

Hanford Low-Level Tank Waste Interim Performance Assessment

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EXECUTIVE SUMMARY

The *Hanford Low-Level Tank Waste Interim Performance Assessment* examines the long-term environmental and human health effects associated with the disposal of the low-level fraction of the Hanford single- and double-shell tank waste in the Hanford Site 200 East Area. This report was prepared as a good management practice to provide needed information about the relationship between the disposal system design and its performance as early as possible in the project cycle. The calculations in this performance assessment show that the disposal of the low-level fraction can meet environmental and health performance objectives.

I. BACKGROUND

The Hanford Site in south-central Washington State has been used extensively as a location for defense materials production by the U.S. Department of Energy (DOE) and its predecessor agencies. Over the last 50 years, radioactive and mixed waste from this production activity has been stored on the Hanford Site, primarily in buried single- and double-shell tanks in the 200 Areas.

As part of Hanford's current mission of environmental restoration, DOE is proceeding with plans to permanently immobilize and dispose of this waste on-site in near-surface low-level tank waste disposal facilities. The plans are based on Revision 6 of the *Hanford Federal Facility Agreement and Consent Order (Tri-Party Agreement)*¹ and on the *Environmental Impact Statement for the Tank Remediation Systems*² (TWRS). These documents call for the waste to be retrieved from the single- and double-shell tanks, then pretreated to separate the low-level fraction from other tank wastes. The low-level fraction will then be immobilized. Over 200,000 m³ (6,000,000 ft³) of low-level waste will be disposed of under this plan. This quantity is among the largest amounts in the DOE Complex and contains one of the largest concentrations of long-lived radionuclides at a low-level waste facility.

¹ Washington State Department of Ecology, United States Environmental Protection Agency, United States Department of Energy, *Hanford Facility Agreement and Consent Order, Sixth Amendment, February 1996*. The document is available from any of the parties.

² *Environmental Impact Statement for the Tank Waste Remediation System, DOE/EIS-189D, U.S. Department of Energy, Washington, D.C., April 1996*. Final version expected in Fall 1996.

DOE Order 5820.2A, Radioactive Waste Management¹ is the primary regulation governing management and disposal of radioactive waste at DOE facilities. The interim performance assessment uses the techniques, methods, and rigor of the final performance assessment described in DOE Order 5820.2A where possible. Much of the data for this interim performance assessment is based on information from other projects or programs. As more of the design effort is completed and more data are collected, the preliminary and final performance assessments, which are required by DOE Order 5820.2A, will be prepared.

II. DATA SOURCES

The data used in the interim performance assessment are documented in Data Packages for the Hanford Low-Level Tank Waste Interim Performance Assessment⁴. The base analysis and sensitivity cases are provided in Definition of the Base Analysis Case of the Interim Performance Assessment³.

Many of the decisions concerning the disposal of the low-level fraction of the Hanford tank waste have not yet been made. These include the choice of waste form, the selection of the disposal site, and the design of the disposal facility. Therefore, enabling assumptions were made.

The release rate of contaminants from the waste form (4.4 parts per million per year) is based on the Request for Proposal⁵ (DOE-RL 1996) issued by the Richland Operations Office for the pretreatment and immobilization of tank waste. Sensitivity cases were also performed for a typical low-level

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- ¹ "Radioactive Waste Management", DOE Order 5820.2A, U.S. Department of Energy, Washington, D.C., September 26, 1988.
- ² F. M. Mann, Data Packages for the Hanford Low-Level Tank Waste Interim Performance Assessment, WMC-SD-WM-RPT-166, Revision 0, Westinghouse Hanford Company, Richland, Washington, July 1995.
- ³ F. M. Mann, C. R. Eiholzer, R. Khaleel, N. W. Kline, A. H. Lu, B. P. McGrail, P. D. Rittmann, and F. Schaittroth, Definition of the Base Analysis Case of the Interim Performance Assessment, WMC-SD-WM-RPT-200, Revision 0, Westinghouse Hanford Company, Richland, Washington, December 1995.
- ⁴ Request for Proposals (RFP) No. DE-RP06-96RL13308, letter from J. D. Wagoner to Prospective Offerors, U.S. Department of Energy, Richland, Washington, February 20, 1996.

waste glass using computer simulation to estimate the rate at which the glass would release the contaminants.

