |
| Barium | 88 | 132 | 16,000 | 700,000 | 1,648 | 5.50E-03 | 1.26E-04 | 5.34E-02 | No |
| Beryllium | 13 | 1.5 | 160 | 7,000 | 63 | 8.13E-02 | 1.86E-03 | 2.06E-01 | Yes |
| Bismuth | 1,193 | — | — | — | — | — | — | — | — |
| Cadmium | 40.8 | 0.56 | 80 | 3,500 | 0.69 | 5.10E-01 | 1.17E-02 | 5.91E+01 | Yes |
| Calcium | 3,030 | 17,200 | — | — | — | — | — | — | No |
| Chlorine | — | — | — | — | 1,000 | — | — | — | — |
| Chromium (total) | 2,756 | 19 | 120,000 | 5.25E+06 | 2,000 | 2.30E-02 | 5.25E-04 | 1.38E+00 | Yes |
| Cobalt | 28 | 16 | 24 | 1,050 | 4.3 | ***1.17E+00*** | 2.67E-02 | ***6.45E+00*** | Yes |
| Copper | 180 | 22 | 3,200 | 140,000 | 284 | 5.63E-02 | 1.29E-03 | 6.33E-01 | Yes |
| Cyanide | 5.6 | — | 48 | 2,100 | 0.97 | 1.17E-01 | 2.67E-03 | ***5.78E+00*** | — |
| Fluoride | 3,421 | 2.8 | 4,800 | 210,000 | 2,884 | 7.13E-01 | 1.63E-02 | ***1.19E+00*** | Yes |
| Formate+$A_2$ | 517 | — | — | — | — | — | — | — | — |
| Glycolate | 839 | — | — | — | — | — | — | — | — |
| Iron | 34,421 | 32,600 | 56,000 | 2.45E+06 | 5,645 | 6.15E-01 | 1.40E-02 | ***6.10E+00*** | Yes |
| Lanthanum | 32 | — | — | — | — | — | — | — | — |
| Lead | 2,163 | 10 | — | 1,000[e] | 3,000 | — | ***2.16E+00*** | 7.21E-01 | Yes |
| Manganese | 7,758 | 512 | 11,200 | 490,000 | 501 | 6.93E-01 | 1.58E-02 | ***1.55E+01*** | Yes |
| Mercury | 91 | 0.013 | 24 | 1,050 | 2.1 | ***3.79E+00*** | 8.67E-02 | ***4.36E+01*** | Yes |
| m-Xylene | 0.0097 | — | 16,000 | 700,000 | 14 | 6.06E-07 | 1.39E-08 | 7.18E-04 | — |

**Table E-11. Comparison of Average Residual Waste Concentrations for Retrieved Tanks (Ancillary Equipment) to Model Toxics Control Act Cleanup Levels. (2 of 2 sheets)**

| Analyte | Residual Concentration[a] (mg/kg) | 90th Percentile Background (mg/kg) | Soil Method B Unrestricted Land Use[b] (mg/kg) | Soil Method C Industrial Land Use[c] (mg/kg) | Soil Concentration Protective of Groundwater[d] (mg/kg) | Ratio of Residual Concentration in Ancillary Equipment Residual Waste to Soil Cleanup Levels | | | Above 90th Percentile Background? |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Method B | Method C | 3-Phase | |
| Nickel | 2,182 | 19 | 1,600 | 70,000 | 130 | ***1.36E+00*** | 3.12E-02 | ***1.67E+01*** | Yes |
| Nitrate | 1,200 | 52 | 568,000 | 2.49E+07 | 180 | 2.11E-03 | 4.83E-05 | ***6.67E+00*** | Yes |
| Nitrite | 601 | — | 24,000 | 1.05E+06 | 13 | 2.50E-02 | 5.72E-04 | ***4.55E+01*** | — |
| Oxalate | 13,646 | — | — | — | — | — | — | — | — |
| o-Xylene | 0.0052 | — | 16,000 | 700,000 | 15 | 3.25E-07 | 7.43E-09 | 3.54E-04 | — |
| Phosphate | 50,571 | 0.79 | — | — | — | — | — | — | Yes |
| Polychlorinated Biphenyls (high risk) | 0.15 | — | 0.50 | 66 | — | 3.00E-01 | 2.29E-03 | — | — |
| Potassium | 854 | 2,150 | — | — | — | — | — | — | No |
| Selenium | 113 | 0.78 | 400 | 17,500 | 5.2 | 2.83E-01 | 6.46E-03 | ***2.17E+01*** | Yes |
| Silicon | 5,581 | 44 | — | — | — | — | — | — | Yes |
| Silver | 257 | 0.17 | 400 | 17,500 | 14 | 6.43E-01 | 1.47E-02 | ***1.89E+01*** | Yes |
| Sodium | 65,810 | 690 | — | — | — | — | — | — | Yes |
| Strontium | 973 | — | 48,000 | 2.10E+06 | 6,758 | 2.03E-02 | 4.63E-04 | 1.44E-01 | — |
| Sulfate | 614 | 237 | — | — | 1,000 | — | — | 6.14E-01 | Yes |
| Thallium | 594 | 0.19 | — | — | 0.71 | — | — | ***8.34E+02*** | Yes |
| Total inorganic carbon as $CO_3$ | — | — | — | — | — | — | — | — | — |
| Total organic carbon | — | — | — | — | — | — | — | — | — |
| Tributyl phosphate | 12,140 | — | 111 | 14,583 | 0.50 | ***1.09E+02*** | 8.32E-01 | ***2.45E+04*** | — |
| Uranium | 100,091 | 3.2 | 240 | 10,500 | 270 | ***4.17E+02*** | ***9.53E+00*** | ***3.71E+02*** | Yes |
| Vanadium | 51 | 85 | 400 | 17,500 | 1,600 | 1.28E-01 | 2.91E-03 | 3.19E-02 | No |
| Xylene (m & p) | 0.012 | — | 16,000[f] | 700,000[f] | 14[f] | 7.50E-07 | 1.71E-08 | 8.57E-04 | — |
| Xylenes | 0.015 | — | 16,000 | 700,000 | 15 | 9.38E-07 | 2.14E-08 | 1.03E-03 | — |
| Zinc | 246 | 68 | 24,000 | 1.05E+06 | 5,971 | 1.03E-02 | 2.34E-04 | 4.12E-02 | Yes |
| Zirconium | 403 | 39.8 | — | — | — | — | — | — | Yes |

Note: **Bolded** ratios indicate exceedances.

[a] RPP-RPT-42323, Rev. 3, "Hanford C-Farm Tank and Ancillary Equipment Residual Waste Inventory Estimates," Appendix D-1.3, "Mean Concentration of C-Farm Sludge Residual Waste (for post retrieval tank samples)."

[b] ECF-Hanford-10-0444, Rev. 3, "Documentation of Standard Method B Soil Cleanup Levels for Unrestricted Land Use."

[c] ECF-HANFORD-10-0453, Rev. 1, "Calculation of Standard Method C Direct Contact Soil Cleanup Levels for Industrial Land Use for the 100 Areas and 300 Area Remedial Investigation/Feasibility Study Reports."

[d] ECF-HANFORD-10-0442, Rev. 2, "Calculation of Nonradiological Soil Concentrations Protective of Groundwater Using the Fixed Parameter 3-Phase Equilibrium Partitioning Equation for the 100 Areas and 300 Area."

[e] The lead cleanup value is the Method A industrial soil cleanup level from Table 745-1 of Washington Administrative Code 173-340-745, "Soil Cleanup Standards for Industrial Properties," subsection (3) Method A industrial soil cleanup levels.

[f] The Xylene (m & p) cleanup values are represented using the calculated cleanup level for m-Xylene.

**Table E-12. Comparison of Tank 241-C-101 Residual Waste Concentrations to Model Toxics Control Act Cleanup Levels.**

| Analyte | Residual Concentration[a] (mg/kg) | 90th Percentile Background (mg/kg) | Soil Method B Unrestricted Land Use[b] (mg/kg) | Soil Method C Industrial Land Use[c] (mg/kg) | Soil Concentration Protective of Groundwater[d] (mg/kg) | Ratio of Residual Concentration in Tank 241-C-101 Residual Waste to Soil Cleanup Levels | | | Above 90th Percentile Background? |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Method B | Method C | 3-Phase | |
| Aluminum | 1,728 | 11,800 | 80,000 | 3.50E+06 | 480,064 | 2.16E-02 | 4.94E-04 | 3.60E-03 | No |
| Bismuth | 486 | — | — | — | — | — | — | — | — |
| Calcium | 2,505 | 17,200 | — | — | — | — | — | — | No |
| Chlorine | 1,344 | — | — | — | 1,000 | — | — | ***1.34E+00*** | — |
| Chromium | 158 | 19 | 120,000 | 5.25E+06 | 2,000 | 1.32E-03 | 3.01E-05 | 7.90E-02 | Yes |
| Fluoride | 754 | 2.8 | 4,800 | 210,000 | 2,884 | 1.57E-01 | 3.59E-03 | 2.61E-01 | Yes |
| Iron | 19,106 | 32,600 | 56,000 | 2.45E+06 | 5,645 | 3.41E-01 | 7.80E-03 | ***3.38E+00*** | No |
| Lanthanum | 34 | — | — | — | — | — | — | — | — |
| Lead | 451 | 10 | — | 1,000[e] | 3,000 | — | 4.51E-01 | 1.50E-01 | Yes |
| Manganese | 156 | 512 | 11,200 | 490,000 | 501 | 1.39E-02 | 3.18E-04 | 3.12E-01 | No |
| Mercury | 65 | 0.013 | 24 | 1,050 | 2.1 | ***2.71E+00*** | 6.19E-02 | ***3.11E+01*** | Yes |
| Nickel | 71 | 19 | 1,600 | 70,000 | 130 | 4.44E-02 | 1.01E-03 | 5.44E-01 | Yes |
| Nitrate | 178,642 | 52 | 568,000 | 2.49E+07 | 180 | 3.15E-01 | 7.19E-03 | ***9.92E+02*** | Yes |
| Nitrite | 12,287 | — | 24,000 | 1.05E+06 | 13 | 5.12E-01 | 1.17E-02 | ***9.31E+02*** | — |
| Oxalate | 184 | — | — | — | — | — | — | — | — |
| Phosphate | 82,567 | 0.79 | — | — | — | — | — | — | Yes |
| Potassium | 189 | 2,150 | — | — | — | — | — | — | No |
| Silicon | 523 | 44 | — | — | — | — | — | — | Yes |
| Sodium | 104,571 | 690 | — | — | — | — | — | — | Yes |
| Strontium | 510 | — | 48,000 | 2.10E+06 | 6,758 | 1.06E-02 | 2.43E-04 | 7.55E-02 | — |
| Sulfate | 16,797 | 237 | — | — | 1,000 | — | — | ***1.68E+01*** | Yes |
| Total inorganic carbon as $CO_3$ | 1,431 | — | — | — | — | — | — | — | — |
| Total organic carbon | 654 | — | — | — | — | — | — | — | — |
| Uranium | 11,241 | 3.2 | 240 | 10,500 | 270 | ***4.68E+01*** | ***1.07E+00*** | ***4.16E+01*** | Yes |
| Zirconium | 8.3 | 39.8 | — | — | — | — | — | — | No |

Note: **Bolded** ratios indicate exceedances.

[a] RPP-RPT-42323, Rev. 3, "Hanford C-Farm Tank and Ancillary Equipment Residual Waste Inventory Estimates," Appendix B-2, "2014 BBI Inventory for SSTs." Inventory = Concentration × Density × Volume.

[b] ECF-Hanford-10-0444, Rev. 3, "Documentation of Standard Method B Soil Cleanup Levels for Unrestricted Land Use."

[c] ECF-HANFORD-10-0453, Rev. 1, "Calculation of Standard Method C Direct Contact Soil Cleanup Levels for Industrial Land Use for the 100 Areas and 300 Area Remedial Investigation/Feasibility Study Reports."

[d] ECF-HANFORD-10-0442, Rev. 2, "Calculation of Nonradiological Soil Concentrations Protective of Groundwater Using the Fixed Parameter 3-Phase Equilibrium Partitioning Equation for the 100 Areas and 300 Area."

[e] The lead cleanup value is the Method A industrial soil cleanup level from Table 745-1 of Washington Administrative Code 173-340-745, "Soil Cleanup Standards for Industrial Properties," subsection (3) Method A industrial soil cleanup levels.

**Table E-13. Comparison of Tank 241-C-102 Residual Waste Concentrations to Model Toxics Control Act Cleanup Levels. (1 of 2 sheets)**

| Analyte | Residual Concentration[a] (mg/kg) | 90th Percentile Background (mg/kg) | Soil Method B Unrestricted Land Use[b] (mg/kg) | Soil Method C Industrial Land Use[c] (mg/kg) | Soil Concentration Protective of Groundwater[d] (mg/kg) | Ratio of Residual Concentration in Tank 241-C-102 Residual Waste to Soil Cleanup Levels | | | Above 90th Percentile Background? |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Method B | Method C | 3-Phase | |
| **Based on Best-Basis Inventory** | | | | | | | | | |
| Aluminum | 144,063 | 11,800 | 80,000 | 3.50E+06 | 480,064 | ***1.80E+00*** | 4.12E-02 | 3.00E-01 | Yes |
| Bismuth | 1,254 | — | — | — | — | — | — | — | — |
| Calcium | 3,425 | 17,200 | — | — | — | — | — | — | No |
| Chlorine | 928 | — | — | — | 1,000 | — | — | 9.28E-01 | — |
| Chromium | 333 | 19 | 120,000 | 5.25E+06 | 2,000 | 2.78E-03 | 6.34E-05 | 1.66E-01 | Yes |
| Fluoride | 2,145 | 2.8 | 4,800 | 210,000 | 2,884 | 4.47E-01 | 1.02E-02 | 7.44E-01 | Yes |
| Iron | 9,121 | 32,600 | 56,000 | 2.45E+06 | 5,645 | 1.63E-01 | 3.72E-03 | ***1.62E+00*** | No |
| Lanthanum | 61 | — | — | — | — | — | — | — | — |
| Lead | 834 | 10 | — | 1,000[e] | 3,000 | — | 8.34E-01 | 2.78E-01 | Yes |
| Manganese | 777 | 512 | 11,200 | 490,000 | 501 | 6.94E-02 | 1.59E-03 | ***1.55E+00*** | Yes |
| Mercury | 3.1 | 0.013 | 24 | 1,050 | 2.1 | 1.29E-01 | 2.95E-03 | ***1.48E+00*** | Yes |
| Nickel | 3,322 | 19 | 1,600 | 70,000 | 130 | ***2.08E+00*** | 4.75E-02 | ***2.55E+01*** | Yes |
| Nitrate | 33,788 | 52 | 568,000 | 2.49E+07 | 180 | 5.95E-02 | 1.36E-03 | ***1.88E+02*** | Yes |
| Nitrite | 9,846 | — | 24,000 | 1.05E+06 | 13 | 4.10E-01 | 9.38E-03 | ***7.46E+02*** | — |
| Oxalate | 658 | — | — | — | — | — | — | — | — |
| Phosphate | 8,499 | 0.79 | — | — | — | — | — | — | Yes |
| Potassium | 622 | 2,150 | — | — | — | — | — | — | No |
| Silicon | 18,241 | 44 | — | — | — | — | — | — | Yes |
| Sodium | 54,931 | 690 | — | — | — | — | — | — | Yes |
| Strontium | 80 | — | 48,000 | 2.10E+06 | 6,758 | 1.67E-03 | 3.81E-05 | 1.18E-02 | — |
| Sulfate | 3,731 | 237 | — | — | 1,000 | — | — | ***3.73E+00*** | Yes |
| Total inorganic carbon as $CO_3$ | 39,125 | — | — | — | — | — | — | — | — |
| Total organic carbon | 964 | — | — | — | — | — | — | — | — |
| Uranium | 8,032 | 3.2 | 240 | 10,500 | 270 | ***3.35E+01*** | 7.65E-01 | ***2.97E+01*** | Yes |
| Zirconium | 2,674 | 39.8 | — | — | — | — | — | — | Yes |

**Table E-13. Comparison of Tank 241-C-102 Residual Waste Concentrations to Model Toxics Control Act Cleanup Levels. (2 of 2 sheets)**

| Analyte | Residual Concentration[a] (mg/kg) | 90th Percentile Background (mg/kg) | Soil Method B Unrestricted Land Use[b] (mg/kg) | Soil Method C Industrial Land Use[c] (mg/kg) | Soil Concentration Protective of Groundwater[d] (mg/kg) | Ratio of Residual Concentration in Tank 241-C-102 Residual Waste to Soil Cleanup Levels | | | Above 90th Percentile Background? |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Method B | Method C | 3-Phase | |
| **Based on Hanford Tank Waste Operations Simulator Inventory** | | | | | | | | | |
| Aluminum | 319,991 | 11,800 | 80,000 | 3.50E+06 | 480,064 | ***4.00E+00*** | 9.14E-02 | 6.67E-01 | Yes |
| Bismuth | 5.3 | — | — | — | — | — | — | — | — |
| Calcium | 1,662 | 17,200 | — | — | — | — | — | — | No |
| Chlorine | 0.013 | — | — | — | 1,000 | — | — | 1.30E-05 | — |
| Chromium | 2.66E+06 | 19 | 120,000 | 5.25E+06 | 2,000 | ***2.22E+01*** | 5.07E-01 | ***1.33E+03*** | Yes |
| Fluoride | 0.33 | 2.8 | 4,800 | 210,000 | 2,884 | 6.88E-05 | 1.57E-06 | 1.14E-04 | No |
| Iron | 3.43E+07 | 32,600 | 56,000 | 2.45E+06 | 5,645 | ***6.13E+02*** | ***1.40E+01*** | ***6.08E+03*** | Yes |
| Lanthanum | 178 | — | — | — | — | — | — | — | — |
| Lead | 183,886 | 10 | — | 1,000[e] | 3,000 | — | ***1.84E+02*** | ***6.13E+01*** | Yes |
| Manganese | 7,797 | 512 | 11,200 | 490,000 | 501 | 6.96E-01 | 1.59E-02 | ***1.56E+01*** | Yes |
| Mercury | 0.14 | 0.013 | 24 | 1,050 | 2.1 | 5.83E-03 | 1.33E-04 | 6.70E-02 | Yes |
| Nickel | 173 | 19 | 1,600 | 70,000 | 130 | 1.08E-01 | 2.47E-03 | ***1.33E+00*** | Yes |
| Nitrate | 2,118 | 52 | 568,000 | 2.49E+07 | 180 | 3.73E-03 | 8.52E-05 | ***1.18E+01*** | Yes |
| Nitrite | 0.14 | — | 24,000 | 1.05E+06 | 13 | 5.83E-06 | 1.33E-07 | 1.06E-02 | — |
| Oxalate | — | — | — | — | — | — | — | — | — |
| Phosphate | 1,329 | 0.79 | — | — | — | — | — | — | Yes |
| Potassium | 64,234 | 2,150 | — | — | — | — | — | — | Yes |
| Silicon | 5,539 | 44 | — | — | — | — | — | — | Yes |
| Sodium | 9,292 | 690 | — | — | — | — | — | — | Yes |
| Strontium | 204 | — | 48,000 | 2.10E+06 | 6,758 | 4.25E-03 | 9.71E-05 | 3.02E-02 | — |
| Sulfate | 8.1 | 237 | — | — | 1,000 | — | — | 8.10E-03 | No |
| Total inorganic carbon as $CO_3$ | 15,053 | — | — | — | — | — | — | — | — |
| Total organic carbon | 232 | — | — | — | — | — | — | — | — |
| Uranium | 8,300 | 3.2 | 240 | 10,500 | 270 | ***3.46E+01*** | 7.90E-01 | ***3.07E+01*** | Yes |
| Zirconium | 199 | 39.8 | — | — | — | — | — | — | Yes |

Note: **Bolded** ratios indicate exceedances.

[a] RPP-RPT-42323, Rev. 3, "Hanford C-Farm Tank and Ancillary Equipment Residual Waste Inventory Estimates," Appendix B-2, "2014 BBI Inventory for SSTs and Appendix C-2, 2014 Residual Inventory." Inventory = Concentration × Density × Volume.

[b] ECF-Hanford-10-0444, Rev. 3, "Documentation of Standard Method B Soil Cleanup Levels for Unrestricted Land Use."

[c] ECF-HANFORD-10-0453, Rev. 1, "Calculation of Standard Method C Direct Contact Soil Cleanup Levels for Industrial Land Use for the 100 Areas and 300 Area Remedial Investigation/Feasibility Study Reports."

[d] ECF-HANFORD-10-0442, Rev. 2, "Calculation of Nonradiological Soil Concentrations Protective of Groundwater Using the Fixed Parameter 3-Phase Equilibrium Partitioning Equation for the 100 Areas and 300 Area."

[e] The lead cleanup value is the Method A industrial soil cleanup level from Table 745-1 of Washington Administrative Code 173-340-745, "Soil Cleanup Standards for Industrial Properties," subsection (3) Method A industrial soil cleanup levels.

**Table E-14. Comparison of Tank 241-C-105 Residual Waste Concentrations to Model Toxics Control Act Cleanup Levels. (1 of 2 sheets)**

| Analyte | Residual Concentration[a] (mg/kg) | 90th Percentile Background (mg/kg) | Soil Method B Unrestricted Land Use[b] (mg/kg) | Soil Method C Industrial Land Use[c] (mg/kg) | Soil Concentration Protective of Groundwater[d] (mg/kg) | Ratio of Residual Concentration in Tank 241-C-105 Residual Waste to Soil Cleanup Levels | | | Above 90th Percentile Background? |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Method B | Method C | 3-Phase | |
| **Based on Best-Basis Inventory** | | | | | | | | | |
| Aluminum | 201,299 | 11,800 | 80,000 | 3.50E+06 | 480,064 | ***2.52E+00*** | 5.75E-02 | 4.19E-01 | Yes |
| Bismuth | 483 | — | — | — | — | — | — | — | — |
| Calcium | 2,571 | 17,200 | — | — | — | — | — | — | No |
| Chlorine | 403 | — | — | — | 1,000 | — | — | 4.03E-01 | — |
| Chromium | 500 | 19 | 120,000 | 5.25E+06 | 2,000 | 4.17E-03 | 9.52E-05 | 2.50E-01 | Yes |
| Fluoride | 1,069 | 2.8 | 4,800 | 210,000 | 2,884 | 2.23E-01 | 5.09E-03 | 3.71E-01 | Yes |
| Iron | 5,299 | 32,600 | 56,000 | 2.45E+06 | 5,645 | 9.46E-02 | 2.16E-03 | 9.39E-01 | No |
| Lanthanum | 3.5 | — | — | — | — | — | — | — | — |
| Lead | 466 | 10 | — | 1,000[e] | 3,000 | — | 4.66E-01 | 1.55E-01 | Yes |
| Manganese | 2,468 | 512 | 11,200 | 490,000 | 501 | 2.20E-01 | 5.04E-03 | ***4.93E+00*** | Yes |
| Mercury | 6.8 | 0.013 | 24 | 1,050 | 2.1 | 2.83E-01 | 6.48E-03 | ***3.26E+00*** | Yes |
| Nickel | 2,156 | 19 | 1,600 | 70,000 | 130 | ***1.35E+00*** | 3.08E-02 | ***1.65E+01*** | Yes |
| Nitrate | 10,571 | 52 | 568,000 | 2.49E+07 | 180 | 1.86E-02 | 4.25E-04 | ***5.87E+01*** | Yes |
| Nitrite | 8,740 | — | 24,000 | 1.05E+06 | 13 | 3.64E-01 | 8.32E-03 | ***6.62E+02*** | — |
| Oxalate | 1,727 | — | — | — | — | — | — | — | — |
| Phosphate | 7,805 | 0.79 | — | — | — | — | — | — | Yes |
| Potassium | 1,117 | 2,150 | — | — | — | — | — | — | No |
| Silicon | 40,130 | 44 | — | — | — | — | — | — | Yes |
| Sodium | 49,481 | 690 | — | — | — | — | — | — | Yes |
| Strontium | 186 | — | 48,000 | 2.10E+06 | 6,758 | 3.88E-03 | 8.86E-05 | 2.75E-02 | — |
| Sulfate | 3,792 | 237 | — | — | 1,000 | — | — | ***3.79E+00*** | Yes |
| Total inorganic carbon as $CO_3$ | 17,013 | — | — | — | — | — | — | — | — |
| Total organic carbon | 5,597 | — | — | — | — | — | — | — | — |
| Uranium | 9,909 | 3.2 | 240 | 10,500 | 270 | ***4.13E+01*** | 9.44E-01 | ***3.67E+01*** | Yes |
| Zirconium | 210 | 39.8 | — | — | — | — | — | — | Yes |

**Table E-14. Comparison of Tank 241-C-105 Residual Waste Concentrations to Model Toxics Control Act Cleanup Levels. (2 of 2 sheets)**

| Analyte | Residual Concentration[a] (mg/kg) | 90th Percentile Background (mg/kg) | Soil Method B Unrestricted Land Use[b] (mg/kg) | Soil Method C Industrial Land Use[c] (mg/kg) | Soil Concentration Protective of Groundwater[d] (mg/kg) | Ratio of Residual Concentration in Tank 241-C-105 Residual Waste to Soil Cleanup Levels | | | Above 90th Percentile Background? |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Method B | Method C | 3-Phase | |
| **Based on Hanford Tank Waste Operations Simulator Inventory** | | | | | | | | | |
| Aluminum | 327,286 | 11,800 | 80,000 | 3.50E+06 | 480,064 | ***4.09E+00*** | 9.35E-02 | 6.82E-01 | Yes |
| Bismuth | 1.4 | — | — | — | — | — | — | — | — |
| Calcium | 3,857 | 17,200 | — | — | — | — | — | — | No |
| Chlorine | 0.0091 | — | — | — | 1,000 | — | — | 9.10E-06 | — |
| Chromium | 1.73E+06 | 19 | 120,000 | 5.25E+06 | 2,000 | ***1.44E+01*** | 3.30E-01 | ***8.65E+02*** | Yes |
| Fluoride | 0.65 | 2.8 | 4,800 | 210,000 | 2,884 | 1.35E-04 | 3.10E-06 | 2.25E-04 | No |
| Iron | 3.64E+07 | 32,600 | 56,000 | 2.45E+06 | 5,645 | ***6.50E+02*** | ***1.49E+01*** | ***6.45E+03*** | Yes |
| Lanthanum | 3.2 | — | — | — | — | — | — | — | — |
| Lead | 247,646 | 10 | — | 1,000[e] | 3,000 | — | ***2.48E+02*** | ***8.25E+01*** | Yes |
| Manganese | 446,615 | 512 | 11,200 | 490,000 | 501 | ***3.99E+01*** | 9.11E-01 | ***8.92E+02*** | Yes |
| Mercury | 7.36E-05 | 0.013 | 24 | 1,050 | 2.1 | 3.07E-06 | 7.01E-08 | 3.52E-05 | No |
| Nickel | 61 | 19 | 1,600 | 70,000 | 130 | 3.81E-02 | 8.71E-04 | 4.68E-01 | Yes |
| Nitrate | 785 | 52 | 568,000 | 2.49E+07 | 180 | 1.38E-03 | 3.16E-05 | ***4.36E+00*** | Yes |
| Nitrite | 0.23 | — | 24,000 | 1.05E+06 | 13 | 9.58E-06 | 2.19E-07 | 1.74E-02 | — |
| Oxalate | — | — | — | — | — | — | — | — | — |
| Phosphate | 1.3 | 0.79 | — | — | — | — | — | — | Yes |
| Potassium | 7.88E+08 | 2,150 | — | — | — | — | — | — | Yes |
| Silicon | 3.76E+07 | — | 44 | — | — | — | — | — | Yes |
| Sodium | 6,046 | 690 | — | — | — | — | — | — | Yes |
| Strontium | 348,540 | — | 48,000 | 2.10E+06 | 6,758 | ***7.26E+00*** | 1.66E-01 | ***5.16E+01*** | — |
| Sulfate | 0.0055 | 237 | — | — | 1,000 | — | — | 5.50E-06 | No |
| Total inorganic carbon as $CO_3$ | 16,645 | — | — | — | — | — | — | — | — |
| Total organic carbon | 485 | — | — | — | — | — | — | — | — |
| Uranium | 1,764 | 3.2 | 240 | 10,500 | 270 | ***7.35E+00*** | 1.68E-01 | ***6.53E+00*** | Yes |
| Zirconium | 14 | — | 39.8 | — | — | — | — | — | No |

Note: **Bolded** ratios indicate exceedances.

[a] RPP-RPT-42323, Rev. 3, "Hanford C-Farm Tank and Ancillary Equipment Residual Waste Inventory Estimates," Appendix B-2, "2014 BBI Inventory for SSTs and Appendix C-2, 2014 Residual Inventory." Inventory = Concentration × Density × Volume.

[b] ECF-Hanford-10-0444, Rev. 3, "Documentation of Standard Method B Soil Cleanup Levels for Unrestricted Land Use."

[c] ECF-HANFORD-10-0453, Rev. 1, "Calculation of Standard Method C Direct Contact Soil Cleanup Levels for Industrial Land Use for the 100 Areas and 300 Area Remedial Investigation/Feasibility Study Reports."

[d] ECF-HANFORD-10-0442, Rev. 2, "Calculation of Nonradiological Soil Concentrations Protective of Groundwater Using the Fixed Parameter 3-Phase Equilibrium Partitioning Equation for the 100 Areas and 300 Area."

[e] The lead cleanup value is the Method A industrial soil cleanup level from Table 745-1 of Washington Administrative Code 173-340-745, "Soil Cleanup Standards for Industrial Properties," subsection (3) Method A industrial soil cleanup levels.

**Table E-15. Comparison of Tank 241-C-107 Residual Waste Concentrations to Model Toxics Control Act Cleanup Levels.**

| Analyte | Residual Concentration[a] (mg/kg) | 90th Percentile Background (mg/kg) | Soil Method B Unrestricted Land Use[b] (mg/kg) | Soil Method C Industrial Land Use[c] (mg/kg) | Soil Concentration Protective of Groundwater[d] (mg/kg) | Ratio of Residual Concentration in Tank 241-C-107 Residual Waste to Soil Cleanup Levels | | | Above 90th Percentile Background? |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Method B | Method C | 3-Phase | |
| Aluminum | 24,089 | 11,800 | 80,000 | 3.50E+06 | 480,064 | 3.01E-01 | 6.88E-03 | 5.02E-02 | Yes |
| Bismuth | 12,466 | — | — | — | — | — | — | — | — |
| Calcium | 613 | 17,200 | — | — | — | — | — | — | No |
| Chlorine | 729 | — | — | — | 1,000 | — | — | 7.29E-01 | — |
| Chromium | 674 | 19 | 120,000 | 5.25E+06 | 2,000 | 5.62E-03 | 1.28E-04 | 3.37E-01 | Yes |
| Fluoride | 7,367 | 2.8 | 4,800 | 210,000 | 2,884 | ***1.53E+00*** | 3.51E-02 | ***2.55E+00*** | Yes |
| Iron | 53,145 | 32,600 | 56,000 | 2.45E+06 | 5,645 | 9.49E-01 | 2.17E-02 | ***9.41E+00*** | Yes |
| Lanthanum | 126 | — | — | — | — | — | — | — | — |
| Lead | 4,405 | 10 | — | 1,000[e] | 3,000 | — | ***4.41E+00*** | ***1.47E+00*** | Yes |
| Manganese | 2,343 | 512 | 11,200 | 490,000 | 501 | 2.09E-01 | 4.78E-03 | ***4.68E+00*** | Yes |
| Mercury | 46 | 0.013 | 24 | 1,050 | 2.1 | ***1.92E+00*** | 4.38E-02 | ***2.20E+01*** | Yes |
| Nickel | 1,200 | 19 | 1,600 | 70,000 | 130 | 7.50E-01 | 1.71E-02 | ***9.20E+00*** | Yes |
| Nitrate | 43,679 | 52 | 568,000 | 2.49E+07 | 180 | 7.69E-02 | 1.76E-03 | ***2.43E+02*** | Yes |
| Nitrite | 26,151 | — | 24,000 | 1.05E+06 | 13 | ***1.09E+00*** | 2.49E-02 | ***1.98E+03*** | — |
| Oxalate | 257 | — | — | — | — | — | — | — | — |
| Phosphate | 57,645 | 0.79 | — | — | — | — | — | — | Yes |
| Potassium | 314 | 2,150 | — | — | — | — | — | — | No |
| Silicon | 1,247 | 44 | — | — | — | — | — | — | Yes |
| Sodium | 74,610 | 690 | — | — | — | — | — | — | Yes |
| Strontium | 208 | — | 48,000 | 2.10E+06 | 6,758 | 4.33E-03 | 9.90E-05 | 3.08E-02 | — |
| Sulfate | 6,289 | 237 | — | — | 1,000 | — | — | ***6.29E+00*** | Yes |
| Total inorganic carbon as $CO_3$ | 7,855 | — | — | — | — | — | — | — | — |
| Total organic carbon | 506 | — | — | — | — | — | — | — | — |
| Uranium | 7,695 | 3.2 | 240 | 10,500 | 270 | ***3.21E+01*** | 7.33E-01 | ***2.85E+01*** | Yes |
| Zirconium | 34 | 39.78 | — | — | — | — | — | — | Yes |

Note: **Bolded** ratios indicate exceedances.

[a] RPP-RPT-42323, Rev. 3, "Hanford C-Farm Tank and Ancillary Equipment Residual Waste Inventory Estimates," Appendix B-2, "2014 BBI Inventory for SSTs."
Inventory = Concentration × Density × Volume

[b] ECF-Hanford-10-0444, Rev. 3, "Documentation of Standard Method B Soil Cleanup Levels for Unrestricted Land Use."

[c] ECF-HANFORD-10-0453, Rev. 1, "Calculation of Standard Method C Direct Contact Soil Cleanup Levels for Industrial Land Use for the 100 Areas and 300 Area Remedial Investigation/Feasibility Study Reports."

[d] ECF-HANFORD-10-0442, Rev. 2, "Calculation of Nonradiological Soil Concentrations Protective of Groundwater Using the Fixed Parameter 3-Phase Equilibrium Partitioning Equation for the 100 Areas and 300 Area."

[e] The lead cleanup value is the Method A industrial soil cleanup level from Table 745-1 of Washington Administrative Code 173-340-745, "Soil Cleanup Standards for Industrial Properties," subsection (3) Method A industrial soil cleanup levels.

**Table E-16. Comparison of Tank 241-C-111 Residual Waste Concentrations to Model Toxics Control Act Cleanup Levels. (1 of 2 sheets)**

| Analyte | Residual Concentration[a] (mg/kg) | 90th Percentile Background (mg/kg) | Soil Method B Unrestricted Land Use[b] (mg/kg) | Soil Method C Industrial Land Use[c] (mg/kg) | Soil Concentration Protective of Groundwater[d] (mg/kg) | Ratio of Residual Concentration in Tank 241-C-111 Residual Waste to Soil Cleanup Levels | | | Above 90th Percentile Background? |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Method B | Method C | 3-Phase | |
| **Based on Best-Basis Inventory** | | | | | | | | | |
| Aluminum | 79,745 | 11,800 | 80,000 | 3.50E+06 | 480,064 | 9.97E-01 | 2.28E-02 | 1.66E-01 | Yes |
| Bismuth | 7,725 | — | — | — | — | — | — | — | — |
| Calcium | 10,965 | 17,200 | — | — | — | — | — | — | No |
| Chlorine | 1,101 | — | — | — | 1,000 | — | — | ***1.10E+00*** | — |
| Chromium | 365 | 19 | 120,000 | 5.25E+06 | 2,000 | 3.04E-03 | 6.95E-05 | 1.82E-01 | Yes |
| Fluoride | 4,022 | 2.8 | 4,800 | 210,000 | 2,884 | 8.38E-01 | 1.92E-02 | ***1.39E+00*** | Yes |
| Iron | 37,530 | 32,600 | 56,000 | 2.45E+06 | 5,645 | 6.70E-01 | 1.53E-02 | ***6.65E+00*** | Yes |
| Lanthanum | 283 | — | — | — | — | — | — | — | — |
| Lead | 3,813 | 10 | — | 1,000[e] | 3,000 | — | ***3.81E+00*** | ***1.27E+00*** | Yes |
| Manganese | 233 | 512 | 11,200 | 490,000 | 501 | 2.08E-02 | 4.76E-04 | 4.65E-01 | No |
| Mercury | 234 | 0.013 | 24 | 1,050 | 2.1 | ***9.75E+00*** | 2.23E-01 | ***1.12E+02*** | Yes |
| Nickel | 13,208 | 19 | 1,600 | 70,000 | 130 | ***8.26E+00*** | 1.89E-01 | ***1.01E+02*** | Yes |
| Nitrate | 73,266 | 52 | 568,000 | 2.49E+07 | 180 | 1.29E-01 | 2.95E-03 | ***4.07E+02*** | Yes |
| Nitrite | 27,412 | — | 24,000 | 1.05E+06 | 13 | ***1.14E+00*** | 2.61E-02 | ***2.08E+03*** | — |
| Oxalate | 263 | — | — | — | — | — | — | — | — |
| Phosphate | 59,809 | 0.79 | — | — | — | — | — | — | Yes |
| Potassium | 932 | 2,150 | — | — | — | — | — | — | No |
| Silicon | 7,077 | 44 | — | — | — | — | — | — | Yes |
| Sodium | 51,336 | 690 | — | — | — | — | — | — | Yes |
| Strontium | 178 | — | 48,000 | 2.10E+06 | 6,758 | 3.71E-03 | 8.48E-05 | 2.63E-02 | — |
| Sulfate | 6,280 | 237 | — | — | 1,000 | — | — | ***6.28E+00*** | Yes |
| Total inorganic carbon as $CO_3$ | 17,295 | — | — | — | — | — | — | — | — |
| Total organic carbon | 728 | — | — | — | — | — | — | — | — |
| Uranium | 11,762 | 3.2 | 240 | 10,500 | 270 | ***4.90E+01*** | ***1.12E+00*** | ***4.35E+01*** | Yes |
| Zirconium | 151 | 39.8 | — | — | — | — | — | — | Yes |

**Table E-16. Comparison of Tank 241-C-111 Residual Waste Concentrations to Model Toxics Control Act Cleanup Levels. (2 of 2 sheets)**

| Analyte | Residual Concentration[a] (mg/kg) | 90th Percentile Background (mg/kg) | Soil Method B Unrestricted Land Use[b] (mg/kg) | Soil Method C Industrial Land Use[c] (mg/kg) | Soil Concentration Protective of Groundwater[d] (mg/kg) | Ratio of Residual Concentration in Tank 241-C-111 Residual Waste to Soil Cleanup Levels | | | Above 90th Percentile Background? |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Method B | Method C | 3-Phase | |
| **Based on Hanford Tank Waste Operations Simulator Inventory** | | | | | | | | | |
| Aluminum | 226,677 | 11,800 | 80,000 | 3.50E+06 | 480,064 | ***2.83E+00*** | 6.48E-02 | 4.72E-01 | Yes |
| Bismuth | 66 | — | — | — | — | — | — | — | — |
| Calcium | 939 | 17,200 | — | — | — | — | — | — | No |
| Chlorine | 3.61E-04 | — | — | — | 1,000 | — | — | 3.61E-07 | — |
| Chromium | 2.99E+07 | 19 | 120,000 | 5.25E+06 | 2,000 | ***2.49E+02*** | ***5.70E+00*** | ***1.49E+04*** | Yes |
| Fluoride | 0.053 | 2.8 | 4,800 | 210,000 | 2,884 | 1.10E-05 | 2.52E-07 | 1.84E-05 | No |
| Iron | 1.12E+09 | 32,600 | 56,000 | 2.45E+06 | 5,645 | ***2.00E+04*** | ***4.57E+02*** | ***1.98E+05*** | Yes |
| Lanthanum | 914 | — | — | — | — | — | — | — | — |
| Lead | 6.26E+06 | 10 | — | 1,000[e] | 3,000 | — | ***6.26E+03*** | ***2.09E+03*** | Yes |
| Manganese | 540 | 512 | 11,200 | 490,000 | 501 | 4.82E-02 | 1.10E-03 | ***1.08E+00*** | Yes |
| Mercury | 2.23E-05 | 0.013 | 24 | 1,050 | 2.1 | 9.29E-07 | 2.12E-08 | 1.07E-05 | No |
| Nickel | 1,641 | 19 | 1,600 | 70,000 | 130 | ***1.03E+00*** | 2.34E-02 | ***1.26E+01*** | Yes |
| Nitrate | 1,760 | 52 | 568,000 | 2.49E+07 | 180 | 3.10E-03 | 7.08E-05 | ***9.78E+00*** | Yes |
| Nitrite | 0.0075 | — | 24,000 | 1.05E+06 | 13 | 3.13E-07 | 7.14E-09 | 5.68E-04 | — |
| Oxalate | — | — | — | — | — | — | — | — | — |
| Phosphate | 5,172 | 0.79 | — | — | — | — | — | — | Yes |
| Potassium | 1.05E+08 | 2,150 | — | — | — | — | — | — | Yes |
| Silicon | 88 | 44 | — | — | — | — | — | — | yes |
| Sodium | 15,003 | 690 | — | — | — | — | — | — | Yes |
| Strontium | 3.14E+06 | — | 48,000 | 2.10E+06 | 6,758 | ***6.54E+01*** | ***1.50E+00*** | ***4.65E+02*** | — |
| Sulfate | 0.0056 | 237 | — | — | 1,000 | — | — | 5.60E-06 | No |
| Total inorganic carbon as $CO_3$ | 69,485 | — | — | — | — | — | — | — | — |
| Total organic carbon | 17 | — | — | — | — | — | — | — | — |
| Uranium | 17,262 | 3.2 | 240 | 10,500 | 270 | ***7.19E+01*** | ***1.64E+00*** | ***6.39E+01*** | Yes |
| Zirconium | 7.9 | 39.8 | — | — | — | — | — | — | No |

Note: **Bolded** ratios indicate exceedances.

[a] RPP-RPT-42323, Rev. 3, "Hanford C-Farm Tank and Ancillary Equipment Residual Waste Inventory Estimates," Appendix B-2, "2014 BBI Inventory for SSTs and Appendix C-2, 2014 Residual Inventory." Inventory = Concentration × Density × Volume.

[b] ECF-Hanford-10-0444, Rev. 3, "Documentation of Standard Method B Soil Cleanup Levels for Unrestricted Land Use."

[c] ECF-HANFORD-10-0453, Rev. 1, "Calculation of Standard Method C Direct Contact Soil Cleanup Levels for Industrial Land Use for the 100 Areas and 300 Area Remedial Investigation/Feasibility Study Reports."

[d] ECF-HANFORD-10-0442, Rev. 2, "Calculation of Nonradiological Soil Concentrations Protective of Groundwater Using the Fixed Parameter 3-Phase Equilibrium Partitioning Equation for the 100 Areas and 300 Area."

[e] The lead cleanup value is the Method A industrial soil cleanup level from Table 745-1 of Washington Administrative Code 173-340-745, "Soil Cleanup Standards for Industrial Properties," subsection (3) Method A industrial soil cleanup levels.

**Table E-17. Comparison of Tank 241-C-112 Residual Waste Concentrations to Model Toxics Control Act Cleanup Levels.**

| Analyte | Residual Concentration[a] (mg/kg) | 90th Percentile Background (mg/kg) | Soil Method B Unrestricted Land Use[b] (mg/kg) | Soil Method C Industrial Land Use[c] (mg/kg) | Soil Concentration Protective of Groundwater[d] (mg/kg) | Ratio of Residual Concentration in Tank 241-C-112 Residual Waste to Soil Cleanup Levels | | | Above 90th Percentile Background? |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Method B | Method C | 3-Phase | |
| Aluminum | 4,837 | 11,800 | 80,000 | 3.50E+06 | 480,064 | 6.05E-02 | 1.38E-03 | 1.01E-02 | No |
| Bismuth | 19,231 | — | — | — | — | — | — | — | — |
| Calcium | 938 | 17,200 | — | — | — | — | — | — | No |
| Chlorine | 1,145 | — | — | — | 1,000 | — | — | ***1.15E+00*** | — |
| Chromium | 842 | 19 | 120,000 | 5.25E+06 | 2,000 | 7.02E-03 | 1.60E-04 | 4.21E-01 | Yes |
| Fluoride | 10,329 | 2.8 | 4,800 | 210,000 | 2,884 | ***2.15E+00*** | 4.92E-02 | ***3.58E+00*** | Yes |
| Iron | 10,227 | 32,600 | 56,000 | 2.45E+06 | 5,645 | 1.83E-01 | 4.17E-03 | ***1.81E+00*** | No |
| Lanthanum | 1.7 | — | — | — | — | — | — | — | — |
| Lead | 198 | 10 | — | 1,000[e] | 3,000 | — | 1.98E-01 | 6.60E-02 | Yes |
| Manganese | 95 | 512 | 11,200 | 490,000 | 501 | 8.48E-03 | 1.94E-04 | 1.90E-01 | No |
| Mercury | 0.38 | 0.013 | 24 | 1,050 | 2.1 | 1.58E-02 | 3.62E-04 | 1.82E-01 | Yes |
| Nickel | 21 | 19 | 1,600 | 70,000 | 130 | 1.31E-02 | 3.00E-04 | 1.61E-01 | Yes |
| Nitrate | 127,622 | 52 | 568,000 | 2.49E+07 | 180 | 2.25E-01 | 5.14E-03 | ***7.09E+02*** | Yes |
| Nitrite | 9,834 | — | 24,000 | 1.05E+06 | 13 | 4.10E-01 | 9.37E-03 | ***7.45E+02*** | — |
| Oxalate | 243 | — | — | — | — | — | — | — | — |
| Phosphate | 70,367 | 0.79 | — | — | — | — | — | — | Yes |
| Potassium | 322 | 2,150 | — | — | — | — | — | — | No |
| Silicon | 6,235 | 44 | — | — | — | — | — | — | Yes |
| Sodium | 100,524 | 690 | — | — | — | — | — | — | Yes |
| Strontium | 146 | — | 48,000 | 2.10E+06 | 6,758 | 3.04E-03 | 6.95E-05 | 2.16E-02 | — |
| Sulfate | 13,578 | 237 | — | — | 1,000 | — | — | ***1.36E+01*** | Yes |
| Total inorganic carbon as $CO_3$ | 6,002 | — | — | — | — | — | — | — | — |
| Total organic carbon | 533 | — | — | — | — | — | — | — | — |
| Uranium | 1,879 | 3.2 | 240 | 10,500 | 270 | ***7.83E+00*** | 1.79E-01 | ***6.96E+00*** | Yes |
| Zirconium | 139 | 39.8 | — | — | — | — | — | — | Yes |

Note: **Bolded** ratios indicate exceedances.

[a] RPP-RPT-42323, Rev. 3, "Hanford C-Farm Tank and Ancillary Equipment Residual Waste Inventory Estimates," Appendix B-2, "BBI Inventory for SSTs." Inventory = Concentration × Density × Volume.
[b] ECF-Hanford-10-0444, Rev. 3, "Documentation of Standard Method B Soil Cleanup Levels for Unrestricted Land Use."
[c] ECF-HANFORD-10-0453, Rev. 1, "Calculation of Standard Method C Direct Contact Soil Cleanup Levels for Industrial Land Use for the 100 Areas and 300 Area Remedial Investigation/Feasibility Study Reports."
[d] ECF-HANFORD-10-0442, Rev. 2, "Calculation of Nonradiological Soil Concentrations Protective of Groundwater Using the Fixed Parameter 3-Phase Equilibrium Partitioning Equation for the 100 Areas and 300 Area."
[e] The lead cleanup value is the Method A industrial soil cleanup level from Table 745-1 of Washington Administrative Code 173-340-745, "Soil Cleanup Standards for Industrial Properties," subsection (3) Method A industrial soil cleanup levels.

**Table E-18. Background Data for Selected Constituents for the Hanford Site. (2 sheets)**

| Analyte Name | Units | Lognormal 90th Percentile Background Value | Maximum Background Value | Source of Background Value |
|---|---|---|---|---|
| Aluminum | mg/kg | 11,800 | 28,800 | DOE/RL-92-24, Vol. 1, Rev. 4 |
| Antimony | mg/kg | 0.13 | 0.39 | ECF-HANFORD-11-0038 |
| Arsenic | mg/kg | 6.5 | 28 | DOE/RL-92-24, Vol. 1, Rev. 4 |
| Barium | mg/kg | 132 | 480 | DOE/RL-92-24, Vol. 1, Rev. 4 |
| Beryllium | mg/kg | 1.5 | 10 | DOE/RL-92-24, Vol. 1, Rev. 4 |
| Boron | mg/kg | 3.9 | 5.9 | ECF-HANFORD-11-0038 |
| Cadmium | mg/kg | 0.56 | 2.9 | ECF-HANFORD-11-0038 |
| Calcium | mg/kg | 17,200 | 105,000 | DOE/RL-92-24, Vol. 1, Rev. 4 |
| Chromium | mg/kg | 19 | 320 | DOE/RL-92-24, Vol. 1, Rev. 4 |
| Cobalt | mg/kg | 16 | 110 | DOE/RL-92-24, Vol. 1, Rev. 4 |
| Copper | mg/kg | 22 | 61 | DOE/RL-92-24, Vol. 1, Rev. 4 |
| Iron | mg/kg | 32,600 | 68,100 | DOE/RL-92-24, Vol. 1, Rev. 4 |
| Lead | mg/kg | 10 | 74 | DOE/RL-92-24, Vol. 1, Rev. 4 |
| Lithium | mg/kg | 13 | 19 | ECF-HANFORD-11-0038 |
| Magnesium | mg/kg | 7,060 | 32,300 | DOE/RL-92-24, Vol. 1, Rev. 4 |
| Manganese | mg/kg | 512 | 1,110 | DOE/RL-92-24, Vol. 1, Rev. 4 |
| Mercury | mg/kg | 0.013 | 0.029 | ECF-HANFORD-11-0038 |
| Molybdenum | mg/kg | 0.47 | 3.2 | ECF-HANFORD-11-0038 |
| Nickel | mg/kg | 19 | 200 | ECF-HANFORD-11-0038 |
| Potassium | mg/kg | 2,150 | 7,900 | DOE/RL-92-24, V.1, Rev.4 |
| Selenium | mg/kg | 0.78 | 0.84 | Ecology Publication #94-115 |
| Silver | mg/kg | 0.17 | 0.27 | ECF-HANFORD-11-0038 |
| Sodium | mg/kg | 690 | 6,060 | DOE/RL-92-24, V.1, Rev.4 |
| Thallium | mg/kg | 0.19 | 0.52 | ECF-HANFORD-11-0038 |
| Uranium | mg/kg | 3.2 | 4.0 | Isotopic Activity Conversion based on DOE/RL-96-12 values |
| Vanadium | mg/kg | 85 | 140 | DOE/RL-92-24, Vol. 1, Rev. 4 |
| Zinc | mg/kg | 68 | 366 | DOE/RL-92-24, Vol. 1, Rev. 4 |
| Zirconium | mg/kg | 9.2 | 26 | DOE/RL-92-24, Vol. 1, Rev. 4 |

**Table E-18. Background Data for Selected Constituents for the Hanford Site. (2 sheets)**

| Analyte Name | Units | Lognormal 90th Percentile Background Value | Maximum Background Value | Source of Background Value |
|---|---|---|---|---|
| Ammonia | mg/kg | 100 | 1,480 | DOE/RL-92-24, Vol. 1, Rev. 4 |
| Chloride | mg/kg | 2.8 | 73 | DOE/RL-92-24, Vol. 1, Rev. 4 |
| Fluoride | mg/kg | 52 | 906 | DOE/RL-92-24, Vol. 1, Rev. 4 |
| Nitrate | mg/kg | 0.79 | 225 | DOE/RL-92-24, Vol. 1, Rev. 4 |
| Phosphate | mg/kg | 237 | 12,600 | DOE/RL-92-24, Vol. 1, Rev. 4 |
| Sulfate | mg/kg | 11,800 | 28,800 | DOE/RL-92-24, Vol. 1, Rev. 4 |

References:

DOE/RL-92-24, 2001, Hanford Site Background: Part 1, Soil Background for Nonradioactive Analyte, Rev. 4, Volume 1, U.S. Department of Energy, Richland Operations Office, Richland, Washington.

DOE/RL-96-12, 1996, Hanford Site Background: Part 2, Soil Background for Radionuclides, Rev. 0, U.S. Department of Energy, Richland Operations Office, Richland, Washington.

ECF-HANFORD-11-0038, 2012, "Soil Background for Interim Use at the Hanford Site," Rev. 0, CH2M HILL Plateau Remediation Company, Richland, Washington.

Ecology Publication No. 94-115, 1994, "Natural Background Soil Metals Concentrations in Washington State," Toxics Cleanup Program, Washington State Department of Ecology, Olympia, Washington.

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Ecology Publication No. 94-115, 1994, "Natural Background Soil Metals Concentrations in Washington State," Toxics Cleanup Program, Washington State Department of Ecology, Olympia, Washington.

ECF-HANFORD-10-0442, 2012, "Calculation of Nonradiological Soil Concentrations Protective of Groundwater Using the Fixed Parameter 3-Phase Equilibrium Partitioning Equation for the 100 Areas and 300 Area," Rev. 1, CH2M HILL Plateau Remediation Company, Richland, Washington.

ECF-Hanford-10-0444, 2013, "Documentation of Standard Method B Soil Cleanup Levels for Unrestricted Land Use," Rev. 3, CH2M HILL Plateau Remediation Company, Richland, Washington.

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RPP-23403, 2013, "Single-Shell Tank Component Closure Data Quality Objectives," Rev. 5, Washington River Protection Solutions, LLC, Richland, Washington.

RPP-RPT-42323, 2015, "Hanford C-Farm Tank and Ancillary Equipment Residual Waste Inventory Estimates," Rev. 3, Appendix D-1.3, "Mean Concentration of C-Farm Sludge Residual Waste (for post retrieval tank samples)," Washington River Protection Solutions, LLC, Richland, Washington.

WAC 173-340, "Model Toxics Control Act – Cleanup," Washington Administrative Code, as amended.

WAC 173-340-740, "Unrestricted Land Use Soil Cleanup Standards," Washington Administrative Code, as amended.

WAC 173-340-745, "Soil Cleanup Standards for Industrial Properties," Washington Administrative Code, as amended.

WAC 173-340-747, "Deriving Soil Concentrations for Groundwater Protection," Washington Administrative Code, as amended.

# APPENDIX F

# DEVELOPMENT OF HETEROGENEOUS MEDIA MODEL AND COMPARISON TO BASE CASE MODEL RESULTS FOR WASTE MANAGEMENT AREA C RCRA CLOSURE ANALYSIS AND AND PERFORMANCE ASSESSMENT

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## Abbreviations and Acronyms

| | |
|---|---|
| 2D | two-dimensional |
| 3D | three-dimensional |
| cm | centimeter |
| EHM | equivalent homogeneous medium |
| HSU | hydrostratigraphic unit |
| L | Liter |
| m | meter |
| MPa | megapascal |
| pCi | picocurie |
| PA | performance assessment |
| RCA | RCRA Closure Analysis |
| RCRA | Resource Conservation and Recovery Act of 1976 |
| s | second |
| S&L | Sisson and Lu |
| STOMP | Subsurface Transport Over Multiple Phases |
| WMA | Waste Management Area |

# APPENDIX F

# DEVELOPMENT OF HETEROGENEOUS MEDIA MODEL AND COMPARISON TO BASE CASE MODEL RESULTS FOR WASTE MANAGEMENT AREA C RCRA CLOSURE ANALYSIS AND PERFORMANCE ASSESSMENT

## F.1 INTRODUCTION

Small-scale laboratory measurements were used to estimate field-scale parameters for the Waste Management Area (WMA) C model (Section 6). Each heterogeneous geologic unit was replaced by an equivalent homogeneous medium (EHM) with macroscopic flow properties. Each heterogeneous unit was assigned its upscaled or effective hydraulic properties; the simulated flow fields calculated the bulk or mean flow behavior at the field scale. Upscaling, in effect, accounts for differences in scale between small, core-scale measurements and large, field-scale modeling.

While the EHM model is the base case for Resource Conservation and Recovery Act of 1976 (RCRA) closure analysis (RCA) performance assessment (PA) modeling, an alternative case is considered here based on the natural moisture content distribution. For heterogeneous media, the natural moisture content distribution, in the absence of anthropogenic recharge, can be used as an indicator of sediment texture (Appendix B). Field-measured moisture contents can then be used as indirect evidence from which estimates of soil hydraulic properties can be inferred.

In the absence of anthropogenic recharge, moisture content data correlate well with sediment texture ("Stochastic analysis of moisture plume dynamics of a field injection experiment" [Ye et al. 2005]). Higher moisture contents are associated with fine-textured sediments and lower moisture contents are associated with coarse-textured sediments. In the absence of anthropogenic recharge, field-measured moisture contents are assumed to be in equilibrium with natural recharge. These inferences, as well as the results of geostatistical analysis of the moisture content database, are used to identify and select hydraulic properties for input into a vadose zone model for WMA C.

An extensive set of moisture content data exists at WMA C for neutron moisture logging of direct push borehole and drywell locations. Using a geostatistical interpretation of the moisture data, an alternative vadose zone conceptual model has been developed, which is denoted as the "Heterogeneous Case" (RPP-CALC-60345, "Heterogeneous Media Model for Waste Management Area C Performance Assessment"). From the three-dimensional (3D) WMA C base case model, three cross sections have been selected to develop two-dimensional (2D) Subsurface Transport Over Multiple Phases (STOMP)©[1] models for both the EHM base case model and heterogeneous case model. The results are compared to identify the impact of heterogeneity for predicting concentrations in the water table.

[1] Subsurface Transport Over Multiple Phases (STOMP)© is copyrighted by Battelle Memorial Institute, 1996.

## F.2 METHODOLOGY FOR DEVELOPING TWO-DIMENSIONAL CROSS-SECTION MODELS FROM THE THREE-DIMENSIONAL MODEL

Two-dimensional cross sections are developed from a 3D moisture content distribution model by interpolating on the grid discretization developed for the 3D STOMP© WMA C RCA and PA model. These selected cross sections form the basis for developing alternative heterogeneous case models based on moisture content data. The details of the approach for developing the 2D cross-sectional model are described in Sections F.2.1 through F.2.3.

### F.2.1 Waste Management Area C RCRA Closure Analysis and Performance Assessment Three-Dimensional STOMP© Model

Figure F-1 (Section 7.3.2.2.1) presents a cutaway section of geologic units in the 3D STOMP© WMA C RCA and PA model domain. The WMA C RCA and PA 3D STOMP©-based model domain is 737.9 m (2,421 ft) northwest to southeast by 795.3 m (2,609 ft) southwest to northeast by 116 m (381 ft), vertically, extending about 12 m (49 ft) below the water table.

For the purpose of developing the heterogeneous geologic models, the moisture content distribution was interpolated on the 3D STOMP© WMA C RCA and PA model domain and then cross sections were developed.

### F.2.2 Development of Three-Dimensional Distributions of Moisture Content

A 3D model of the distribution of moisture content has been developed based on a geostatistical evaluation of soil moisture data collected at WMA C. An extensive set of moisture content data and information exists at WMA C from neutron moisture logging of direct push borehole and drywell locations. These moisture content data have been collected long after the occurrence of past leaks and discharges at the farm (RPP-CALC-60345), and therefore are regarded as representing the vadose zone at equilibrium with natural recharge. A geostatistical analysis of the moisture content data yielded vertical as well as horizontal correlation length scales for moisture content. The experimental variograms for moisture content used in the geostatistical analysis were fit with an exponential model having a vertical correlation length of ~15 m and a horizontal correlation length of ~85 m. Subsequent krigging yielded a heterogeneous moisture distribution, which, unlike the EHM approximation, captures a higher level of spatial variability of moisture content and associated variability in hydraulic properties (RPP-CALC-60345). Figure F-2 represents the plan view of 3D WMA C RCA and PA model domain and krigged moisture content based on the level of discretization of the model domain. Figure F-3 (RPP-CALC-60345) presents the location of the different cross sections of the model; Figure F-4 and Figure F-5 show the 2D cross sections of the model.

### F.2.3 Development of Two-Dimensional STOMP©-Based Models from Three-Dimensional Models

**F.2.3.1 Base Case Two-Dimensional Model.** From the 3D base case model, 2D models were extracted for three different cross sections for comparison to the heterogeneous case model-based cross sections. Figure F-6 shows the location of the selected cross sections. These cross sections

were selected to be in the same locations as the cross section B-B' and cross section C-C' shown in Figure F-3. Two orthogonal directions were chosen to represent behavior in different directions. Only cross section 1 slices through the tanks. Heterogeneity was only considered for the H1 and H2 units because of lack of moisture data for the deeper units.

**F.2.3.1.1 Interpretation of the Three-Dimensional Moisture Model.** The following steps were followed to develop the geology of the heterogeneous model from the moisture content model.

1. Four different moisture content bands were used to define the heterogeneous layers in the H1 and H2 units based on the histogram of the observed moisture content data reported in RPP-CALC-60345. These moisture content bands qualitatively correlate with the sand/silt content of the sediments as inferred from the characterization of vadose zone sediments within WMA C (PNNL-15503, "Characterization of Vadose Zone Sediments Below the C Tank Farm: Borehole C4297 and RCRA Borehole 299-E27-22"). Typically, increasing volumetric moisture content from 6% to >10% reflects increasing silt content in the sediments. Based on the characterization of vadose zone sediments in WMA C (PNNL-15503), it is observed that <6% moisture content is associated with sediments with no, or negligible, silt content (primarily sand or gravelly sand), while sediment with >10% volumetric moisture content is silt-dominated. For volumetric moisture contents within 6% and 10%, the increasing moisture content is understood to reflect increasing silt content. To define the moisture content bands for the purpose of model parameterization, two additional classes are introduced, one with 6% to 8% and the other with 8% to 10% volumetric moisture content. The four moisture content bands are summarized below:

    - 2% to 6% – correlates to sand with some gravel fraction
    - 6% to 8% – correlates to sandy units with minor silt fraction
    - 8% to 10% – correlates to sandy-silty sand units
    - >10% – correlates to predominantly silty units.

2. The moisture content values from the moisture model were interpolated on the 3D STOMP© model grid.

3. The STOMP© model zonation number for each of the model grid blocks was printed out along with the moisture content values.

4. The base case 3D STOMP© model has five different hydrostratigraphic units (HSUs) defined as implemented in STOMP© as rock/soil zones:

    - Backfill – gravel-dominated
    - H1 – gravel-dominated unit
    - H2 – sand-dominated unit
    - H3 – gravel-dominated unit
    - Aquifer.

5. Four additional rock/soil zones are introduced corresponding to the four moisture content bands by altering the original zones. These four zones are added within the WMA C model domain defined by the krigged area in Figure F-6 (red rectangular box). For areas outside this box, the original five rock/soil zones are retained, thus leading to total of nine different rock/soil zones.

6. Generate 2D models for the heterogeneous case and the base case along three selected cross sections. Figure F-7, Figure F-8, and Figure F-9 contrast the geologic representation of the RCA and PA base case model and the heterogeneous model for the selected cross sections.

**F.2.3.2 Vadose Zone Hydraulic Properties for Different Units.** Table F-1 shows the vadose zone hydraulic properties for the HSUs defined in the base case model. For the heterogeneous case, hydraulic properties for four additional zones/layers have been selected that compare favorably with the moisture content data under current recharge conditions.

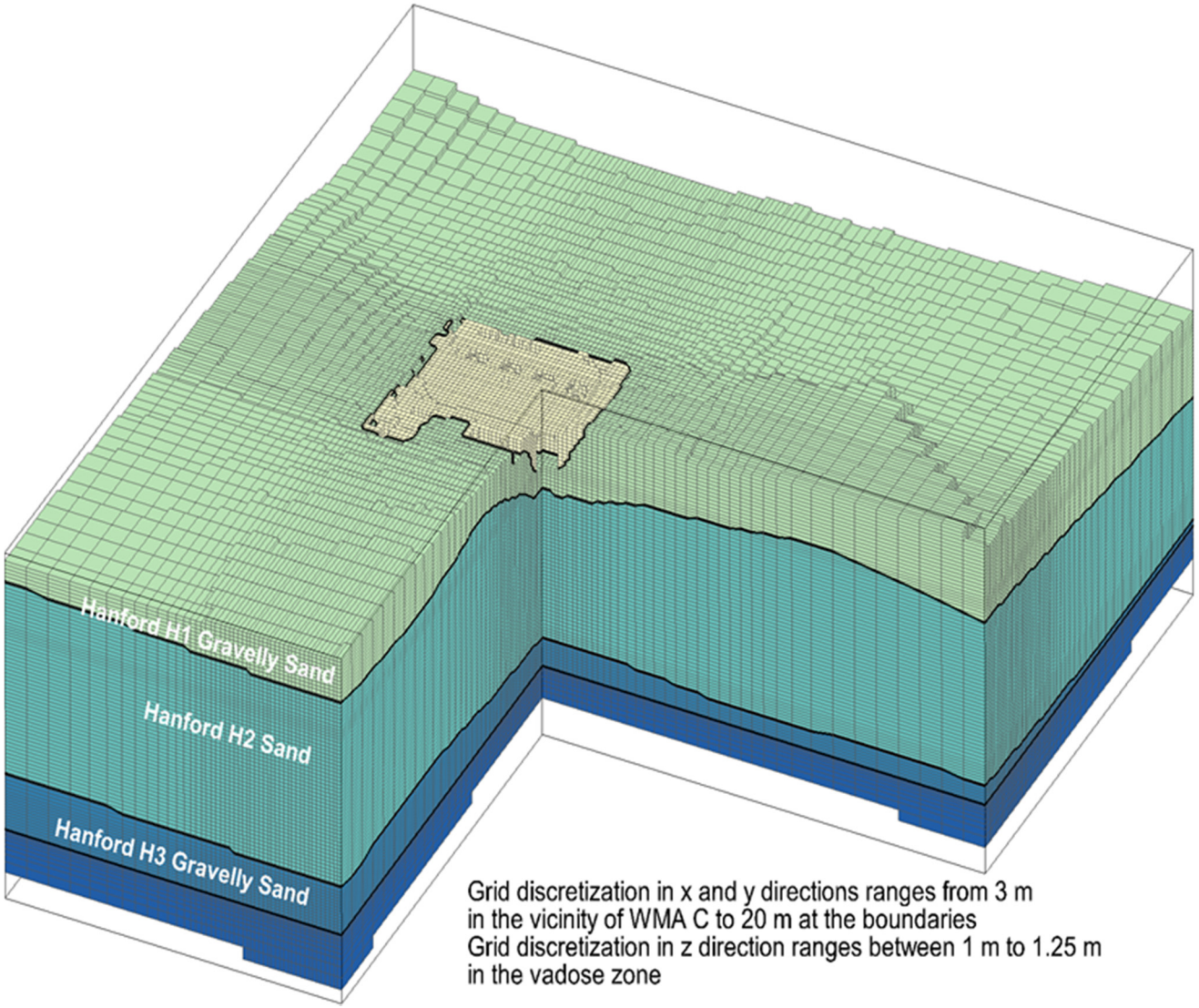
The hydraulic properties for the new zones/layers have been selected by analyzing 44 Integrated Disposal Facility sandy samples as presented in Appendix B, Basis for Development of Vadose Zone Hydraulic Properties at Waste Management Area C. Figure F-10 shows the moisture retention curves and unsaturated hydraulic conductivity curves for the 44 Integrated Disposal Facility samples. Four samples out of the 44 samples were selected to represent the new moisture content-based units. The four samples were chosen such that the resulting moisture content distribution at unit gradient condition corresponds to the moisture content bands represented by the samples. Figure F-11 shows the moisture retention curves and unsaturated hydraulic conductivity curves for the four new units that correlate with the four zones based on moisture content. Table F-2 summarizes the properties for all the new units.

Moisture-dependent anisotropy was applied to the 2D cross-section model derived from the 3D base case model to be consistent with the upscaling methodology used for EHM-based models. However, the impact of anisotropy was assumed to be represented by the heterogeneous distribution of sediments and was therefore not applied for the 2D heterogeneous models.

**F.2.3.2.1 Contaminant Source and Model Output.** For each cross-sectional model, an arbitrary source concentration of 1,000 pCi/m$^3$ of $^{99}$Tc (in bulk volume) was injected into the subsurface at the base of the backfill material beginning in the calendar year 2020. Here the objective was to compare the transport behavior of the contaminant between the EHM and heterogeneous model. Figure F-12 shows the location of the source and the point of calculation for all the cases. The vertical location of the contaminant mass is positioned 68 m above the water table. The output concentrations were observed at a point of calculation 100 m downgradient from the source location.

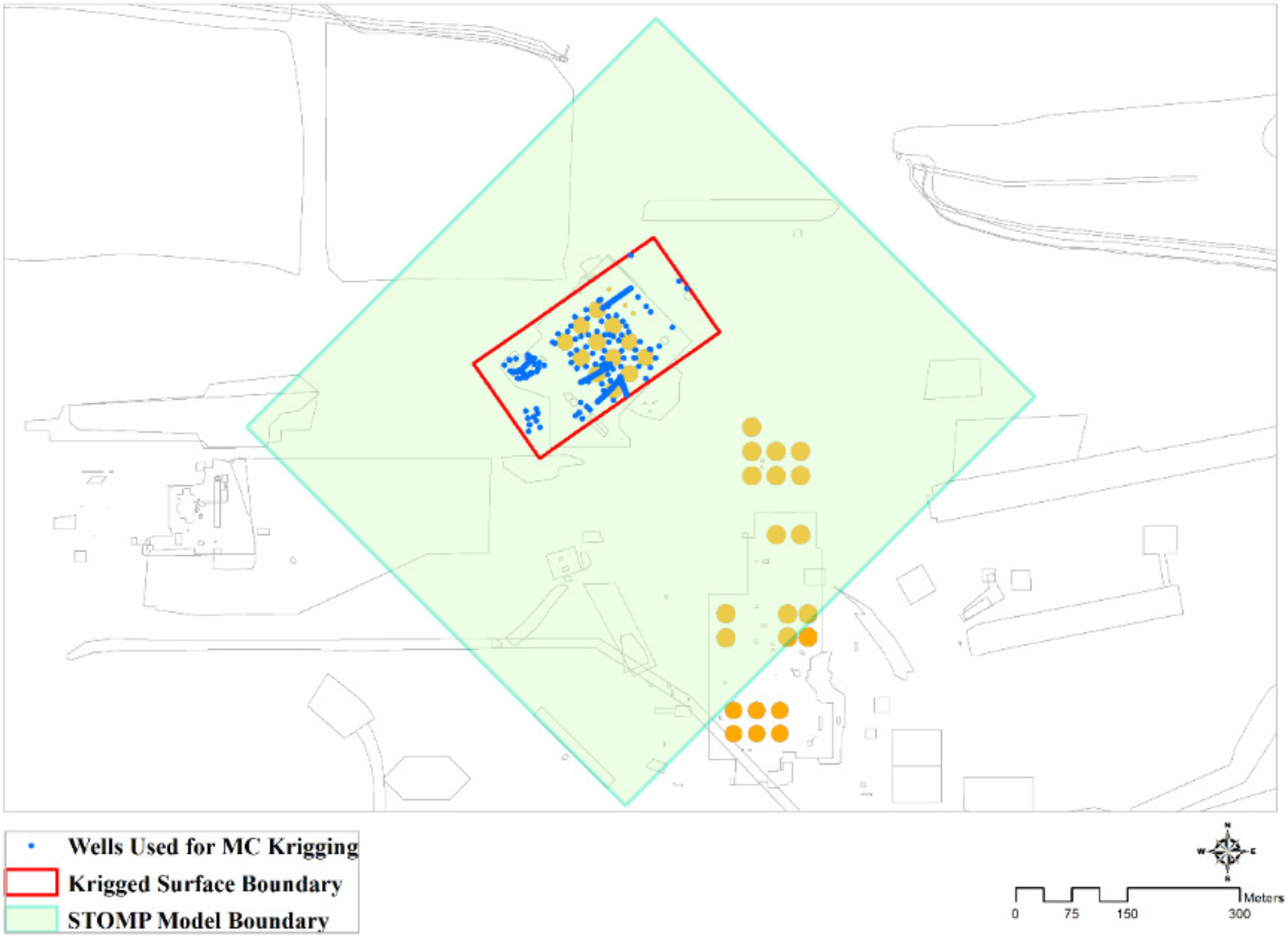
**F.2.3.2.2 Recharge Rate.** A 3.5 mm/yr recharge rate corresponding to long-term recharge rate for the WMA C base model domain was applied throughout the simulation duration.

**Figure F-1. Geologic Layers in the Three-Dimensional Waste Management Area C RCRA Closure Analysis and Performance Assessment Model.**




RCRA = Resource Conservation and Recovery Act of 1976 WMA = Waste Management Area

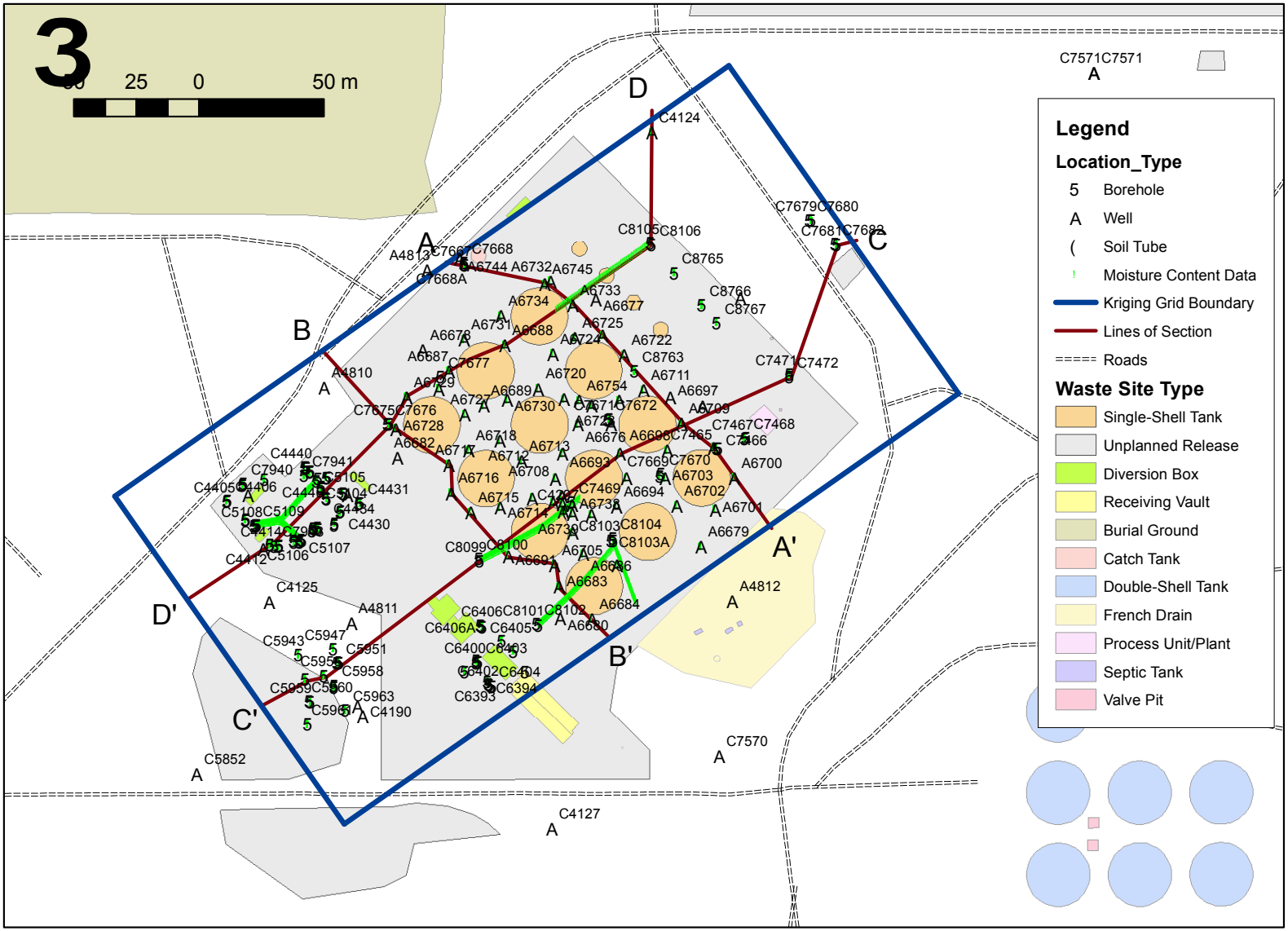
**Figure F-2. Plan View of Waste Management Area C RCRA Closure Analysis and Performance Assessment Model and Moisture Content-Based Model.**




RCRA = Resource Conservation and Recovery Act of 1976

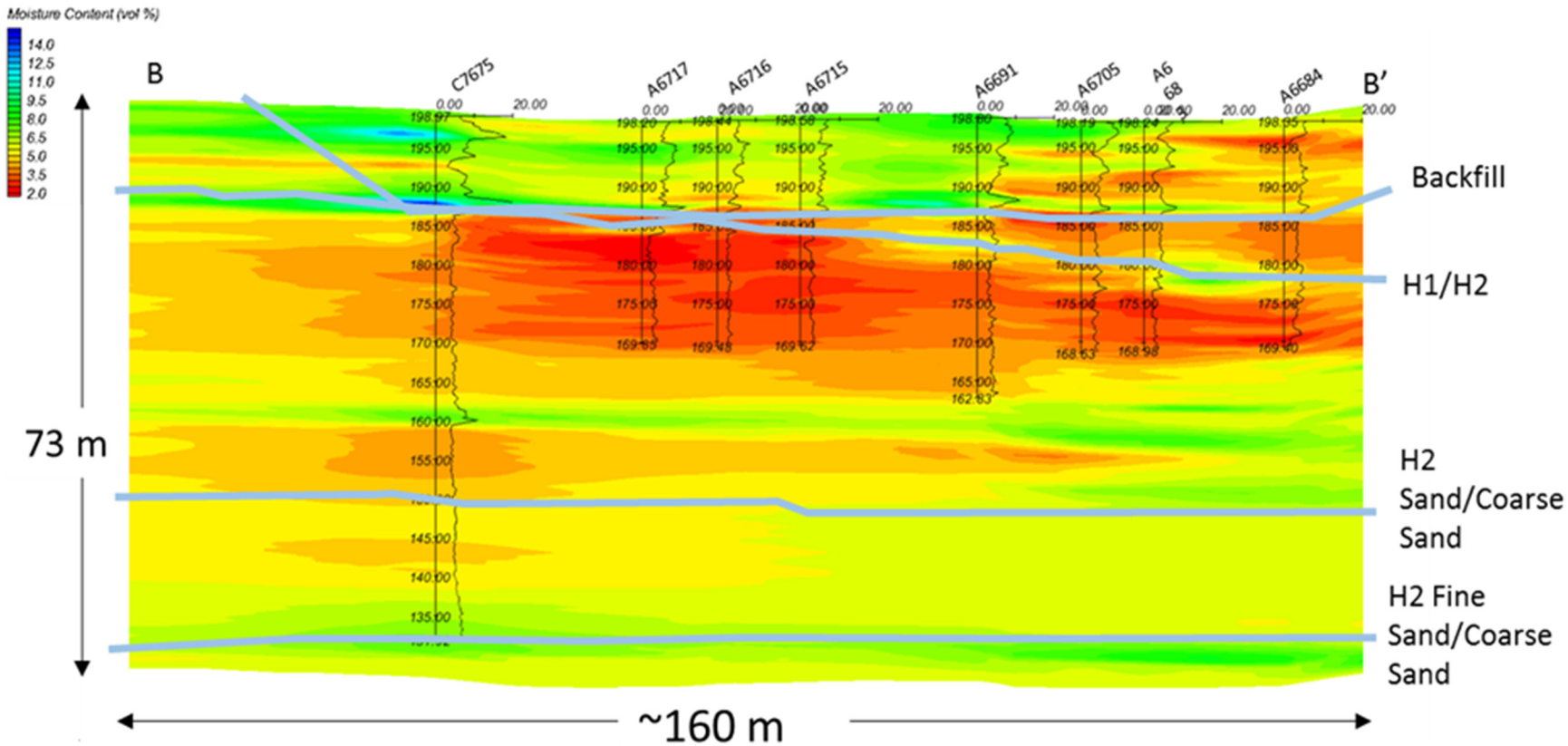
Subsurface Transport Over Multiple Phases (STOMP)© is copyrighted by Battelle Memorial Institute, 1996.

**Figure F-3. Waste Management Area C Basemap with Moisture Content (vol %) Data Locations.**



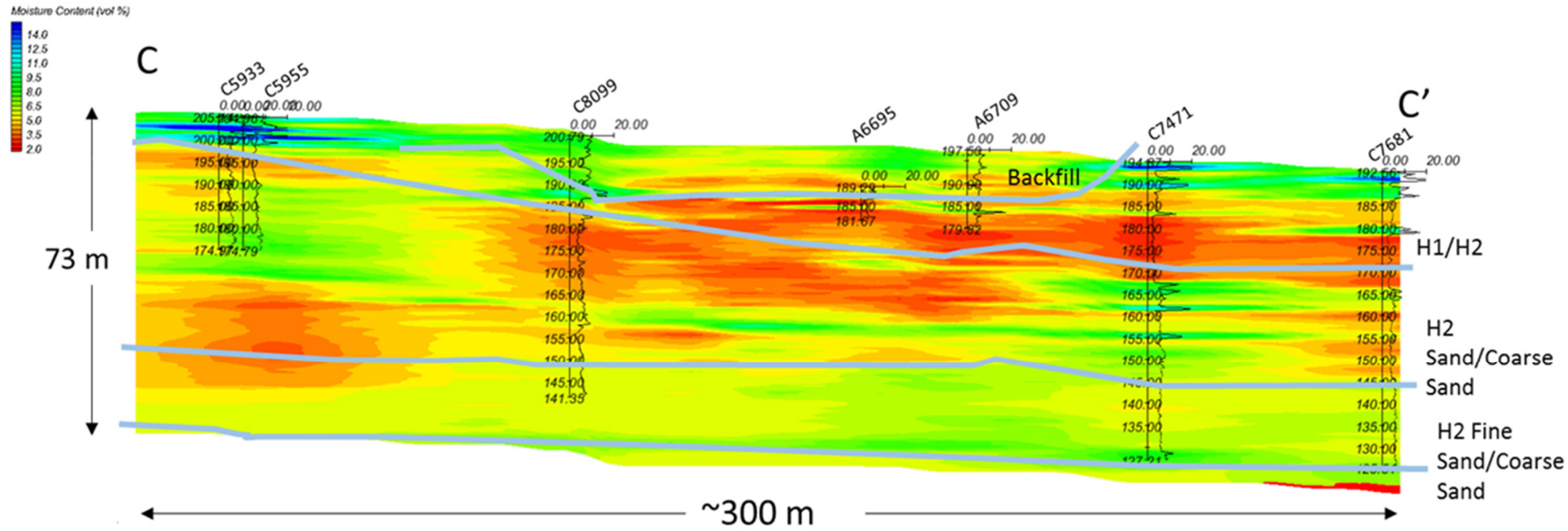

Reference: RPP-CALC-60345, "Heterogeneous Media Model for Waste Management Area C Performance Assessment."

**Figure F-4. Cross Section B-B' with Continuous Contours for Moisture Content (vol %) Interpolation.**



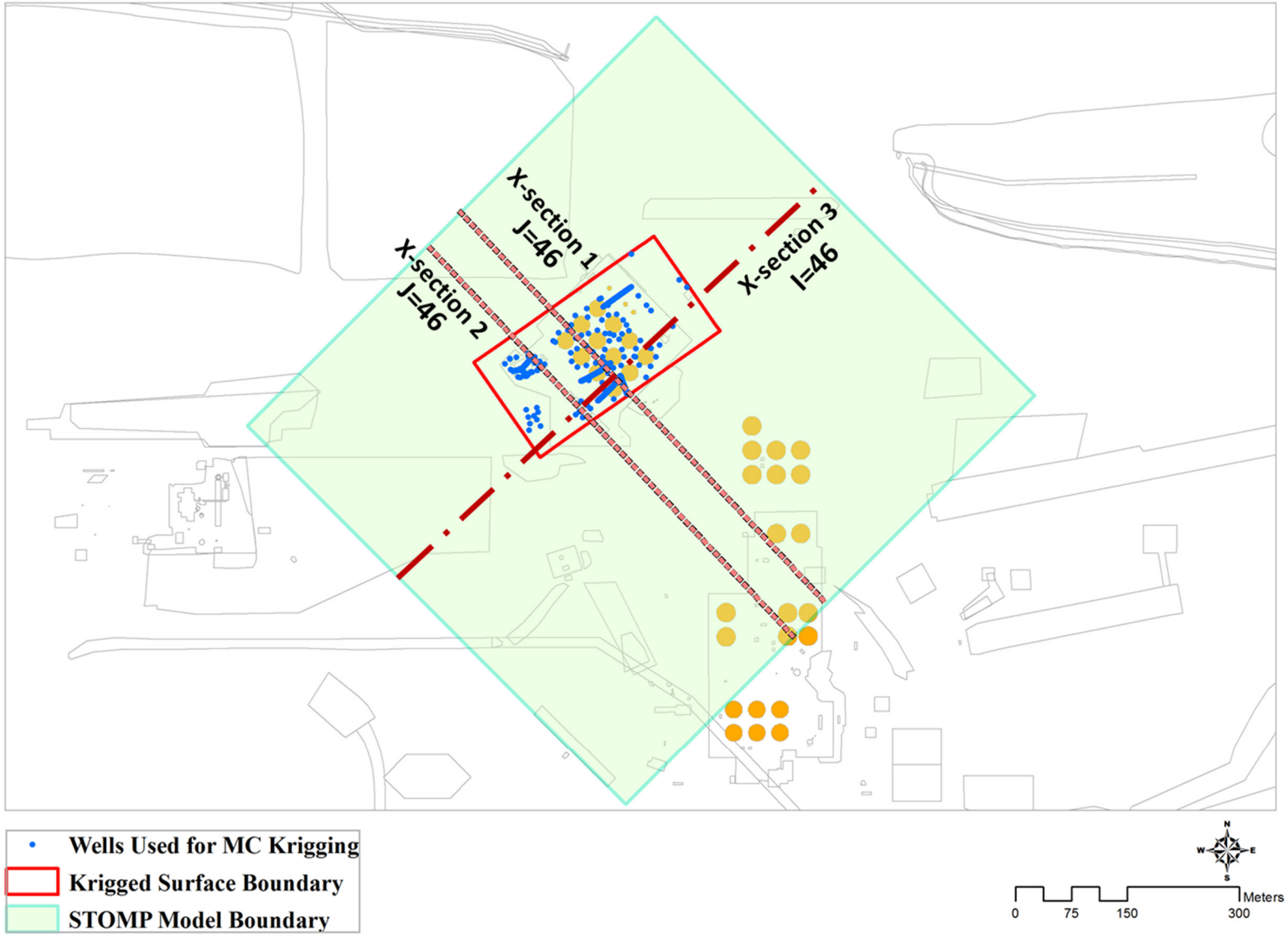

Reference: RPP-CALC-60345, "Heterogeneous Media Model for Waste Management Area C Performance Assessment."

**Figure F-5. Cross Section C-C' with Continuous Contours for Moisture Content (vol %) Interpolation.**




Reference: RPP-CALC-60345, "Heterogeneous Media Model for Waste Management Area C Performance Assessment."

**Figure F-6. Location of Selected Cross Sections for the Two-Dimensional Models.**




Subsurface Transport Over Multiple Phases (STOMP)© is copyrighted by Battelle Memorial Institute, 1996.