The location of the disposal facility is assumed to be in the Hanford Site 200 East Area, just southwest of the PUREX facility. The disposal facility is assumed to consist of-

- a surface cover (to minimize the amount of water or other intrusion entering the facility),
- a sand-gravel capillary barrier (to divert water around the waste form), and
- a concrete vault that is assumed to degrade in 500 years.

Geologic, hydraulic, geochemical, and water infiltration data obtained for the 200 Area plateau were used in this analysis and are considered to be representative of the disposal area.

The inventory of contaminants in the waste form is based on estimates for the tank waste inventory and using a conservative estimate to project the low-level fraction of radionuclides immobilized in the waste form after the pretreatment and immobilization processes. The tank waste inventory estimate is based on computer simulations of the production reactor history and the known reprocessing histories. The estimate for the most important radionuclide in this analysis (⁹⁹Tc) are in agreement with actual tank sampling data.

Now mark of this data is there - what are the sources? Consistent with current info.

III. RESULTS

A. Introduction

Performance objectives were established⁷ to protect the following:

- The general public
- The inadvertent intruder
- Groundwater resources
- Surface water resources
- Air resources.

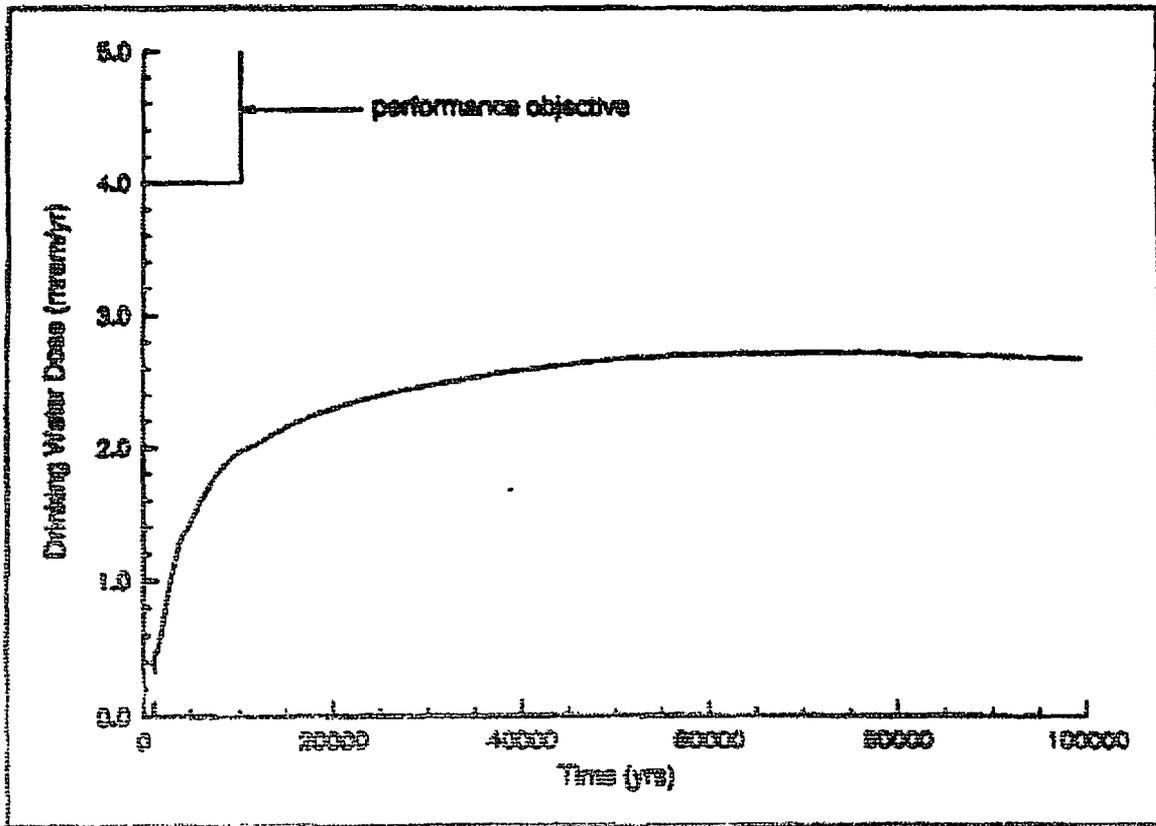
The three-dimensional PORFLOW computer code was used to simulate the flow and transport of contaminants from the waste form through the vadose zone to the groundwater. The three-dimensional VAM3D-CG computer code simulated the flow and