**Figure F-7. View along Cross Section 1 (North to South) Shown in Figure F-6.**

**The left hand figure has the original 5 rock/soil zones (hydrostratigraphic units) while the right hand figure has 4 additional rock/soil zones to incorporate the moisture content bands-based heterogeneity within the krigged area shown in Figure F-6.**

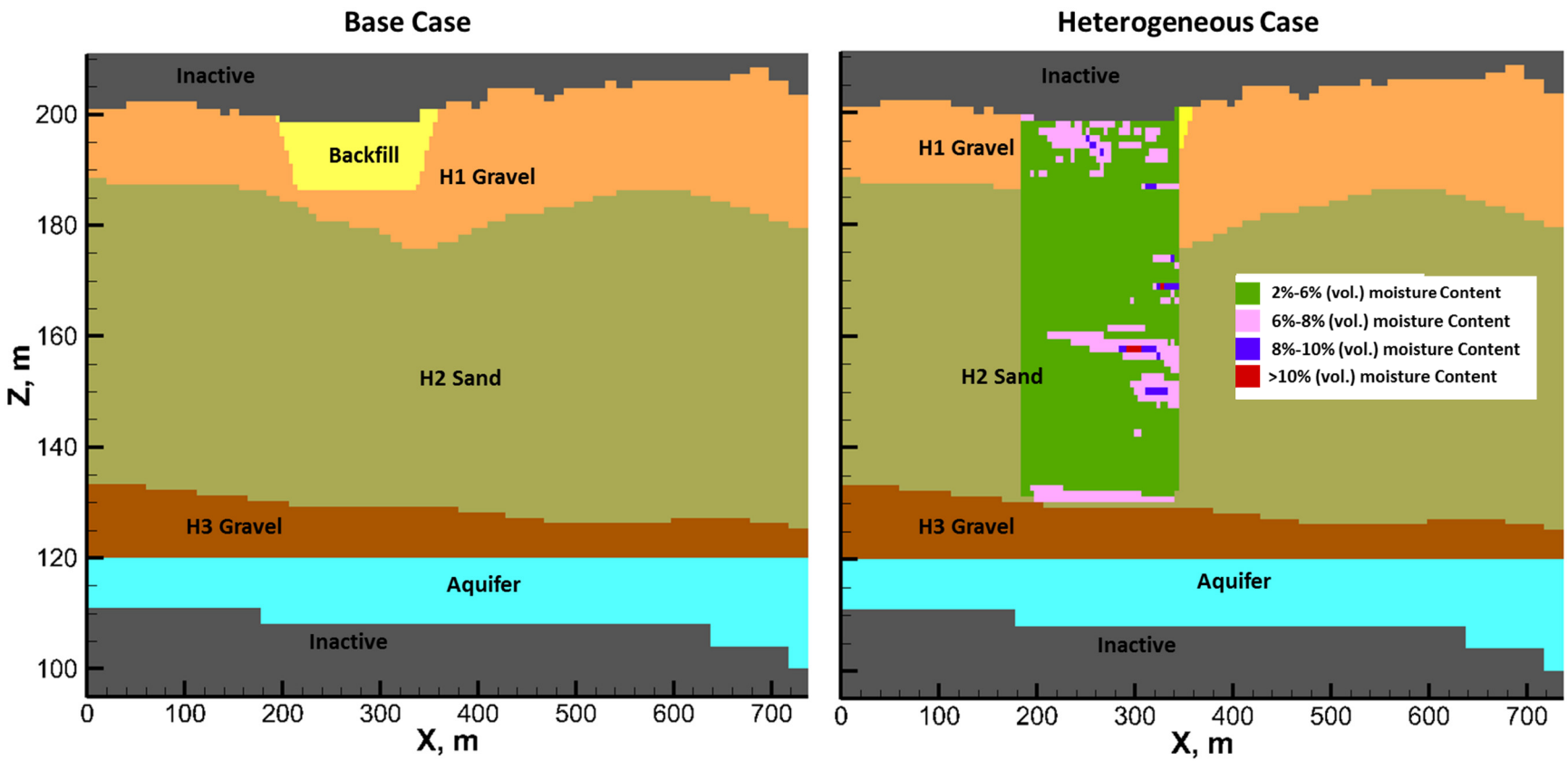


**Figure F-8. View along Cross Section 2 (North to South) Shown in Figure F-6.**

**The left hand figure has the original 5 rock/soil zones (hydrostratigraphic units) while the right hand figure has 4 additional rock/soil zones to incorporate the moisture content bands-based heterogeneity within the krigged area shown in Figure F-6.**

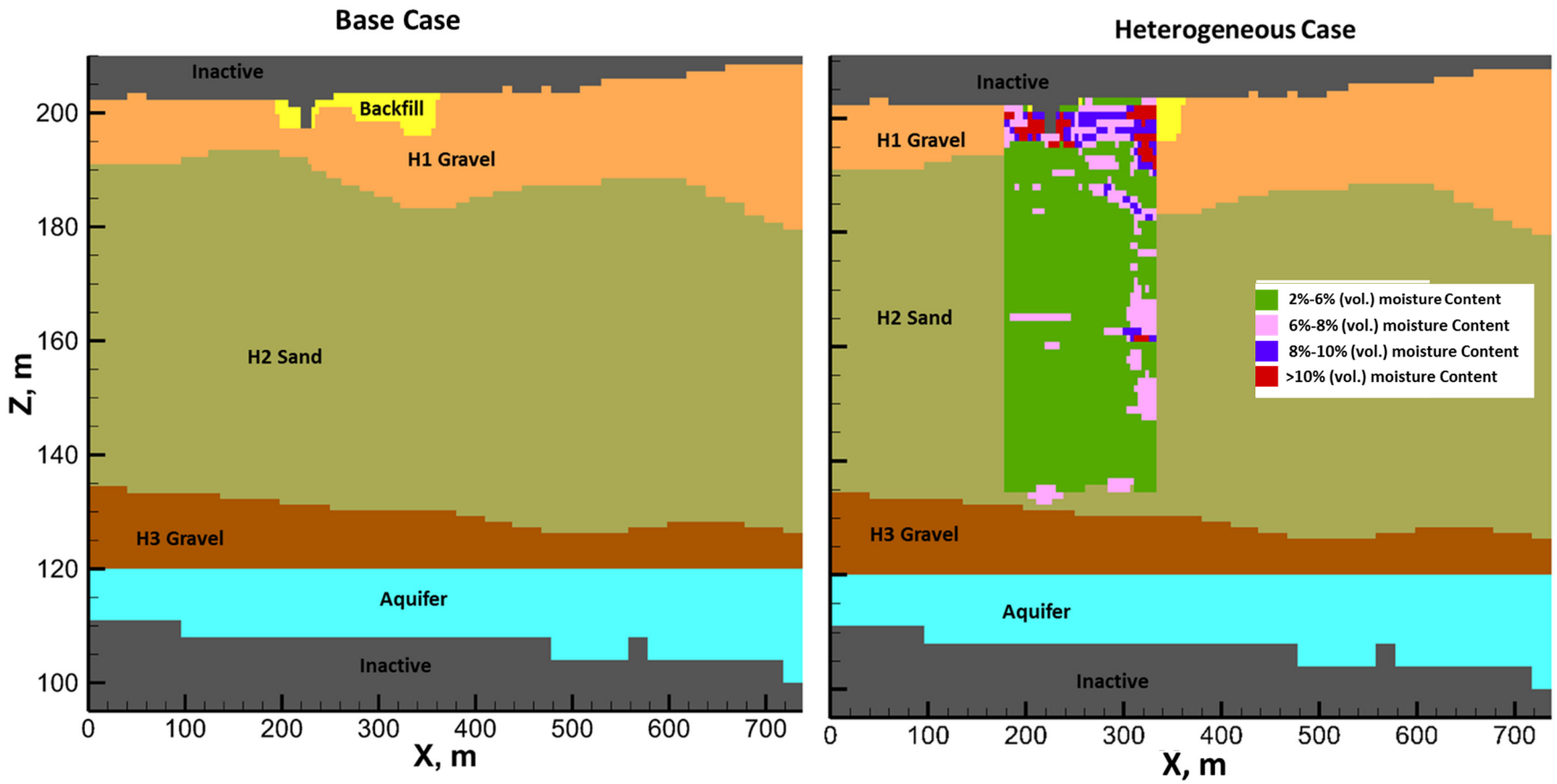


**Figure F-9. View along Cross Section 3 (West to East) Shown in Figure F-6.**

**The left hand figure has the original 5 rock/soil zones (hydrostratigraphic units) while the right hand figure has 4 additional rock/soil zones to incorporate the moisture content bands-based heterogeneity within the krigged area shown in Figure F-6.**

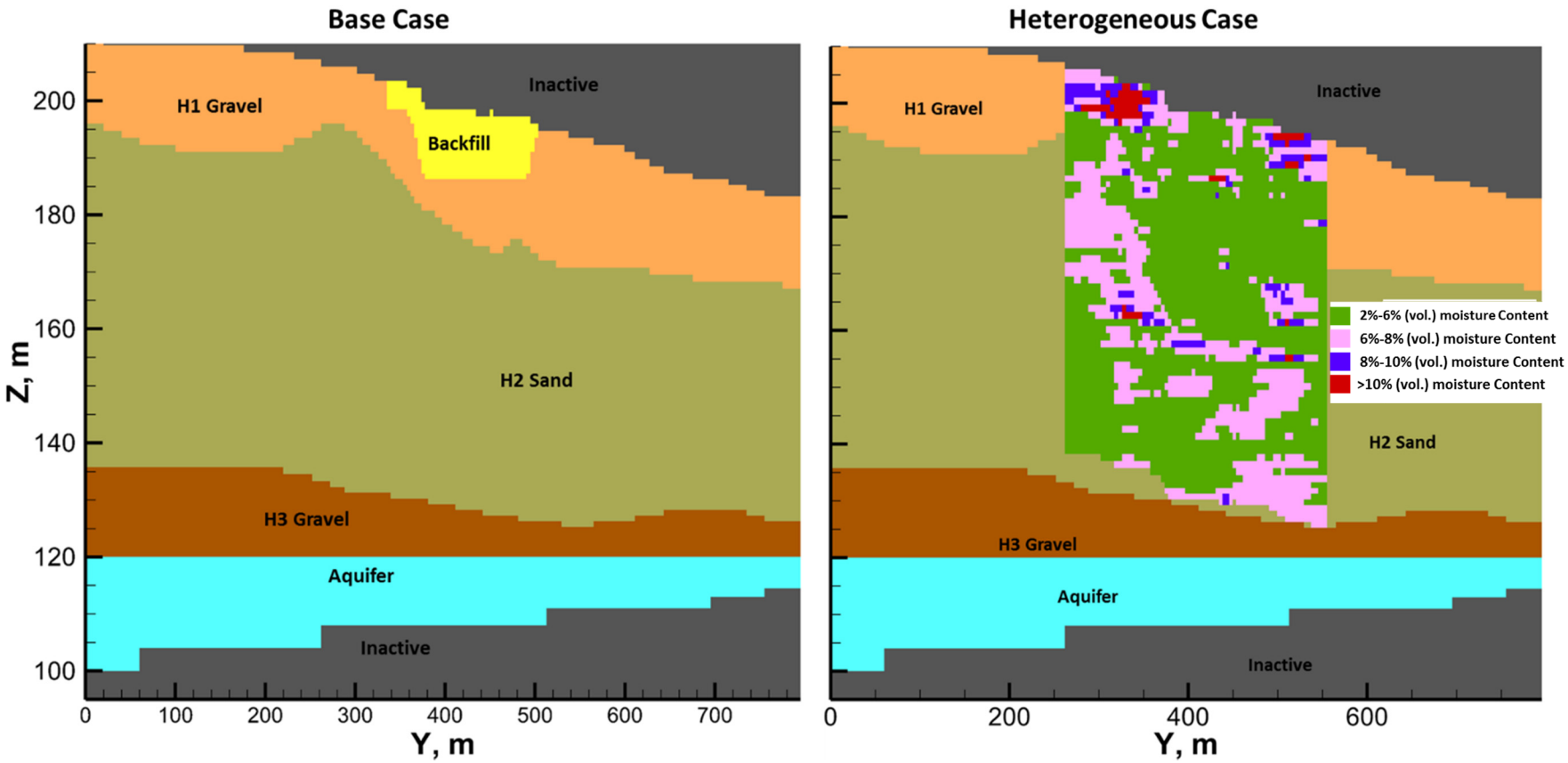


**Table F-1. Vadose Zone Hydraulic Properties for Waste Management Area C Hydrostratigraphic Units (Appendix B).**

| Hydrostratigraphic Unit | $\theta_s$ | $\theta_r$ | α (1/cm) | n | ℓ | Fitted $K_s$ (cm/s) |
|---|---|---|---|---|---|---|
| Backfill Gravelly Unit | 0.138 | 0.010 | 0.021 | 1.374 | 0.5 | 5.60E-04 |
| H1 and H3 Gravelly Units | 0.171 | 0.011 | 0.036 | 1.491 | 0.5 | 7.70E-04 |
| H2 Sand-Dominated Unit | 0.315 | 0.039 | 0.063 | 2.047 | 0.5 | 4.15E-03 |

θs = Saturated water content
θr = Residual water content
α = van Genuchten alpha
n = van Genuchten n
ℓ = Pore size connectivity factor
$K_s$ = Saturated Conductivity

## F.3 RESULTS

The STOMP© modeling results are presented in this section for the base case and the heterogeneous case. Comparisons are made for simulated moisture contents and contaminant breakthrough curves.

### F.3.1 Moisture Content Prediction

The simulated moisture content values from the STOMP© models were compared to the observed moisture profiles from two wells (C4297 and 299-E27-22). Moisture content data at boreholes C4297 (located near tank 241-C-105) and 299-E27-22 (outside the tank) were obtained from PNNL-15503. The borehole C4297 is in close proximity to cross section 1 (Figure F-13). Figure F-14 shows a comparison of simulated steady-state moisture contents from the cross section 1 model and measured moisture profile for borehole C4297, and Figure F-15 does the same for well 299-E27-22. As indicated, for a recharge of 3.5 mm/yr, the simulated moisture content profile (blue line) for cross section 1 compares well with the measurements (black circles) for both the base case (EHM approximation) and the heterogeneous case. In the heterogeneous case, the model simulation also shows higher moisture contents observed at depth.

### F.3.2 Matric Potential Measurements

Table F-3 summarizes the average moisture content and the average filter paper-based matric potential measurements for the two borehole samples C4297 (near tank 241-C-105) and 299-E27-22 (Figure F-13), and the model-predicted average moisture content and matric potential values for both cases. As indicated, the simulated steady-state moisture contents (0.06) for the Hanford H2 unit compare well with field-measured moisture contents for both the cases (Table F-3). However, when compared to the model results, the simulated matric potentials for the Hanford H2 unit were much smaller in magnitude (~ -150 cm) for both cases. The base case results in a smoothing of the model estimates. By contrast, the filter paper-based soil matric potentials are point measurements, and are not consistent with the smoothing resulting from the use of averaged upscaled or effective properties for the large grid blocks used in RCA and PA simulations. Therefore, the variability of filter paper-based point measurements is inherently larger compared to that based on RCA and PA simulations using homogenized upscaled

properties. In addition, the error bar for filter paper measurements is rather large (0.1 to 0.2 MPa or ~1,000 to ~2,000 cm). Similar arguments are applicable to the heterogeneous case. Soil moisture measurements are typically more accurate than matric potential measurements, and the matric potential variability is typically larger than the soil moisture variability. Nonetheless, the overall characterization data are consistent with the relatively dry moisture regime predicted by the RCA and PA simulations. The deviation in soil matric potential values is due to a mismatch between the modeling scale and the measurement scale.

### F.3.3 Calculation of Technetium-99 Concentration

The breakthrough curves of $^{99}$Tc for both cases for three different cross-section models are presented in Figure F-16, Figure F-17, and Figure F-18.

Table F-4 summarizes all the $^{99}$Tc transport model results for all the cases. In all three cross-sectional models, the base case shows a higher peak concentration than the heterogeneous model. In cross section 3, the heterogeneous case shows a much lower concentration than the base case because the contrast is greater: there is more heterogeneity than in the other cross sections.

Peak concentrations for the heterogeneous model and the base case are very similar, with the heterogeneities leading to a smearing of the contaminant plume, resulting in a slightly lower peak concentration than the base case. The good agreement between the two models supports the use of the base case model for the post-closure evaluation of releases of residuals.

## F.4 CONCLUSIONS

The following summarizes the conclusions of the alternative heterogeneous conceptual model.

- Calculated moisture contents are in very good agreement with field measurements for both the base case and the heterogeneous case.

- The peak concentrations are in good agreement between the two models, with the peak for the heterogeneous cases slightly lower than the base cases. These results support the use of the EHM modeling approach for the post-closure period when the flow is in equilibrium with natural recharge.

**Figure F-10. Moisture Retention Curves and Unsaturated Hydraulic Conductivity Curves for the 44 Integrated Disposal Facility Samples.**

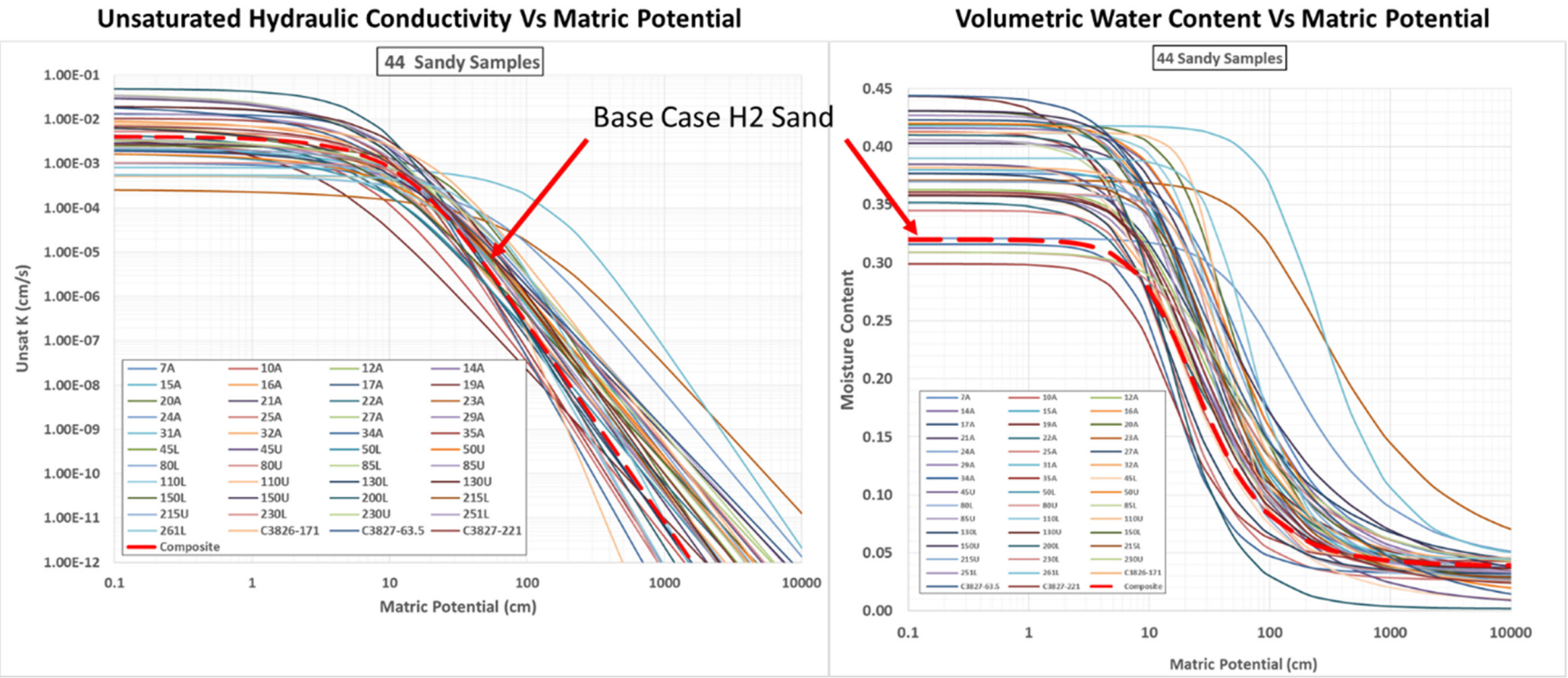
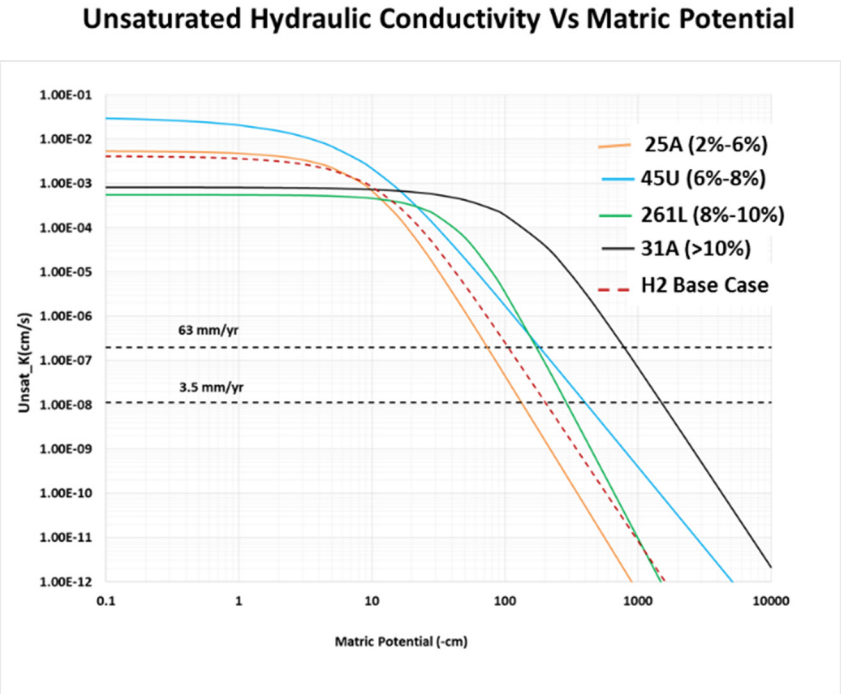


**Figure F-11. Moisture Retention Curves and Unsaturated Hydraulic Conductivity Curves for the Four New Units.**



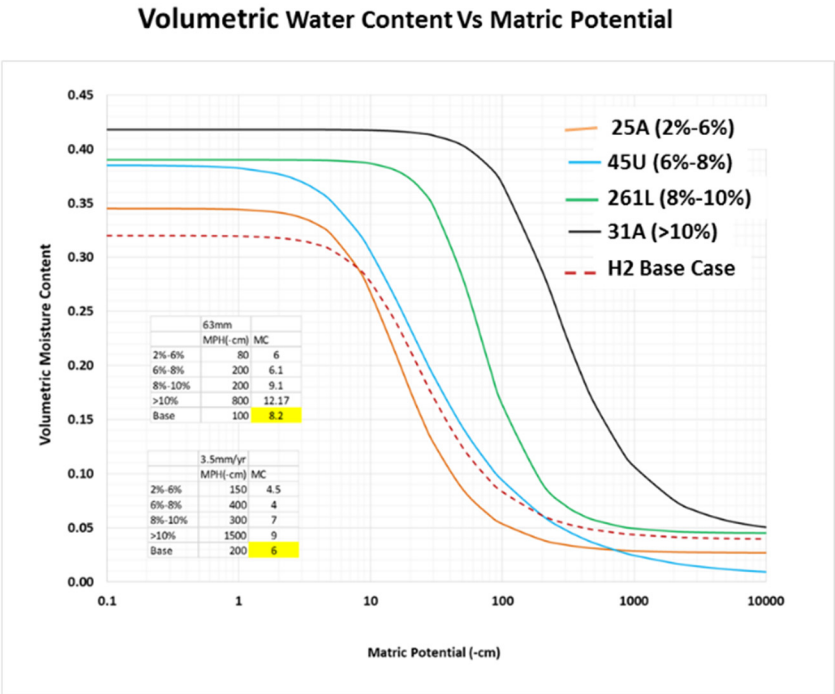



**Table F-2. Summary of Vadose Zone Hydraulic Properties for the New Units (Appendix B).**

| Samples (Moisture Content zones) | $\theta_s$ | $\theta_r$ | α (1/cm) | n | ℓ | Fitted $K_s$ (cm/s) |
|---|---|---|---|---|---|---|
| 25A (2%-6%) | 0.345 | 0.0267 | 0.0842 | 2.158 | 0.5 | 5.40E-03 |
| 45U (6%-8%) | 0.385 | 0.0050 | 0.0880 | 1.664 | 0.5 | 3.24E-02 |
| 261L (8%-10%) | 0.390 | 0.0450 | 0.0191 | 2.485 | 0.5 | 5.54E-04 |
| 31A (>10%) | 0.418 | 0.0444 | 0.0058 | 2.012 | 0.5 | 8.21E-04 |

**Figure F-12. Location of Contaminant Source and Point of Calculation.**

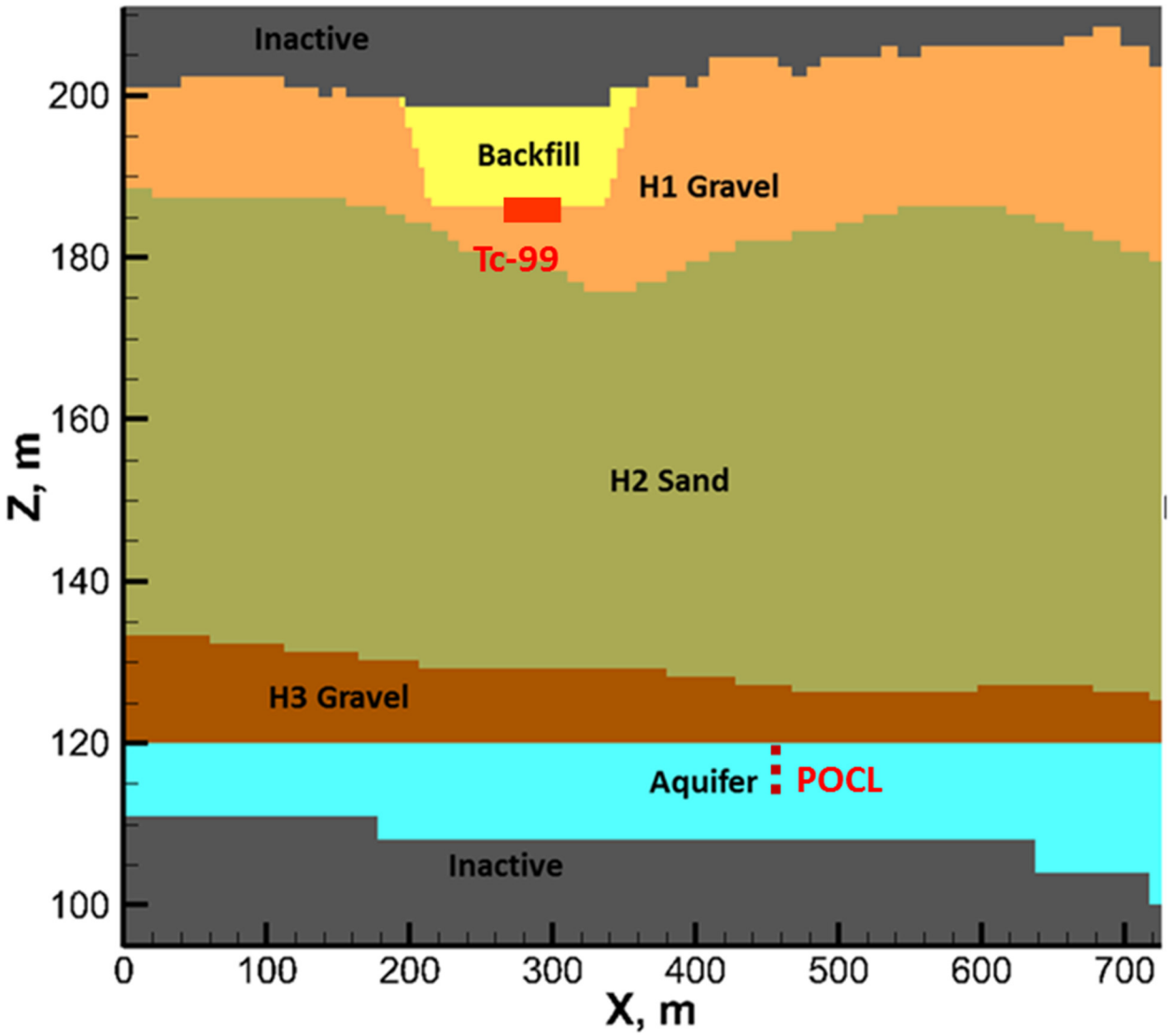


**Figure F-13. Location of Well C4297 and 299-E27-22 Relative to Cross Section 1.**

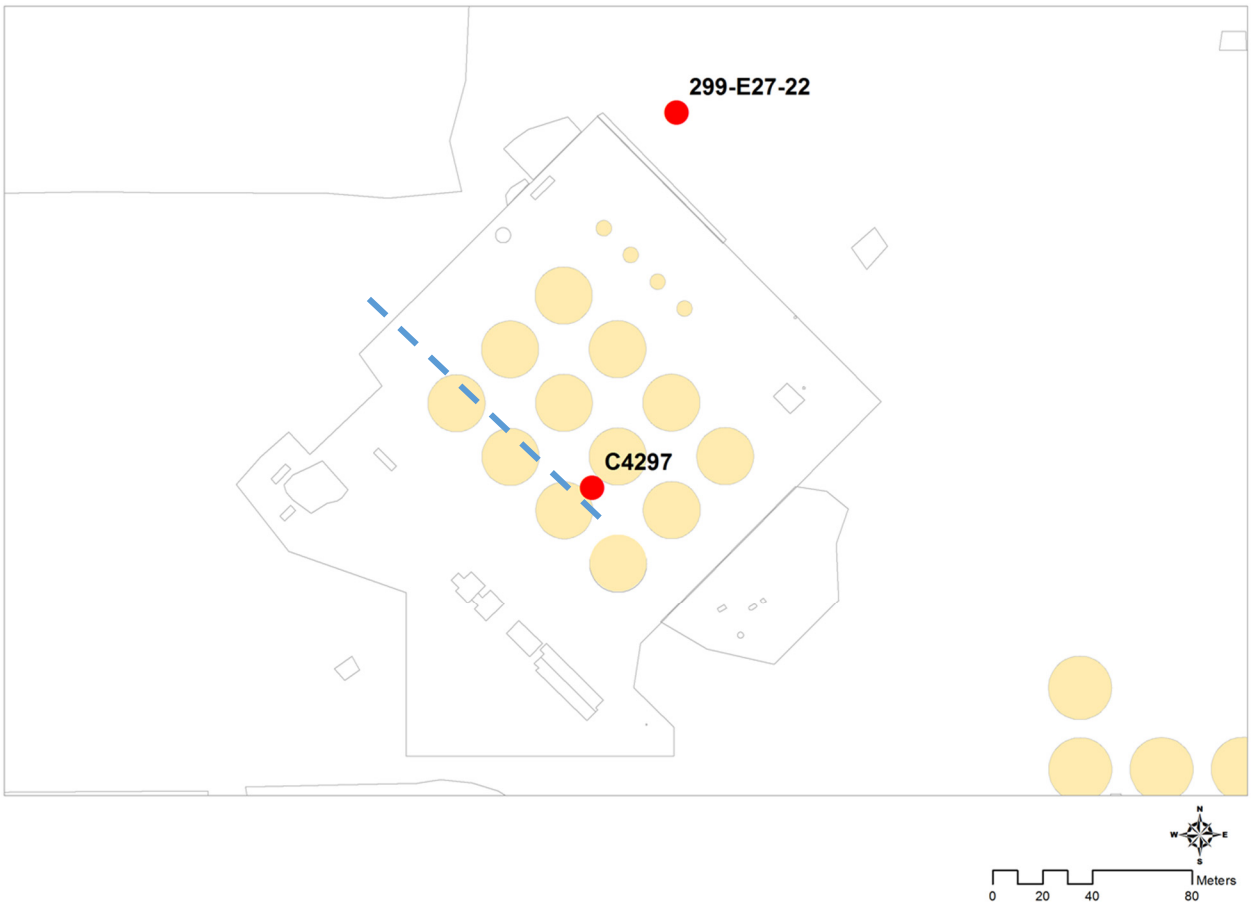
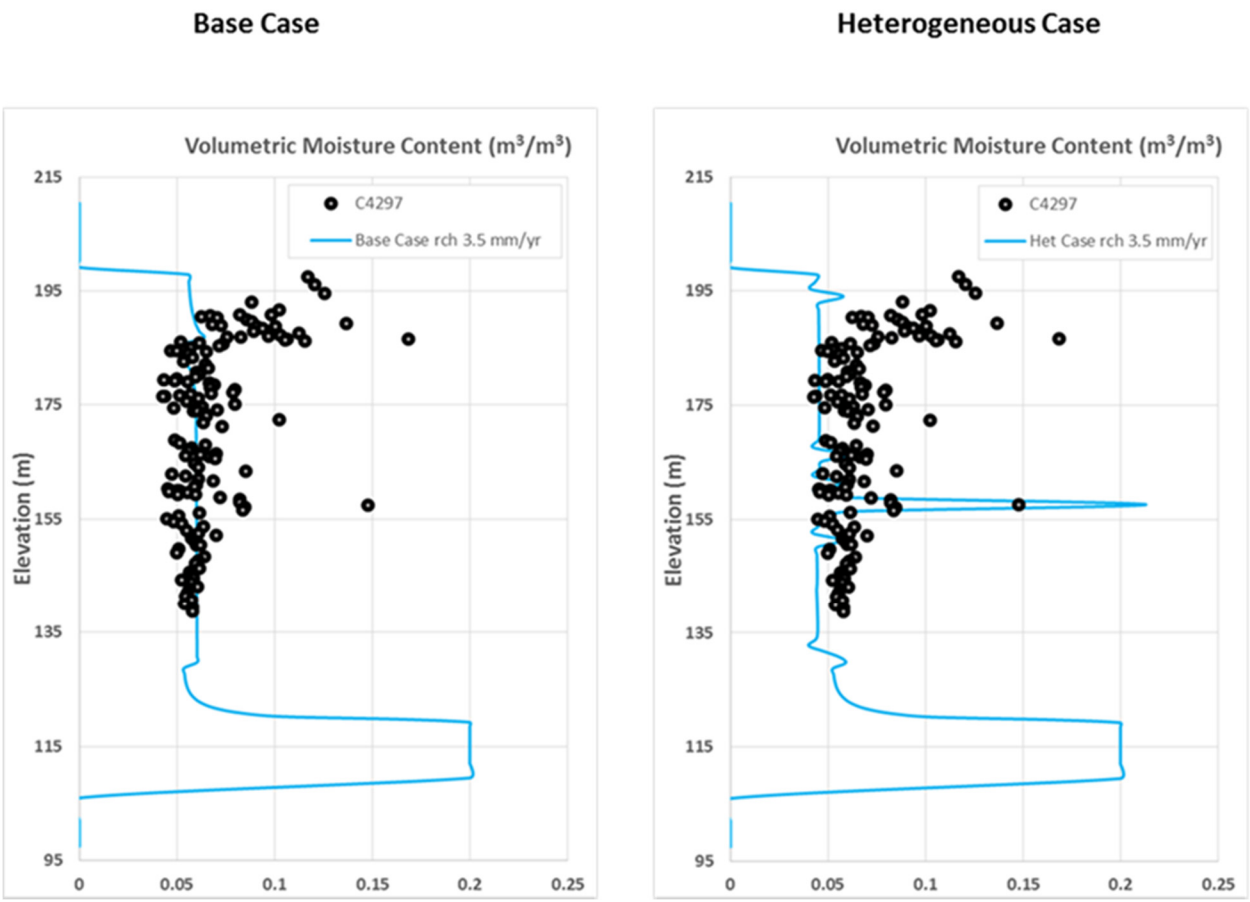
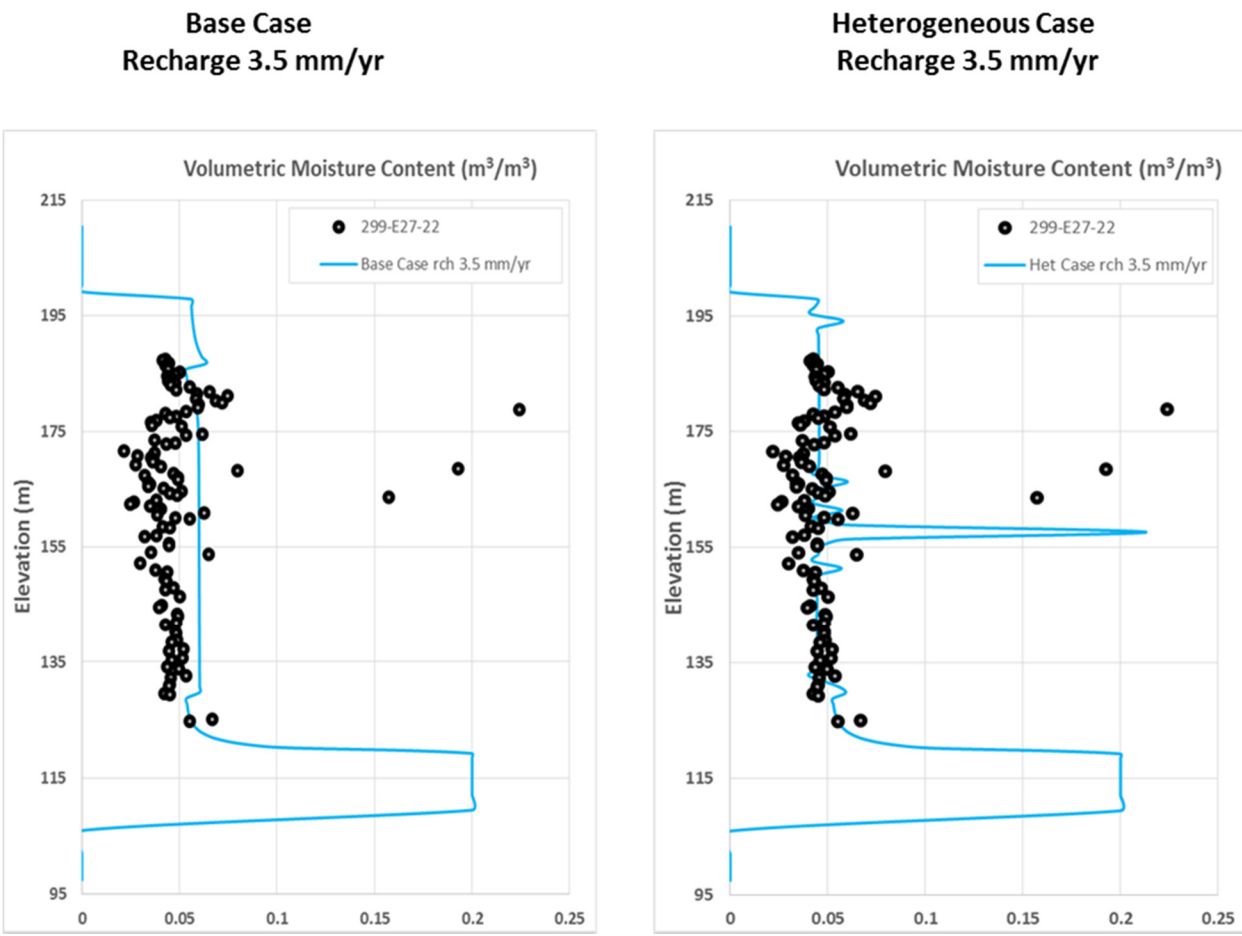


**Figure F-14. Comparison of Measured (C4297) and Simulated Moisture Contents for (a) Base Case (Equivalent Homogeneous Medium) Model, and (b) Heterogeneous Model for Cross Section 1.**




(a) (b)

**Figure F-15. Comparison of Measured (299-E27-22) and Simulated Moisture Contents for (a) Base Case (Equivalent Homogeneous Medium) Model, and (b) Heterogeneous Model for Cross Section 1.**




(a) (b)

**Table F-3. Average Moisture and Matric Potentials for Borehole Samples Inside and Outside of Waste Management Area C.**

| Borehole | C4297 (inside tank farm) | 299-E27-22 (outside tank farm) |
|---|---|---|
| Mean moisture content * | 0.060 | 0.046 |
| Mean matric potential (-cm) | 498.45 | 1,616.43 |

*Gravimetric data were converted to volumetric moisture content using an assumed sediment bulk density of 1.7 g $cm^{-3}$.

Source: PNNL-15503, "Characterization of Vadose Zone Sediments Below the C Tank Farm: Borehole C4297 and RCRA Borehole 299-E27-22."

**Figure F-16. Technetium-99 Breakthrough Curves for Cross Section 1.**

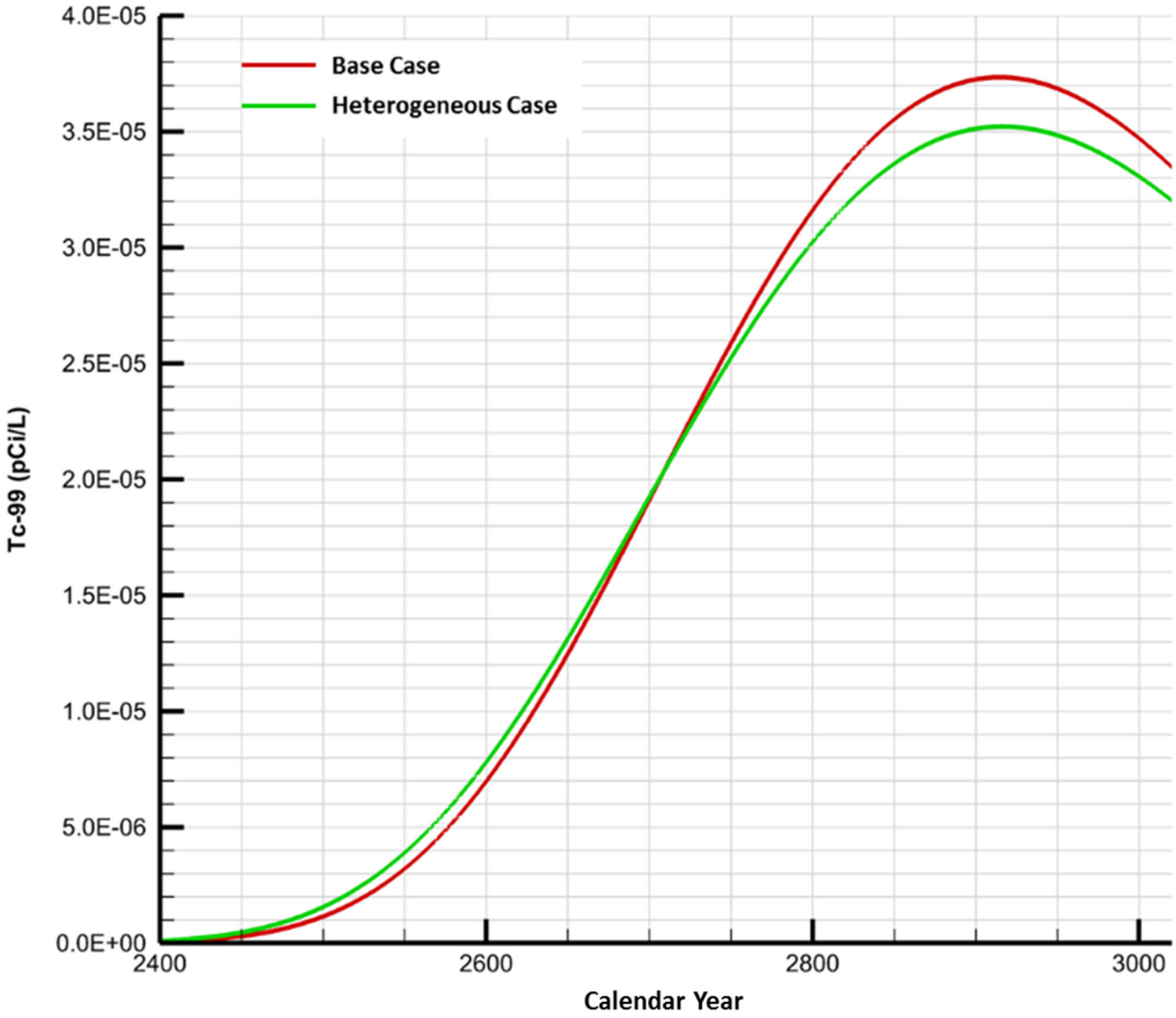


**Figure F-17. Technetium-99 Breakthrough Curves for Cross Section 2.**

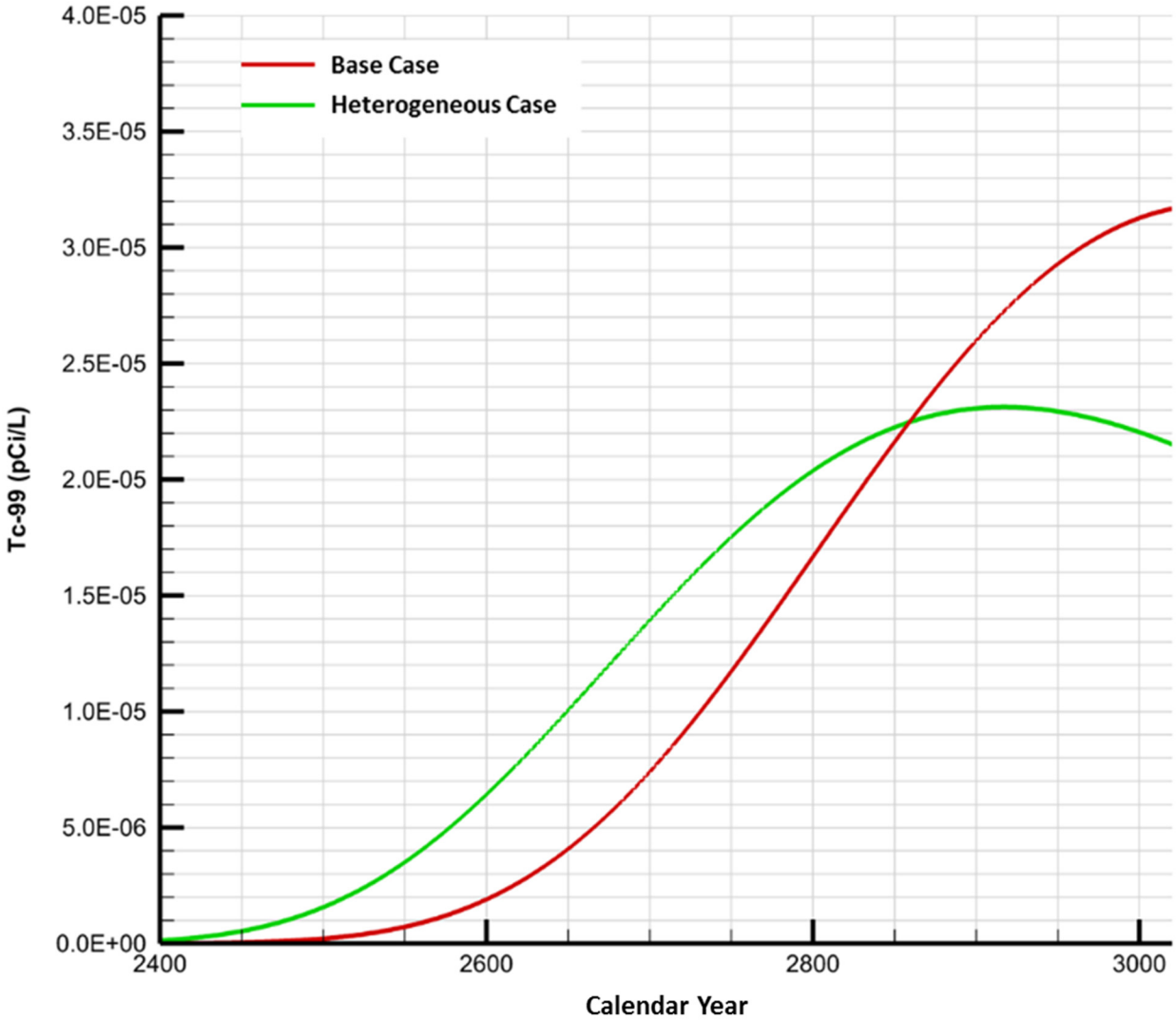


**Figure F-18. Technetium-99 Breakthrough Curves for Cross Section 3.**

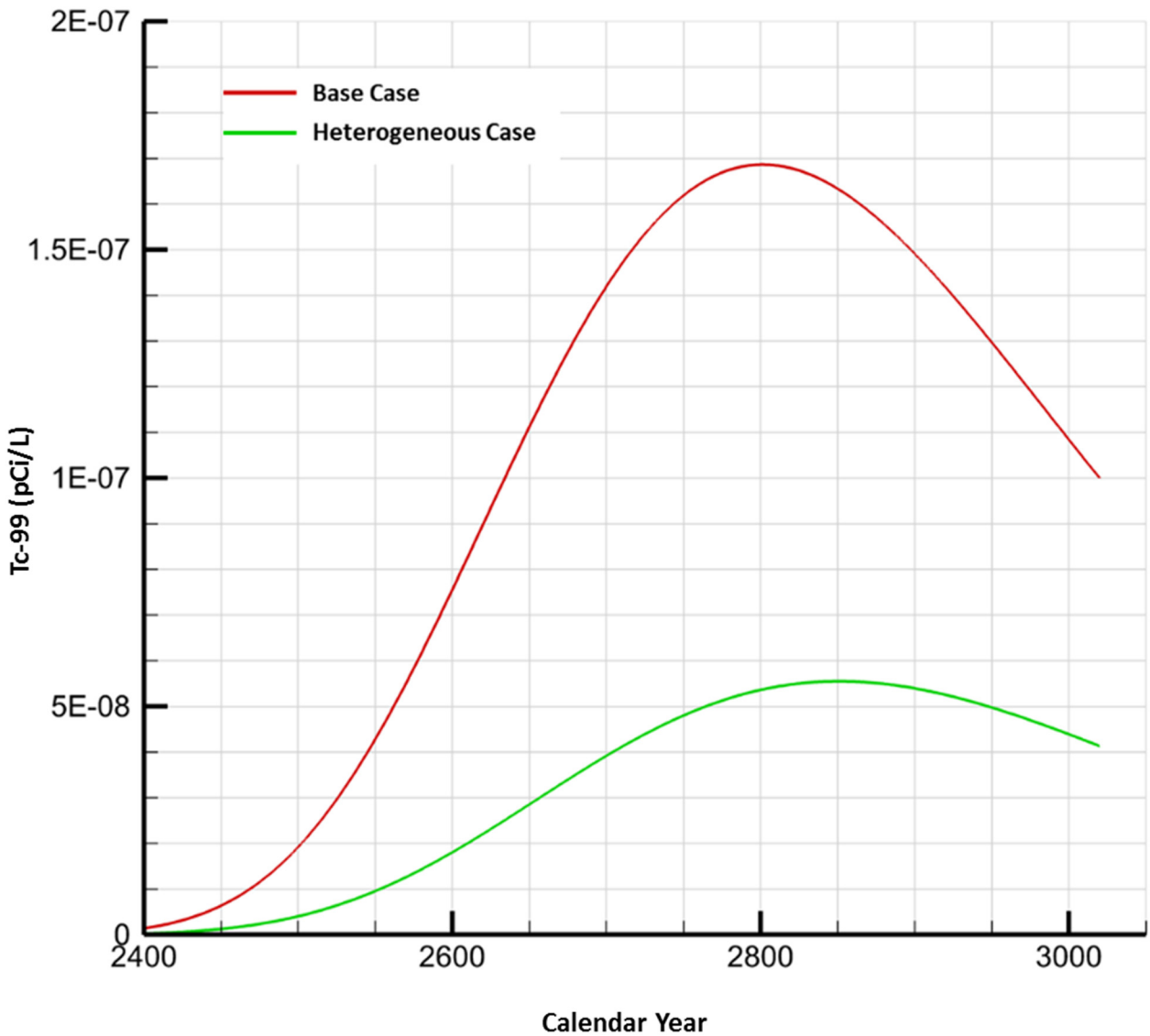



**Table F-4. Summary of Technetium-99 Transport Model Results.**

| Cross Section | Time of Breakthrough (Calendar Year) | | Time of Peak (Calendar Year) | | Peak Concentration (pCi/L) | |
|---|---|---|---|---|---|---|
| | Base Case | Heterogeneous Case | Base Case | Heterogeneous Case | Base Case | Heterogeneous Case |
| 1 | 2226 | 2210 | 2916 | 2916 | 3.73E-05 | 3.52E-5 |
| 2 | 2253 | 2205 | >3000 | 2918 | >3.16E-5 | 2.31E-5 |
| 3 | 2212 | 2232 | 2798 | 2843 | 1.69E-7 | 5.44E-8 |

## F.5 REFERENCES

PNNL-15503, 2008, "Characterization of Vadose Zone Sediments Below the C Tank Farm: Borehole C4297 and RCRA Borehole 299-E27-22," Rev. 1, Pacific Northwest National Laboratory, Richland, Washington.