⁷ Performance Objectives of the Tank Waste Remediation Systems Low-Level Waste Disposal Program, WMC-EP-0826, Revision 0, Westinghouse Hanford Company, Richland, Washington, December 1994.

transport in the groundwater. The results from PORFLOW and VAM3D-CG were combined with inventory and dosimetry data using the INTEG code to provide concentrations in groundwater and dose rates. Explicit calculations were conducted to 100,000 years after disposal with extrapolations used to extend the results to 65 million years. For inadvertent intruder analyses, a spreadsheet was used with calculations extending from 100 to 1,000 years.

Because of the very slow release of contaminants from the waste form (hundreds of thousands of years), the estimated concentration of radionuclides in the groundwater does not show a peak, but rather a broad plateau (see, for example, the beta/photon drinking water dose rate shown in Figure ES-1). This contrasts with most other environmental assessments, where the contaminant release time is short compared to the contaminant travel time resulting in a peaked response.

Figure ES-1. Beta/Photon Drinking Water Dose Rates for the Base Analysis Case at a Well 100 Meters Downgradient from the Disposal Facility. The performance objective is 4.0 mrem i. a year for the first 10,000 years.



B. Protection of the General Public

Table ES-1 compares the performance objectives for protecting the general public with the results from the base analysis case calculations over the time of compliance (10,000 years). The estimated all-pathways doses are significantly lower than the performance objectives. The sensitivity cases show that for the all-pathways performance objective to be exceeded would require one or more of the following:

- A waste form not meeting the specifications in the Request for Proposal
- A high infiltration rate and a disposal facility design without a sand-gravel diverter
- A significantly larger inventory of selenium, technetium, or uranium.

During the first 10,000 years (the time of compliance), the estimated doses are at most 1/3 of the performance objective (25 mrem in a year as stated in the DOE order). ^{99Tc is} estimated to contribute 58 percent of this dose. The peak all-pathways dose (23 mrem in a year) is estimated to occur at about 50,000 years. At the peak, uranium and its daughters are the main contributors.

The other two performance measures (all-pathways including other Hanford actions and a design that produces doses as low as reasonably achievable [ALARA]) are not expected to exceed 100 mrem in a year or 500 persons-rem per year at any time.

Table ES-1. Comparison of Estimated Impacts with Performance Objectives for Protecting the Public. Time of Compliance is 10,000 Years. Place of Compliance is Well 100 Meters Downgradient of Facility.

| Performance Measure | Performance Objective | Estimated Impact |
|---|-----------------------|------------------|
| All-pathways [mrem in a year] | 25.0 | 6.4 |
| All-pathways, including other Hanford Site sources [mrem in a year] | 100.0 | <19.0 |
| ALARA (all-pathways) [persons-rem/y] | 500.0 | 5.0 |

C. Protection of Inadvertent Intruders

Table ES-2 compares the estimated impacts to the performance objectives for protecting the inadvertent intruder (the values for which are given in the DOE order). A one-time dose (an acute exposure) scenario as well as a continuous exposure scenario (a homesteader) are defined. Both performance objectives are met.

The acute dose (estimated assuming a person drills a well through the disposal facility) is much less than the performance objective. The continuous dose (which includes the ingestion of contaminated food and water, the inhalation of air, and direct radiation exposure) is over a factor of 3 lower than the performance objective. At the time of compliance (500 years) ¹³⁵Sr contributes over 95 percent of the dose.

Table ES-2. Comparison of Estimated Impacts with Performance Objectives for Protecting the Inadvertent Intruder. Time of Compliance is 500 years.

| Performance Measure | Performance Objective | Estimated Impact |
|-------------------------------------|-----------------------|------------------|
| Acute exposure [rem] | 500. | 5.5 |
| Continuous exposure [rem in a year] | 100. | 27.5 |

D. Protection of Groundwater Resources

Table ES-3 compares the estimated impacts to the performance objectives for protecting the groundwater resources. The performance objectives are based on the federal drinking water standards. The time of compliance is 10,000 years and the point of compliance is at a well 100 meters down gradient of the disposal facility. The estimated impact from beta emitters is a factor of 2 less than the performance objectives and a factor of 5 less than the performance objective for the alpha emitters. The concentration of radium is insignificant.

The most important drivers are the inventory of technetium and uranium, the release rate from the waste form, the amount of mixing in the aquifer, and the area of the disposal facility. For the impact for alpha emitters, the amount of retardation experienced by the uranium isotopes in the vadose zone is also important.

Table ES-3. Comparison of Estimated Impacts with Performance Objectives for Protecting Groundwater Resources. Time of Compliance is 10,000 Years. Place of Compliance is a Well 100 Meters Downgradient of Facility.

| Performance Measure | Performance Objective | Estimated Impact |
|---------------------------------------|-----------------------|------------------|
| Beta/Photon Emitters [mrem in a year] | 4. | 2.0 |
| Alpha emitters [pCi/l] | 15. | 1.7 |
| Ra [pCi/l] | 3. | <0.001 |

For the most part, other geotechnical data (water infiltration rate, hydraulic parameters, and geochemical factors) are less important, because they mainly affect the time at which the plateau is reached. However, there are two exceptions. If the water infiltration rate is a factor of 5 lower than assumed (which is 0.5 mm/y for the first 1,000 years [the period during which the surface barrier is assumed to function] and 3.0 mm/y thereafter), then the most mobile radionuclides do not reach the groundwater in significant quantities during the compliance period. Alternatively, if the infiltration rate is a factor of 30 higher than assumed and if no capillary barrier is in place to divert the infiltration, then the uranium group arrives in significant amounts at the water table during the compliance period.

The beta/gamma drinking water dose rate is not estimated to exceed 4 mrem in a year for 750,000 years, reaching a maximum value of 14 mrem in a year at the end of the simulation period (65 million years). The concentration of alpha emitters is estimated never to exceed 15.0 pCi/l, reaching a maximum of 9.2 pCi/l at 50,000 years.

E. Protection of Surface Water Resources

Table ES-4 displays a comparison of the estimated impacts to the performance objectives for protecting the surface water resources. The time of compliance is 10,000 years and the point of compliance is at a well intersecting the groundwater just before the groundwater mixes with the Columbia River. Because of the large flow of the Columbia River, tremendous mixing occurs in the river and the predicted impacts would be far lower. The estimated impacts are over an order of magnitude lower than the performance objectives. The calculations indicate that the impacts never reach the values given as performance objectives.

Table ES-4. Comparison of Estimated Impacts with Performance Objectives for Protecting Surface Water Resources. Time of Compliance is 10,000 Years. Point of Compliance is a Well just before the Groundwater Mixes with the Columbia River.

| Performance Measure | Performance Objective | Estimated Impact |
|---------------------------------------|-----------------------|------------------|
| Beta/Photon Emitters [mrem in a year] | 1. | 0.070 |
| Alpha emitters [pCi/l] | 15. | 0.058 |
| Ra [pCi/l] | 3. | <0.001 |

F. Protection of Air Resources

Table ES-5 compares the estimated impacts to the performance objectives for protecting air resources (the values for which are given in federal clean air regulations). The time of compliance is 10,000 years and the point of compliance is just above the disposal facility. The estimated impacts are significantly lower than the values prescribed in the performance objectives.