Resource Conservation and Recovery Act of 1976, 42 USC 6901, et seq.

RPP-CALC-60345, 2016, "Heterogeneous Media Model for Waste Management Area C Performance Assessment," Rev. 0, Washington River Protection Solutions, LLC, Richland, Washington.

Ye, M., R. Khaleel, T. J. Yeh, 2005, "Stochastic analysis of moisture plume dynamics of a field injection experiment," Water Resources Research, Vol. 41, W03013.

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# APPENDIX G

## COMPARISON OF SELECTED MODEL RESULTS FOR ALTERNATIVE 2B FROM THE TANK CLOSURE AND WASTE MANAGEMENT ENVIRONMENTAL IMPACT STATEMENT FOR WASTE MANAGEMENT AREA C WITH EQUIVALENT RESULTS USING THE WASTE MANAGEMENT AREA C PERFORMANCE ASSESSMENT BASE CASE MODEL

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## LIST OF TERMS

| | |
|---|---|
| PA | performance assessment |
| RCA | Resource Conservation and Recovery Act of 1976 (RCRA) Closure Analysis |
| STOMP | Subsurface Transport Over Multiple Phases (computer code) |
| TC&WM EIS | Tank Closure and Waste Management Environmental Impact Statement |
| WMA | Waste Management Area |

# APPENDIX G

# COMPARISON OF SELECTED MODEL RESULTS FOR ALTERNATIVE 2B FROM THE TANK CLOSURE AND WASTE MANAGEMENT ENVIRONMENTAL IMPACT STATEMENT FOR WASTE MANAGEMENT AREA C WITH EQUIVALENT RESULTS USING THE WASTE MANAGEMENT AREA C PERFORMANCE ASSESSMENT BASE CASE MODEL

The purpose of this appendix is to compare, to the extent possible, the model developed for the Waste Management Area (WMA) C Resource Conservation and Recovery Act of 1976 (RCRA) closure analysis (RCA) and performance assessment (PA) to results from DOE/EIS-0391, "Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington" (TC&WM EIS). The intent is to show the similarities and differences between the models, and to demonstrate that both models are appropriate for their intended purposes. The extent to which the two models can be directly compared is limited, given the different modeling objectives, spatial scales and levels of detail in the treatment of the engineered barrier system. However, a comparison provides perspectives on interpreting modeling results within the context of the modeling objectives.

## G.1 GENERAL DESCRIPTION OF ALTERNATIVE 2B RESULTS USING THE 2012 TANK CLOSURE AND WASTE MANAGEMENT ENVIRONMENTAL IMPACT STATEMENT MODEL FOR WASTE MANAGEMENT AREA C

The analysis in the TC&WM EIS supports U.S. Department of Energy decisions regarding proposed actions to retrieve, treat, and dispose of tank waste; decommission the Fast Flux Test Facility; and expand waste disposal capacity at Hanford. The TC&WM EIS evaluates the potential sitewide cumulative environmental impacts and cost consequences associated with 11 proposed alternatives for tank closure, including the preferred alternative to retrieve at least 99% of the tank waste and institute landfill closure of the single-shell tank farms. The TC&WM EIS describes groundwater impacts in terms of the concentrations of $^{129}$I, $^{99}$Tc, chromium, nitrate, $^{3}$H (tritium), $^{238}$U, and total uranium at prescribed polygonal "lines of interest" or "barriers," including one that surrounds WMA C and WMA A-AX. The results at a line of interest or barrier represent the outcome of vadose zone model results evaluated using Subsurface Transport Over Multiple Phases (STOMP)©[1] (Appendix N of DOE/EIS-0391) input to a groundwater flow field developed in MODFLOW[2] (Appendix L of DOE/EIS-0391), with concentration calculated using a proprietary particle-tracking code (Appendix O of DOE/EIS-0391).

The TC&WM EIS evaluated a local-scale vadose zone-only model representing WMA C, and used the vadose zone releases from this model as a source to a regional groundwater model to estimate the impacts of residual wastes and past releases originating in WMA C at specific points for analysis. However, the groundwater impact results reported in Appendix O of DOE/EIS-0391 do not distinguish between the impacts caused by the residual wastes, past leaks,

[1] Subsurface Transport Over Multiple Phases (STOMP)© is copyrighted by Battelle Memorial Institute, 1996.
[2] MODFLOW software has been developed and distributed by the U.S. Geological Survey, Washington, D.C.

and releases in WMA C from those originating in other tank farms in the A Complex of the 200 East Area. In addition, the point of analyses in the TC&WM EIS groundwater impact analysis are not coincident with the 100 meter point of calculation prescribed by DOE M 435.1-1, Radioactive Waste Management Manual. Instead, the TC&WM EIS reported cumulative results from facilities at a number of polygonal "lines of analysis" that are shown in Figure G-1. The line of analysis most relevant to WMA C is the "A Barrier," at which the cumulative contributions and impacts from tank farm residual waste and past leaks from WMAs C, A, and AX, and other nearby double-shell tank farm facilities are evaluated in groundwater. The WMA C PA provides concentration-based results along a hypothetical line of analysis located 100 m downgradient of the WMA C fenceline. The line of analysis is divided into nine segments to account for the spatial distribution of the impacts along the line of analysis resulting from the spatial distribution of sources within WMA C. The results for each segment distinguish between the impacts caused by residuals from the different tanks and ancillary equipment, including pipelines within WMA C, and integrate the individual results into a composite concentration.

Therefore, while the "A Barrier" results are not directly comparable to the PA model results, they still provide the best available comparison point between the analyses, and are summarized here (Table G-1). According to the groundwater transport analysis results of Preferred Alternative 2B at A Barrier (found in Table O-26 in Appendix O of DOE/EIS-0391), the peak concentrations of radionuclides $^{99}$Tc and $^{129}$I at A Barrier related to tank residuals are 160 pCi/L and 0.1 pCi/L, respectively, with the years of peak arrival being 3685 and 3896, respectively. The peak concentrations of chromium and nitrate are 5 µg/L and 536 µg/L, respectively, with the years of peak arrival being 3451 and 3614, respectively. The peak concentrations of radionuclides $^{99}$Tc and $^{129}$I related to ancillary equipment at A Barrier are 31 pCi/L and 0.1 pCi/L, respectively, with the years of peak arrival being 3610 and 3694, respectively. The peak concentrations of chromium and nitrate are 1 µg/L and 183 µg/L, respectively, with the years of peak arrival being 3647 and 3606, respectively (Table O-22 in Appendix O of DOE/EIS-0391).

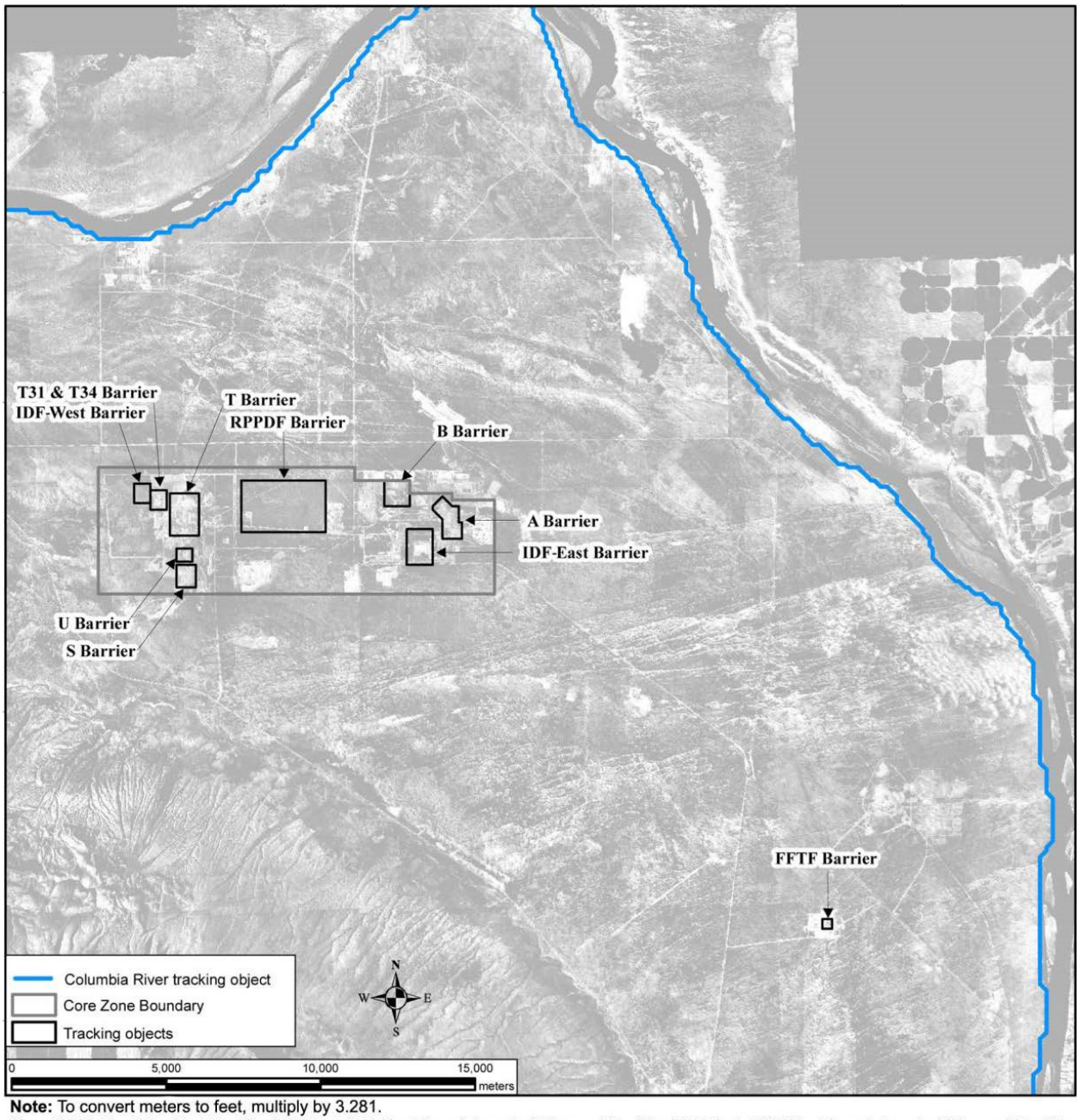
## G.2 GENERAL APPROACH FOR COMPARISON OF THE ALTERNATIVE 2B RESULTS USING RCRA CLOSURE ANALYSIS AND PERFORMANCE ASSESSMENT AND THE 2012 TANK CLOSURE AND WASTE MANAGEMENT ENVIRONMENTAL IMPACT STATEMENT MODELS OF WASTE MANAGEMENT AREA C

To compare the WMA C PA and TC&WM EIS models for consistency, it was necessary to modify the base case results to provide a common technical basis between the two models. The tank residual waste inventory, residual waste release functions, and spatial and temporal recharge from the small-scale TC&WM EIS WMA C vadose zone-only model were introduced into the WMA C PA vadose zone-groundwater model.

As a metric for comparisons, Appendix U of DOE/EIS-0391 includes a figure that shows the modeling results for Alternative 2B for the $^{129}$I radionuclide fluxes exiting the vadose zone. The results from this plot are compared against similar results using similar source term and

assumption for Alternative 2B using the PA model of WMA C. To facilitate this comparison, the tank residual waste inventory, residual waste release functions, and spatial and temporal recharge from the small-scale TC&WM EIS WMA C vadose zone-only model were introduced into the WMA C PA vadose zone-groundwater model.

**Figure G-1. Lines of Analysis in the Tank Closure and Waste Management Environmental Impact Statement.**




**Note:** To convert meters to feet, multiply by 3.281.
**Key:** FFTF=Fast Flux Test Facility; IDF-East=200-East Area Integrated Disposal Facility; IDF-West=200-West Area Integrated Disposal Facility; RPPDF=River Protection Project Disposal Facility; T31 & T34=trenches 31 and 34.

Excerpted from DOE/EIS-0391, "Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington," Appendix O, pp. O-16.

**Table G-1. Peak Constituent of Potential Concern Concentrations and Time of Occurrence (Calendar Year) at the A Barrier Calculated in the Environmental Impact Statement Associated with All Tank Residuals and Ancillary Equipment.**

| Radionuclide | Tank Residuals (Calendar Year Time of Peak) | Ancillary Equipment (Calendar Year Time of Peak) |
|---|---|---|
| Tc-99 | 160 pCi/L (3685) | 31 pCi/L (3610) |
| I-129 | 0.1 pCi/L (3896) | 0.1 pCi/L (3694) |
| **Contaminant** | | |
| Cr | 5 µg/L (3451) | 1 µg/L (3647) |
| Nitrate | 536 µg/L (3614) | 183 µg/L (3606) |

Values excerpted from DOE/EIS-0391, "Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington" Tables O-22 and O-26.

Other elements of the models are similar. As in the WMA C PA, the assumed end state of the tanks evaluated in DOE/EIS-0391 was that the single-shell tank waste system would be filled with grout to immobilize residual waste, prevent long-term degradation of the tanks, and discourage intruder access. The closed tank system would be covered with an engineered modified RCRA Subtitle C barrier with a design life of 500 years. The TC&WM EIS STOMP©-based vadose zone model incorporates a number of elements that are similar in approach to the WMA C PA model:

- Residual waste inventory in tanks and ancillary equipment
- Three-dimensional representation of geology, hydraulic properties, and grid geometry
- Temporal and spatial variability of net infiltration at the ground surface
- Temporal variability of radionuclide and non-radiological contaminant introduction (i.e., source term) at specific horizontal locations and vertical depths
- Water and radionuclide and non-radiological contaminant output fluxes at specified locations (referred to in STOMP© as surfaces)
- Radionuclide and non-radiological contaminant movement through, and exit from the vadose zone.

Unlike the WMA C PA, the TC&WM EIS modeling methodology calculates the following outside of STOMP©:

- Contaminant movement in the groundwater to various calculation points
- Concentrations calculated at a contiguous polygon surrounding WMA C and WMA A-AX in the saturated-zone model (referred to in DOE/EIS-0391 as "A Barrier").

## G.3 COMPARISONS OF MODEL INPUTS FOR 2012 TANK CLOSURE AND WASTE MANAGEMENT ENVIRONMENTAL IMPACT STATEMENT AND PERFORMANCE ASSESSMENT MODELS OF WASTE MANAGEMENT AREA C

The primary areas where the models differ internally involve inventory estimates, waste release rates, geological description and hydrological properties, the partitioning coefficients and dispersivity applied to certain radionuclides, and the spatial distribution of recharge rates. The following discussion describes these differences and any adjustments made to the WMA C PA model so that the two model predictions could be compared.

### G3.1 Inventory Estimates

DOE/ORP-2003-02, Environmental Impact Statement for Retrieval, Treatment, and Disposal of Tank Waste and Closure of Single-Shell Tanks at the Hanford Site, Richland, WA: Inventory and Source Term Data Package provides the estimated radionuclide inventory present at each tank farm as of December 1, 2002. According to Table M-24 in Appendix M of DOE/EIS-0391, the estimated quantities of $^{129}$I under tank closure Alternative 2B are 0.00993 of $^{129}$I. The alternatives analysis evaluated impacts from the tank farms as entities, not individual tanks; thus, the tank residual wastes are composited into a single source for the entire tank farm. The TC&WM EIS model represents the residual wastes in the tanks as a uniform concentration distributed across an area that approximately encompasses the 100- and 200-series tanks of the tank farm (Figure G-2). The residual waste inventory estimates have been revised since the issuance of DOE/EIS-0391 because more waste has been retrieved from the tanks, and the new inventory is based on direct measurement of the end state of the retrieval. The WMA C PA includes the updated information.

For the purpose of comparing the two model results for Alternative 2B, the WMA C PA model was modified to run with the TC&WM EIS inventory estimates and an approximation of the TC&WM EIS release area in its evaluation.

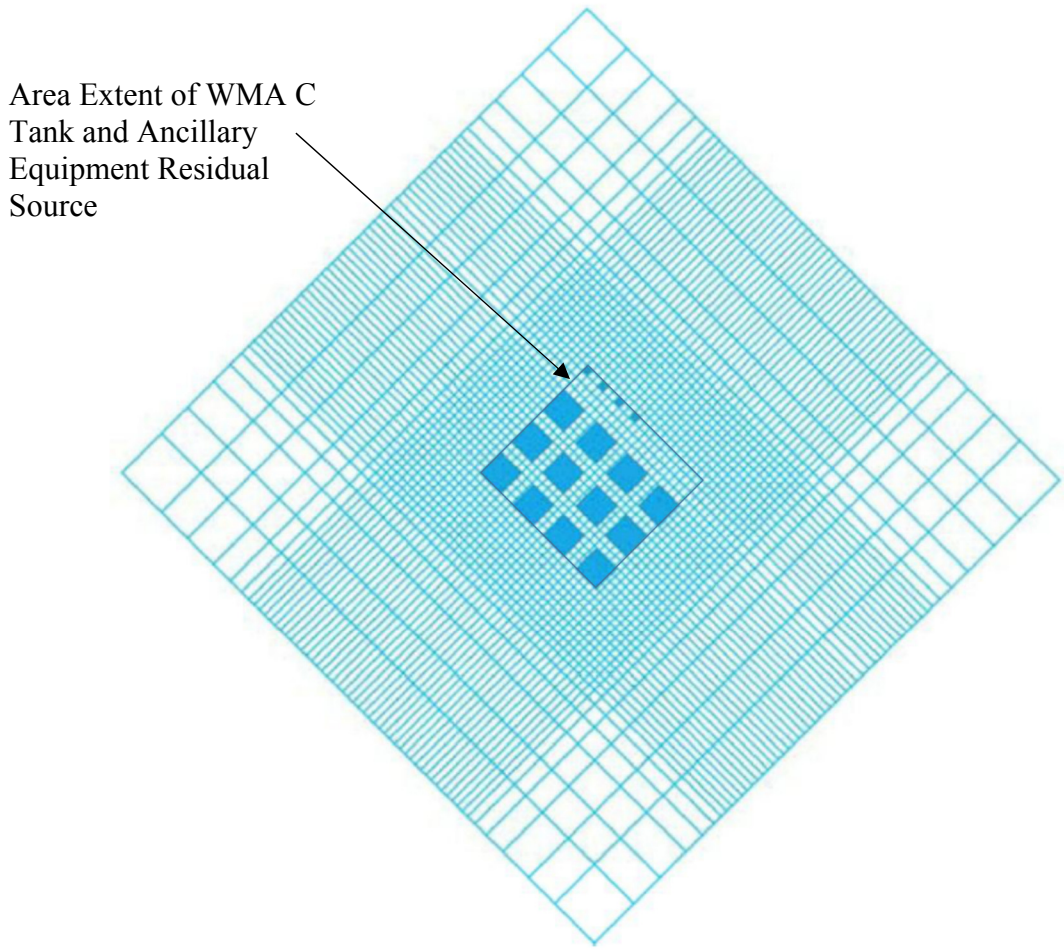
### G3.2 Inventory Release Rates

DOE/EIS-0391 calculated the release of contaminants from stabilized tank grout using a partitioning-limited, advective-flow release model (Table M-2 of Appendix M of DOE/EIS-0391). In this model, only the rate of water movement through the waste volume, and the partitioning of the contaminant between the solid and liquid phases of the waste volume, control the release of contaminants from the waste form to the vadose zone (Appendix M of DOE/EIS-0391). Contaminant concentrations are assumed to maintain equilibrium between the liquid and solid phases within the pore space of the waste form according to the contaminant's partitioning coefficient in the waste form material. The amount of contaminant mass exiting the waste form is therefore equal to the quantity of liquid exiting from the waste form and the concentration of the contaminant in that liquid.

For the purpose of comparing the two model results of Alternative 2B, the WMA C PA model was run using the TC&WM EIS (2012) release function for $^{129}$I in its evaluation. Equations M-1

through M-8 in Appendix M of DOE/EIS-0391 provide the basis for the release models used to develop the release functions for the solid sources. Summarized rates of release for $^{129}I$ developed according to this model are presented in Table G-2.

**Figure-G-2. STOMP© Model Horizontal Grid Distribution Showing the Source Area for the Waste Management Area C Tank Residual Component of the Tank Closure and Waste Management Environmental Impact Statement.**




Excerpted and adapted from Figure N-4, Appendix N of DOE/EIS-0391, "Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington."

Subsurface Transport Over Multiple Phases (STOMP)© is copyrighted by Battelle Memorial Institute, 1996.

WMA = Waste Management Area

## G3.3 Recharge

In the TC&WM EIS release model calculations, the quantity of liquid exiting from the waste form is assumed to equal the water infiltrating into it. The water infiltrating into the waste form is assumed to be equal to the net infiltration at the surface, which is subject to change according to the conditions at the surface such as natural vegetation or the presence of an engineered barrier. Figure M-2 in Appendix M of DOE/EIS-0391 displays the time series of net infiltration

rates applicable to tank farms (Figure G-3). For WMA C, the background conditions represent a steady-state net infiltration rate of 3.5 mm/yr. The disturbed conditions (100 mm/yr) coincide with the beginning of tank farm operations and the assumed closure of the farm in 2050. The cap conditions follow closure, and last 500 years until the cap becomes degraded and the net infiltration reverts to the background value. The net infiltration applied to surfaces outside the WMA C source area does not change from the background conditions throughout the simulation period.

**Table G-2. Summary of Rates of Release for Iodine-129.**

| Year | I-129 Release Rate (Ci/yr) |
|---|---|
| 2050 | 4.57E-06 |
| 2267 | 4.09E-06 |
| 2510 | 3.81E-06 |
| 2550 | 2.64E-05 |
| 2551 | 2.46E-05 |
| 2592 | 2.12E-05 |
| 2639 | 1.78E-05 |
| 2695 | 1.44E-05 |
| 2764 | 1.10E-05 |
| 2854 | 7.62E-06 |
| 2984 | 4.15E-06 |
| 3223 | 6.07E-07 |
| 4515 | 0 |

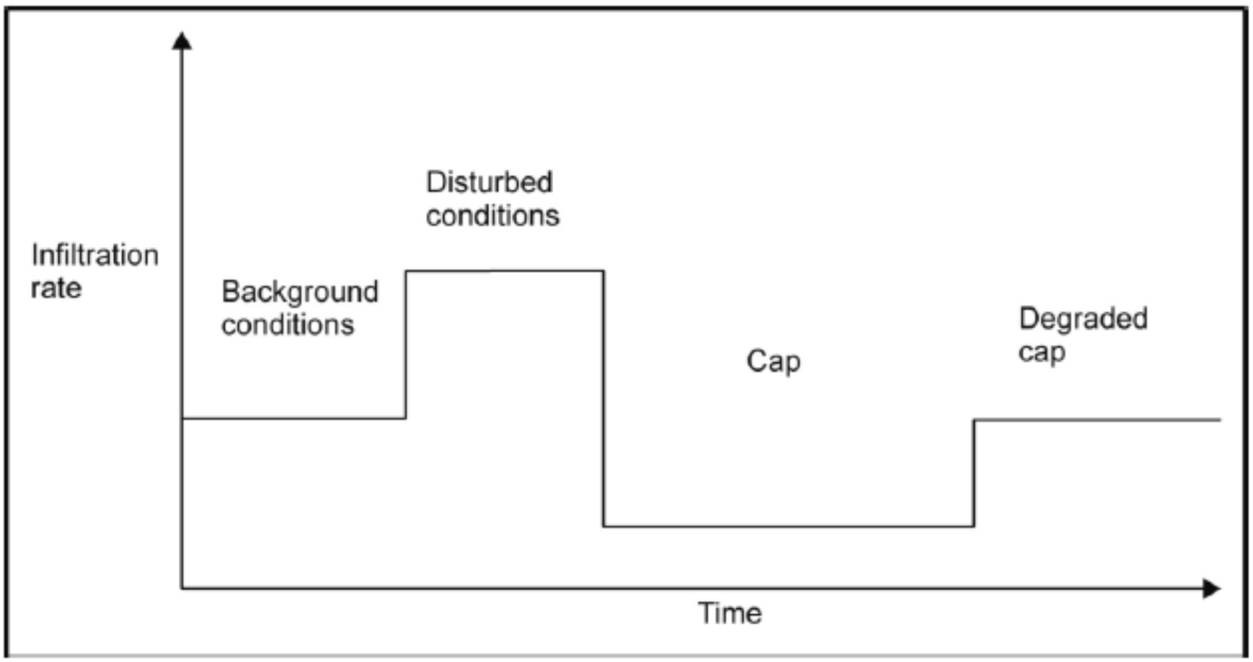
Values based on Equations M-1 through M-8 in Appendix M of DOE/EIS-0391, "Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington."

For the purpose of comparing the two models of Alternative 2, the WMA C PA model was run using the TC&WM EIS recharge sequence in its evaluation.

## G3.4 Hydrogeologic Framework and Hydrologic Properties

In the TC&WM EIS geologic model, most of the vadose zone consists of units identified as Hanford sand with a layer of Hanford gravel at the bottom and another layer of Hanford gravel existing about two-thirds the depth from the surface to groundwater. Both gravel units vary in thickness, and the shallower sand is not continuous and is not present in the southeastern corner of the model (Figure G-4). The TC&WM EIS geologic model does not account for the presence of the WMA C tanks and ancillary equipment. The volumes associated with those features remain active in the model and unchanged from the natural system. The TC&WM EIS developed hydraulic properties for the Hanford sand and gravel units according to the procedure described in Section N.3.6.1 in Appendix N of DOE/EIS-0391.

**Figure G-3. Time Series of Net Infiltration Tank Closure and Waste Management Environmental Impact Statement.**




Excerpted from Figure M-1, Appendix M of DOE/EIS-0391, "Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington."

**Figure G-4. Waste Management Area C Vadose Zone Stratigraphy as Depicted in the Tank Closure and Waste Management Environmental Impact Statement.**

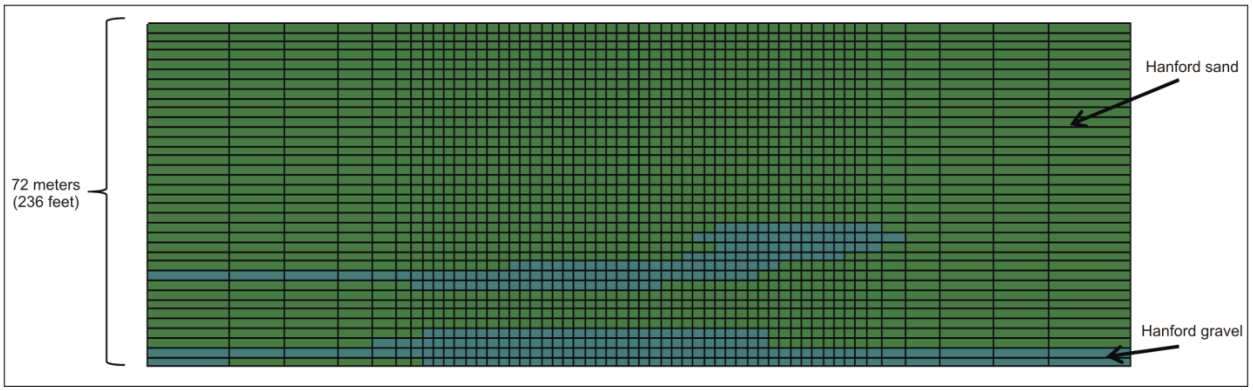



**Figure U–58. West-to-East Cross Section of Vadose Zone Lithology for C Tank Farm**

Excerpted from Figure U-58, Appendix U of DOE/EIS-0391, "Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington"; green is Hanford Sand and blue is Hanford Gravel).

For the purpose of comparing the two model results for Alternative 2B, the WMA C PA model was not modified, and includes the geology and hydraulic properties developed for the PA using local scale information on the hydrogeologic conditions at WMA C. In the PA model of WMA C, the inactive nodal areas representing the tanks and selective ancillary equipment

volumes were treated as active using hydraulic properties being used to represent properties of Hanford H2 Sand hydrostratigraphic unit.

### G3.5 Partitioning Coefficients and Dispersivity

The TC&WM EIS model applied a constant partitioning coefficient value of 0 mL/g to $^{129}$I. The WMA C PA base case analysis partitioning coefficient value for $^{129}$I is 0.2 mL/g in fine-grained material. This value is then adjusted downward for the different hydrogeologic units in the WMA C PA model according to the estimated gravel content associated with those hydrogeologic units.

The TC&WM EIS model applied the same longitudinal and transverse dispersivity values of 1 m and 0.1 m, respectively, to all hydrogeologic units. The WMA C PA base case analysis vadose zone longitudinal and transverse dispersivity values vary according to the hydrogeologic unit. For Hanford H2 Sand, the longitudinal and transverse dispersivity values are 25 cm and 2.5 cm, respectively. For backfill and both Hanford H1 and H3 Sandy Gravel/Gravelly Sand, the longitudinal and transverse dispersivity values are 20 cm and 2.0 cm, respectively.

For the purpose of comparing the two model results for Alternative 2B, the PA model of WMA C was run with constant partitioning coefficient values of 0 mL/g to $^{129}$I, respectively for all hydrogeologic units. The longitudinal and transverse dispersivity values for the hydrogeologic units remained the same as in the WMA C PA base case.

## G.4 COMPARISON OF SELECTED RESULTS FOR ALTERNATIVE 2B USING THE PERFORMANCE ASSESSMENT AND TANK CLOSURE AND WASTE MANAGEMENT ENVIRONMENTAL IMPACT STATEMENT MODELS OF WASTE MANAGEMENT AREA C

The WMA C base case was run with the adaptations described in Sections G.2 and G.3. The flux of $^{129}$I into the water table generated by this analysis was compared to the results presented in Figure U-122 in Appendix U of DOE/EIS-0391, which is replicated as Figure G-5. Comparable results of the WMA C PA model are shown in Figure G-6.

The time series releases of $^{129}$I to the groundwater calculated in both models include two relative maxima, and there is negligible difference between the two peak values calculated by the different models. The primary difference between the model results is that the WMA C model shows the release of $^{129}$I to the groundwater continuing throughout the simulation period. This tail of the release rate curve is a consequence of the inclusion of the aquifer in the WMA C PA model, which introduces some persistence of transport between the capillary fringe and water table.

The results of the comparison show that the two models are capable of producing consistent results. To make the comparison meaningful, several differences in inputs had to be reconciled, e.g., the radionuclide inventory and release functions associated with the release of the radionuclides from the grout. When these differences are reconciled, the two models agree well.

**Figure G-5. Tank Closure and Waste Management Environmental Impact Statement Analysis of Iodine-129 Flux from the Vadose Zone into the Aquifer for Alternative 2b (Baseline) and Three Flux Reduction Sensitivity Cases.**

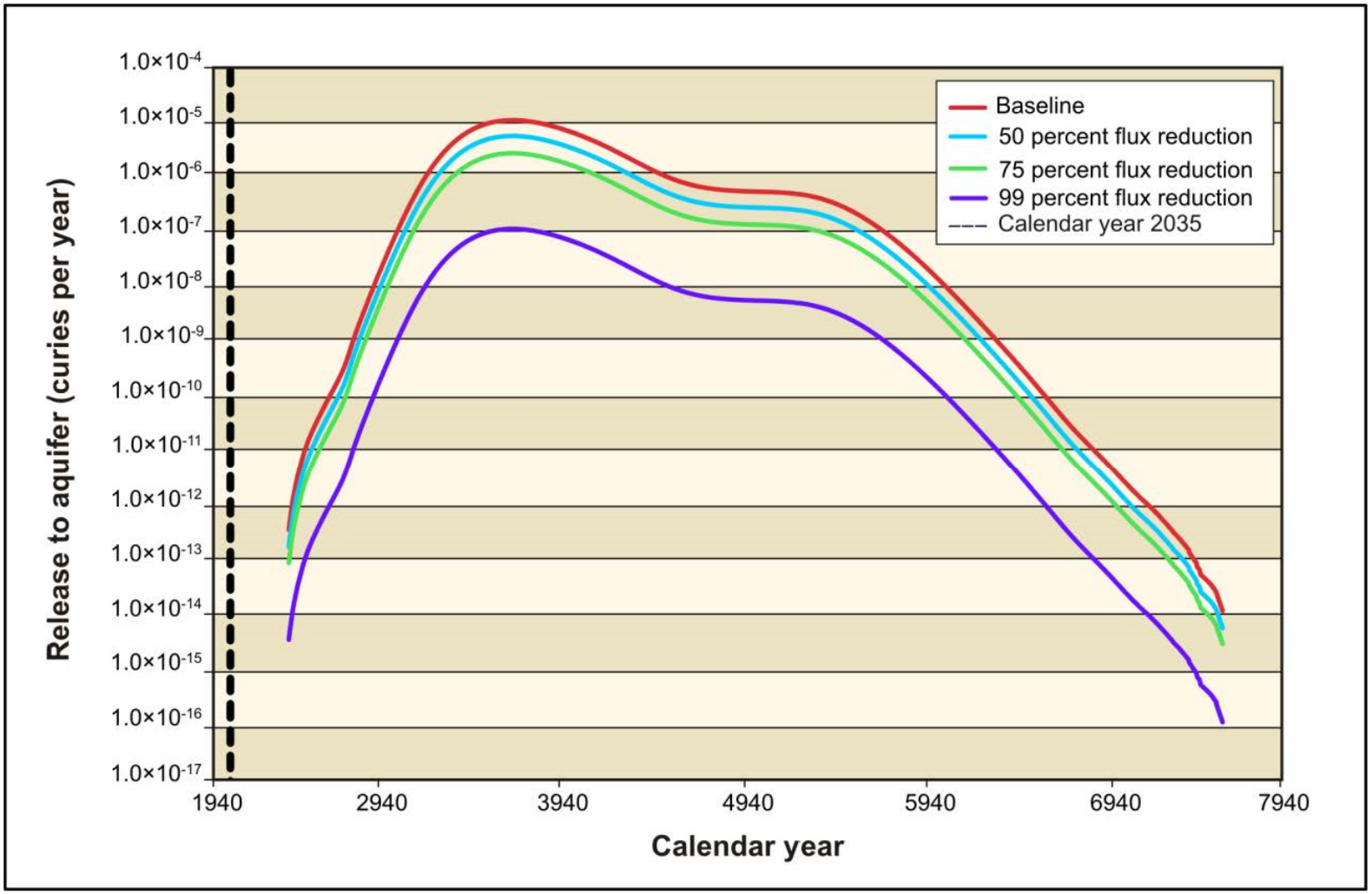
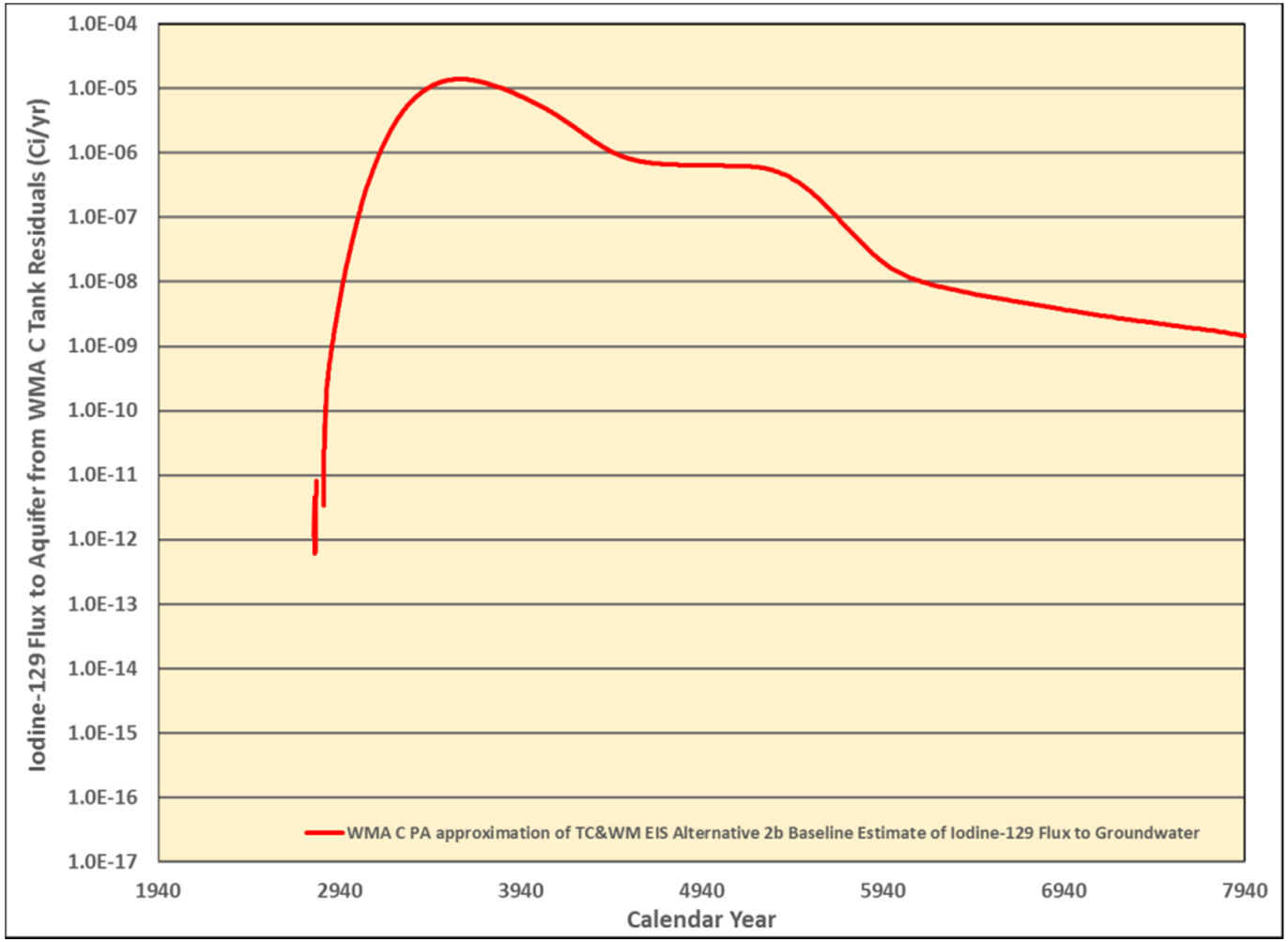



**Figure U–122. Iodine-129 Flux to Aquifer Versus Time, C Tank Farm, Tank Residuals**

Excerpted from Figure U-122, Appendix U of DOE/EIS-0391, "Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington."

**Figure G-6. Waste Management Area C Performance Assessment Evaluation of Tank Closure and Waste Management Environmental Impact Statement Alternative 2b Model of Iodine-129 Flux from the Vadose Zone into the Aquifer.**




PA = performance assessment
TC&WM EIS = Tank Closure and Waste Management Environmental Impact Statement
WMA = Waste Management Area

Reference: DOE/EIS-0391, "Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington."

## G.5 REFERENCES

DOE/EIS-0391, 2012, "Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington," U.S. Department of Energy, Office of River Protection, Richland, Washington.
Appendix M, Release to Vadose Zone
Appendix N, Vadose Zone Flow and Transport
Appendix O, Groundwater Transport Analysis
Appendix U, Supporting Information for the Long-Term Cumulative Impact Analyses

DOE M 435.1-1, 1999, Radioactive Waste Management Manual, U.S. Department of Energy, Washington, D.C.

DOE/ORP-2003-02, 2003, Environmental Impact Statement for Retrieval, Treatment, and Disposal of Tank Waste and Closure of Single-Shell Tanks at the Hanford Site, Richland, WA: Inventory and Source Term Data Package, Rev. 0, U.S. Department of Energy, Office of River Protection, Richland, Washington.

Resource Conservation and Recovery Act of 1976, 42 USC 6901, et seq.

# APPENDIX H

# LIST OF FEATURES, EVENTS AND PROCESSES APPLIED TO WASTE MANAGEMENT AREA C PERFORMANCE ASSESSMENT

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# LIST OF TERMS

## Abbreviations and Acronyms

| | |
|---|---|
| DOE | U.S. Department of Energy |
| FEP | Features, Events, and Processes |
| IAEA | International Atomic Energy Agency |
| ISAM | Improvement of Safety Assessment Methodologies |
| PA | performance assessment |
| WMA | Waste Management Area |

# APPENDIX H

# LIST OF FEATURES, EVENTS AND PROCESSES APPLIED TO WASTE MANAGEMENT AREA C

## H.1 BACKGROUND ON FEATURES, EVENTS AND PROCESSES EVALUATION

The use of Features, Events, and Processes (FEPs) is a well-established approach for improving the traceability and transparency of a performance assessment (PA). The intent of the use of FEPs is to identify conditions that may occur in the future that may affect the ability of the disposal system to perform successfully.

In general, the process of using FEPs consists of four steps: (1) identifying a comprehensive list of FEPs, (2) screening the comprehensive list to a manageable number, (3) describing the relationships between the FEPs, and (4) arranging them into calculational cases, or scenarios, for the safety assessment. Differences between published FEP evaluation approaches are comprised of differences between methods for one of these steps, or different ordering of the steps. For instance, the original scenario development procedure described in NUREG/CR-1667 (SAND80-1429), "Risk Methodology for Geologic Disposal of Radioactive Waste: Scenario Selection Procedure" only calls for screening the full scenarios, whereas more recent scenario development approaches emphasize screening at the FEP level (SKB Technical Report 95-22, "The Use of Interaction Matrices for Identification, Structuring, and Ranking of FEPs in a Repository System") or screening both FEPs and full scenarios (SAND94-0482, "Scenario Development for the Waste Isolation Pilot Plant: Building Confidence in the Assessment"). Despite the differences in approaches and ordering, the concepts of these four steps are the same for all scenario development procedures.

Considerable international effort has been expended to develop comprehensive FEP lists for geological (deep) disposal systems. There is only one approach that has been used for this step: collection and elicitation of expert opinion. Excellent summaries of the comprehensive FEP lists for geological disposal have been provided by Chapman et al. (SKI Report 95:26, "Systems Analysis, Scenario Construction and Consequence Analysis Definition for SITE-94") and by Guzowski and Newman (SAND93-7100, "Preliminary Identification of Potentially Disruptive Scenarios at the Greater Confinement Disposal Facility, Area 5 of the Nevada Test Site"). Chapman et al. (SKI Report 95:26) suggest that a comprehensive list of FEPs for a geological disposal system in Sweden was comprised of over 1,200 entries (SKI Technical Report 93:27, "SITE-94 Scenario Development FEP Audit List Preparation: Methodology and Presentation").

Work on formal scenario development for near-surface disposal is more recent and based heavily on the prior geological disposal literature. The International Atomic Energy Agency (IAEA) (IAEA-ISAM-1, "Safety Assessment Methodologies for Near Surface Disposal Facilities, Results of a co-ordinated research project, Volume 1: Review and enhancement of safety assessment approaches and tools") published the first comprehensive set of FEPs for near-surface disposal based on the results of the Improvement of Safety Assessment Methodologies (ISAM) coordinated research program. This FEP list was an adaptation of a

geological disposal comprehensive FEP list for near-surface conditions (IAEA-ISAM-1), and was audited against previously developed site-specific FEP lists for near-surface disposal [e.g., AECL-MISC-295, "Preliminary Safety Analysis Report (PSAR) for the Intrusion Resistant Underground Structure (IRUS)"], providing a good degree of confidence that the list was substantially complete and reliable. This international FEP list is attached to this report as Appendix A.

FEP approaches have also been used increasingly within the U.S. Department of Energy (DOE) Environmental Management and Tank Waste programs (e.g., "2002 LLW Repository PCSC – FEP Consideration [Phifer 2011]; FCRD-USED-2011-000297, "Features, Events and Processes for the Disposal of Low Level Radioactive Waste – FY 2011 Status Report"). Lists of Hanford-relevant FEPs have been developed [BHI-01573, "Groundwater/Vadose Zone Integration Project – The Application of Feature, Event, and Process Methodology at the Hanford Site"; WMP-22922, "Prototype Hanford Features, Events, and Processes (HFEP) Graphical User Interface"] and applied to recent PAs (WCH-520, "Performance Assessment for the Environmental Restoration Disposal Facility, Hanford Site, Washington"). The Hanford FEP lists differ in some regards from the international FEP list, mainly in being focused at a very fine level of detail, which has limited their utility in PAs.

While FEP analyses have been widely used, they have also been identified to have a number of drawbacks. In particular, as a bottom-up approach, they seek to identify all conditions of concern, without necessarily focusing on the key issues. As a result, they have in some cases led to large amounts of effort, but without a commensurate improvement in the traceability of the PA.

As a result of these issues with FEP-based analyses, in recent years there has been increasing attention given to safety function approaches in structuring PAs. Recent guidance on the conduct of PAs has de-emphasized the importance of purely FEP-based approaches, and has instead recommended a blended approach (NEA Report 6923,"Methods of Safety Assessment of Geological Disposal Facilities for Radioactive Waste, Outcomes of the NEA MeSA Initiative"). These approaches are reviewed in the next section.

## H.2 INTRODUCTION TO SAFETY FUNCTIONS

The drawbacks to the FEPs process have led to a more recent emphasis in the literature on the use of an alternative approach to identifying conditions that need to be included in the PA. Increasingly, the literature on PA emphasizes the use of safety functions as either a replacement for FEP analyses or as an augmentation of FEP analyses (e.g., SKB Technical Report TR-10-45, "FEP report for the safety assessment SR-Site"; NEA Report 6923). A safety function is a feature of the system that provides a specific function that is relevant to the performance (or safety) of the facility. The set of these safety functions presents a high-level summary of the strategy by which the performance of the disposal system is assured. In addition to providing a technical approach to development of scenarios, the use of safety functions is beneficial in emphasizing the overall safety strategy with stakeholders.

Increasingly, PAs include both FEP evaluations as a bottom-up approach and safety functions as a top-down approach to identifying conditions that need to be evaluated in the PA ("A methodology for scenario development based on understanding of long-term evolution of geological disposal systems" [Wakasugi et al. 2012]; "Natural and Engineering Barriers – the Safety Concept Basis for LILW Repository in Vrbina, Krško" [Virsek et al. 2014]). In this hybrid approach, FEPs are used in a more targeted manner than the traditional FEPs concept. In the hybrid approach, FEPs are identified that may affect the ability of the safety function to provide assurance of performance in the future. That is, FEPs are identified that may degrade or modify the performance of the safety function in some way. For instance, performance of an engineered cover system may be influenced by a wide variety of FEPs that would change the rate of water movement through it. These FEPs might include (for example) mechanical changes to the cover soil, changes in the vegetation on top of the cover, climate changes that lead to different precipitation patterns on top of the cover, loss of institutional control leading to onsite irrigation, and so on. Since all of these FEPs influence the system in a similar manner (i.e., changes in water flow through the cover), sensitivity analyses that vary this safety function represent an aggregated view of the potential negative effects of a suite of FEPs. In this way, the PA can be organized to evaluate a large number of FEPs with fewer sensitivity cases and scenarios.

## H.3 SAFETY CONCEPT AND SAFETY FUNCTIONS FOR WASTE MANAGEMENT AREA C

The safety concept is the overall approach by which a disposal system is intended to provide the performance required in regulation. The safety concept can be thought of as the set of safety functions, acting together in concert, to provide that performance. Ideally, the safety functions represent multiple and redundant barriers, so that the loss of one or some of the safety functions continues to result in adequate performance of the overall system. A set of safety functions for Waste Management Area (WMA) C is shown in Table H-1. The goal of the PA is to evaluate these safety functions, to provide reasonable assurance of performance even when some of the safety functions are lost or degraded through time or disruptive events.

A significant part of the safety concept lies in the land ownership of the Central Plateau by DOE. It is noteworthy that all of the technical calculations that are presented in a PA of WMA C are predicated on the loss of the first two safety functions: loss of institutional control of the Central Plateau by DOE, followed by loss of societal memory that the Hanford Site existed. If either or both of these safety functions remain in place, the radiological impacts of releases or residual wastes from WMA C are very low and greatly delayed in time, as shown in the TC&WM EIS analyses for tank residual wastes (DOE/EIS-0391, "Final Tank Closure and Waste Management Environmental Impact Statement for the Hanford Site, Richland, Washington"). In the assessment context of PAs conducted under DOE O 435.1, Radioactive Waste Management (see Section 2), both of these safety functions are assumed to disappear after 100 years.

**Table H-1. Safety Functions, Associated Features, Events, and Processes, and Potentially Deleterious Features, Events, and Processes Identified for the Waste Management Area C Residual Waste Performance Assessment. Details for individual Features, Events, and Processes and associated numbers identified in this table can be found in Section H.4. (6 sheets)**

| Designation | | Description | Associated FEPs | Deleterious FEPs | Associated Analyses |
|---|---|---|---|---|---|
| I1 | Institutional Control | By DOE O 435.1, Radioactive Waste Management, it is assumed that control of the site will be retained for 100 years. A strong potential exists that the U.S. government will retain control of the site for a much more extended period of time. DOE O 458.1, Radiation Protection of the Public and the Environment requires that plans for management and disposal of wastes provide for institutional controls and long-term stewardship. DOE P 454.1, Use of Institutional Controls identifies how that stewardship is to be carried out. | 1.1.06<br>1.1.09<br>1.1.10<br>1.4 (all) | | Treated conservatively in all |
| I2 | Societal memory | Societal memory is represented by records, deed restrictions, and other passive controls that would warn someone that additional care should be taken in the area. For a member of the public to come onsite to experience exposures to contamination from Waste Management Area (WMA) C, records that the Hanford Site existed would need to be forgotten or ignored. DOE O 458.1 requires record keeping that would lessen the likelihood of this occurrence. DOE P 454.1 identifies how that stewardship is to be carried out. | 1.1.06<br>1.1.09<br>1.1.10<br>1.4 (all) | | Treated conservatively in all |
| I3 | Exposure | By DOE O 435.1, it is assumed that a post-closure well is established 100 m downgradient at the point of highest exposure. It is highly unlikely that this situation will occur, and potential wells in other locations would produce much lower impacts to a member of the public. Furthermore, even if control of the site is lost, the 100 m boundary for WMA C lies under the A Complex, and does not represent a realistic exposure point. Exposures would be more likely to occur further downgradient. | 1.1 (all)<br>1.4 (all)<br>3.3 (all)<br>2.2.13(intruder)<br>2.3.03<br>2.3.08<br>2.3.09<br>2.3.13<br>2.4 (all) | | Treated conservatively in all |

**Table H-1. Safety Functions, Associated Features, Events, and Processes, and Potentially Deleterious Features, Events, and Processes Identified for the Waste Management Area C Residual Waste Performance Assessment. Details for individual Features, Events, and Processes and associated numbers identified in this table can be found in Section H.4. (6 sheets)**

| Designation | | Description | Associated FEPs | Deleterious FEPs | Associated Analyses |
|---|---|---|---|---|---|
| S1 | Site characteristics | WMA C is a semi-arid site with low precipitation. The Central Plateau is remote from members of the public, with a substantial buffer area under U.S. Department of Energy (DOE) control. The vadose zone is thick, with long travel times in the vadose zone. | 2.3.01<br>2.3.02<br>2.3.03<br>2.3.07<br>2.3.07<br>2.3.08<br>2.3.09<br>2.3.10<br>2.3.11<br>2.3.12<br>2.3.13 | | All |
| EB1 | RCRA Cover (infiltration reduction) | The final design cover has not yet been established, but is believed to be able to produce very low initial flow rates. Over some period of time this function may deteriorate, with the rate of deterioration associated with a variety of processes. | 1.1.02<br>1.1.08<br>1.1.12<br>1.2.04<br>1.2.07<br>1.3.01<br>1.3.02<br>1.3.04<br>1.3.06<br>1.3.07<br>1.3.08<br>1.4 (all)<br>2.1.05<br>2.3.01<br>2.3.02<br>2.3.07<br>2.3.08<br>2.3.10<br>2.3.11<br>2.3.12<br>2.3.13 | 1.1.08<br>1.1.12<br>1.2.04<br>1.2.07<br>2.3.08<br>2.3.12<br>2.3.13 | INF0 – INF4<br>Treated in GoldSim©<br>uncertainty analysis |

**Table H-1. Safety Functions, Associated Features, Events, and Processes, and Potentially Deleterious Features, Events, and Processes Identified for the Waste Management Area C Residual Waste Performance Assessment. Details for individual Features, Events, and Processes and associated numbers identified in this table can be found in Section H.4. (6 sheets)**

| Designation | | Description | Associated FEPs | Deleterious FEPs | Associated Analyses |
|---|---|---|---|---|---|
| EB2 | RCRA Cover (depth of disposal) | Limitation of types of potential inadvertent human intrusion by depth of disposal. | 1.1.02<br>1.1.05<br>1.4 (all) | | Intrusion |
| EB3 | Steel Shell (permeability) | The function of the carbon steel shell to limit flow through the tank is not currently explicitly accounted for in the performance assessment. The shell is part of the overall assessment of low flow through the tank for long periods of time. Its potential eventual failure is considered as part of the generic barrier failure cases. DIF4 explores what happens if the tank behaves *better* than expected, and retains integrity for thousands of years, allowing ingrowth of progeny before releases commence. | 1.1.02<br>2.1.05<br>2.1.08 | | DIF4 |
| EB4 | Steel Shell (chemical) | The carbon steel shell will corrode over a period of time, leaving behind corrosion products of (primarily) iron oxides. These corrosion products are highly sorptive and tend to produce reducing conditions that are highly advantageous for limiting solubilities of key radionuclides, particularly technetium. | 1.1.02<br>2.1.05<br>2.1.09 | | None |
| EB5 | Tank structure (structural) | The dome and walls provide structural support preventing subsidence of the closed facility. | 1.1.02<br>1.2.03<br>2.1.05 | | No credible deleterious FEPs |
| EB6 | Tank structure (intrusion) | The tank structure provides a barrier to intrusion. | 1.1.02<br>1.4.03<br>2.1.05 | | Intrusion analysis |
| EB7 | Tank structure (chemical) | The concrete of the tank acts to condition the chemistry of the waste residuals, with sorption characteristic of high pH environments. | 1.1.02<br>2.1.05<br>2.1.09 | | Treated in GoldSim© uncertainty analysis GRT4 (Barrier analysis) |
| EB8 | Tank structure (permeability) | The concrete of the tank structure is substantially intact and provides a barrier to flow into the tank. | 1.1.02<br>1.2.03<br>2.1.05 | 1.2.03 | GRT1, GRT2, GRT3 |

**Table H-1. Safety Functions, Associated Features, Events, and Processes, and Potentially Deleterious Features, Events, and Processes Identified for the Waste Management Area C Residual Waste Performance Assessment. Details for individual Features, Events, and Processes and associated numbers identified in this table can be found in Section H.4. (6 sheets)**

| Designation | | Description | Associated FEPs | Deleterious FEPs | Associated Analyses |
|---|---|---|---|---|---|
| EB9 | Grout in tank (permeability) | The grout acts to limit water flow through the facility, making releases dominated by diffusion from the waste. | 1.1.02<br>1.1.03<br>1.1.04<br>1.1.05<br>1.1.08<br>1.2.03<br>2.1.04 | 1.1.08<br>1.2.03 | GRT1, GRT2, GRT3 |
| EB10 | Grout in Tank (chemical) | The grout acts to condition the chemistry of the waste residuals, with sorption characteristic of high pH environments. | 1.1.02<br>2.1.04<br>2.1.09 | | Treated in GoldSim© uncertainty analysis<br>GRT4 (Barrier analysis) |
| EB11 | Grout in tank (structural) | The grout provides structural support preventing subsidence of the closed facility. | 1.1.02<br>2.1.04 | | No credible deleterious FEPs |
| EB12 | Grout (intrusion) | The structural strength of the grout provides a barrier to intrusion. | 1.1.02<br>1.4.03<br>2.1.04<br>2.2.13 | | Intrusion analysis |
| EB13 | Tank Base Mat (permeability) | The tank base mat, if intact, will provide a barrier that will limit flow and contaminant transport from the tank residual wastes situated at the tank bottom into the underlying vadose zone sediments. | 1.1.02<br>2.1.05 | 2.1.05 | GRT0<br>GRT1<br>GRT2<br>GRT3 (Barrier analysis) |
| EB14 | Tank Base Mat (chemical) | The concrete pad is anticipated to continue to provide a high pH environment, with associated sorption, for an extended time in the future. | 1.1.02<br>2.1.05<br>2.1.09<br>2.1.10 | | GoldSim© uncertainty analysis |
| EB15 | Pipelines (permeability) | The pipelines, if intact, provide a delay to releases of waste in ancillary equipment. | 2.1.06 | | All |
| AP1 | Grout (air pathway) | Limitation of releases to air owing to low air permeability and long pathway to the surface. | 2.1.12<br>2.3.07<br>3.1.04<br>3.2.09<br>3.2.10 | | Air pathway analysis |

**Table H-1. Safety Functions, Associated Features, Events, and Processes, and Potentially Deleterious Features, Events, and Processes Identified for the Waste Management Area C Residual Waste Performance Assessment. Details for individual Features, Events, and Processes and associated numbers identified in this table can be found in Section H.4. (6 sheets)**

| Designation | | Description | Associated FEPs | Deleterious FEPs | Associated Analyses |
|---|---|---|---|---|---|
| WF1 | Residual Waste (chemical) | The residual waste is recalcitrant by nature, providing limitations to the amount and rate of release of contamination from it upon contact with water. | 2.1.01<br>2.1.02<br>2.1.12<br>3.1 (all)<br>(except 3.1.06)<br>3.2 (all)<br>(except 3.2.08) | 2.1.1 | RLS1<br>INV0, INV1, INV2<br>GoldSim© uncertainty |
| VZ1 | Vadose zone thickness | The vadose zone is thick with slow rates of water flow, leading to long delay times in the vadose zone. | 2.2.01<br>2.2.02<br>2.2.03<br>2.2.05<br>2.2.07<br>2.2.08<br>2.2.09<br>2.2.12<br>2.3.02<br>3.1.01<br>3.2.07 | 1.1.01<br>2.2.12 | VZP0<br>VZP1<br>VZP2<br>VZP3<br>VZP4<br>VZP5<br>VZP6<br>VZP7<br>Treated in GoldSim© uncertainty analysis<br>VZP9 (Barrier analysis) |
| VZ2 | Sorption on vadose zone soils | Vadose zone soils sorb some of the contaminants of potential concern, delaying their arrival at the water table. A number of key contaminants are not believed to sorb significantly. | 1.4.07<br>2.2.08<br>2.2.09<br>2.3.02<br>3.2.03<br>3.2.04<br>3.2.05<br>3.2.06<br>3.2.07 | 1.4.07<br>2.2.08<br>3.2.03 | Treated in GoldSim© uncertainty analysis<br>VZP6 |
| VZ3 | Dispersion in vadose zone | Spreading of contaminants in the vadose zone, dispersing them and decreasing concentrations. | 2.2.01<br>2.2.02<br>2.2.03<br>2.2.05<br>2.2.07<br>2.3.02 | 2.2.12 | Treated in GoldSim© uncertainty analysis<br>VZP7 |

**Table H-1. Safety Functions, Associated Features, Events, and Processes, and Potentially Deleterious Features, Events, and Processes Identified for the Waste Management Area C Residual Waste Performance Assessment. Details for individual Features, Events, and Processes and associated numbers identified in this table can be found in Section H.4. (6 sheets)**

| Designation | | Description | Associated FEPs | Deleterious FEPs | Associated Analyses |
|---|---|---|---|---|---|
| SZ1 | Water flow in saturated zone | Advective flow in the saturated zone leading to dilution of the contaminants. | 1.2.10<br>1.3.01<br>1.3.02<br>1.3.03<br>1.3.07<br>1.4.10<br>2.2.03<br>2.2.05<br>2.2.07<br>2.3.03<br>2.3.04<br>3.1.01<br>3.2.07 | 1.3.01<br>1.3.02<br>1.3.03<br>1.3.07<br>2.3.03 | Treated in GoldSim© uncertainty analysis<br>GWP0<br>GWP1<br>GWP2<br>GWP3 (Barrier analysis) |
| SZ2 | Sorption on saturated zone soils | Saturated zone soils sorb some of the contaminants of potential concern, delaying their arrival at the point of compliance. A number of key contaminants are not believed to sorb significantly. | 2.2.08<br>2.2.09<br>3.2.03<br>3.2.04<br>3.2.07 | | Treated in GoldSim© uncertainty analysis |
| SZ3 | Dispersion in saturated zone | Spreading of the plume in the saturated zone, adding dilution to the contaminant plume and lowering concentrations. | 2.2.03<br>2.2.05<br>2.2.07 | | Treated in GoldSim© uncertainty analysis |
| SZ4 | Dilution in well | Dilution caused by pumping a groundwater well to the surface where it is useable and accessible by a member of the public. | 1.4.10<br>2.2.13<br>3.2.07<br>3.2.12<br>3.3.01<br>3.3.02<br>3.3.04 | | By groundwater protection rule, not taken into account. Groundwater concentrations at each point in space used for all analyses. |

FEPs = Features, Events, and Processes RCRA = Resource Conservation and Recovery Act of 1976

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DOE O 435.1 also introduces another administrative safety function into the analysis: the point of compliance. If the first two safety functions (institutional control and societal memory) are lost, DOE O 435.1 requires an assumption that a groundwater well is installed 100 m from the disposal facility in the location of peak concentration. This assumption means that relatively little credit is given for delay and dilution in the groundwater aquifer. Even in the event that memory of the Hanford Site is lost, people would not necessarily move to the Central Plateau and use untreated groundwater as their water source. People further downgradient or people not using groundwater would necessarily be more protected than the PA calculates. The regulation, therefore, provides an additional layer of safety to the results of the analyses via this safety function.

The remaining parts of the safety concept involve the use of the engineering and geological setting to provide multiple and redundant barriers to the release and migration of residual wastes from tanks and ancillary equipment. The barriers can be divided into one of three types: hydrological safety functions, chemical safety functions, and structural safety functions. The safety concept calls for backfilling the tanks with grout, leading to a highly stable underground structure. The resulting monolith of grout contained in the tank can be assumed to maintain its ability to support the soil overburden for very long periods of time. The hydrological safety functions limit the contact of water with the residual wastes, limit that rate at which contamination can be released and transported through the environment to the compliance point, and provide dilution of contamination through dispersion and mixing with clean surrounding water. The chemical safety functions are intended to decrease the solubility and increase the sorption of key contaminants, and to provide a stable and passive chemical environment for the engineered barriers.

As discussed above, the purpose of the PA is to evaluate the safety concept to provide reasonable assurance of performance of the safety concept, even in the event that one or more of the safety functions are lost or are degraded in time. It is therefore reasonable to ask which FEPs might affect a particular safety function in a way that might degrade its function, or to cause the safety function to act differently than expected.

This approach can be used to identify a set of sensitivity analyses that can be used to explore the implications of the loss of safety functions, while at the same time exploring the implications of aggregated FEPs that might affect the safety function in similar ways. The structure of the PA for WMA C will therefore be to identify sensitivity cases and alternative models for the safety functions shown in Table H-1, and to examine what happens in the PA model when the safety function behaves differently than expected, is degraded compared to a base case, or is lost entirely. Particular attention will be given to any FEPs identified that might affect multiple safety functions simultaneously.

The safety functions identified for the WMA C post-closure period are presented in Table H-1 along with the associated FEPs and potentially deleterious FEPs. This table was generated from a workshop of senior PA experts, and represents the collective view of that group. The workshop was held in Denver April 20 – 21, 2015, with the goal of evaluating FEPs as they relate to WMA C and mapping the FEPs to safety functions. The attendee list is below.

WRPS/INTERA/Hanford

- Marcel Bergeron
- Matt Kozak
- Mike Connelly
- Alaa Aly
- Mick Apted
- Randy Arthur
- Bob Andrews

SRR/SRNL/ Savannah River

- Roger Seitz
- Kent Rosenberger
- Steve Hommel

PNNL/Hanford

- Vicky Freedman

The workshop was undertaken to evaluate which FEPs had the potential to affect safety functions within the 10,000-year sensitivity and uncertainty analysis period. It therefore allowed the FEP team to screen out some FEPs that may be expected to occur over extremely long time periods (e.g., orogeny). The presumption in the FEP screening was that continental glaciation will not occur within 10,000 years, so FEPs associated with such extreme changes were screened out. All other FEPs that have a reasonable likelihood of occurrence in 10,000 years were evaluated for their potential effects on the safety functions.

## H.4 INTERNATIONAL FEATURES, EVENTS, AND PROCESSES LIST WITH EVALUATIONS OF APPLICABILITY TO WASTE MANAGEMENT AREA C

This section contains an adaptation of Appendix C of IAEA-ISAM-1. The ISAM FEPs list is a list of FEPs relevant to the assessment of long-term safety of near-surface disposal facilities, which attempts to be comprehensive within reasonable bounds. Because these FEPS are an adaptation of the FEPs used for near-surface disposal facilities, the term repository is used to refer to the disposal system. It consists of 141 FEPs, each of which has an identifying number. The numbers reflect a classification system, as shown in Figure H-1. At its center, the classification scheme includes processes related to contaminant release, migration and exposures (radionuclide and contaminant factors). The next tier are the features of the disposal system (wastes, engineered and natural barriers and human behaviour) and events and processes which may cause the system to evolve (environment factors). Further out, there are processes and events originating outside the disposal system, but which act upon it (external factors). These external factors (or external FEPs) are often considered to be scenario-generating FEPs.

Examination of the FEPs list shows a distinction between those that are descriptive of the system and how it functions and those that have been included in the FEPs list because they have potentially disruptive effects on the disposal system. This distinction has been used to

characterize how the FEPs act on WMA C safety functions, with the results documented in Section H.3.

**Figure H-1. Feature, Event, and Process Numbering Classification System.**

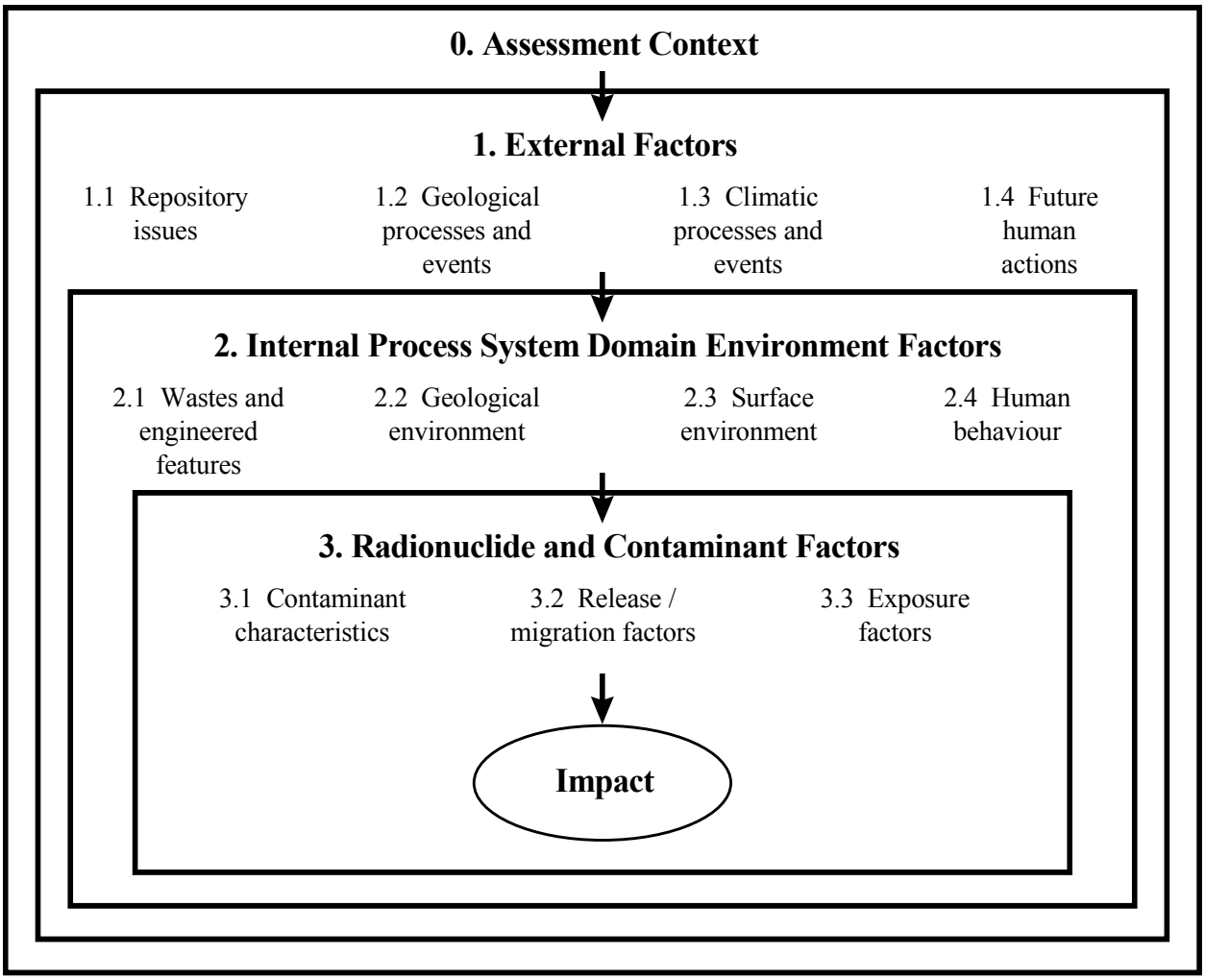


Figure excerpted from IAEA-ISAM-1, "Safety Assessment Methodologies for Near Surface Disposal Facilities, Results of a co-ordinated research project, Volume 1: Review and enhancement of safety assessment approaches and tools."

For the sake of clarity, the full list of FEPs from IAEA-ISAM-1 is included here in the same format as the original publication (refer to the list below). A new addition to the description of each FEP is a short commentary on the applicability of the FEP to the WMA C PA, and a short statement of what negative impact (if any) the FEP may have on the performance of WMA C, and how it affects safety functions.

## H.5 MAPPING SAFETY FUNCTIONS TO FEATURES, EVENTS AND PROCESSES

Application of the IAEA FEPs list to the WMA C safety functions, discussed in Section H.4, leads to a mapping of applicable FEPs to each safety function. This mapping is shown in

Table H-2. A number of the FEPs have been evaluated as not applicable to WMA C, either because of the geological or geographical location, because of the assessment context, or because of the time frame of the analysis, which rules out FEPs requiring very long geological times for their occurrence. These FEPs are denoted with N in the table (for not applicable). FEPs applicable to a particular safety function are denoted with an X, whereas if the FEP is not applicable to the safety function it is left blank.

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**Table H-2. Applicability of Features, Events, and Processes to Waste Management Area C Safety Functions. (1 of 3 sheets)**

**X denotes applicable to Waste Management Area C, N denotes not applicable. See Feature, Event, and Process (FEP) list for discussion and justification.**

| FEP | Safety Function | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | I1 | I2 | I3 | S1 | EB1 | EB2 | EB3 | EB4 | EB5 | EB6 | EB7 | EB8 | EB9 | EB10 | EB11 | EB12 | EB13 | EB14 | EB15 | AP1 | WF1 | VZ1 | VZ2 | VZ3 | SZ1 | SZ2 | SZ3 | SZ4 |
| 1.1.01 | | | X | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1.1.02 | | | X | | X | X | X | X | X | X | X | X | X | X | X | X | X | X | | | | | | | | | | |
| 1.1.03 | | | X | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1.1.04 | | | X | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1.1.05 | | | X | | | X | | | | | | | | | | | | | | | | | | | | | | |
| 1.1.06 | X | X | X | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1.1.07 | | | X | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1.1.08 | | | X | | X | | | | | | | | | | | | | | | | | | | | | | | |
| 1.1.09 | X | X | X | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1.1.10 | X | X | X | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1.1.11 | | | X | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1.1.12 | | | X | | X | | | | | | | | | | | | | | | | | | | | | | | |
| 1.2.01 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| 1.2.02 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| 1.2.03 | | | | | | | | | X | | | X | X | | | | | | | | | | | | | | | |
| 1.2.04 | | | | | X | | | | | | | | | | | | | | | | | | | | | | | |
| 1.2.05 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| 1.2.06 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| 1.2.07 | | | | | X | | | | | | | | | | | | | | | | | | | | | | | |
| 1.2.08 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| 1.2.09 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| 1.2.10 | | | | | | | | | | | | | | | | | | | | | | | | | X | | | |
| 1.3.01 | | | | | X | | | | | | | | | | | | | | | | | | | | X | | | |
| 1.3.02 | | | | | X | | | | | | | | | | | | | | | | | | | | X | | | |
| 1.3.03 | | | | | | | | | | | | | | | | | | | | | | | | | X | | | |
| 1.3.04 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| 1.3.05 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| 1.3.06 | | | | | X | | | | | | | | | | | | | | | | | | | | | | | |
| 1.3.07 | | | | | X | | | | | | | | | | | | | | | | | | | | X | | | |
| 1.3.08 | | | | | X | | | | | | | | | | | | | | | | | | | | | | | |
| 1.3.09 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| 1.3.10 | | | | | | X | | | | | | | | | | | | | | | | | | | | | | |
| 1.4.01 | X | X | X | | X | | | | | | | | | | | | | | | | | | | | | | | |
| 1.4.02 | X | X | X | | X | | | | | | | | | | | | | | | | | | | | | | | |
| 1.4.03 | X | X | X | | X | | | | | X | | | | | | X | | | | | | | | | | | | |
| 1.4.04 | X | X | X | | X | | | | | | | | | | | | | | | | | | | | | | | |
| 1.4.05 | X | X | X | | X | | | | | | | | | | | | | | | | | | | | | | | |
| 1.4.06 | X | X | X | | X | | | | | | | | | | | | | | | | | | | | | | | |
| 1.4.07 | X | X | X | | X | | | | | | | | | | | | | | | | | | X | | | | | |
| 1.4.08 | X | X | X | | X | | | | | | | | | | | | | | | | | | | | | | | |
| 1.4.09 | X | X | X | | X | | | | | | | | | | | | | | | | | | | | | | | |
| 1.4.10 | X | X | X | | X | | | | | | | | | | | | | | | | | | | | X | | | |

**Table H-2. Applicability of Features, Events, and Processes to Waste Management Area C Safety Functions. (2 of 3 sheets)**

**X denotes applicable to Waste Management Area C, N denotes not applicable. See Feature, Event, and Process (FEP) list for discussion and justification.**

| FEP | Safety Function | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | I1 | I2 | I3 | S1 | EB1 | EB2 | EB3 | EB4 | EB5 | EB6 | EB7 | EB8 | EB9 | EB10 | EB11 | EB12 | EB13 | EB14 | EB15 | AP1 | WF1 | VZ1 | VZ2 | VZ3 | SZ1 | SZ2 | SZ3 | SZ4 |
| 1.4.11 | X | X | X | | X | | | | | | | | | | | | | | | | | | | | | | | |
| 1.4.12 | X | X | X | | X | | | | | | | | | | | | | | | | | | | | | | | |
| 1.4.13 | X | X | X | | X | | | | | | | | | | | | | | | | | | | | | | | |
| 1.4.14 | X | X | X | | X | | | | | | | | | | | | | | | | | | | | | | | |
| 1.4.15 | X | X | X | | X | | | | | | | | | | | | | | | | | | | | | | | |
| 2.1.01 | | | | | | | | | | | | | | | | | | | | | X | | | | | | | |
| 2.1.02 | | | | | | | | | | | | | | | | | | | | | X | | | | | | | |
| 2.1.03 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| 2.1.04 | | | | | | | | | | | | | X | X | X | X | | | | | | | | | | | | |
| 2.1.05 | | | | | | | X | X | X | X | X | X | | | | | X | X | | | | | | | | | | |
| 2.1.06 | | | | | | | | | | | | | | | | | | | X | | | | | | | | | |
| 2.1.07 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2.1.08 | | | | | | | X | | | | | | | | | | | | | | | | | | | | | |
| 2.1.09 | | | | | | | | X | | | X | | | X | | | X | X | | | | | | | | | | |
| 2.1.10 | | | | | | | | | | | | | | | | | | X | | | | | | | | | | |
| 2.1.11 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| 2.1.12 | | | | | | | | | | | | | | | | | | | | X | X | | | | | | | |
| 2.1.13 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| 2.1.14 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| 2.1.15 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| 2.2.01 | | | | | | | | | | | | | | | | | | | | | | X | | X | | | | |
| 2.2.02 | | | | | | | | | | | | | | | | | | | | | | X | | X | | | | |
| 2.2.03 | | | | | | | | | | | | | | | | | | | | | | X | | X | X | | X | |
| 2.2.04 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| 2.2.05 | | | | | | | | | | | | | | | | | | | | | | X | | X | X | | X | |
| 2.2.06 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| 2.2.07 | | | | | | | | | | | | | | | | | | | | | | X | | X | X | | | |
| 2.2.08 | | | | | | | | | | | | | | | | | | | | | | X | X | | | X | | |
| 2.2.09 | | | | | | | | | | | | | | | | | | | | | | X | X | | | X | | |
| 2.2.10 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| 2.2.11 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| 2.2.12 | | | | | | | | | | | | | | | | | | | | | | X | | | | | | |
| 2.2.13 | | | X | | | | | | | | | | | | | | | | | | | | | | | | | X |
| 2.3.01 | | | | X | X | | | | | | | | | | | | | | | | | | | | | | | |
| 2.3.02 | | | | X | X | | | | | | | | | | | | | | | | | X | X | X | | | | |
| 2.3.03 | | | X | X | | | | | | | | | | | | | | | | | | | | | X | | | |
| 2.3.04 | | | | X | | | | | | | | | | | | | | | | | | | | | X | | | |
| 2.3.05 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| 2.3.06 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| 2.3.07 | | | | X | X | | | | | | | | | | | | | | | | | X | | | | | | |
| 2.3.08 | | | X | X | X | | | | | | | | | | | | | | | | | | | | | | | |
| 2.3.09 | | | X | X | | | | | | | | | | | | | | | | | | | | | | | | |
| 2.3.10 | | | | X | X | | | | | | | | | | | | | | | | | | | | | | | |

**Table H-2. Applicability of Features, Events, and Processes to Waste Management Area C Safety Functions. (3 of 3 sheets)**

**X denotes applicable to Waste Management Area C, N denotes not applicable. See Feature, Event, and Process (FEP) list for discussion and justification.**

| FEP | Safety Function | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | I1 | I2 | I3 | S1 | EB1 | EB2 | EB3 | EB4 | EB5 | EB6 | EB7 | EB8 | EB9 | EB10 | EB11 | EB12 | EB13 | EB14 | EB15 | AP1 | WF1 | VZ1 | VZ2 | VZ3 | SZ1 | SZ2 | SZ3 | SZ4 |
| 2.3.11 | | | | X | X | | | | | | | | | | | | | | | | | | | | | | | |
| 2.3.12 | | | | X | X | | | | | | | | | | | | | | | | | | | | | | | |
| 2.3.13 | | | X | X | X | | | | | | | | | | | | | | | | | | | | | | | |
| 2.3.14 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| 2.4.01 | | | X | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2.4.02 | | | X | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2.4.03 | | | X | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2.4.04 | | | X | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2.4.05 | | | X | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2.4.06 | | | X | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2.4.07 | | | X | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2.4.08 | | | X | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2.4.09 | | | X | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2.4.10 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| 2.4.11 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| 3.1.01 | | | | | | | | | | | | | | | | | | | | | | X | | | X | | | |
| 3.1.02 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| 3.1.03 | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 3.1.04 | | | | | | | | | | | | | | | | | | | | X | | | | | | | | |
| 3.1.05 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| 3.1.06 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| 3.2.01 | | | | | | | | | | | | | | | | | | | | | X | | | | | | | |
| 3.2.02 | | | | | | | | | | | | | | | | | | | | | X | | | | | | | |
| 3.2.03 | | | | | | | | | | | | | | | | | | | | | X | | X | | | | | |
| 3.2.04 | | | | | | | | | | | | | | | | | | | | | X | | X | | | | | |
| 3.2.05 | | | | | | | | | | | | | | | | | | | | | X | | X | | | | | |
| 3.2.06 | | | | | | | | | | | | | | | | | | | | | X | | X | | | | | |
| 3.2.07 | | | | | | | | | | | | | | | | | | | | | X | X | X | | X | X | | |
| 3.2.08 | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N | N |
| 3.2.09 | | | | | | | | | | | | | | | | | | | | X | X | | | | | | | |
| 3.2.10 | | | | | | | | | | | | | | | | | | | | X | X | | | | | | | |
| 3.2.11 | | | | | | | | | | | | | | | | | | | | | X | | | | | | | |
| 3.2.12 | | | | | | | | | | | | | | | | | | | | | X | | | | | | | |
| 3.2.13 | | | | | | | | | | | | | | | | | | | | | X | | | | | | | |
| 3.3.01 | | | X | | | | | | | | | | | | | | | | | | | | | | X | | | |
| 3.3.02 | | | X | | | | | | | | | | | | | | | | | | | | | | X | | | |
| 3.3.03 | | | X | | | | | | | | | | | | | | | | | | | | | | | | | |
| 3.3.04 | | | X | | | | | | | | | | | | | | | | | | | | | | X | | | |
| 3.3.05 | | | X | | | | | | | | | | | | | | | | | | | | | | | | | |
| 3.3.06 | | | X | | | | | | | | | | | | | | | | | | | | | | | | | |
| 3.3.07 | | | X | | | | | | | | | | | | | | | | | | | | | | | | | |
| 3.3.08 | | | X | | | | | | | | | | | | | | | | | X | | | | | | | | |

| **ASSESSMENT CONTEXT** | 0 |
|---|---|
| **Definition:** Factors that the analyst will consider in determining the scope of the analysis. These may include factors related to regulatory requirements, definition of desired calculation end-points, requirements in a particular phase of assessment, description of the domain of concern and a description of the target groups in the assessment. Decisions at this point will affect the phenomenological scope of a particular phase of assessment, i.e. what "physical FEPs" will be included. | |
| **Comment**: *"Assessment Context" is a category in the International FEP List and is subdivided into individual FEPs.* | |

| **Assessment endpoints** | 0.01 |
|---|---|
| **Definition:** The long-term human *health and environmental effects or risks that may arise from the disposed wastes and repository. These FEPs include health or environmental effects of concern in an* assessment (what effect and to whom/what), and health or environmental effects ruled to be of no concern. | |
| ***Comment:*** *From the disposed radioactive waste to the health impact to humans, various indicators and associated criteria can be defined to serve as assessment endpoints. Which one to choose, will depend on the purpose of the assessment. The indicator most frequently considered is the radiation dose or risk to man, often represented by the annual dose rate or risk to a member of a "critical group" of potentially most exposed individuals (see FEP 0.06).* | |

***Key concepts, examples, and related FEPs***

| | | |
|---|---|---|
| *Annual individual dose* | *Lifetime individual risk* | *Increase in radiation levels in the environment* |
| *Annual individual risk* | *Radionuclide concentration in the environment* | *Release or concentration of non-radiological toxic contaminants* |
| *Collective doses* | *Flux through engineered barriers* | *Dose to biota other than man* |
| *Lifetime individual dose* | *Flux from geosphere to biosphere* | *Collective risk* |
| *Collective effective dose* | | |

***Application to WMA C:*** *Addressed in DOE Order 435.1.*

***Potentially deleterious FEP****: Not applicable*

| **Timescales of concern** | 0.02 |
|---|---|
| **Definition:** The time periods over which the disposed wastes and repository may present some significant human health or environmental hazard. | |
| ***Comment:*** *These may correspond to the timescale over which the safety of the disposed wastes and repository is estimated or discussed. In some countries national regulations set a limit up to which quantitative assessment is required, with more qualitative arguments to demonstrate safety being sufficient at later times.* | |

| | | |
|---|---|---|
| ***Key concepts, examples, and related FEPs*** | | |
| *Until peak doses occur* | *500 – 10 000 years* | *0 – 500 years* |
| *> 60 000 years* | *10 000 – 60 000 years* | |
| ***Application to WMA C:*** *Addressed in DOE Order 435.1.* | | |
| ***Potentially deleterious FEP****: Not applicable* | | |

| | |
|---|---|
| **Spatial domain of concern** | 0.03 |
| **Definition:** The domain over which the disposed wastes and repository may present some significant human health or environmental hazard. | |
| ***Comment:*** *This may correspond to the spatial domain over which the safety of the disposed wastes and repository is estimated, or the domain which is necessary to model in order to develop an understanding of the movement of contaminants and exposures. This may be limited by the purpose of the assessment, for example if the performance of a component of the total system have to be assessed.* | |
| ***Key concepts, examples, and related FEPs*** | |
| *Description of the spatial domain of concern* | |
| ***Application to WMA C:*** *Addressed in DOE Order 435.1.* | |
| ***Potentially deleterious FEP****: Not applicable* | |

| | | |
|---|---|---|
| **Repository assumptions** | | 0.04 |
| **Definition:** The assumptions that are made in the assessment about the construction, operation, closure and administration of the repository. | | |
| ***Comment:*** *For example, most post-closure assessments make the assumption that a repository has been successfully closed, although, in practice such decisions may be delayed or be the subject of uncertainty* | | |
| ***Key concepts, examples, and related FEPs*** | | |
| *Description of the construction, operation, closure and operation of the repository* | *Repository has been successfully closed* | *Change in volume of disposed waste* |
| | *Waste emplacement configuration has change* | *Change in repository design* |
| ***Application to WMA C:*** *Addressed in the performance assessment. See Sections 1-3 for a summary.* | | |
| ***Potentially deleterious FEP****: Uncertainties in repository assumptions are addressed in sensitivity analyses for various safety functions. PA Maintenance is required to address changes in actual disposal relative to assumptions in the PA.* | | |

| **Future human action assumptions** | 0.05 |
|---|---|
| **Definition:** The assumptions made in the assessment concerning general boundary conditions for assessing future human actions. | |
| ***Comment:*** *For example, it can be expected that human technology and society will develop over the timescales of relevance for repository safety assessment. However, this development is unpredictable. Therefore, it is usual to make some assumptions in order to constrain the range of future human activities that are considered.* | |
| ***Key concepts, examples, and related FEPs*** | |
| *Only present day technologies will be considered* *Only technologies practised in the past will be considered* *Description of human society development* *Description of general human society* *The past is an accurate reflection of the future* | |
| ***Application to WMA C:*** *Addressed in DOE Order 435.1.* | |
| ***Potentially deleterious FEP****: Not applicable* | |

| **Future human behaviour (target group) assumptions** | 0.06 |
|---|---|
| **Definition:** The assumptions made concerning potentially exposed individuals or population groups that are considered in the assessment. | |
| ***Comment:*** *Doses or risks are usually estimated for critical groups (individuals or groups) thought to be representative of the individuals or population groups that may be at highest risk or receive the highest doses as a result of the disposed wastes and repository. This is the accepted approach for assessing radiological risk or dose to members of the public resulting from a source of radioactive release to the environment. To assess the doses or risks at times in the far future, when the characteristics of potentially exposed populations are unknown, a hypothetical critical group, or groups, is/are usually defined* | |
| ***Key concepts, examples, and related FEPs*** | |
| *Description of an actual critical group* *Description of a hypothetical critical group* | |
| ***Application to WMA C:*** *Addressed in DOE Order 435.1.* | |
| ***Potentially deleterious FEP****: Not applicable DOE Order 435.1 requires evaluation at the location and time of peak concentration during the compliance period, so deleterious assumptions are part of the application of the FEP.* | |

| **Dose response assumptions** | 0.07 |
|---|---|
| **Definition:** Those assumptions made in an assessment in order to convert received dose to a measure of risk to an individual or population. | |

***Comment:*** *Usually this will refer to individual human dose response, e.g. by a dose-risk conversion factor where the factor is the probability of a specified health effect per unit of radiation exposure. If other organisms are considered then a risk to individual organisms or a species might be considered. The variation of a given response or human health effect (e.g. cancer incidence, cancer mortality) with the amount of radiation dose an individual or a group of individuals received is referred to as the dose-response relation. It is not possible to determine the shape of the dose response curve at low doses with any precision, because the incidence of health effects is very low. A linear dose-response relation with no dose threshold is generally assumed cautious (See ICRP 60).*

***Key concepts, examples, and related FEPs***

*None*

***Application to WMA C:*** *Addressed in DOE Order 435.1.*

***Potentially deleterious FEP****: Not applicable*

| **Assessment purpose** | 0.08 |
|---|---|

**Definition:** The purpose for which the assessment is being undertaken.

***Comment:*** *The aim of the assessment is likely to depend on the stage in the repository development project at which the assessment is carried out and may also affect the scope of assessment*

***Key concepts, examples, and related FEPs***

| | | |
|---|---|---|
| *Site selection* | *Demonstrate the feasibility of a disposal concept* | *Public confidence* |
| *Demonstrate regulatory compliance* | *Rehabilitation of contaminated site* | *System optimization* |
| *Concept design* | | |

***Application to WMA C:*** *Addressed in the performance assessment. See Section 2.*

***Potentially deleterious FEP****: Not applicable*

| **Regulatory requirements and exclusions** | 0.09 |
|---|---|

**Definition:** The specific terms or conditions in the national regulations or guidance related to all stages of the repository that will influence the post closure safety assessment.