Table ES-5. Comparison of Estimated Impacts with Performance Objectives for Protecting Air Resources. Time of Compliance is 10,000 Years. Place of Compliance is just above the disposal facility.

| Performance Measure | Performance Objective | Estimated Impact |
|--|-----------------------|-------------------|
| Radon [pCi m ⁻³ a ⁻¹] | 20. | <0.001 |
| Other radionuclides [mrem in a year] | 10. | <10 ⁻⁶ |

IV. DISCUSSION

Because of the early stage of this project, conservative assumptions have been used. Given such assumptions, it is gratifying that all the estimated impacts meet the performance objectives.

The numerous sensitivity cases that were run show that the results presented in this assessment are quite robust. The computer simulations of dissolution rates for low-level glass (LD6-5412) show that the 4.4 parts per million per year rate can be met. Concerning radionuclide inventory, the calculations are most sensitive to the amount of technetium. For the base analysis case no credit is taken for enhanced chemical separation

or separation occurring during immobilization. Possible increases in the amounts of ⁹⁰Sr and ¹³⁷Cs over the amounts assumed in the base analysis case have no significant impacts at the intruder time of compliance of 500 years. Computer simulations of flow and transport under a wide variety of conditions show that slightly increased impacts may occur, but that most changes would result in larger decreases. Finally, calculations show that disposing of some of the tank waste in the existing TWRS grout vaults, which are east of the PUREX facility, will not significantly affect the results.

The preliminary and final performance assessments (required by DOE Order 5820.2A) will benefit from knowledge of the waste form, the disposal facility location, and the disposal facility design as well as from an extensive data collection activity for the generation of site-specific estimates for geochemical data, hydraulic parameters, and water infiltration rates and waste form release rates. The performance assessments are expected to show that the on-site disposal of the low-level Hanford tank waste can meet the performance objectives with a high degree of assurance.

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1.0 INTRODUCTION

1.1 PURPOSE

The purpose of this interim performance assessment is to examine the long-term environmental effects of the planned Hanford Low-Level Tank Waste Disposal Facility as early as possible in its project life. That facility is proposed for the disposal of low-level radioactive waste that is derived from the treatment of waste currently stored in the Hanford single- and double-shell tanks. The Hanford tank waste will be separated into high-level and low-level components with the low-level component immobilized, ready for placement in the disposal facility.

This interim performance assessment is being prepared as a good management practice to provide information needed about the relationship between the disposal system performance and its design. Department of Energy (DOE) Order 5820.2A, *Radioactive Waste Management* (DOE 1988a) is the primary regulation governing management and disposal of radioactive waste at DOE facilities. This assessment uses the techniques, methods, and rigor of the final performance assessment described in DOE Order 5820.2A where possible. Unlike the database for a final performance assessment, much of which is based on experiment and is design specific, much of the database for this assessment is based on information from other projects or programs. As more of the design effort is completed and more data are collected, the preliminary and final performance assessments, which are required by DOE Order 5820.3A, will be prepared.

1.2 BACKGROUND

This section provides background information on the Hanford Site and on other recent environmental assessments prepared at the Hanford Site. This document builds on earlier Hanford performance assessments and on previous efforts to analyze the long-term effects of various design options of the disposal facility.

1.2.1 The Hanford Site

The Hanford Site, in south-central Washington State (Figure 1-1), has been used extensively as a location for defense materials production by DOE its predecessors, the U.S. Atomic Energy Commission and the U.S. Energy Research and Development Administration. Starting in the 1940s, Hanford Site operations were dedicated primarily to producing nuclear weapons materials. In the 1960s, operations were expanded to producing electricity from a dual-purpose reactor, conducting diverse research projects, and managing waste. In the late 1960s, the Hanford site's original mission ended.

Today, the Site's mission is environmental restoration, energy-related research, and technology development. A large inventory of radioactive and mixed waste from the decades of nuclear materials production has been accumulated in buried single- and double-shell tanks in the Hanford Site 200 Areas.

As part of the new mission, DOE is proceeding with plans to permanently dispose of this waste. The plans are based on Revision 4 of the Hanford Federal Facility Agreement and Consent Order (Tri-Party Agreement) (Ecology 1996-1) and on the Record of Decision for the Tank Waste Remediation Systems Environmental Impact Statement (DOE 1996). These documents call for the waste to be retrieved from Hanford's single- and double-shell tanks, then pretreated to separate the low-level fraction (renamed low-activity fraction) from the high-level and transuranic waste. Both fractions will then be immobilized.