***Comment:*** *Regulatory requirements and exclusions may be expressed in terms of release, dose or risk limits or targets to individuals or populations effective over a specified timescale; they may also make demands about procedures following closure of the repository. In some regulations, the long-term scenarios to be assessed are specified, or some scenarios or events are specifically ruled out of consideration.*

| | | |
|---|---|---|
| ***Key concepts, examples, and related FEPs*** | | |
| *Independence of safety from control* | *Environmental protection standards* | *Multi-factor safety case* |
| *Optimization* | *Quality assurance* | *Radiological protection standards* |
| *Effects in the future* | *Quality control* | |
| ***Application to WMA C:*** *Addressed in DOE Order 435.1.* | | |
| ***Potentially deleterious FEP****: Not applicable* | | |

| | |
|---|---|
| **Model and data issues** | 0.10 |
| **Definition:** Model and data issues in the context of a safety assessment, refers to general (i.e. methodological) issues affecting the assessment modelling process and use of data during the process. | |
| ***Comment:*** *A post-closure safety assessment is an attempt to quantify the exposure or risk posed by a radioactive waste disposal site to future generations of humanity and their environment. Intrinsically, to do this one can say that the observations needed for the safety assessment of a site should be carried out for the life span of the proposed disposal facility. However, this is neither physically possible nor desirable. The only viable approach to perform a complete radiological safety assessment is to try to obtain as much observational data as possible, on a limited time scale, and then simulate the future behaviour of the disposal system through what is known as a model.* | |

| | | |
|---|---|---|
| ***Key concepts, examples, and related FEPs*** | | |
| *Treatment of uncertainty* | *Modelling studies* | *Data availability* |
| *Method of handling site data* | *Model and data reduction/simplification* | *Application of conservatism* |
| *Assessment philosophy* | | |
| ***Application to WMA C:*** *Addressed in the performance assessment. See Sections 1 – 3 for a summary.* | | |
| ***Potentially deleterious FEP****: Not applicable* | | |

| | |
|---|---|
| **EXTERNAL FACTORS** | 1 |
| **Definition:** FEPs with causes or origin outside the disposal system domain, i.e. natural or human factors of a more global nature and their immediate effects. Included in this category are decisions related to repository design, operation and closure since these are outside the temporal boundary of the disposal system domain for post-closure assessment. | |
| ***Comment:*** *"External Factors" is a category in the International FEP List and is divided into sub-categories.* | |

| **REPOSITORY ISSUES** | 1.1 |
|---|---|
| **Definition:** Decisions on designs and waste allocation (repository type), and also events related to site investigation, operations and closure (site context). | |
| ***Comment:*** *"Repository Issues" is a sub-category of External Factors in the International FEP List and is divided into individual FEPs.* | |

| **Site investigation** | 1.1.01 |
|---|---|
| **Definition:** FEPs related to the investigations that are carried out at a potential repository site in order to characterize the site both prior to repository excavation and during construction and operation. | |
| ***Comment:*** *Site investigation activities provide detailed site-specific performance assessment data and information necessary for the safety case to demonstrate the suitability of the site and to establish baseline conditions* | |

***Key concepts, examples, and related FEPs***

| | | |
|---|---|---|
| *Geography and demography* | *Aquifer tests* | *Ecological features* |
| *Meteorology and climatology (regional and local)* | *Investigative boreholes* | *Pre-operational monitoring programme* |
| *Geology and seismology* | *Biosphere characteristics* | *Hydrogeology characteristics* |
| *Hydrology characteristics* | *Natural resources* | *Geohydrological characteristics* |
| *Geotechnical characteristics* | *Geochemical characteristics* | *Geomorphology characteristics* |

***Application to WMA C:*** *Relevant to the performance assessment. See Section 4 for a discussion of site investigations.*

***Potentially deleterious FEP****: Drywells and boreholes may have the potential to provide relative fast paths through the vadose zone under some wetting conditions. Alternative conceptual models with preferential flow paths through the vadose zone are included in the PA.*

| **Design, repository** | 1.1.02 |
|---|---|
| **Definition:** FEPs related to the design of the repository including both the safety concept, i.e. the general features of design and how they are expected to lead to a satisfactory performance, and the more detailed engineering specification for excavation, construction and operation. | |
| ***Comment:*** *The repository design and construction is established in a general way in the disposal concept for the repository which is based on expected host lithology characteristics, waste and backfill characteristics, construction technology, and economics. Repository design includes the principle design features that are designed to provide long-term isolation of disposed waste, minimize the need for continued active maintenance after site closure, and improve the site's natural characteristics in order to protect public health and the environment. There may, nevertheless, be a range of engineering design and construction options still open. As the repository project proceeds, and more detailed site-specific information becomes available, the range of options may be constrained and decisions will be made. At any stage, repository safety assessments may only analyse a subset of the total range of option. (See FEP 1.103).* | |

| ***Key concepts, examples, and related FEPs*** | |
|---|---|
| *The general repository design features (e.g. host lithology, waste form, backfill, waste packages, construction technology, etc.)* | *The principle design criteria or considerations for normal and abnormal condition*<br>*Operational monitoring programme* |
| ***Application to WMA C:*** *Relevant to the performance assessment. See Section 4.*<br>***Potentially deleterious FEP****: Not applicable* | |

| **Construction, repository** | 1.1.03 |
|---|---|
| **Definition:** FEPs related to the construction (e.g., excavation) of shafts, tunnels, disposal galleries, silos, trenches, vaults, etc. of a repository, as well as the stabilisation of these openings and installation/assembly of structural elements according to the design criteria. | |
| ***Comment:****. Repository construction refers to the implementation of the design considerations and specifically to the construction of features of the repository necessary to provide long-term isolation of disposed waste, minimize the need for continued active maintenance after site closure, and improve the site's natural characteristics in order to protect public health and the environment. In addition, it includes the construction methods. (See FEP 1.102).* | |
| ***Key concepts, examples, and related FEPs*** | |
| *Drilling of borehole*<br>*Excavation of trenches, holes, vaults*<br>*Construction equipment* | *Construction of walls, floors, mounds, layers of mounds*<br>*Site plans, engineering drawing, and construction specifications*<br>*Control and diversion of water*<br>*Site preparations* |
| ***Application to WMA C:*** *Relevant to the performance assessment. For WMA C this relates both to past facility construction (Section 4), and to emplacement of grout and cover.*<br>***Potentially deleterious FEP****: Potential degradation of safety functions associated with the engineered components of the system may result from failure of quality control. A range of cover performance is assumed in various sensitivity cases.* | |

| **Emplacement of wastes and backfilling** | 1.1.04 |
|---|---|
| **Definition:** FEPs related to the placing of wastes (usually in containers) at their final position within the repository and placing of buffer and/of backfill materials in the disposal zone. | |
| ***Comment:*** *Some waste types and inventories may require special waste emplacement arrangements to simplify the disposal practice, to ensure safety or to ensure structure stability in the repository area. The backfill material is used to refill excavated portions of the repository or any void spaces left unfilled after waste has been emplaced (see also FEP 1.1.07).* | |

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|---|
| ***Key concepts, examples, and related FEPs*** |
| *Emplacement method* *Filling of void spaces between the containers and in the rest of the repository* *Covering of waste in-between containers* |
| *Waste emplacement configuration* |
| ***Application to WMA C:*** *Relevant to the performance assessment with respect to the infill grout emplacement and cover emplacement.* |
| ***Potentially deleterious FEP****: Safety functions associated with the grout and cover may be degraded by incorrect emplacement of the materials. Emplacement of grout must take due account of heat of hydration and shrinkage A range of cover performance is assumed in various sensitivity cases.* |

| **Closure, repository** | 1.1.05 |
|---|---|
| **Definition:** FEPs related to the cessation of waste disposal operations at a site, the backfilling and sealing of boreholes type facilities, and the capping and covering of trenches, vaults, etc. | |
| ***Comment:*** *The term closure refers to the status of, or an action directed at a disposal facility at the end of its operational life. A disposal facility is placed under permanent closure usually after completion of waste emplacement, by covering a near surface disposal facility, by backfilling and/or sealing of a borehole type facility, and termination and completion of activities in any associated structure. The intention of repository capping and sealing is to prevent infiltrating water as well as human access to the wastes. Individual sections of a repository may be closed in sequence, but closure usually refers to final closure of the whole repository, and will probably include removal of surface installations. The schedule and procedure for capping, sealing and closure may need to be considered in the assessment.* | |
| ***Key concepts, examples, and related FEPs*** | |
| *Trench/vault capping* *Backfilling of boreholes* *Decontamination and decommissioning plan* | |
| *Site stabilisation* *Removal of surface structures* *Post-operational monitoring programme* | |
| *Cover construction* *Closure procedures* *Closure compartments* | |
| ***Application to WMA C:*** *Relevant to the performance assessment with respect to the infill grout emplacement and cover emplacement.* | |
| ***Potentially deleterious FEP****: Safety functions associated with the grout and cover may be degraded by incorrect closure. Emplacement of grout must take due account of heat of hydration and shrinkage. A range of cover performance is assumed in various sensitivity cases.* | |

| **Records and markers, repository** | 1.1.06 |
|---|---|
| **Definition:** FEPs related to the retention of records of the content and nature of a repository after closure and also the placing of permanent markers at or near the site. | |
| ***Comment:*** *It is expected that records will be kept to allow future generations to recall the existence and nature of the repository following closure. In some countries, the use of site markers has been proposed where the intention is that the location and nature of the repository might be recalled even in the event of a lapse of present-day administrative controls.* | |

| | | |
|---|---|---|
| ***Key concepts, examples, and related FEPs*** | | |
| *Records of the content and nature of the repository* | *Disposal unit and boundary markers* | *Site markers* |
| | *Archive of the records* | |
| ***Application to WMA C:*** *Addressed as part of institutional control assumptions in DOE Order 435.1.* | | |
| ***Potentially deleterious FEP****: Safety functions associated with institutional control are treated conservatively by requirements in DOE Order 435.1. Reduction of these safety functions is not credible.* | | |

| | |
|---|---|
| **Waste allocation** | 1.1.07 |
| **Definition:** FEPs related to the choices on allocation of wastes to the repository, including waste type(s) and amount(s). | |
| ***Comment:*** *The waste type and waste allocation is established in a general way in the repository disposal concept. There may, however, be a number of options concerning these factors. Final decisions may not be made until the repository is operating and will be subject to regulation. In safety assessments, assumptions may need to be made about future waste arisings and future waste allocation strategies (see also FEP 1.1.04).* | |

| | | |
|---|---|---|
| ***Key concepts, examples, and related FEPs*** | | |
| *Waste allocation description* | *Future waste allocation strategies* | *Waste acceptance criteria for the repository* |
| *Future waste arisings* | *Projected inventories* | |
| ***Application to WMA C:*** *Not applicable for tank closure. The FEP relates to future waste arisings.* | | |
| ***Potentially deleterious FEP****: Not applicable* | | |

| | |
|---|---|
| **Quality control** | 1.1.08 |
| **Definition:** FEPs related to quality assurance and control procedures and tests during the design, construction and operation of the repository, as well as the manufacture of the waste forms, containers and engineered features. | |
| ***Comment:*** *It can be expected that a range of quality control measures will be applied during construction and operation of the repository, as well as to the manufacture of the waste forms, containers etc. In an assessment these may be invoked to avoid analysis of situations which, it is expected, can be prevented by quality control. There may be specific regulations governing quality control procedures, objectives and criteria.* | |

| | | |
|---|---|---|
| ***Key concepts, examples, and related FEPs*** | | |
| *Defects in construction of disposal system* | *Improper or faulty waste emplacement and backfilling* | *Defects during the conditioning of the waste* |
| *Defects in the construction of container* | | *Defects in cap constructions* |

***Application to WMA C:*** *Relevant grout emplacement, and cover emplacement.*

***Potentially deleterious FEP****: Safety functions associated with grout and cover may be degraded if there is a failure of quality control. A range of cover performance is assumed in various sensitivity cases.*

| **Schedule and planning** | 1.1.09 |
|---|---|
| **Definition:** FEPs related to the sequence of events and activities occurring during repository excavation, construction, waste emplacement and sealing. | |
| ***Comment:*** *Relevant events may include phased construction of units and emplacement of wastes, backfilling, sealing, capping and closure of sections of the repository after wastes are emplaced, and monitoring activities to provide data on the transient behaviour of the system or to provide input to the final assessment. The sequence of events and time between events may have implications for long term performance, e.g. decline of activity and heat production from the wastes, material degradation, chemical and hydraulic changes during a prolonged "open" phase.* | |
| ***Key concepts, examples, and related FEPs***<br>*Phased construction of units*<br>*Planning of monitoring activities to provide data on the transient behaviour of the system*<br>*Phased emplacement of wastes, backfilling, sealing, capping and closure of sections of the repository* | |
| ***Application to WMA C:*** *Project timing assumed in the performance assessment is consistent with assumptions in the TC&WM EIS.*<br>***Potentially deleterious FEP****: Alterations in project timing have the potential to affect safety functions associated with the grout and cover. Not foreseen as a significant issue while tanks are relatively intact.* | |

| **Administrative control, repository site** | 1.1.10 |
|---|---|
| **Definition:** FEPs related to measures to control events at or around the repository site, both during the operational period and after closure. | |
| ***Comment:*** *The responsibility for administrative control of the site before closure of the repository during the construction and operational phases, and subsequently following closure of the repository may not be the same. Furthermore, the type of administrative control may vary depending on the stage in the repository lifetime.* | |
| ***Key concepts, examples, and related FEPs***<br>*None* | |
| ***Application to WMA C:*** *Addressed in multiple DOE Orders and policies. See Section 2.*<br>***Potentially deleterious FEP****: Safety functions associated with institutional control are treated conservatively by requirements in DOE Order 435.1. Reduction of these safety functions is not credible.* | |

| **Monitoring of repository** | 1.1.11 |
|---|---|
| **Definition:** FEPs related to any monitoring that is carried out during operations or following closure of sections of, or the total, repository. This includes monitoring for operational safety and also monitoring of parameters related to the long-term safety and performance. | |
| ***Comment:*** *The extent and requirement for such monitoring activities may be determined by repository design and host lithology, regulations and public pressure.* | |
| ***Key concepts, examples, and related FEPs*** | |
| *Pre-operational monitoring programme* *Post-operational monitoring programme* *Operational monitoring programme* | |
| ***Application to WMA C:*** *Will be addressed in the performance maintenance plan.* | |
| ***Potentially deleterious FEP****: Not applicable, although potential preferential pathways through the vadose zone are addressed.* | |

| **Accidents and unplanned events** | 1.1.12 |
|---|---|
| **Definition:** FEPs related to accidents and unplanned events during construction, waste emplacement and closure, which might have an impact on long-term performance or safety. | |
| ***Comment:****. Accidents are events that are outside the range of normal operations although the possibility that certain types of accident may occur should be anticipated in repository operational planning. Unplanned events include accidents but could also include deliberate deviations from operational plans.* | |
| ***Key concepts, examples, and related FEPs*** | |
| *Deviations from operations in response to an accident* *Unexpected waste arising during operations* *Increase in waste delivery* | |
| *Reduction in waste delivery* *Unexpected geological event* *Earlier than anticipated container failure* | |
| *Earlier than anticipated cap failure* *Deliberate deviations from operational plans* | |
| ***Application to WMA C:*** *Relevant to the performance assessment.* | |
| ***Potentially deleterious FEP****: Early degradation of cap safety function from unanticipated events; unexpected geological event may lead to early degradation of hydraulic safety functions in the engineered system. Early failure of barriers is addressed in sensitivity cases.* | |

| **Retrievability** | 1.1.13 |
|---|---|
| **Definition:** FEPs related to any special design, emplacement, operational or administrative measures that might be applied or considered in order to enable or ease retrieval of wastes. | |
| ***Comment:*** *Designs may specifically allow for retrieval or rule it out. In some cases, an interim period might be planned, between waste emplacement and final repository closure, during which time retrieval is possible.* | |

***Key concepts, examples, and related FEPs***

*None*

***Application to WMA C:*** *Not relevant to the tank closure performance assessment. Waste has been retrieved to the extent practicable as documented in Retrieval Completion Certifications.*

***Potentially deleterious FEP****: Not applicable*

| **GEOLOGICAL PROCESSES AND EFFECTS** | 1.2 |
|---|---|
| **Definition:** Processes arising from the wider geological setting and long-term processes | |
| ***Comment****. "Geological Processes and Effects" is a sub-category of External Factors in the International FEP List and is divided into individual FEPs.* | |

| **Orogeny and related tectonic processes at plate boundaries** | 1.2.01 |
|---|---|
| **Definition:** Rock deformation and translation (commonly referred to as tectonics) of this nature arises when rock masses belonging to different plates either collide against each other or slide past each other. Literally speaking, orogeny is the process of formation of mountains, often occurring over periods of a few million years, but up to several tens of millions of years. | |
| ***Comment:*** *By present geological usage, orogeny is the process by which structures within mountain areas were formed through processes that include thrusting, folding and faulting in the lithosphere. The latter h is the name given to the rigid, outermost layer of the earth, made up predominantly of solid rock which are affected by processes such as metamorphism, plutonism, and, at great depth (>10 km), by plastic folding. .*<br><br>*The term folding is generally used to imply the shortening of strata that results from the formation of fold structures on a broad scale, and sometimes has the connotation of general deformation of which the actual folding is only a part. A fault is a fracture in the Earth's crust accompanied by displacement of one side of the fracture relative to the other, from a few cm to several kilometres. Orogenic belts are typically characterized by compressive reverse faults as this lead to crustal shortening and duplication of geological formations. Transform faults typically occur where crustal plates slide past each other without colliding (e.g. the St. Andrea fault in California) and the relative displacement can be in the order of thousands of kilometers. Fractures and joints may be caused by compressional or tenisonal forces in the earth crust but do not present displacement between the rocks on each side. These forces may result in the reactivation of of existing faults or, less likely, in the generation of new ones*<br><br>*It is important to acknowledge that orogenic processes experience periods of quiescence alternating with periods of paroxismand that such periods are not necessarily synchronous along the whole length of an orogenic belt.*<br><br>***Implications to near-surface disposal systems:*** *This type of movements should be considered with great care since orogenic processes can lead, in areas of active collision (e.g. Chile, Turkey, Iran, Morocco) to the propagation of fault and thrust planes up to the surface. In such events (see seismicity) extreme ground fracturing, faulting could lead to breakage of containment barriers* | |

| ***Key Concepts, examples, and related FEPs*** | | |
|---|---|---|
| *Collision of the Earth's crustal plates* | *Faulting and folding of lithosphere: Thin skinned tectonics vs. Thick skinned tectonics* | *Granitic to granodioritic batholiths; calc-alkaline igneous activity* |
| *Transcurrent, strike-slip faults* | *Metamorphism, anatexis (partial melting/ migmatization), and plastic folding in the inner and deeper layer* | *Orogeny,* |
| *Thrusts: low-angle reverse faults;* | | *Neotectonics* |
| *Subduction zones* | | |
| ***Application to WMA C:*** *Not relevant on the time scale of the performance assessment.* | | |
| ***Potentially deleterious FEP****: Not applicable* | | |

| **Anorogenic and within-plate tectonic processes (Deformation, elastic, plastic or brittle)** | | 1.2.02 |
|---|---|---|
| **Definition:** FEPs related to the physical deformation of geological structures in the interior of continental or oceanic plates in response to stress fields generated either at plate margins or in regions of anomalous stress. This includes mainly faulting and fracturing of rocks and, less frequently, also their compression and folding rocks. | | |
| ***Comment.*** *The term folding is generally used for the compression of strata in the formation of fold structures on a broad scale, and sometimes has the connotation of general deformation of which the actual folding is only a part. A fault is a fracture in the Earth's crust accompanied by displacement of one side of the fracture relative to the other, from a few centimetres to a few kilometres on scale. Fractures may be caused by compressional or tensional forces in the Earth's crust. Such forces may result in the activation of existing faults and, less likely, the generation of new faults.* | | |
| ***Implications to near-surface disposal systems:*** *Within the timescales of concern, deformation is unlikely to have an effect on near-surface disposal systems* | | |
| ***Key Concepts, examples, and related FEPs*** | | |
| *Faulting: normal, extensional faults* | *Fracturing* | *Basin and range* |
| *Extrusion* | *Compression of rocks* | *Continental; break- up* |
| *Neotectonics* | *Rifting, rift valleys* | *Uplift axes* |
| *Alkaline volcanism, volcanoes* | *Horst and grabens* | *Stress field* |
| *Dyke swarms* | *Jointing, master joints* | *Cross-fabrics* |
| *Fractures* | *Hot springs* | |
| ***Application to WMA C:*** *Not relevant on the time scale of the performance assessment.* | | |
| ***Potentially deleterious FEP****: Not applicable* | | |

| **Seismicity** | 1.2.03 |
|---|---|

**Definition:** FEPs related to seismic events and the potential for seismic events. Rapid relative movements within the Earth's crust, usually along existing faults or geological interfaces cause a seismic event. The accompanying release of energy may result in ground movement and/or rupture, e.g. earthquakes.

***Comment:*** *Seismic events may result in changes in the physical properties of rocks due to stress changes and induced hydrological changes. Seismic events are most common in tectonically active or volcanically active regions at crustal plate margins, less commonly they also occur in the interior of continental/oceanic plates. The seismic waves that are generated by a tectonic or volcanic disturbance of the ocean floor may result in a seismic (giant) sea wave, known as a tsunami. These may be amplified by submarine soft sediment slumps along steep continental margins. In extreme cases, soil liquefaction has been reported in areas where soils and sedimentary strata of appropriate moisture content and composition are subjected to strong seismic shaking.*

***Key Concepts, examples, and related FEPs***

| | | |
|---|---|---|
| *Change in the physical properties of rocks due to stress changes* | *Faulting* | *Seismic swarms* |
| *Hydrological changes* | *Tsunami* | *Soil liquefaction* |
| | *Earthquakes* | *Aftershocks* |

***Application to WMA C:*** *Relevant to the performance assessment in considering the longevity of safety functions for the engineered barriers.*

***Potentially deleterious FEP****: The primary potential effects on the disposal system is degradation of hydraulic safety functions of the tank, grout, and base mat. Other safety functions would be unaffected. Potential for preferential pathways is considered in the sensitivity cases.*

| **Volcanic and magmatic activity** | 1.2.04 |
|---|---|

**Definition:** FEPs related to volcanic and magmatic activities. Magma is molten, mobile rock material, generated below the Earth's crust, which gives rise to igneous rocks when solidified. Magmatic activity occurs when there is intrusion of magma into the crust. A volcano is a vent or fissure in the Earth's surface through which molten or part-molten materials (lava) may flow, and ash and hot gases be expelled.

***Comment:*** *The high temperatures and pressures associated with volcanic and magmatic activity may result in permanent changes in the surrounding rocks; this process is referred to as metamorphism but is not confined to volcanic and magmatic activity (see FEP 1.2.05). Intrusive magmatic activity refers to the process of emplacement of magma in pre-existing rock. Extrusive magmatic activity refers to the process whereby magma are ejected onto the surface of the Earth.*

***Key Concepts, examples, and related FEPs***

| | | |
|---|---|---|
| *Temperature and pressure rise* | *Intrusive magmatic activity* | *Pyroclastic explosion / flow / cloud* |
| *Change in surrounding rocks* | *Extrusive magmatic activity* | *Fumaroles* |
| *Slope tilting* | *Lava flows* | *Hydrothermal alteration* |
| | *$CO_2$ emissions* | |

***Application to WMA C:*** *Relevant to WMA C as potential ash fall from future volcanic events in the region.*

***Potentially deleterious FEP****: The effect of prior eruptions is included in the paleo record of infiltration. The effects of past ash fall events is therefore included in the uncertainty range in infiltration.*

| **Metamorphism** | 1.2.05 |
|---|---|
| **Definition:** FEPs induced by the mineralogical and structural adjustment of solid rock to physical and chemical conditions, which have been imposed by the action of heat (T>200 C) and pressure at great depths (usually several kilometres) beneath the Earth's surface or near magmatic activity. | |
| ***Comment:*** *Metamorphic processes are unlikely to be important at typical repository depths, but past metamorphic history of a host lithology may be very important to understanding its present-day characteristics.*<br>***Implications to near-surface disposal systems:*** *Within the timescales of concern, metamorphism is unlikely to have an effect on near-surface disposal systems.* | |
| ***Key Concepts, examples, and related FEPs***<br>*Metamorphic history of a host lithology* | |
| ***Application to WMA C:*** *Not relevant on the time scale of the performance assessment.*<br>***Potentially deleterious FEP****: Not applicable* | |

| **Hydrothermal activity** | 1.2.06 |
|---|---|
| **Definition:** FEPs associated with high temperature groundwater, including processes such as density-driven groundwater flow and hydrothermal alteration of minerals in the rocks through which the high temperature groundwater flows. | |
| ***Comment:*** *Groundwater temperature is determined by the large-scale geological and petrophysical properties of the rock formations (e.g. radiogenic heat formation, thermal conductivity), as well as the hydrogeological characteristics (e.g. hydraulic conductivity) of the rock and by the tectonic environment. (neotectonic deformation, extension).*<br>***Implications to near-surface disposal systems:*** *Within the timescales of concern, hydrothermal activity is unlikely to have an effect on typical near-surface disposal systems.* | |
| ***Key Concepts, examples, and related FEPs***<br>*Hydrothermal synthesis* — *Hydrothermal alterations of minerals in the rocks* — *Scalding springs*<br>*Density driven groundwater flow* — *Hydrothermal metamorphism* | |
| ***Application to WMA C:*** *Not relevant to the WMA C geological setting.*<br>***Potentially deleterious FEP****: Not applicable* | |

| **Erosion and sedimentation** | 1.2.07 |
|---|---|
| **Definition:** FEPs related the large-scale (geological) removal and accumulation of rocks and sediments, with associated changes in topography and geological/hydrogeological conditions of the repository host lithology. | |
| ***Comment:*** *Erosion is the process or group of processes whereby the earthy and rocky materials of the Earth's crust are loosened, dissolved, or worn away, and simultaneously removed from one place to another, by natural agencies that include weathering, solution, corrosion, and transportation. Compare FEP 2.3.12, which is concerned with more local processes over shorter periods of time. Sedimentation is the act or process of forming or accumulating sediment in layers, including such processes as the separation of rock particles from the material from which the sediment is derived, the transportation of these particles to the site of deposition or settling of the particles, the chemical and other (diagenetic) changes occurring in the sediment, and the ultimate consolidation of the sediment into solid rock.*<br><br>***Implications to near-surface disposal systems:*** *Within the timescales of concern, large scale erosion and sedimentation are unlikely to have an effect on near-surface disposal systems.* | |
| ***Key Concepts, examples, and related FEPs***<br>*Change in topography, uplift* — *Deposition of sediment* — *Stream erosion*<br>*Coastal erosion* — *Changes in geological conditions* — *Changes in hydrogeological conditions* | |
| ***Application to WMA C:*** *Relevant to the performance assessment in considering the longevity of safety functions for the engineered cover.*<br><br>***Potentially deleterious FEP****: The primary potential effects on the disposal system is degradation of the infiltration safety functions of the cover. Other safety functions would be unaffected. Potential increases in infiltration through the cover are addressed in sensitivity cases.* | |

| **Diagenesis and pedogenesis** | 1.2.08 |
|---|---|
| **Definition:** The processes by which deposited sediment, at or near the Earth's surface are formed into rocks by compaction, cementation and crystallisation, i.e. under conditions of temperature and pressure normal to the upper few kilometres of the earth's crust. | |
| ***Comment:*** *Diagenesis include all the chemical, physical, and biological changes, modifications, or transformations undergone by a sediment after its initial deposition, and during and after its lithification, exclusive or surficial alteration (weathering) and metamorphism. It embraces those non-destructive or reconstructive processes (e.g., consolidation, compaction, cementation, reworking, authigenesis, replacement, solution, precipitation, crystallisation, oxidation, reduction, leaching, hydration, polymerisation, adsorption, bacterial action, and formation of concretions) that occur under conditions of pressure and temperature that are normal to the surficial or outer part of the Earth's crust.*<br><br>*Pedogenesis represents the mode of origin of soils, with reference to the factors responsible for the formation of "solum", or true soil, from unconsolidated parent material. Pedogenesis may have an effect on the behaviour of near surface disposal systems as it involves geohydrologic, atmospheric and biological processes (burrowing animals, plant roots activity/invasion) operation at or near surface on time scales of few hundred to thousands of years*<br><br>***Implications to near-surface disposal systems:*** *Within the timescales of concern, diagenesis is unlikely to have an effect on near-surface disposal systems* | |

| |
|---|
| ***Key Concepts, examples, and related FEPs*** <br> *None* |
| ***Application to WMA C:*** *Not relevant to the WMA C geological setting.* <br> ***Potentially deleterious FEP****: Not applicable* |

| **Salt diapirism and dissolution** | 1.2.09 |
|---|---|
| **Definition:** The long-term evolution of salt formations. Diapirism is the lateral or vertical intrusion or upwelling of either buoyant or non-buoyant rock into overlying strata (the overburden) from a source layer. Dissolution of the salt may occur where the evolving salt formation is in contact with groundwater with salt content below saturation. | |
| ***Comment:*** *Diapirism is most commonly associated with salt formations where a salt diapir comprises a mass of salt that has flowed in a ductile manner from a source layer and pierces or intrudes into the over-lying rocks. The term can also be applied to magmatic or migmatic intrusion.* <br> ***Implications to near-surface disposal systems:*** *Within the timescales of concern, salt diapirism and dissolution are unlikely to have an effect on near-surface disposal system.* | |
| ***Key Concepts, examples, and related FEPs*** <br> *Diapirism* *Brine pockets* | |
| ***Application to WMA C:*** *Not relevant to the WMA C geological setting.* <br> ***Potentially deleterious FEP****: Not applicable* | |

| **Hydrological/hydrogeological response to geological changes** | 1.2.10 |
|---|---|
| **Definition:** FEPs related to changes in the hydrological or hydrogeological regime arising from the large-scale geological changes listed in FEPs 1.2.01 to 1.2.09. | |
| ***Comment:*** *These could include changes of hydrological boundary conditions due to effects of erosion on topography, changes of hydraulic properties of saturated and unsaturated zones due to changes in rock stress or fault movements, or a change in the geochemical behaviour of the saturated and unsaturated zones. In and below low-permeability geological formations, hydrogeological conditions may evolve very slowly and often reflect past geological conditions, i.e. be in a state of disequilibrium* | |
| ***Key Concepts, examples, and related FEPs*** <br> *Geochemical change* *Changes in hydraulic properties* *Changes of hydrological boundary conditions* | |
| ***Application to WMA C:*** *Regional scale geological changes may influence the Columbia River, which has a controlling influence on aquifer flow under the Central Plateau.* <br> ***Potentially deleterious FEP****: Potential effects on the saturated zone flow safety functions. Variations in saturated zone flow are considered in sensitivity analyses.* | |

| **CLIMATIC PROCESSES AND EFFECTS** | 1.3 |
|---|---|
| **Definition:** Processes related to global climate change and consequent regional effects. | |
| **Comment:** "Climatic Processes and Effects" is a sub-category of External Factors in the International FEP List and is divided into individual FEPs. | |

| **Climate change, global** | 1.3.01 |
|---|---|
| **Definition:** FEPs related to the possible future, and evidence for past, long-term change of global climate. This is distinct from resulting changes that may occur at specific locations according to their regional setting and also climate fluctuations, c.f. FEP 1.3.02. | |
| ***Comment:*** *The last two million years of the Quaternary have been characterized by glacial/interglacial cycling. According to the Milankovitch Theory, the Quaternary glacial/interglacial cycles are caused by long term changes in seasonal and latitudinal distribution of incoming solar radiation which are due to the periodic variations of the Earth's orbit about the Sun (Milankovitch cycles). The direct effects are magnified by factors such as changes in ice, vegetation and cloud cover, and atmospheric composition.* | |
| ***Key Concepts, examples, and related FEPs*** | |
| *Description of global climate changes* | *Changes in ice, vegetation and cloud cover* | *Isostatic movement (c.f. FEP 1.3.03)* |
| *Changes in atmospheric composition* | *Greenhouse effect* | *Glaciation (large scale)* |
| *Eustatic change (c.f. FEP 1.3.03)* | | |
| ***Application to WMA C:*** *Climate change may affect infiltration and saturated zone flow safety functions. However, global climate changes are expressed locally in these processes. See FEP 1.3.02. See Section 3 for a discussion of the basis for long term precipitation estimation.* | |
| ***Potentially deleterious FEP****: Not relevant.* | |

| **Climate change, regional and local** | 1.3.02 |
|---|---|
| **Definition:** FEPs related to the possible future changes, and evidence for past changes, of climate at the repository site. This is likely to occur in response to global climate change, but the changes will be specific to situation, and may include shorter-term fluctuations, c.f. FEP 1.3.01. | |
| ***Comment:*** *Climate is characterized by a range of factors including temperature, humidity, precipitation and pressure as well as other components of the climate system such as oceans, ice and snow, biota and the land surface. The Earth's climate varies by location and for convenience broad climate types have been distinguished in assessments, e.g. tropical, savannah, mediterranean, temperate, boreal and tundra. Climatic changes lasting only a few decades are referred to as climatic fluctuations. These are unpredictable at the current state of knowledge although historical evidence indicates the degree of past fluctuations.* | |

***Key Concepts, examples, and related FEPs***

| | | |
|---|---|---|
| *Climate fluctuations* | *Description of regional and local climate change* | *Increase/decrease in temperature* |
| *Increase/decrease in precipitation)* | | |

***Application to WMA C:*** *Climate change may affect infiltration and saturated zone flow. However, global climate changes are expressed locally in these processes. See FEP 1.3.01. See Section 3 for a discussion of the basis for long term precipitation estimation.*

***Potentially deleterious FEP****: Changes in infiltration associated with climate change are uncertain. Regional scale modelling shows either increases or decreases in future infiltration, with the magnitude of the changes within the pattern of the paleo record. The response of the aquifer system to climate change is uncertain. Climate change may potentially affect safety functions for the cover and for the saturated zone. Ranges of infiltration and aquifer flow are considered in sensitivity cases.*

**Sea level change** 1.3.03

**Definition:** FEPs related to changes in sea level, which may occur as a result of global (eustatic) change and regional geological change, e.g. isostatic movements.

***Comment:*** *The component of sea-level change involving the interchange of water between land ice and the sea is referred to as eustatic change. As ice sheets melt so the ocean volume increases and sea levels rise. Sea level at a given location will also be affected by vertical movement of the land mass, e.g. depression and rebound due to glacial loading and unloading, referred to as isostatic change (c.f. FEP 1.3.01).*

***Key Concepts, examples, and related FEPs***

| | | |
|---|---|---|
| *Flooding* | *Saline intrusion into repository or geosphere* | *Change in the hydrogeological regime* |

***Application to WMA C:*** *Sea level change may affect Columbia River stage, with subsequent influence on aquifer flow.*

***Potentially deleterious FEP****: Potential effect on saturated zone safety functions by alteration of the gradient.*

**Periglacial effects** 1.3.04

**Definition:** FEPs related to the physical processes and associated landforms in cold but ice-sheet-free environments. This may be at the immediate margins of former and existing glaciers and ice sheets or an environment in which frost actions is dominant.

***Comment:*** *An important characteristic of periglacial environments is the seasonal change from winter freezing to summer thaw with large water movements and potential for erosion. The frozen subsoils are referred to as permafrost. Meltwater of the seasonal thaw is unable to percolate downwards due to permafrost and saturates the surface materials, this can result in a mass movement called solifluction (literally soil-flow). Permafrost layers may isolate the deep hydrological regime from surface hydrology, or flow may be focused at "taliks" (localized unfrozen zones, e.g. under lakes, large rivers or at regions of groundwater discharge).*

***Key Concepts, examples, and related FEPs***

| | | |
|---|---|---|
| *Large water movement* | *Strong seasonal influences* | *Permafrost* |
| *Erosion* | *Soil flow (movement) – solifluction* | *Saturation of surface materials* |

***Application to WMA C:*** *Not relevant on the time scale of the performance assessment. However, pollen data records provide information that extends through past glacial cycles. See Section 3.*

***Potentially deleterious FEP****: Not applicable*

| **Glacial and ice sheet effects, local** | 1.3.05 |
|---|---|

**Definition:** FEPs related to the effects of glaciers and ice sheets within the region of a repository, e.g. changes in the geomorphology, erosion, meltwater and hydraulic effects. This is distinct from the effect of large ice masses on global and regional climate, c.f. FEPs 1.3.01, 1.3.02.

***Comment:*** *Erosional processes (abrasion, over-deepening) associated with glacial action, especially advancing glaciers and ice sheets, and with glacial meltwaters beneath the ice mass and at the margins, can lead to morphological changes in the environment e.g. U-shaped valleys, hanging valleys, fjords and drumlins. Depositional features associated with glaciers and ice sheets include moraines and eskers. The pressure of the ice mass on the landscape may result in significant and even depression of the regional crustal plate.*

***Key Concepts, examples, and related FEPs***

*Erosional processes (abrasion, over-deepening)*

*Hydrogeological change*

*Transportation and depositional processes and features (Moraines Eskers)*

*Morphological changes (Hanging valleys, Fjords, Drumlins)*

*Depression of the regional crustal plate*

***Application to WMA C:*** *Not relevant on the time scale of the performance assessment.*

***Potentially deleterious FEP****: Not applicable*

| **Warm climate effects (tropical and desert)** | 1.3.06 |
|---|---|

**Definition:** FEPs related to warm tropical and desert climates, including seasonal effects, and meteorological and geomorphological effects special to these climates.

***Comment:*** *Regions with a tropical climate may experience extreme weather patterns (monsoons, hurricanes), that could result in flooding, storm surges, high winds etc. with implications for erosion and hydrology. The high temperatures and humidity associated with tropical climates result and soils are generally thin. In arid climates, total rainfall, erosion and recharge may be dominated by infrequent storm events.*

***Key Concepts, examples, and related FEPs***

| | | |
|---|---|---|
| *Extreme weather patterns* | *Alkali flats* | *Effective recharge* |
| *Monsoons* | *Infrequent storm events* | *Change in hydrological regime* |
| *Hurricanes* | *High rainfall* | *Rapid biological degradation* |
| *Flooding* | *High winds* | *Erosion* |
| *Storm surges* | | |

***Application to WMA C:*** *Relevant in evaluation of the infiltration rate. See Section 3.*

***Potentially deleterious FEP****: Effects are included in estimates and uncertainties in the infiltration rate.*

**Hydrological/hydrogeological response to climate changes** 1.3.07

**Definition:** FEPs related to changes in the hydrological and hydrogeological regime, e.g. recharge, sediment load and seasonality, in response to climate change in a region.

***Comment:*** *The hydrology and hydrogeology of a region is closely coupled to climate. Climate controls the amount of precipitation and evaporation, seasonal ice cover and thus the soil water balance, extent of soil saturation, surface runoff and groundwater recharge. Vegetation and human actions may modify these responses.*

***Key Concepts, examples, and related FEPs***

| | | |
|---|---|---|
| *Change in groundwater recharge* | *Change in regional precipitation/infiltration/evaporation* | *Change in surface runoff* |
| *Change in sediment load* | *Change in seasonal ice cover* | *Increase in groundwater velocity* |
| *Change in soil water balance* | | *Creation of local ponds* |

***Application to WMA C:*** *Relevant in evaluating the infiltration rate.*

***Potentially deleterious FEP****: This FEP has the potential to affect the cover infiltration safety function. Effects of climate change on infiltration are included in the range of rates derived from the paleo record on precipitation. Potential anthropogenic effects are within the range of past climates. See Section 3.*

**Ecological response to climate changes** 1.3.08

**Definition:** FEPs related to changes in ecology, e.g. vegetation, plant and animal populations, in response to climate change in a region.

***Comment:*** *The ecology of an environment is linked to climate. Ecological adaptation has allowed flora and fauna to survive and exploit even the most hostile of environments. For example, cacti have evolved to survive extreme heat and desiccation of the desert environment, and certain plant species complete their entire lifecycle over very short time periods following rare rain events in the desert. Some tree and plant species have evolved to survive natural events such as forest fires, and may require them to complete their lifecycle*

| |
|---|
| ***Key Concepts, examples, and related FEPs*** |
| *Desert formation* *Change in animal life* *Ecological adaptation* |
| *Change in vegetation* |
| ***Application to WMA C:*** *Relevant in evaluating the infiltration rate.* |
| ***Potentially deleterious FEP****: This FEP has the potential to affect the cover infiltration safety function by altering the plant community over the waste. Variation in infiltration rates are considered, barrier testing has included conditions following loss of vegetation.* |

| **Human response to climate changes** | 1.3.09 |
|---|---|
| **Definition:** FEPs related to changes in human behaviour, e.g. habits, diet, size of communities, in response to climate change in a region. | |
| ***Comment:*** *Human response is closely linked to climate. Climate affects the abundance and availability of natural resources such as water, as well as the types of crops that can be grown. The more extreme a climate, the greater the extent of human control over these resources is necessary to maintain agricultural productivity, e.g. through the use of dams, irrigation systems, controlled agricultural environments (greenhouses).* | |
| ***Key Concepts, examples, and related FEPs*** | |
| *Change in human habits* *Increase/decrease in usage of irrigation systems* *Effect of climate change on water availability* | |
| *Effect of climate change on food chain* *Change in population density* *Construction of dams* | |
| *Change in agricultural activities/products* *Change in diet* | |
| ***Application to WMA C:*** *Addressed in the exposure assessment requirements in DOE Order 435.1.* | |
| ***Potentially deleterious FEP****: Not applicable.* | |

| **Other geomorphologic changes** | 1.3.10 |
|---|---|
| **Definition:** FEPs related to geomorphologic (also known as physiography) changes on a regional and local scale, i.e. the general configuration of the Earth's surface. | |
| ***Comment:*** *Geomorphology refers to the classification, description, nature, origin and development of present landforms and their relationships to underlying structures, and of the history of geologic changes as recorded by these surface features. The term is especially applied to the generic interpretation of landforms, but has also been restricted to features produced only by erosion and deposition.* | |
| ***Key Concepts, examples, and related FEPs*** | |
| *Denudation* | |

***Application to WMA C:*** *Relevant in to WMA C in the morphological changes associated with adding the cover, with increased depth to the waste.*

***Potentially deleterious FEP****: Not applicable*

| **FUTURE HUMAN ACTIONS (ACTIVE)** | 1.4 |
|---|---|
| **Definition:** Human actions and regional practices, in the post-closure period, that can potentially affect the performance of the engineered and/or geological barriers, e.g. intrusive actions, but not the passive behaviour and habits of the local population, c.f. 2.4. | |
| ***Comment:*** *Human Actions (Active)" is a sub-category of the External Factors in the International FEP List and is divided into individual FEPs.* | |

| **Human influences on climate** | 1.4.01 |
|---|---|
| **Definition:** FEPs related to human activities that could affect the change of climate either globally or in a region. | |
| ***Comment:*** *These activities could be intentional or unintentional, with an indirect influence more than a direct influence on the climate.* | |
| ***Key Concepts, examples, and related FEPs*** | |
| *De-forestation* *Emissions of 'greenhouse' gases such as $CO_2$ and $CH_4$* | |
| ***Application to WMA C:*** *Relevant in evaluating the infiltration rate. Projected anthropogenic effects on future climates may be either increases or decreases in infiltration rate.* | |
| ***Potentially deleterious FEP****: This FEP has the potential to affect the cover infiltration safety function. Effects of climate change on infiltration are included in the range of rates derived from the paleo record on precipitation. Potential anthropogenic effects are within the range of past climates.* | |

| **Motivation and knowledge issues (inadvertent/deliberate human actions)** | 1.4.02 |
|---|---|
| **Definition:** FEPs related to the degree of knowledge of the existence, location and/or nature of the repository. Also, reasons for deliberate interference with, or intrusion into, a repository after closure with complete or incomplete knowledge. | |
| ***Comment:*** *Some future human actions e.g. see FEPs 1.4.03 and 1.4.04, could directly impact upon the repository performance. Many assessments distinguish between:*<br>- *inadvertent actions, which are actions taken without knowledge or awareness of the repository, and*<br>- *deliberate actions, which are actions that are taken with knowledge of the repository's existence and location, e.g. deliberate attempts to retrieve the waste, malicious intrusion and sabotage.*<br>*Intermediate cases, of intrusion with incomplete knowledge, could also occur.* | |

***Key Concepts, examples, and related FEPs***

*Human intrusion (instigate mechanical processes*

*Incomplete knowledge intrusion)*

*Deliberate actions e.g. war, sabotage, waste recovery, malicious intrusion*

*Inadvertent actions e.g. exploratory drilling, resource mining, archaeological intrusion*

***Application to WMA C:*** *Not relevant for the WMA C performance assessment, since this FEP relates to probability of occurrence of inadvertent intrusion, which is not taken credit for in the assessment. Advertent intrusion is generally excluded from consideration in the international community of performance assessment.*

***Potentially deleterious FEP****: Not applicable.*

| **Drilling activities (human intrusion)** | 1.4.03 |
|---|---|
| **Definition:** FEPs related to any type of drilling activity near the repository. | |
| ***Comment:*** *These activities may be taken with or without knowledge of the repository and in fact is a subgroup of FEP 1.4.02.* | |

***Key Concepts, examples, and related FEPs***

*Exploratory and/or exploitation drilling for natural resources and raw materials*

*Drilling for research or site characterization studies*

*Water well drilling*

*Drilling for waste injection*

*Drilling for hydrothermal resources*

*Extraction of valuable components of the disposed waste*

***Application to WMA C:*** *Relevant to the intrusion scenario.*

***Potentially deleterious FEP****: Addressed in the evaluation of inadvertent intrusion.*

| **Mining and other underground activities (human intrusion)** | 1.4.04 |
|---|---|
| **Definition:** FEPs related to any type of mining or excavation activity carried out near the repository. | |
| ***Comment:*** *These activities may be taken with or without knowledge of the repository and in fact is a subgroup of FEP 1.4.02.* | |

***Key Concepts, examples, and related FEPs***

*Resource mining;*

*Excavation for industry;*

*Geothermal energy production*

*Mine drillings*

*Shaft construction, underground construction and tunnelling*

*Recovery of repository materials (re-use of waste)*

*The presence of mine galleries - after closure*

*Malicious intrusion, sabotage or war*

*Injection of liquid wastes and other fluids*

*Scientific underground investigation*

*Underground nuclear testing*

***Application to WMA C:*** *Drilling activities accounted for in the drilling intrusion scenario. Other mining activities excluded based on lack of resources as WMA C. Potential for intrusive activities is also limited by depth of waste disposal and presence of intrusion barriers.*

***Potentially deleterious FEP****: Not applicable.*

| **Un-intrusive site investigation** | 1.4.05 |
|---|---|

**Definition:** FEPs related to airborne, geophysical or other surface-based investigation of a repository site after repository closure

***Comment:*** *Such investigation, e.g. prospecting for geological resources, might occur after information of the location of a repository had been lost. The evidence of the repository itself, e.g. discovery of an old shaft, might itself prompt investigation, including research of historical archives.*

***Key Concepts, examples, and related FEPs***

*Prospecting for geological resources*

*Investigation of an old shaft*

*Research of historical archives*

***Application to WMA C:*** *Not relevant as this FEP relates to probabilities of intrusion, which are not taken credit for in the performance assessment.*

***Potentially deleterious FEP****: Not applicable.*

| **Surface excavations** | 1.4.06 |
|---|---|

**Definition:** FEPs related to any type of human activities during surface excavations that can potentially affect the performance of the engineered and/or natural (geological) barriers, or the exposure pathways.

***Comment:*** *This FEP relates to the surface environment. Strictly speaking, excavation refers to an act or process of removing soil and or rock materials from one location and transporting them to another. This may include, for example, digging, blasting, breaking, loading and hauling, which may result in direct human intrusion in the case of a near-surface repository.*

***Key Concepts, examples, and related FEPs***

| | | |
|---|---|---|
| *Quarrying, trenching, ploughing* | *Dredging of sediments in estuaries* | *Shallow excavations for site investigations* |
| *Digging, blasting, breaking, loading, hauling* | *Excavation for construction (earthworks)* | *Excavation for military purposes* |
| *Recycling of materials* | *Excavation for storage or disposal* | |

***Application to WMA C:*** *Home construction basement scenario excluded based on depth of waste disposal and presence of intrusion barriers.*

***Potentially deleterious FEP****: Not applicable.*

| **Pollution** | 1.4.07 |
|---|---|

**Definition:** FEPs related to any type of human activities associated with pollution that can potentially affect the performance of the engineered and/or natural (geological) barriers, or the exposure pathways.

***Comment:*** *As used here, it refers to the alteration of the chemical composition of the surface environment in the vicinity of the repository, in such a way that the performance of the disposal system is influenced.*

***Key Concepts, examples, and related FEPs***

| | | |
|---|---|---|
| *Acid rain* | *Soil pollution* | *Groundwater pollution* |
| *Chemical liquid waste disposal* | *Soil fertilization* | |

***Application to WMA C:*** *Relevant to WMA C in potential changes to the degradation rates of the engineered barriers. Effects of past leaks on vadose zone properties.*

***Potentially deleterious FEP****: Potential effects in engineered barrier safety functions related to flow reduction. Effects of past leaks on vadose zone properties.*

| **Site development** | 1.4.08 |
|---|---|

**Definition:** FEPs related to any type of human activities during site development that can potentially affect the performance of the engineered and/or natural (geological) barriers, or the exposure pathways

| | | |
|---|---|---|
| ***Comment:*** *As used here, site development refers to alterations to the surface environment after memory of the repository has been lost. These alterations may result in direct human intrusion in the near-surface facility, or to an alteration of the host lithology or topography.* | | |
| ***Key Concepts, examples, and related FEPs*** | | |
| *Site occupation* | *Construction of roads, houses, buildings, dams, etc.* | *Residential, industrial, transport and road construction* |
| *Levelling of hills (e.g., airport lay out)* | *Human modification of the site drainage* | *Land reclamation/extension* |
| ***Application to WMA C:*** *Relevant to WMA C in potential changes to the degradation rates of the cover.* | | |
| ***Potentially deleterious FEP****: Potential effects in the cover function for infiltration considered in sensitivity cases.* | | |

| | |
|---|---|
| **Archaeology** | 1.4.09 |
| **Definition:** FEPs related to any type of human activities associated with archaeology that can potentially affect the performance of the engineered and/or natural (geological) barriers, or the exposure pathways. | |
| ***Comment:*** *As used here, the FEP refers to archaeological investigations in the surface environment.* | |
| ***Key Concepts, examples, and related FEPs*** | |
| *Archaeological, inadvertent human intrusion* | *Archaeological artefacts find during construction* |
| ***Application to WMA C:*** *Not relevant as this FEP relates to probabilities of intrusion, which are not taken credit for in the performance assessment.* | |
| ***Potentially deleterious FEP****: Not applicable.* | |

| | |
|---|---|
| **Water management (wells, reservoirs, dams)** | 1.4.10 |
| **Definition:** FEPs related to groundwater and surface water management including water extraction, reservoirs, dams, and river management. | |
| ***Comment:*** *Water is a valuable resource and water extraction and management schemes provide increased control over its distribution and availability through construction of dams, barrages, canals, pumping stations and pipelines. Groundwater and surface water may be extracted for human domestic use (e.g. drinking water, washing), agricultural uses (e.g. irrigation, animal consumption) and industrial uses. Extraction and management of water may affect the movement of radionuclides to and in the surface environment.* | |

***Key Concepts, examples, and related FEPs***

*Waterworks*

*Artificial mixing of lakes*

*Reservoirs*

*Industrial usage*

*Human effects on water potential*

*Chemical liquid waste disposal*

*Intentional artificial groundwater recharge/discharge by humans*

*Dam, barrage, canals, pumping stations and pipeline building*

*Desalination of water in estuaries and marines*

*Drainage systems*

*Extraction of contaminated water from aquifer via a well*

*Impoundment of water for fishing/fish farming, bathing*

*Groundwater/surface water extraction for irrigation, animal consumption, drinking water, washing*

*Salt production*

***Application to WMA C:*** *Water management activities on the Columbia River have the potential to affect river stage.*

***Potentially deleterious FEP****: Potential effects on the saturated zone safety functions are consider in sensitivity cases for aquifer flow.*

| **Social and institutional developments** | 1.4.11 |
|---|---|

**Definition:** FEPs related to changes in social patterns and degree of local government, planning and regulation.

***Comment:*** *The decisions made in future concerning social and institutional development may have a significant influence on the disposal system, e.g., if a change in land use is promulgated or a change in the regulatory requirements.*

***Key Concepts, examples, and related FEPs***

*Loss of archives/records, loss/degradation of societal memory*

*Changes in planning controls and environmental legislation*

*Demographic change and urban development*

*Changes in land use*

*Change in regulatory requirements*

*Change in institutional control*

***Application to WMA C:*** *Excluded from consideration in DOE Order 435.1.*

***Potentially deleterious FEP****: Not applicable.*

| **Technological developments** | **1.4.12** |
|---|---|

**Definition:** FEPs related to future developments in human technology and changes in the capacity and motivation to implement technologies. This may include retrograde developments, e.g. loss of capacity to implement a technology.

| |
|---|
| ***Comment:*** *Of interest are those technologies that might change the capacity of man to intrude deliberately or otherwise into a repository, to cause changes that would affect the movement of contaminants, to affect the exposure or its health implications. Technological developments are likely but may not be predictable especially at longer times into the future. In most assessments, assumptions are made to limit the scope of consideration.* |
| ***Key Concepts, examples, and related FEPs***<br>*Retrograde developments* *Loss of capacity to implement technology* |
| ***Application to WMA C:*** *Excluded from consideration in DOE Order 435.1.*<br>***Potentially deleterious FEP****: Not applicable.* |

| **Remedial actions** | 1.4.13 |
|---|---|
| **Definition:** FEPs related to actions that might be taken following repository closure to remediate problems with a waste repository that, either, was not performing to the standards required, had been disrupted by some natural event or process, or had been inadvertently or deliberately damaged by human actions. | |
| ***Comment:*** | |
| ***Key Concepts, examples, and related FEPs***<br>*None* | |
| ***Application to WMA C:*** *Excluded from consideration in DOE Order 435.1.*<br>***Potentially deleterious FEP****: Not applicable.* | |

| **Explosions and crashes** | 1.4.14 |
|---|---|
| **Definition:** FEPs related to deliberate or accidental explosions and crashes such as might have some impact on a closed repository, e.g. underground nuclear testing, aircraft crash on the site, acts of war. | |
| ***Comment:*** | |
| ***Key Concepts, examples, and related FEPs***<br>*Intrusions by war, sabotage, terrorism* *Likelihood of crashes onto surface facilities, e.g. plane crashes*<br>*Underground nuclear testing* | |
| ***Application to WMA C:*** *Potentially relevant to the performance of the cover, but very low probability of occurrence.*<br>***Potentially deleterious FEP****: Potential relevance to the surface barrier safety function for infiltration. However, it is excluded from consideration based on very low probability of occurrence.* | |

| DISPOSAL SYSTEM DOMAIN: ENVIRONMENTAL FACTORS | 2 |
|---|---|
| **Definition:** Features and processes occurring within that spatial and temporal (post-closure) domain whose principal effect is to determine the evolution of the physical, chemical, biological and human conditions of the domain that are relevant to estimating the release and migration of radionuclides and consequent exposure to man. | |
| ***Comment:*** *"Disposal System Domain: Environmental Factors" is a category in the International FEP List and is divided into sub-categories.* | |

| WASTES AND ENGINEERED FEATURES | 2.1 |
|---|---|
| **Definition:** Features and processes within the waste and engineered components of the disposal system. (output – source term characteristics) | |
| ***Comment:*** *"Wastes and Engineered Features" is a sub-category of Disposal Domain:Environmental Factors in the International FEP List and is divided into individual FEPs.*<br>*Note that FEPs 2.1.01 to 2.1.06 describe the features in the disposal system, in other words, a description of the system as it is constructed, whereas FEPs 2.1.07 to 2.1.11 describe the processes or the changes in the disposal system.* | |

| Inventory, radionuclide and other material | 2.1.01 |
|---|---|
| **Definition:** FEPs related to the total content of the repository of a given type of material, substance, element, individual radionuclides, total radioactivity or inventory of toxic substances. | |
| ***Comment:*** *The FEP often refers to content of radionuclides but the content of other materials, e.g. steels, other metals, concrete or organic materials, could be of interest.* | |
| ***Key Concepts, examples, and related FEPs*** | |
| *Radionuclide content* *Concrete or organic material content* *Steel and other metal content* | |

| Waste form materials, characteristics and degradation processes | 2.1.02 |
|---|---|
| **Definition:** FEPs related to the physical, chemical, biological characteristics of the waste form at the time of disposal and as they may evolve in the repository, including FEPs which are relevant specifically as waste degradation processes. | |
| ***Comment:*** *The waste form will usually be conditioned prior to disposal, e.g. by solidification and inclusion of grout materials. The waste form is a component of the waste package. The waste characteristics will evolve due to various processes that will be affected by the physical and chemical conditions of the repository environment. Processes that are relevant specifically as waste degradation processes, as compared to general evolution of the near field, are included in this FEP.* | |

| ***Key Concepts, examples, and related FEPs*** | | |
|---|---|---|
| *Physical degradation* | *Ash* | *Activated metal* |
| *Chemical degradation* | *Cloves, clothing, plastics, paper wood* | *Sludges, evaporation residue, compacted solids, filters* |
| *Solid matrix of resin, bitumen, cement* | *Spent sources* | |
| ***Application to WMA C:*** *Relevant to the performance assessment.* | | |
| ***Potentially deleterious FEP****: Uncertainties in the inventory of residual waste and its chemical and physical form. Uncertainty in the final amounts of waste in as-yet unretrieved tanks.* | | |

| **Container materials, characteristics and degradation/failure processes** | | 2.1.03 |
|---|---|---|
| **Definition:** FEPs related to the physical, chemical, biological characteristics of the container at the time of disposal and as they may evolve in the repository, including FEPs that are relevant specifically as container degradation/failure processes. | | |
| ***Comment:*** *The container refers to the vessel into which the waste form is placed for handling, transportation, storage and or disposal. It is also the outer barrier protecting the waste from external intrusions. The container is a component of the waste package.* | | |
| ***Key Concepts, examples, and related FEPs*** | | |
| *Container degradation/failure processes* | *Concrete containers* | *Lead containers* |
| *Metal drums* | *Stainless steel containers* | |
| ***Application to WMA C:*** *Not relevant to the performance assessment. Waste is not containerized* | | |
| ***Potentially deleterious FEP****: Not applicable.* | | |

| **Buffer/backfill materials, characteristics and degradation processes** | 2.1.04 |
|---|---|
| **Definition:** FEPs related to the physical, chemical, biological characteristics of the buffer and/or backfill at the time of disposal and as they may evolve in the repository, including FEPs that are relevant specifically as buffer/backfill degradation processes. (Effect on hydrology / flow) | |
| ***Comment:*** *Buffer and backfill are sometimes used synonymously. In some HLW/spent fuel concepts, the term buffer is used to mean material immediately surrounding a waste container and having some chemical and/or mechanical buffering role whereas backfill is used to mean material used to fill other underground openings. However, in ILW/LLW concepts the term backfill is used to describe the material placed between waste containers, which may have a chemical role. Buffer/backfill materials may include clays, cement and mixtures of cement with aggregates, e.g. of crushed rock.*<br>*The buffer/backfill characteristics will evolve due to various processes that will be affected by the physical and chemical conditions of the repository environment. Processes, which are relevant specifically as buffer/backfill degradation processes, as compared to general evolution of the near field, are included in this FEP.* | |

| |
|---|
| ***Key Concepts, examples, and related FEPs*** |
| *Buffer/backfill degradation processes* *Clay, cement, sand, soil* *Mixture of clay and crushed rock* |
| *Bentonite clay* |
| ***Application to WMA C:*** *Relevant to the performance assessment as the grout infill.* |
| ***Potentially deleterious FEP****: Uncertainty in the performance of the grout is considered in sensitivity and uncertainty analysis.* |

| **Engineered barrier system characteristics and degradation processes** | 2.1.05 |
|---|---|
| **Definition:** FEPs related to the design, physical, chemical, hydraulic etc. characteristics of the cavern/tunnel/shaft seals at the time of sealing and closure and also as they may evolve in the repository, including FEPs which are relevant specifically as cavern/tunnel/shaft seal and cap degradation processes. (Effect on hydrology / flow – change over time). | |
| ***Comment:*** *Cavern/tunnel/shaft seal and cap failure may result from gradual degradation processes, or may be the result of a sudden event. The importance is that alternative routes for groundwater flow and radionuclide transport may be created along the various layers and tunnels and/or shafts and associated EDZ (see FEP 2.2.01).* | |
| ***Key Concepts, examples, and related FEPs*** | |
| *Engineered caps (cover)* *Intrusion resistance caps* *Cap materials: clay, concrete* | |
| *Cover degradation* | |
| ***Application to WMA C:*** *Relevant to the performance assessment as the tank structure, base mat, and cover system.* | |
| ***Potentially deleterious FEP****: Uncertainties in the current state and long term performance of the engineered barriers is addressed in sensitivity and uncertainty analysis.* | |

| **Other engineered features materials, characteristics and degradation processes** | 2.1.06 |
|---|---|
| **Definition:** FEPs related to the physical, chemical, biological characteristics of the engineered features (other than containers, buffer/backfill, caps and seals) at the time of disposal and also as they may evolve in the repository, including FEPs which are relevant specifically as degradation processes acting on the engineered features. | |
| ***Comment:*** *Examples of other engineered features are rock bolts, shotcrete, tunnel liners, silo walls, any services and equipment not removed before closure. The engineered features, materials and characteristics will evolve due to various processes that will be affected by the physical and chemical conditions of the repository environment. Processes which are relevant specifically as degradation processes acting on the features, as compared to general evolution of the near field, are be included in this FEP.* | |

| ***Key Concepts, examples, and related FEPs*** | | |
|---|---|---|
| *Trenches, holes, vaults*<br>*Walls, floors, mounds, layers of mounds*<br>*Rock bolts, tunnel liners, silo walls* | *Reduction in flow through structures due to impermeable membrane and subsequent degradation of impermeable membrane* | *Cut-off walls*<br>*Degradation processes* |
| ***Application to WMA C:*** *Relevant to pipes and structures associated with ancillary equipment.*<br>***Potentially deleterious FEP****: Not applicable, as the ancillary equipment is treated conservatively in the base case,* | | |

| **Mechanical processes and conditions (in wastes and EBS)** | | 2.1.07 |
|---|---|---|
| **Definition:** FEPs related to the mechanical processes that affect the wastes, containers, seals and other engineered features, and the overall mechanical evolution of near field with time. This includes the effects of hydraulic and mechanical loads imposed on wastes, containers and repository components by the surrounding geology. | | |
| ***Comment:*** | | |
| ***Key Concepts, examples, and related FEPs*** | | |
| *Waste and container compression*<br>*Container collapse*<br>*Buffer swelling pressure*<br>*Material volume changes* | *Subsidence as a result of compression of waste and cover layers*<br>*Fracture formation in vault, backfill, joints, cover materials, host geology (local fractures)* | *Container movement*<br>*Differential behaviour of joints*<br>*Tunnel roof or lining collapse* |
| ***Application to WMA C:*** *Relevant to the performance assessment in the influence of the FEP to conditions of the base mat.*<br>***Potentially deleterious FEP****: Potential degradation in the current state and future evolution of the base mat hydraulic safety function which is considered in the sensitivity and uncertainty analysis.* | | |

| **Hydraulic/hydrogeological processes and conditions (in wastes and EBS)** | 2.1.08 |
|---|---|
| **Definition:** FEPs related to the hydraulic/hydrogeological processes that affect the wastes, containers, seals and other engineered features, and the overall hydraulic/hydrogeological evolution of near field with time. This includes the effects of hydraulic/hydrogeological influences on wastes, containers and repository components by the surrounding geology. | |
| ***Comment:*** | |

| ***Key Concepts, examples, and related FEPs*** | | |
|---|---|---|
| *Failure of drainage system*<br>*Failure of cut-off walls*<br>*Failure of cap/cover* | *Modification of pore water by cover caused by chemical*<br>*Interaction of vault material with pore water*<br>*pH change* | *Osmotic effects*<br>*Infiltration and movement of fluids in the repository environment*<br>*Resaturation/desaturation of the repository or its components* |
| *Failure of the joints*<br>*Bathtubbing*<br>*Fracturing of concrete components*<br>*Effect of cap+cover+backfill*<br>*Influence of climate change*<br>*Influence of saline intrusion*<br>*Gas mediated water flow*<br>*Interaction of backfill with pore water*<br>*pH change*<br>*Redox change*<br>*Sulphate attack*<br>*Effect of chelating agents* | *Redox potential change*<br>*Mineralization*<br>*Modification of pore water by cover*<br>*Interaction of container material with pore water*<br>*Matrix corrosion*<br>*Gas generation*<br>*Polymer degradation (high integrity containers)*<br>*Mineralization change*<br>*Osmotic effect*<br>*Interaction of vault materials with host groundwater*<br>*Carbonation* | *Water flow and contaminant transport paths within the repository*<br>*Induced fluid effects caused by temperature change*<br>*-Pressure change*<br>*-Natural convection*<br>*-Viscosity*<br>*Reduction in flow through structures due to grouting*<br>*Chloride attack*<br>*Sulphate attack*<br>*Colloid formation* |
| ***Application to WMA C:*** *Relevant to the performance assessment in the influence of the FEP to release and transport of waste from tanks and ancillary equipment.*<br>***Potentially deleterious FEP****: Uncertainty in the current state and future evolution of the safety functions of the waste, grout, tank, and base mat is considered in the sensitivity and uncertainty analysis* | | |

| **Chemical/geochemical processes and conditions (in wastes and EBS)** | 2.1.09 |
|---|---|
| **Definition:** FEPs related to the chemical/geochemical processes that affect the wastes, containers, seals and other engineered features, and the overall chemical/geochemical evolution of near field with time. This includes the effects of chemical/geochemical influences on wastes, containers and repository components by the surrounding geology. | |
| ***Comment:*** | |

| ***Key Concepts, examples, and related FEPs*** | | |
|---|---|---|
| *Chemical interaction of backfill with pore water* | *Chemical interaction of waste with pore water* | *Induced galvanic metallic corrosion* |
| *pH changes* | *Metallic corrosion processes (general and pitting)* | *Polymer degradation (high integrity containers)* |
| *Redox changes* | *Polymer degradation (resins)* | *Chemical interaction of backfill with containers (including overpacks)* |
| *Sulphate attack* | *Osmotic effects* | *Induced galvanic metallic corrosion* |
| *Osmotic effects* | *Chemical interaction of containers (including overpacks) with pore water* | *Polymer degradation (high integrity containers)* |
| *Chemical interaction of vault materials with pore water* | *Metallic corrosion* | *Chemical interaction of non-radioactive waste components with radioactive waste components* |
| *pH changes* | *Polymer degradation (high integrity containers)* | *pH changes* |
| *Redox potential changes* | *Osmotic effects* | *Redox potential changes* |
| *Chemical interaction of vault materials with host groundwater* | *Chemical interaction of waste with containers* | *Change in chemical reaction rate caused by temperature change* |
| *Carbonation* | *Precipitation/dissolution reactions* | *Electrochemical processes* |
| *Chloride attack* | *Evolution of redox (Eh) and acidity/alkalinity (pH) etc.* | *Chemical conditioning and buffering processes* |
| *Sulphate attack* | *Silting/pore closure* | |
| | *Geochemical changes* | |
| ***Application to WMA C:*** *Relevant to the performance assessment in the influence of the FEP to release and transport of waste from tanks and ancillary equipment.* | | |
| ***Potentially deleterious FEP****: Uncertainty in the current state and future evolution of the chemical safety functions of the waste, grout, tank, and base mat is considered in the sensitivity and uncertainty analysis.* | | |

| **Biological/biochemical processes and conditions (in wastes and EBS)** | 2.1.10 |
|---|---|
| **Definition:** FEPs related to the biological/biochemical processes that affect the wastes, containers, seals and other engineered features, and the overall biological/biochemical evolution of near field with time. This includes the effects of biological/biochemical influences on wastes, containers and repository components by the surrounding geology. | |
| ***Comment:*** | |

***Key Concepts, examples, and related FEPs***

*Microbial growth and poisoning*

*Microbially/biologically mediated processes*

*Effect of organic material*

*Microbial/biological effects of evolution of redox (Eh) and acidity/alkalinity (pH), etc.*

*Effect of organic materials*

*Change in microbial caused by change in temperature*

***Application to WMA C:*** *Relevant to the performance assessment in the influence of the FEP to release and transport of waste from tanks and ancillary equipment.*

***Potentially deleterious FEP****: Uncertainty in the current state and future evolution of the chemical safety functions of the waste, grout, tank, and base mat is considered in the sensitivity and uncertainty analysis.*

| **Thermal processes and conditions (in wastes and EBS)** | 2.1.11 |
|---|---|

**Definition:** FEPs related to the thermal processes that affect the wastes, containers, seals and other engineered features, and the overall thermal evolution of the near field with time. This includes the effects of heat on wastes, containers and repository components from the surrounding geology.

***Comment:***

***Key Concepts, examples, and related FEPs***

*Temperature evolution*

*Differential elastic response*

*Non-elastic response*

*Fracture aperture changes caused by the temperature change*

*Change in microbial activity*

*Radiogenic, chemical and biological heat production from the wastes*

*Chemical heat production from engineered features, e.g. concrete hydration*

*Change in chemical reaction rates e.g. corrosion*

*Temperature dependence of physical/chemical/ biological/hydraulic processes, e.g. corrosion and re-saturation*

*Fluid pressure, density viscosity changes*

*Induced chemical changes caused by the temperature change*

***Application to WMA C:*** *Applicable in the performance assessment, but heat generated in residual waste for expected retrievals is negligible.*

***Potentially deleterious FEP****: Potential heat generation in tanks that retain substantial amounts of unretrievable waste, leading to effects on flow through the waste and EBS.*

| **Gas sources and effects (in wastes and EBS)** | 2.1.12 |
|---|---|

**Definition:** FEPs within and around the wastes, containers and engineered features resulting in the generation of gases and their subsequent effects on the repository system.

***Comment:*** *Gas production may result from degradation and corrosion of various waste, container and engineered feature materials, as well as radiation effects. The effects of gas production may change local chemical and hydraulic conditions, and the mechanisms for radionuclide transport, i.e. gas-induced and gas-mediated transport.*

| ***Key Concepts, examples, and related FEPs*** | | |
|---|---|---|
| *Explosion* | *Gas generation* | *Degradation of vault, overpacks or backfill (instigate mechanical processes)* |
| *Pressurisation* | *Corrosion* | *Chemical interaction of containers (including overpacks) with pore water* |
| *Radiation effects* | *Decomposition of organic matter (microbial)* | *Chemical interaction of waste with containers* |
| | | *Chemical interaction of backfill with containers (including overpacks)* |
| ***Application to WMA C:*** *Relevant to the performance assessment in analyses of releases to the atmosphere.* | | |
| ***Potentially deleterious FEP****: Not applicable.* | | |

| **Radiation effects (in wastes and EBS)** | | 2.1.13 |
|---|---|---|
| **Definition:** FEPs related to the effects that result from the radiation emitted from the wastes that affect the wastes, containers, seals and other engineered features, and the overall radiogenic evolution of the near field with time. | | |
| ***Comment:*** *Examples of relevant effects are ionization, radiolytic decomposition of water (radiolysis), radiation damage to waste matrix or container materials, helium gas production due to alpha decay.* | | |
| ***Key Concepts, examples, and related FEPs*** | | |
| *Radiolysis* | *Irradiation effects on metals, concrete* | *Concrete degradation* |
| *Decay product gas generation* | *Polymer degradation (resins and high integrity containers)* | *Metallic degradation* |
| ***Application to WMA C:*** *Applicable in the performance assessment, but negligible.* | | |
| ***Potentially deleterious FEP****: None identified..* | | |
| **Nuclear criticality** | | 2.1.14 |
| **Definition:** FEPs related to the possibility and effects of spontaneous nuclear fission chain reactions within the repository. | | |
| ***Comment:*** *A chain reaction is the self-sustaining process of nuclear fission in which each neutron released from a fission triggers, on average, at least one other nuclear fission. Nuclear criticality requires a sufficient concentration and localized mass (critical mass) of fissile isotopes (e.g. U-235, Pu-239) and also presence of neutron moderating materials in a suitable geometry; a chain reaction is liable to be damped by the presence of neutron absorbing isotopes (e.g. Pu-240).* | | |
| ***Key Concepts, examples, and related FEPs*** | | |
| *Radiological criticality* | | |

***Application to WMA C:*** *Not relevant to the tank closure performance assessment. Waste inventory screened for potential for criticality.*

***Potentially deleterious FEP****: Not applicable.*

| **Extraneous materials** | 2.1.15 |
|---|---|
| **Definition:** | |
| ***Comment:*** | |
| ***Key Concepts, examples, and related FEPs***<br>*None* | |
| ***Application to WMA C:*** *Not relevant.*<br>***Potentially deleterious FEP****: Not applicable.* | |

| **GEOLOGICAL ENVIRONMENT** | 2.2 |
|---|---|
| **Definition:** The features and processes of the geological environment surrounding the repository including, for example, the hydrogeological, geomechanical and geochemical features and processes, both in pre-emplacement state and as modified by the presence of the repository and other long-term changes. | |
| ***Comment:*** *"Geological Environment" is a sub-category in the International FEP List and is divided into individual FEPs.*<br>*Note that FEPs 2.2.01 to 2.2.06 describe the features in the disposal system, in other words, a description of the features of the system as it is constructed, whereas FEPs 2.2.07 to 2.2.11 describe the processes or the changes in the disposal system..* | |

| **Disturbed zone, host lithology** | 2.2.01 |
|---|---|
| **Definition:** FEPs related to the host lithology zone around the repository or any other underground openings that may be mechanically disturbed during construction, and the properties and characteristics as they may evolve both before and after repository closure. | |
| ***Comment:*** *The disturbed zone may have different properties to the undisturbed host lithology, e.g. opening of fractures or change of hydraulic properties due to stress relief.* | |
| ***Key Concepts, examples, and related FEPs***<br>*Fracture formed by the construction* *Change of hydraulic properties due to stress relief* | |
| ***Application to WMA C:*** *Relevant as the excavation zone for the tank farm.*<br>***Potentially deleterious FEP****: Not applicable.* | |

| **Host lithology** | 2.2.02 |
|---|---|
| **Definition:** FEPs related to the properties and characteristics of the lithology in/on which the repository is sited (excluding the zone disturbed by the construction) as they may evolve both before and after repository closure. In most cases, this FEP will be associated with the unsaturated zone. | |
| ***Comment:*** *Relevant properties include thermal and hydraulic conductivity, compressive and shear strength, porosity etc. In most cases, this FEP will be associated with the unsaturated zone (See FEP 2.2.03).* | |
| ***Key Concepts, examples, and related FEPs*** | |
| *Thermal and hydraulic conductivity* *Porosity* *Description of the host lithology* | |
| *Compressive and shear strength* | |
| ***Application to WMA C:*** *Relevant. Here host lithology is considered the H2 sand in which the facility resides.* | |
| ***Potentially deleterious FEP****: Uncertainties in the lithology and its properties could lead to mischaracterization of the vadose zone safety functions.* | |

| **Lithological units, other** | 2.2.03 |
|---|---|
| **Definition:** FEPs related to the properties and characteristics of the lithology other than the host lithology as they may evolve both before and after repository closure. | |
| ***Comment:*** *These lithological units are those that make up the region in which the repository is located. These units are identified in the geological investigations of the region. Each geological unit is characterized according to its geometry and its general physical properties and characteristics. Details concerning inhomogeneity and uncertainty associated with each unit are included in the characterization. In most cases, this FEP will be associated with the saturated zone (See FEP 2.2.02).* | |
| ***Key Concepts, examples, and related FEPs*** | |
| *Non-uniform stratigraphy* *Heterogeneity* *Description of the lithology units* | |
| ***Application to WMA C:*** *Relevant. Here "other lithological units" are those below WMA C (i.e. not the "host" lithology).* | |
| ***Potentially deleterious FEP****: Uncertainties in the lithology and its properties could lead to mischaracterization of the vadose zone and saturated zone safety functions.* | |

| **Discontinuities, large scale (in geosphere)** | 2.2.04 |
|---|---|
| **Definition:** FEPs related to the properties and characteristics of discontinuities in and between the saturated and unsaturated zones, including faults, shear zones, intrusive dykes and interfaces between different rock types. | |
| ***Comment:*** | |

| |
|---|
| ***Key Concepts, examples, and related FEPs*** |
| *Fault* *Shear zones* *Interfaces between different rock types* |
| *Intrusive dykes* |
| ***Application to WMA C:*** *None identified.* |
| ***Potentially deleterious FEP****: Not applicable.* |

| | |
|---|---|
| **Contaminant transport path characteristics (in geosphere)** | 2.2.05 |
| **Definition:** FEPs related to the properties and characteristics of smaller discontinuities and features within saturated and unsaturated zones that are expected to be the main paths for contaminant transport through the geosphere, as they may evolve both before and after repository closure. | |
| ***Comment:*** *Groundwater flow and contaminant transport through rocks may occur in a variety of systems depending on the rock characteristics. Porous flow is predominantly through pores in the medium or through the interstitial spaces between small grains of materials. Fracture flow is predominantly along fractures in the rock which represent the only connected open spaces. Changes in the contaminant transport path characteristics due to the repository construction or its chemical influence etc. are included.* | |
| ***Key Concepts, examples, and related FEPs*** | |
| *Fracture flow* *Fracture-matrix interaction* *Porous flow* | |
| ***Application to WMA C:*** *Relevant and considered in sensitivity and uncertainty analysis using alternative conceptual models.* | |
| ***Potentially deleterious FEP****: Not applicable.* | |

| | |
|---|---|
| **Mechanical processes and conditions (in geosphere)** | 2.2.06 |
| **Definition:** FEPs related to the mechanical processes that affect the saturated and unsaturated zones, and the overall evolution of conditions with time. This includes the effects of changes in condition, e.g. rock stress, due to the excavation, construction and long-term presence of the repository. | |
| ***Comment:*** | |
| ***Key Concepts, examples, and related FEPs*** | |
| *Subsidence* *Upliftment* | |
| ***Application to WMA C:*** *Not relevant.* | |
| ***Potentially deleterious FEP****: None identified.* | |

| **Hydraulic/hydrogeological processes and conditions (in geosphere)** | | 2.2.07 |
|---|---|---|
| **Definition:** FEPs related to the hydraulic and hydrogeological processes that affect the saturated and unsaturated zones, and the overall evolution of conditions with time. This includes the effects of changes in condition, e.g. hydraulic head, due to the excavation, construction and long-term presence of the repository. | | |
| ***Comment:*** *The hydrogeological regime is the characterization of the composition and movement of water through the relevant geological formations in the repository region and the factors that control this. This requires knowledge of the recharge and discharge zones, the groundwater flow systems, saturation, and other factors that may drive the hydrogeology, such as density effects due to salinity gradients or temperature gradients. Changes of the hydrogeological regime due to the construction and/or presence of the repository are included.* | | |
| ***Key Concepts, examples, and related FEPs*** | | |
| *Saline intrusion* | *Groundwater discharge to surface water, Soil, Estuary, Seas, Wells* | *Saturated/unsaturated conditions* |
| *Darcy flow* | *Channelling and preferential flow pathways* | *Flow between two aquifers* |
| *Non-Darcy flow* | *Aquifer(groundwater) discharge/recharge (e.g. well)* | *Infiltration* |
| *Fracture flow* | | *Flow direction* |
| ***Application to WMA C:*** *Relevant and considered in sensitivity and uncertainty analysis.* | | |
| ***Potentially deleterious FEP****: None identified.* | | |

| **Chemical/geochemical processes and conditions (in geosphere)** | | 2.2.08 |
|---|---|---|
| **Definition:** FEPs related to the chemical and geochemical processes that affect the saturated and unsaturated zones, and the overall evolution of conditions with time. This includes the effects of changes in condition, e.g. Eh, pH, due to the excavation, construction and long-term presence of the repository. | | |
| ***Comment:*** *The hydrochemical regime refers to the groundwater chemistry in the geological formations in the repository region, and the factors that control this. This requires knowledge of the groundwater chemistry including speciation, solubility, complexants, redox (reduction/oxidation) conditions, rock mineral composition and weathering processes, salinity and chemical gradients. Changes of the hydrochemical regime due to the construction and/or presence of the repository are included.* | | |
| ***Key Concepts, examples, and related FEPs*** | | |
| *pH change* | *pH effects of cement on the environment, soil, etc* | *Effect of non-radioactive solute plume* |
| *Redox potential changes* | *Mineralization changes* | |
| ***Application to WMA C:*** *Relevant.* | | |
| ***Potentially deleterious FEP****: Potential effects of past leaks on the H2 sand below the tank farm.* | | |

| **Biological/biochemical processes and conditions (in geosphere)** | **2.2.09** |
|---|---|
| **Definition:** FEPs related to the biological and biochemical processes that affect the saturated and unsaturated zones, and the overall evolution of conditions with time. This includes the effects of changes in condition, e.g. microbe populations, due to the construction and long-term presence of the repository. | |
| ***Comment:*** | |
| ***Key Concepts, examples, and related FEPs*** | |
| *Generating of chelating agents* *Influences on redox potential* *Microbiology-enhanced mobility* | |
| *Influences on pH* *Change in microbe population* | |
| ***Application to WMA C:*** *Relevant primarily in the potential effect on sorption coefficients in the geosphere.* | |
| ***Potentially deleterious FEP****: None identified.* | |

| **Thermal processes and conditions (in geosphere)** | **2.2.10** |
|---|---|
| **Definition:** FEPs related to the thermal processes that affect the saturated and unsaturated zones, and the overall evolution of conditions with time. This includes the effects of changes in condition, e.g. temperature, due to the construction and long-term presence of the repository. | |
| ***Comment:*** *Geothermal regime refers to sources of geological heat, the distribution of heat by conduction and transport (convection) in fluids, and the resulting thermal field or gradient. Changes of the geothermal regime due to the construction and/or presence of the repository are included* | |
| ***Key Concepts, examples, and related FEPs*** | |
| *Bio-heat* *Chemical reactions* *Change in temperature* | |
| ***Application to WMA C:*** *Not relevant except if future tank retrievals leave behind more waste than anticipated, with associated heat generation.* | |
| ***Potentially deleterious FEP****: Not applicable.* | |

| **Gas sources and effects (in geosphere)** | 2.2.11 |
|---|---|
| **Definition:** FEPs related to natural gas sources and production of gas within the geosphere and also the effect of natural and repository produced gas on the geosphere, including the transport of bulk gases and the overall evolution of conditions with time. | |
| ***Comment:*** *Gas movement in the geosphere will be determined by many factors including the rate of production, gas permeability and solubility, and the hydrostatic pressure regime.* | |
| ***Examples*** | |
| *Natural gas intrusion* | |

***Application to WMA C:*** *Not relevant.*

***Potentially deleterious FEP****: Not applicable.*

| **Undetected features (in geosphere)** | 2.2.12 |
|---|---|
| **Definition:** FEPs related to natural or man-made features within the geology that may not be detected during the site investigation. | |
| ***Comment:*** *Examples of possible undetected features are fracture zones, brine pockets or old mine workings. Some physical features of the repository environment may remain undetected during site surveys and even during pilot tunnel excavations. The nature of the geological environment will indicate the likelihood that certain types of undetected features may be present and the site investigation may be able to place bounds on the maximum size or minimum proximity to such features.* | |
| ***Key Concepts, examples, and related FEPs*** | |
| *Boreholes (drillings)*<br>*Mine shafts or mine galleries* | *Faults, shear zones, Breccia pipes, Lava tubes, Intrusive dykes* □ *Gas or brine pockets* |
| ***Application to WMA C:*** *Potentially relevant, but none identified.*<br>***Potentially deleterious FEP****: Potential presence of undetected major undetected feature in the vadose zone such as a clastic dike is considered as a sensitivity case.* | |

| **Geological resources** | 2.2.13 |
|---|---|
| **Definition:** FEPs related to natural resources within the geosphere, particularly those that might encourage investigation or excavation at or near the repository site. | |
| ***Comment:*** *Geological resources could include oil and gas, solid minerals, water, and geothermal resources. For a near-surface repository, quarrying of near-surface deposits, e.g. sand, gravel or clay, may be of interest* | |
| ***Key Concepts, examples, and related FEPs*** | |
| *Oil and gas*<br>*Sand, gravel, clay* | *Solid minerals* *Water* |
| ***Application to WMA C:*** *Relevant, only for potential use of water resources.*<br>***Potentially deleterious FEP****: None identified. Water resources included in the analysis.* | |

| **SURFACE ENVIRONMENT** | 2.3 |
|---|---|
| **Definition:** The features and processes within the surface environment, including near-surface aquifers and unconsolidated sediments but excluding human activities and behaviour, see 1.4 and 2.4.. | |
| ***Comment:*** *Surface Environment" is a sub-category in the International FEP List and is divided into individual FEPs*<br>*Note that FEPs 2.3.01 to 2.3.06 describe the features in the disposal system, in other words, a description of the features of the system as it is constructed, whereas FEPs 2.3.07 to 2.3.11 describe the processes or the changes in the disposal system.* | |

| **Topography and morphology** | **2.3.01** |
|---|---|
| **Definition:** FEPs related to the relief and shape of the surface environment and its evolution. | |
| ***Comment:*** *This FEP refers to local land form and land form changes with implications for the surface environment, e.g. plains, hills, valleys, and effects of river and glacial erosion thereon. In the long term, such changes may occur as a response to geological changes, see 1.3.* | |
| ***Key Concepts, examples, and related FEPs***<br>*Land forms* *Hills* *Valleys*<br>*Plains* | |
| ***Application to WMA C:*** *Relevant, the closure cover changes the local topography.*<br>***Potentially deleterious FEP****: None identified.* | |

| **Soil and sediment** | **2.3.02** |
|---|---|
| **Definition:** FEPs related to the characteristics of the soils and sediments and their evolution. | |
| ***Comment:*** *Different soil and sediment types, e.g. characterized by particle-size distribution and organic content, will have different properties with respect erosion/deposition and contaminant sorption etc.* | |
| ***Key Concepts, examples, and related FEPs***<br>*Soil and sediment development* *Soil conversion* | |
| ***Application to WMA C:*** *Potentially relevant. Potential movement of sand dunes onsite. However, dune migration to the site would require regional changes in air currents.*<br>***Potentially deleterious FEP****: May cause changes in the recharge safety function considered in sensitivity and uncertainty analysis.* | |

| **Aquifers and water-bearing features, near surface** | 2.3.03 |
|---|---|
| **Definition:** FEPs related to the characteristics of aquifers and water-bearing features within a few metres of the land surface and their evolution. | |
| ***Comment:*** *Aquifers are water-bearing features geological units or near-surface deposits that yield significant amounts of water to wells or springs. The presence of aquifers and other water-bearing features will be determined by the geological, hydrological and climatic factors.* | |
| ***Key Concepts, examples, and related FEPs***<br>*Weathered aquifer* *Fractured aquifer* *Description of aquifers in repository region*<br>*Sandy aquifer* | |
| ***Application to WMA C:*** *Relevant.*<br>***Potentially deleterious FEP****: Uncertainties in aquifer properties may lead to mischaracterization of the aquifer safety function.* | |

| **Lakes, rivers, streams and springs** | 2.3.04 |
|---|---|
| **Definition:** FEPs related to the characteristics of terrestrial surface water bodies and their evolution. | |
| ***Comment:*** *Streams, rivers and lakes often act as boundaries on the hydrogeological system. They usually represent a significant source of dilution for materials (including) radionuclides entering these systems, but in hot dry environments, where evaporation dominates, concentration is possible.* | |
| ***Key Concepts, examples, and related FEPs***<br>*Description of lakes, rivers, streams and springs in the repository region* | |
| ***Application to WMA C:*** *Not relevant owing to the DOE Order 435.1 assessment point. Discharges to the Columbia River are excluded from the analysis. However, the Columbia exerts an indirect influence on the system through its influence on the aquifer gradient.*<br>***Potentially deleterious FEP****: Not applicable* | |

| **Coastal features** | 2.3.05 |
|---|---|
| **Definition:** FEPs related to the characteristics of coasts and the near shore, and their evolution. Coastal features include headlands, bays, beaches, spits, cliffs and estuaries. | |
| ***Comment:*** *The processes operating on these features, e.g. active erosion, deposition, longshore transport, determine the development of the system and may represent a significant mechanism for dilution or accumulation of materials (including radionuclides) entering the system.* | |

| ***Key Concepts, examples, and related FEPs*** | | |
|---|---|---|
| *Description of the coastal features in the repository region* | *Coastal surge* | *Temperature change* |
| *Headlands, Bays, Beaches, Spits* | *Storm* | *Recharge* |
| *Cliffs, Estuaries* | *tsunami* | *Bed-load processes* |
| *Coastal erosion* | *Groundwater discharge to estuary, shore* | *Flooding* |
| *Saline intrusion* | *Bioturbation* | *Plant/animal uptake/metabolism* |
| *Salinity changes* | *Tidal currents* | *Sand dune encroachment* |
| *Sedimentation* | *Sea spray* | *Coastal currents* |
| *Resuspension* | *Behaviour of coastal waters and marine sediment* | *Description of coastal features in vicinity of repository* |
| *Volatilisation* | *Estuarine changes* | *Beach development* |
| ***Application to WMA C:*** *Not relevant.* | | |
| ***Potentially deleterious FEP****: Not applicable.* | | |

| **Marine features** | 2.3.06 |
|---|---|
| **Definition:** FEPs related to the characteristics of seas and oceans, including the seabed, and their evolution. Marine features include oceans, ocean trenches, shallow seas, and inland seas. | |
| ***Comment:*** *Processes operating on these features such as erosion, deposition, thermal stratification and salinity gradients, determine the development of the system and may represent a significant mechanism for dilution or accumulation of materials (including radionuclides) entering the system.* | |

| ***Key Concepts, examples, and related FEPs*** | | |
|---|---|---|
| *Ocean trenches, shallow seas* | *Marine sediment transport and deposition* | *Vertical mixing and isolation* |
| *inland seas, Oceans* | *Groundwater discharge towards sea* | *Salinity changes* |
| *Sedimentation* | *Sea spray* | *Plant/animal uptake/metabolism* |
| *Resuspension* | *Sediment transport* | *Bed-load processes* |
| *Volatilisation* | *Sea currents* | *Description of marine features in vicinity of repository* |
| *Tidal currents* | *Temperature change* | *Recharge* |
| *Marine currents* | | |
| ***Application to WMA C:*** *Not relevant.* | | |
| ***Potentially deleterious FEP****: Not applicable.* | | |

| **Atmosphere** | 2.3.07 |
|---|---|
| **Definition:** FEPs related to the characteristics of the atmosphere, including capacity for transport, and their evolution. | |
| ***Comment:*** | |
| ***Key Concepts, examples, and related FEPs*** | |
| *Physical transport of gases* *Chemical and photochemical reactions* *Aerosols and dust in the atmosphere* | |
| ***Application to WMA C:*** *Relevant to the performance objectives in Order 435.1. Effects of atmospheric FEPs are also relevant in a stylized way through the infiltration rate.* | |
| ***Potentially deleterious FEP****: None identified.* | |

| **Vegetation** | 2.3.08 |
|---|---|
| **Definition:** FEPs related to the characteristics of terrestrial and aquatic vegetation both as individual plants and in mass, and their evolution. | |
| ***Comment:*** | |
| ***Key Concepts, examples, and related FEPs*** | |
| *Chemical changes caused by plants* *Description of the vegetation in vicinity of repository* | |

***Application to WMA C:*** *Relevant to the estimation of recharge.*

***Potentially deleterious FEP****: Potential changes to vegetation may affect cover infiltration safety function (considered in sensitivity and uncertainty analysis).*

| **Animal populations** | | 2.3.09 |
|---|---|---|
| **Definition:** FEPs related to the characteristics of the terrestrial and aquatic animals both as individual animals and as populations, and their evolution. | | |
| ***Comment:*** | | |
| ***Key Concepts, examples, and related FEPs*** | | |
| *Animal diets* | *External contamination of animals* | *Description of the animal population in vicinity of repository* |
| ***Application to WMA C:*** *Relevant. The effects of native animal populations are embedded in the assumptions regarding cover performance and general infiltration rates. Historic recharge data considers very long time frames with varying climate.* | | |
| ***Potentially deleterious FEP****: None identified.* | | |

| **Meteorology** | | 2.3.10 |
|---|---|---|
| **Definition:** FEPs related to the characteristics of weather and climate, and their evolution. | | |
| ***Comment:*** *Meteorology is characterized by precipitation, temperature, pressure and wind speed and direction. The variability in meteorology should be included so that extreme events such as drought, flooding, storms and snow melt are identified.* | | |
| ***Key Concepts, examples, and related FEPs*** | | |
| *Rainfall* | *Climate fluctuation* | *Hurricanes* |
| *Snowfall* | *Dew-freezing cycles* | *High rainfall / Flooding* |
| *Flooding related to high precipitation* | *Wet-dry cycles* | *Temperature* |
| *Storms related to strong winds* | *Seasonality* | *Tsunamis* |
| ***Application to WMA C:*** *Relevant to the estimation of recharge.* | | |
| ***Potentially deleterious FEP****: Potential changes to climate may affect infiltration safety function are considered in sensitivity and uncertainty analysis.* | | |

| **Hydrological regime and water balance (near-surface)** | 2.3.11 |
|---|---|
| **Definition:** FEPs related to near-surface hydrology at a catchment scale and also soil water balance, and their evolution. | |

| | | |
|---|---|---|
| ***Comment:*** *The hydrological regime is a description of the movement of water through the surface and near-surface environment. It includes the movement of materials associated with the water such as sediments and particulate. Extremes such as drought, flooding, storms and snowmelt may be relevant.* | | |
| ***Key Concepts, examples, and related FEPs*** | | |
| *Surface run-off to marines/estuaries* | *Groundwater discharge to surface water, soils, estuaries/marines* | *Change in lake or reservoir levels* |
| *River flow to marines/estuaries* | *Water discharge/recharge processes that effecting radionuclide content* | *Alkali flats* |
| *Evaporation* | *Stream silting* | *Stream and river flow changes* |
| *Evapotranspiration* | | *River meander* |
| *Infiltration* | | *Stream flow* |
| ***Application to WMA C:*** *Relevant to the estimation of recharge.* | | |
| ***Potentially deleterious FEP****: Potential changes in surface conditions may affect infiltration safety function are considered in sensitivity and uncertainty analysis.* | | |

| | |
|---|---|
| **Erosion and deposition** | 2.3.12 |
| **Definition:** FEPs related to all the erosional and depositional processes that operate in the surface environment, and their evolution. | |
| ***Comment:*** *Relevant processes may include fluvial and glacial erosion and deposition, denudation, eolian erosion and deposition. These processes will be controlled by factors such as the climate, vegetation, topography and geomorphology.* | |

| | | |
|---|---|---|
| ***Key Concepts, examples, and related FEPs*** | | |
| *Deposition* | *Coastal erosion due to rise and fall of lea level (Greenhouse effect)* | *Erosion by wave action, landslides or rockfalls* |
| *Wind erosion related to storms* | *Landsliding (instigate mechanical processes)* | *Agriculture erosion* |
| *Erosion related to flooding* | *Erosion (instigate mechanical processes)* | *Erosion of cover* |
| *Erosion related to glaciation* | | *Weathering* |
| ***Application to WMA C:*** *Relevant to the estimation of recharge.* | | |
| ***Potentially deleterious FEP****: Potential changes in surface conditions may affect infiltration safety function are considered in sensitivity and uncertainty analysis.* | | |

| | |
|---|---|
| **Ecological/biological/microbial systems** | 2.3.13 |
| **Definition:** FEPs related to living organisms and relations between populations of animals, plants and their evolution. | |

| |
|---|
| ***Comment:*** *Characteristics of the ecological system include the vegetation regime, and natural cycles such as forest fires or flash floods that influence the development of the ecology. The plant and animal populations occupying the surface environment are an intrinsic component of its ecology. The wide range of processes that define the ecological system regulates their behaviour and population dynamics. Human activities have significantly altered the natural ecology of most environments.* |
| ***Key Concepts, examples, and related FEPs*** |
| *Ecological and biological features* *Chemical changes caused by micro-organisms* *Chemical changes caused by plants* |
| ***Application to WMA C:*** *Relevant to the estimation of recharge.* |
| ***Potentially deleterious FEP****: Potential changes in ecology may affect infiltration safety function are considered in sensitivity and uncertainty analysis.* |

| **Animal/Plant intrusion** | 2.3.14 |
|---|---|
| **Definition:** Animal and plant intrusion leading to vault or trench disruption. | |
| ***Comment:*** | |
| ***Key Concepts, examples, and related FEPs*** | |
| *Seeds* *Root intrusion (instigate mechanical processes)* *Animal intrusion (instigate mechanical processes)* | |
| *Burrowing animals* *Bio-intrusion by plants and animals* | |
| ***Application to WMA C:*** *Not relevant. Precluded by depth of disposal. Considered in barrier design and testing.* | |
| ***Potentially deleterious FEP****: Not applicable.* | |

| **HUMAN BEHAVIOUR** | 2.4 |
|---|---|
| **Definition:** The habits and characteristics of the individuals or populations, e.g. critical groups, to whom exposures are calculated, not including intrusive or other activities which will have an impact on the performance of the engineered or geological barriers, see 1.4. | |
| ***Comment:*** *"Human Behaviour (passive)" is a sub-category in the International FEP List and is divided into individual FEPs.* | |

| **Human characteristics (physiology, metabolism)** | 2.4.01 |
|---|---|
| **Definition:** FEPs related to characteristics, e.g. physiology, metabolism, of individual humans. | |
| ***Comment:*** *Physiology refers to body and organ form and function. Metabolism refers to the chemical and biochemical reactions, which occur within an organism, or part of an organism, in connection with the production and use of energy.* | |

| |
|---|
| ***Key Concepts, examples, and related FEPs*** |
| *Physiological and metabolism description of humans that will be the subject of the assessment* |
| ***Application to WMA C:*** *Relevant to dose factors. Addressed in DOE orders and standards (DOE-STD-1196-2011)* |
| ***Potentially deleterious FEP****: Not applicable.* |

| **Adults, children, infants and other variations** | 2.4.02 |
|---|---|
| **Definition:** FEPs related to considerations of variability, in individual humans, of physiology, metabolism and habits. | |
| ***Comment:*** *Children and infants, although similar to adults, often have characteristic differences, e.g. metabolism, respiratory rates, habits (e.g. pica, ingestion of soil) which may lead to different exposure characteristics.* | |
| ***Key Concepts, examples, and related FEPs*** | |
| *None* | |
| ***Application to WMA C:*** *Relevant to dose factors. Addressed in DOE orders and standards (DOE-STD-1196-2011)* | |
| ***Potentially deleterious FEP****: Not applicable.* | |

| **Diet and fluid intake** | 2.4.03 |
|---|---|
| **Definition:** FEPs related to intake of food and water by individual humans and the compositions and origin of intake. | |
| ***Comment:****. The human diet refers to the range of food products consumed by humans.* | |
| ***Key Concepts, examples, and related FEPs*** | |
| *Diet* | *Description of the human diet and assumptions regarding quantities/volume* |
| ***Application to WMA C:*** *Relevant to exposure factors for Order 435.1 all pathways analysis.* | |
| ***Potentially deleterious FEP****: Not applicable.* | |

| **Habits (non-diet-related behaviour)** | 2.4.04 |
|---|---|
| **Definition:** FEPs related to non-diet related behaviour of individual humans, including time spent in various environments, pursuit of activities and uses of materials. | |

***Comment:*** *The human habits refer to the time spent in different environments in pursuit of different activities and other uses of materials. Agricultural practices and human factors such as culture, religion, economics and technology will influence the diet and habits. Smoking, ploughing, fishing, and swimming are examples of behaviour that might give rise to particular modes of exposure to environmental contaminants.*

***Key Concepts, examples, and related FEPs***

| | | |
|---|---|---|
| *Human habits* | *Location of shielding factors* | *Bathing* |
| *Resource usage* | *Impoundment of water* | *Description of human habits and behaviour* |
| *Storage of products* | *Fishing/fish farming* | *Air filtration* |
| *Ventilation* | | |

***Application to WMA C:*** *Relevant to exposure factors for Order 435.1 all pathways analysis.*

***Potentially deleterious FEP****: Not applicable.*

| **Community characteristics** | 2.4.05 |
|---|---|

**Definition:** FEPs related to characteristics, behaviour and lifestyle of groups of humans that might be considered as target groups in an assessment.

***Comment:*** *Relevant characteristics might be the size of a group and degree of self-sufficiency in food stuffs/diet. For example, hunter/gathering describes a subsistence lifestyle employed by nomadic or semi-nomadic groups who roam relatively large areas of land hunting wild game and/or fish, and gathering native fruits, berries, roots and nuts, to obtain their dietary requirements.*

***Key Concepts, examples, and related FEPs***

| | |
|---|---|
| *Demographic changes* | *General human society description* |

***Application to WMA C:*** *Addressed in Order 435.1 guidance.*

***Potentially deleterious FEP****: Not applicable.*

| **Food and water processing and preparation** | 2.4.06 |
|---|---|

**Definition:** FEPs related to treatment of foodstuffs and water between raw origin and consumption.

***Comment:*** *Once a crop is harvested or an animal slaughtered it may be subject to a variety of storage, processing and preparational activities prior to human or livestock consumption. These may change the radionuclide distribution and/or content of the product. For example, radioactive decay during storage, chemical processing, washing losses and cooking losses during food preparation.*

*Water sources may be treated prior to human or livestock consumption, e.g. chemical treatment and/or filtration.*

| |
|---|
| ***Key Concepts, examples, and related FEPs*** |
| *Water filtration* *Food processing* |
| ***Application to WMA C:*** *Relevant to exposure factors for Order 435.1 all pathways analysis.* |
| ***Potentially deleterious FEP****: Not applicable.* |

| | |
|---|---|
| **Dwellings** | 2.4.07 |
| **Definition:** FEPs related to houses or other structures or shelter in which humans spend time. | |
| ***Comment:*** *Dwellings are the structures which humans live in. The materials used in their construction and their location may be significant factors for determining potential radionuclide exposure pathways.* | |
| ***Key Concepts, examples, and related FEPs*** | |
| *Construction of buildings, houses* *Ventilation* *Location and shielding factors* | |
| *Site occupation* | |
| ***Application to WMA C:*** *Relevant to exposure factors for Order 435.1 all pathways analysis.* | |
| ***Potentially deleterious FEP****: Not applicable.* | |

| | |
|---|---|
| **Wild and natural land and water use** | 2.4.08 |
| **Definition:** FEPs related to use of natural or semi-natural tracts of land and water such as forest, bush and lakes. | |
| ***Comment:*** *Special foodstuffs and resources may be gathered from natural land and water, which may lead to significant modes of exposure.* | |
| ***Key Concepts, examples, and related FEPs*** | |
| *Natural and semi-natural environments* | |
| ***Application to WMA C:*** *Relevant to exposure factors for Order 435.1 all pathways analysis.* | |
| ***Potentially deleterious FEP****: Not applicable.* | |

| | |
|---|---|
| **Rural and agricultural land and water use (incl. fisheries)** | 2.4.09 |
| **Definition:** FEPs related to use of permanently or sporadically agriculturally managed land and managed fisheries. | |

| | | |
|---|---|---|
| ***Comment:*** *An important set of processes are those related to agricultural practices, their effects on land form, hydrology and natural ecology, and also their impact in determining uptake through food chains and other exposure paths.* | | |
| ***Key Concepts, examples, and related FEPs*** | | |
| *Use of land for agriculture* | *Land use change* | *Fishing/ fish farming in estuaries/marines* |
| *Ploughing* | *Fertilization* | |
| ***Application to WMA C:*** *Relevant to exposure factors for Order 435.1 all pathways analysis.* | | |
| ***Potentially deleterious FEP****: Not applicable.* | | |

| | | |
|---|---|---|
| **Urban and industrial land and water use** | | 2.4.10 |
| **Definition:** FEPs related to urban and industrial developments, including transport, and their effects on hydrology and potential contaminant pathways. | | |
| ***Comment:*** *Human populations are concentrated in urban areas in modern societies. Significant areas of land may be devoted to industrial activities. Water resources may be diverted over considerable distances to serve urban and/or industrial requirements.* | | |
| ***Key Concepts, examples, and related FEPs*** | | |
| *Water works* | *Water extraction through wells* | *De-salination of water* |
| *Urban and industrial environments* | *Water extraction for irrigation* | *Human water extraction* |
| ***Application to WMA C:*** *Not relevant to analyses conducted for exposures under Order 435.1 all pathways analysis. Subsistence farmer scenario is more conservative.* | | |
| ***Potentially deleterious FEP****: Not applicable.* | | |

| | | |
|---|---|---|
| **Leisure and other uses of environment** | | 2.4.11 |
| **Definition:** FEPs related to leisure activities, the effects on the surface environment and implications for contaminant exposure pathways. | | |
| ***Comment:*** *Significant areas of land, water, and coastal areas may be devoted to leisure activities e.g., water bodies for recreational uses, mountains/wilderness areas for hiking and camping activities.* | | |
| ***Key Concepts, examples, and related FEPs*** | | |
| *Recreational land use* | *Impoundment of water for bathing* | *Beach development* |
| ***Application to WMA C:*** *Not relevant to analyses conducted for exposures under Order 435.1 all pathways analysis. Subsistence farmer scenario is more conservative.* | | |
| ***Potentially deleterious FEP****: Not applicable.* | | |

| RADIONUCLIDE/CONTAMINANT FACTORS | 3 |
|---|---|
| **Definition:** FEPs that take place in the disposal system domain that directly affect the release and migration of radionuclides and other contaminants, or directly affect the dose to members of a critical group from given concentrations of radiotoxic and chemotoxic species in environmental media. | |
| ***Comment:*** *"Disposal System Domain: Radionuclide Factors" is a category in the International FEP List and is divided into sub-categories..* | |

| CONTAMINANT CHARACTERISTICS | 3.1 |
|---|---|
| **Definition:** The characteristics of the radiotoxic and chemotoxic species that might be considered in a post-closure safety assessment. | |
| ***Comment:*** *"Contaminant Characteristics" is a sub-category in the International FEP List and is divided into individual FEPs.* | |

| Radioactive decay and in-growth | 3.1.01 |
|---|---|
| **Definition:** Radioactivity is the spontaneous disintegration of an unstable atomic nucleus resulting in the emission of sub-atomic particles. Radioactive isotopes are known as radionuclides. Where a parent radionuclide decays to a daughter radionuclide so that the population of the daughter radionuclide increases this is known as in-growth. | |
| ***Comment:*** *In post-closure assessment models, radioactive decay chains are often simplified, e.g. by neglecting the shorter-lived radionuclides in transport calculations, or adding dose contributions from shorter-lived radionuclides to dose factors for the longer-lived parent in dose calculations* | |
| ***Key Concepts, examples, and related FEPs*** | |
| *Production of aqueous progeny* *Radon emanation* | |
| ***Application to WMA C:*** *Relevant.* | |
| ***Potentially deleterious FEP****: Not applicable.* | |

| Chemical/organic toxin stability | 3.1.02 |
|---|---|
| **Definition:** FEPs related to chemical stability of chemotoxic species. | |
| ***Comment:*** | |
| ***Key Concepts, examples, and related FEPs*** | |
| *None* | |

***Application to WMA C:*** *Not relevant in this performance assessment, which is focused only on radiological exposures.*

***Potentially deleterious FEP****: Not applicable.*

| **Inorganic solids/solutes** | 3.1.03 |
|---|---|
| **Definition:** FEPs related to the characteristics of inorganic solids/solutes that may be considered. | |
| ***Comment:*** | |
| ***Key Concepts, examples, and related FEPs***<br>*Source terms content* | |
| ***Application to WMA C:*** *Relevant.*<br>***Potentially deleterious FEP****: None identified.* | |

| **Volatiles and potential for volatility** | 3.1.04 |
|---|---|
| **Definition:** FEPs related to the characteristics of radiotoxic and chemotoxic species that are volatile or have the potential for volatility in repository or environmental conditions. | |
| ***Comment:*** *Some radionuclides may be isotopes of gaseous elements (e.g. Kr isotopes) or may form volatile compounds. Gaseous radionuclides or species may arise from chemical or biochemical reactions, e.g. metal corrosion to yield hydrogen gas and microbial degradation of organic material to yield methane and carbon dioxide.* | |
| ***Key Concepts, examples, and related FEPs***<br>*None* | |
| ***Application to WMA C:*** *Relevant. Addressed in atmospheric release and radon release analyses.*<br>***Potentially deleterious FEP****: Not applicable.* | |

| **Organics and potential for organic forms** | 3.1.05 |
|---|---|
| **Definition:** FEPs related to the characteristics of radiotoxic and chemotoxic species that are organic or have the potential to form organics in repository or environmental conditions. | |
| ***Comment:*** | |

| |
|---|
| ***Key Concepts, examples, and related FEPs*** <br> *Source term content* |
| ***Application to WMA C:*** *Relevant, but concentrations of organic species in residual waste are low and their effects have been screened out.* <br> ***Potentially deleterious FEP****: Not applicable.* |

| **Noble gases** | 3.1.06 |
|---|---|
| **Definition:** FEPs related to the characteristics of noble gases. | |
| ***Comment:*** *Radon and thoron are special cases, see FEP 3.3.08.* | |
| ***Key Concepts, examples, and related FEPs*** <br> *None* | |
| ***Application to WMA C:*** *Not relevant.* <br> ***Potentially deleterious FEP****: Not applicable.* | |

| **CONTAMINANT RELEASE/MIGRATION FACTORS** | 3.2 |
|---|---|
| **Definition:** The processes that directly affect the release and/or migration of radionuclides in the disposal system domain. | |
| ***Comment:*** *"Release/Migration Factors" is a sub-category in the International FEP List and is divided into individual FEPs.* | |

| **Dissolution, precipitation and crystallisation, contaminant** | 3.2.01 |
|---|---|
| **Definition:** FEPs related to the dissolution, precipitation and crystallisation of radiotoxic and chemotoxic species under repository or environmental conditions. | |
| ***Comment:*** *Dissolution is the process by which constituents of a solid dissolve into solution. Precipitation and crystallisation are processes by which solids are formed out of liquids. Precipitation occurs when chemical species in solution react to produce a solid that does not remain in solution. Crystallisation is the process of producing pure crystals of an element, molecule or mineral from a fluid or solution undergoing a cooling process.* | |

| ***Key Concepts, examples, and related FEPs*** | |
|---|---|
| *Chemical reactions caused by dissolution and precipitation of radionuclides* | *Caused by chemical interaction of backfill with pore water* |
| *Change in mineralization* | *Caused by chemical interaction of non-radioactive waste with radioactive waste* |
| *Caused by chemical interaction of vault material with pore water* | *Caused by a change in temperature* |
| ***Application to WMA C:*** *Relevant.* | |
| ***Potentially deleterious FEP****: Potential rapid waste dissolution may affect the safety function of the waste dissolution (considered in sensitivity and uncertainty analysis).* | |

| **Speciation and solubility, contaminant** | | 3.2.02 |
|---|---|---|
| **Definition:** FEPs related to the chemical speciation and solubility of radiotoxic and chemotoxic species in repository or environmental conditions. | | |
| ***Comment:*** *The solubility of a substance in aqueous solution is an expression of the degree to which it dissolves. Factors such as temperature and pressure affect solubility, as do the pH and redox conditions. These factors affect the chemical form and speciation of the substance. Thus different species of the same element may have different solubilities in a particular solution. Porewater and groundwater speciation and solubility are very important factors affecting the behaviour and transport of radionuclides* | | |
| ***Key Concepts, examples, and related FEPs*** | | |
| *Species equilibrium change caused by change in temperature* | *Solubility change caused by change in temperature*<br>*Solubility* | *Solubility change caused by chemical interaction between waste and pore water* |
| ***Application to WMA C:*** *Relevant to chemical behaviour of contaminants in residual waste.* | | |
| ***Potentially deleterious FEP****: Uncertainties in chemical behaviour may affect the chemical safety functions.* | | |

| **Sorption/desorption processes, contaminant** | 3.2.03 |
|---|---|
| **Definition:** FEPs related to sorption/desorption of radiotoxic and chemotoxic species in repository or environmental conditions. | |
| ***Comment:*** *Sorption describes the physico-chemical interaction of dissolved species with a solid phase. Desorption is the opposite effect. Sorption processes are very important for determining the transport of radionuclides in groundwater. Sorption is often described by a simple partition constant ($K_d$) which is the ratio of solid phase radionuclide concentration to that in solution. This assumes that sorption is reversible, reaches equilibrium rapidly, is independent of variations in water chemistry or mineralogy along the flow path, the solid-water ratio, or concentrations of other species. More sophisticated approaches involve the use of sorption isotherms.* | |

| ***Key Concepts, examples, and related FEPs*** | | |
|---|---|---|
| *Sorption*<br>*Chemical reactions caused by adsorption or desoption*<br>*Anion exclusion effects* | *Effect of sorption*<br>*Caused by chemical interaction of waste with pore water* | *Caused by chemical interaction of non-radioactive waste with radioactive waste*<br>*Sorption change caused by change in temperature* |
| ***Application to WMA C:*** *Relevant to chemical behaviour of contaminants in residual waste.*<br>***Potentially deleterious FEP****: Uncertainties in chemical behaviour may affect the chemical safety functions (different release assumptions are considered in the sensitivity and uncertainty analysis).* | | |

| **Colloids, contaminant interactions and transport with** | | 3.2.04 |
|---|---|---|
| **Definition:** FEPs related to the transport of colloids and interaction of radiotoxic and chemotoxic species with colloids in repository or environmental conditions. | | |
| ***Comment:*** *Colloids are particles in the nanometre to micrometre size range which can form stable suspensions in a liquid phase. Metastable solid phases are unstable thermodynamically but exist due to the very slow kinetics of their alteration into more stable products. Colloids are present in groundwater and may also be produced during degradation of the wastes or engineered barrier materials.*<br>*Colloids may influence radionuclide transport in a variety of ways: retarding transport by sorption of aqueous radionuclide species and subsequent filtration; or, enhancing transport by sorption and transport with flowing groundwater* | | |
| ***Key Concepts, examples, and related FEPs*** | | |
| *Colloid formation*<br>*Caused by chemical interaction of waste with pore water* | *Caused by chemical interaction of backfill with pore water*<br>*Colloid transport* | *Caused by chemical interaction of non-radioactive waste with radioactive waste* |
| ***Application to WMA C:*** *Potentially relevant to transport behaviour of contaminants, but considered unlikely to play a role in this environment (DOE-ORP-2008-01, page 22-12).*<br>***Potentially deleterious FEP****: Not applicable.* | | |

| **Chemical/complexing agents, effects on contaminant speciation/transport** | 3.2.05 |
|---|---|
| **Definition:** FEPs related to the modification of speciation or transport of radiotoxic and chemotoxic species in repository or environmental conditions due to association with chemical and complexing agents. | |

| |
|---|
| ***Comment:*** *This FEP refers to any chemical agents that are present in the repository system and the effects that they may have on the release and migration of radionuclides from the repository environment. Chemical agents may be present in the wastes or in repository materials or introduced, e.g. from spillage during repository construction and operation, e.g. oil, hydraulic fluids, organic solvents. Chemical agents may be used during construction and operation, e.g. in drilling fluids, as additives to cements and grouts etc.* |
| ***Key Concepts, examples, and related FEPs***<br>*Effects of chelating agents*<br>*Caused by chemical interaction of waste with pore water*<br>*Caused by chemical interaction of backfill with pore water*<br>*Caused by chemical interaction of non-radioactive waste with radioactive waste*<br>*Microbial* |
| ***Application to WMA C:*** *Potentially relevant to chemical safety functions, but of minimal effect owing to low concentrations of organic material in residual waste.*<br>***Potentially deleterious FEP****: Potential for decrease in chemical safety functions.* |

| **Microbial/biological/plant-mediated processes, contaminant** | 3.2.06 |
|---|---|
| **Definition:** FEPs related to the modification of speciation or phase change due to microbial/biological/plant activity. | |
| ***Comment:*** *Microbial activity may facilitate chemical transformations of various kinds.* | |
| ***Key Concepts, examples, and related FEPs***<br>*Microbial-enhanced mobility* | |
| ***Application to WMA C:*** *Potentially relevant to chemical safety functions, but of minimal effect owing to low concentrations of organic material providing negligible energy source for microbes.*<br>***Potentially deleterious FEP****: Potential for decrease in chemical safety functions. Uncertainties in sorption are addressed in sensitivity and uncertainty analyses.* | |

| **Water-mediated transport of contaminants** | 3.2.07 |
|---|---|
| **Definition:** FEPs related to transport of radiotoxic and chemotoxic species in groundwater and surface water in aqueous phase and as sediments in surface water bodies. | |
| ***Comment:*** *Water-mediated transport of radionuclides includes all processes leading to transport of radionuclides in water. Radionuclides may travel in water as aqueous solutes (including dissolved gases), associated with colloids (see FEP 3.2.04) or, if flow conditions permit, with larger particulates/sediments.* | |

***Key Concepts, examples, and related FEPs***

*Multiphase transport processes*

*Surface water aqueous transport*

*Transport by surface run-off*

*Transport in water bodies*

*Percolation*

*Capillary rise*

*Groundwater transport*

*Infiltration*

*Dual flow systems*

*Advection, i.e. movement with the bulk movement of the fluid (in fractures, failed joints and matrix)*

*Molecular diffusion, i.e. random movement of individual atoms or molecules within the fluid*

*Dispersion, i.e. the spread of spatial distribution with time due to differential advection*

*Matrix diffusion, i.e. the diffusion or micro-advection of solute/colloids etc. into non-flowing pores*

*Transport of colloids*

*Percolation, i.e. movement of the fluid under gravity*

*Transport processes between surface water and porous media*

*Isotopic dilution.*

*Mass dilution*

*Discharge of radionuclides to sea*

*Fracture-matrix interaction*

*Discharge of radionuclides to foreshore*

*Transport of suspended sediment*

***Application to WMA C:*** *Relevant and addressed in the performance assessment.*

***Potentially deleterious FEP****: Not applicable.*

| **Solid-mediated transport of contaminants** | 3.2.08 |
|---|---|

**Definition:** FEPs related to transport of radiotoxic and chemotoxic species in solid phase, for example large-scale movements of sediments, landslide, solifluction and volcanic activity.

***Comment:***

***Key Concepts, examples, and related FEPs***

*Resuspension/deposition*

*Land slides*

*Rock falls*

*Rain splash*

*Transport by suspended sediments (sedimentation)*

*Erosion*

*Solid material release*

*Solid phase transport by water*

*Wet Deposition*

*Washout*

***Application to WMA C:*** *Not relevant owing to depth of disposal and facility stability.*

***Potentially deleterious FEP****: Not applicable.*

| **Gas-mediated transport of contaminants** | | | 3.2.09 |
|---|---|---|---|
| **Definition:** FEPs related to transport of radiotoxic and chemotoxic species in gas or vapour phase or as fine particulate or aerosol in gas or vapour. | | | |
| ***Comment:*** *Radioactive gases may be generated from the wastes, e.g. C-14-labelled carbon dioxide or methane. Radioactive aerosols or particulates may be transported along with non-radioactive gases, or gases may expel contaminated groundwater ahead of them* | | | |
| ***Key Concepts, examples, and related FEPs*** | | | |
| *Gas mediated water flow* | *Gas phase processes* | *Barometric pumping* | |
| *Gaseous release* | *Diffusion* | *Overpressurization* | |
| *Atmospheric gas transport* | *Atmospheric aerosol transport* | | |
| ***Application to WMA C:*** *Relevant and addressed in the performance assessment.* | | | |
| ***Potentially deleterious FEP****: None identified.* | | | |

| **Atmospheric transport of contaminants** | | 3.2.10 |
|---|---|---|
| **Definition:** FEPs related to transport of radiotoxic and chemotoxic species in the air as gas, vapour, fine particulate or aerosol. | | |
| ***Comment:*** *Radionuclides may enter the atmosphere from the surface environment as a result of a variety of processes including transpiration, suspension of radioactive dusts and particulates or as aerosols. The atmospheric system may represent a significant source of dilution for these radionuclides. It may also provide exposure pathways e.g. inhalation, immersion.* | | |
| ***Key Concepts, examples, and related FEPs*** | | |
| *Sea spray* | *Aerosol transport due to waves, wind* | |
| ***Application to WMA C:*** *Relevant and addressed in the performance assessment.* | | |
| ***Potentially deleterious FEP****: None identified.* | | |

| **Animal, plant and microbe mediated transport of contaminants** | 3.2.11 |
|---|---|
| **Definition:** FEPs related to transport of radiotoxic and chemotoxic species as a result of animal, plant and microbial activity. | |
| ***Comment:*** *Burrowing animals, deep rooting species and movement of contaminated microbes are included* | |

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|---|---|---|
| ***Key Concepts, examples, and related FEPs*** | | |
| *Discharge of radionuclides to soil layer (biotic intrusion)* | *Transport mediated by flora and fauna* | *Bioturbation* |
| *Animal/Plant intrusion* | *Uptake and desorption* | *Intake and emission by animals* |
| ***Application to WMA C:*** *Not relevant owing to depth of disposal and facility design except the potential for microbially mediated transport. Microbes have a potential effect on chemical safety functions (changes in sorption) but these are expected to be small owing to small concentrations of energy sources for microbes in the vadose zone.* | | |
| ***Potentially deleterious FEP****: Potential changes to chemical safety functions.* | | |

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|---|---|
| **Human-action-mediated transport of contaminants** | 3.2.12 |
| **Definition:** FEPs related to transport of radiotoxic and chemotoxic species as a direct result of human actions. | |
| ***Comment:****. Human-action-mediated transport of contaminants includes processes such as drilling into or excavation of the repository, the dredging of contaminated sediments from lakes, rivers and estuaries and placing them on land. Earthworks and dam construction may result in the significant movement of solid material from one part of the biosphere to another. Ploughing results in the mixing of the top layer of agricultural soil, usually on an annual basis.* | |

| | | |
|---|---|---|
| ***Key Concepts, examples, and related FEPs*** | | |
| *Dredging of sediments* | *Ploughing* | *Water abstraction* |
| ***Application to WMA C:*** *Relevant to intrusion analyses and evaluation of all pathways exposure analysis.* | | |
| ***Potentially deleterious FEP****: None identified.* | | |

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|---|---|
| **Foodchains, uptake of contaminants in** | 3.2.13 |
| **Definition:** FEPs related to incorporation of radiotoxic and chemotoxic species into plant or animal species that are part of the possible eventual food chain to humans. | |
| ***Comment:*** *Plants may become contaminated either as a result of direct deposition of radionuclides onto their surfaces or indirectly as a result of uptake from contaminated soils or water via the roots. Animals may become contaminated with radionuclides as a result of ingesting contaminated plants, or directly as a result of ingesting contaminated soils, sediments and water sources, or via inhalation of contaminated particulates, aerosols or gases.* | |

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|---|---|---|
| ***Key Concepts, examples, and related FEPs*** | | |
| *Plant/animal uptake in a marine/estuarine* | *Crops and natural and semi-natural flora and fauna* | *Internal transfer of radionuclides within animals* |
| *External contamination of animals* | | |
| ***Application to WMA C:*** *Relevant to post-intrusion analyses and evaluation of all pathways exposure analysis.* | | |
| ***Potentially deleterious FEP****: None identified.* | | |

| **EXPOSURE FACTORS** | **3.3** |
|---|---|
| **Definition:** Processes and conditions that directly affect the dose to members of the critical group, from given concentrations of radionuclides in environmental media. | |
| ***Comment:*** *Exposure Factors" is a sub-category in the International FEP List and is divided into individual FEPs.* | |

| **Drinking water, foodstuffs and drugs, contaminant concentrations in** | 3.3.01 |
|---|---|
| **Definition:** FEPs related to the presence of radiotoxic and chemotoxic species in drinking water, foodstuffs or drugs that may be consumed by human. | |
| ***Comment:*** | |
| ***Key Concepts, examples, and related FEPs*** | |
| *Internal transfer of radionuclides within animals* *Crops and natural and semi-natural flora and fauna* | |
| ***Application to WMA C:*** *Relevant to and considered in exposure scenarios* | |
| ***Potentially deleterious FEP****: None identified.* | |

| **Environmental media, contaminant concentrations in** | 3.3.02 |
|---|---|
| **Definition:** FEPs related to the presence of radiotoxic and chemotoxic species in environmental media other than drinking water, foodstuffs or drugs. | |
| ***Comment:****. The comparison of calculated contaminant concentrations in environmental media with naturally-occurring concentrations of similar species or species of similar toxic potential, may provide alternative or additional criteria for assessment less dependent on assumptions of human behaviour.* | |
| ***Key Concepts, examples, and related FEPs*** | |
| *None* | |
| ***Application to WMA C:*** *Relevant to and considered in exposure scenarios* | |
| ***Potentially deleterious FEP****: None identified.* | |

| **Non-food products, contaminant concentrations in** | 3.3.03 |
|---|---|
| **Definition:** FEPs related to the presence of radiotoxic and chemotoxic species in human manufactured materials or environmental materials that have special uses, e.g. clothing, building materials, peat. | |

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| ***Comment:*** *Contaminants may be concentrated in non-food products to which humans are exposed. For example, building materials, natural fibres or animal skins used in clothing, and the use of peat for fuel.* |
| ***Key Concepts, examples, and related FEPs***<br>*None* |
| ***Application to WMA C:*** *Not relevant to Order 435.1 exposure scenarios*<br>***Potentially deleterious FEP****: Not applicable.* |

| **Exposure modes** | 3.3.04 |
|---|---|
| **Definition:** FEPs related to the exposure of man (or other organisms) to radiotoxic and chemotoxic species. | |
| ***Comment:*** | |
| ***Key Concepts, examples, and related FEPs***<br>*Direct radiation from airborne plumes of radioactive materials*<br>*Injection through wounds*<br>*Cutaneous absorption of some species.*<br>*External exposure through water or sediment*<br>*Dermal exposure*<br>*Immersion in contaminated water bodies*<br>*Ingestion (internal exposure) from drinking or eating contaminated water or foodstuffs*<br>*Inhalation (internal exposure) from inhaling gaseous or particulate radioactive materials*<br>*External exposure as a result of direct irradiation from radionuclides deposited on, or present on, the ground, buildings or other objects.* | |
| ***Application to WMA C:*** *Relevant to and considered in exposure scenarios*<br>***Potentially deleterious FEP****: None identified.* | |

| **Dosimetry** | 3.3.05 |
|---|---|
| **Definition:** FEPs related to the dependence between radiation or chemotoxic effect and amount and distribution of radiation or chemical agent in organs of the body. | |
| ***Comment:*** *Dosimetry involves the estimation of radiation dose to individual organs, tissues, or the whole body, as a result of exposure to radionuclides. The radiation dose will depend on: the form of exposure, e.g. ingestion or inhalation of radionuclides leading to internal exposure or proximity to concentrations of radionuclides leading to external exposure; the metabolism of the radioelement and physico-chemical form if inhaled or ingested, which will determine the extent to which the radionuclide may be taken up and retained in body tissues; and the energy and type of radioactive emissions of the radionuclide which will affect the distribution of energy within tissues of the body.* | |

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| ***Key Concepts, examples, and related FEPs***<br>*None* |
| ***Application to WMA C:*** *Relevant to and considered in exposure scenarios*<br>***Potentially deleterious FEP****: None identified.* |

| **Radiological toxicity/effects** | 3.3.06 |
|---|---|
| **Definition:** FEPs related to the effect of radiation on man or other organisms. | |
| ***Comment:*** *Radiation effects are classified as somatic (occurring in the exposed individual), genetic (occurring in the offspring of the exposed individual), stochastic (the probability of the effect is a function of dose received), non-stochastic (the severity of the effect is a function of dose received and no effect may be observed below some threshold).* | |
| ***Key Concepts, examples, and related FEPs***<br>*None* | |
| ***Application to WMA C:*** *Not relevant to dose and concentration endpoints in the Order 435.1 analysis.*<br>***Potentially deleterious FEP****: Not applicable.* | |

| **Non-radiological toxicity/effects** | 3.3.07 |
|---|---|
| **Definition:** FEPs related to the effects of chemotoxic species on man or other organisms. | |
| ***Comment:*** | |
| ***Key Concepts, examples, and related FEPs***<br>*None* | |
| ***Application to WMA C:*** *Not relevant to radiological endpoints in the Order 435.1 performance assessment. Will be addressed in complementary analyses.(Groundwater protection criteria???) – may need to include some non-rads????*<br>***Potentially deleterious FEP****: Not applicable.* | |

| **Radon and radon daughter exposure** | **3.3.08** |
|---|---|
| **Definition:** FEPs related to exposure to radon and radon daughters. | |

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| ***Comment:*** *Radon and radon daughter exposure is considered separately to exposure to other radionuclides because the behaviour of radon and its daughter, and the modes of exposure, are different to other radionuclides.*<br><br>*Radon (Rn-222) is the immediate daughter of radium (Ra-226). It is a noble gas with a half-life of about 4 days and decays through a series of very short-lived radionuclides (radon daughters), with half-lives of 27 minutes or less, to a lead isotope (Pb-210) with a half-life of 21 years. The principal mode of exposure is through the inhalation of radon daughters attached to dust particles, which may deposit in the respiratory system.* |
| ***Key Concepts, examples, and related FEPs***<br><br>*Radon emanation* |
| ***Application to WMA C:*** *Relevant to the performance assessment. Evaluated as radon flux endpoint in the Order 435.1 analysis.*<br><br>***Potentially deleterious FEP****: None identified.* |

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