The two products (the small volume of high-level immobilized waste and the much larger volume of low-activity waste) will be disposed of in different locations. The high-level waste will be stored on the Hanford Site until disposed of in a federal geologic repository. The low-activity immobilized waste will be disposed of on the Hanford Site in a near-surface disposal system. Over 200,000 m³ (6,000,000 ft³) of low-activity immobilized waste will be disposed under this plan. This is among the largest amounts within the DOE Complex (DOE 1995) and has one of the largest inventories of long-lived radionuclides at a low-level waste disposal facility.

1.2.2 Previous Hanford Performance Assessments

1.2.2.1 Overview. This interim performance assessment builds on the previous performance assessments prepared for the Hanford Site. Performance assessments that have been prepared under the requirements of DOE Order 5820.2A for other Hanford Site disposal actions are discussed in the following paragraphs. These documents are in various stages of review and approval. All performance assessments prepared under Order 5820.2A are reviewed by the Peer Review Panel (established by the order) for technical adequacy. This panel performs a preliminary review, a completeness review, and a final review for each performance assessment. Then, DOE-Headquarters reviews the documents and may provide approval for the disposal action if the performance assessment satisfies the requirements of Order 5820.2A.

1.2.2.2 Performance Assessment of Grouted Double-Shell Tank Waste Disposal at Hanford (Kincaid 1995). The grout performance assessment dealt with disposing of low-level liquid waste from the double-shell tanks. The waste was to be combined with cement, flyash, and clay to form a grout, which would be poured into large subsurface vaults located to the east of the 200 East Area.

The grout performance assessment was approved in principle by the Peer Review Panel (Wilhite 1994). DOE (Lytle 1995) found that the analysis performed in this document was "technically adequate and provides reasonable assurance that the selected performance objectives would be met." Noting, however, that the grout project had been canceled, DOE also stated that a new or revised performance assessment would be needed for routine disposal of waste in the Grout Disposal Facility.

1.2.2.3 Performance Assessment for the Disposal of Low-Level Waste in the 200 West Area Burial Grounds (Wood 1994b). The 200 West Area solid waste performance assessment dealt with the solid waste from operations at the Hanford Site and from other sites. This waste is placed into trenches in the western part of the 200 West Area and then covered with a Resource Conservation and Recovery Act of 1976 (RCRA)-compliant barrier. The Peer Review Panel found the performance assessment to be technically acceptable. The 200 West Area performance assessment has been "conditionally accepted" by DOE-Headquarters (Cowan 1996). The conditions being related to added documentation.

1.2.2.4 Performance Assessment for the Disposal of Low-Level Waste in the 200 East Area Waste Burial Grounds (Wood 1996). The 200 East Area solid waste performance assessment addresses waste that is similar to that addressed in the 200 West Area performance assessment. However, the disposal trenches for this waste are in the northern part of the 200 East Area. The final performance assessment for this action has been submitted to DOE for review.

1.2.2.5 Environmental Remediation Disposal Facility Performance Assessment (Wood 1995). The Environmental Remediation Disposal Facility (ERDF) accepts waste generated by the cleanup of the Hanford Site. Most of this waste is expected to be contaminated soil. Trenches are planned to be the main means of disposal at the facility. A preliminary performance assessment has been written for ERDF. Because ERDF is regulated under the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA), this performance assessment will not be submitted to the Peer Review Panel. However, a remedial investigation and feasibility study report (DOE-RL 1993d) was written.

1.2.3 Previous Work Related to the Proposed Disposal Action

The long-term environmental impact of various design features for the low-level tank waste disposal facility has been analyzed. The first analysis is given in Revision 0 of *Impacts of Disposal System Design Options on Low-Level Glass Waste Disposal System Performance* (Rawlins 1994). Revision 1 (Mann 1995d) updated that analysis based on better data and on the comments received concerning Revision 0. However, neither report is as comprehensive as this performance assessment.

1.2.4 Review of Data Packages for Interim Performance Assessment

Some of the information used for the interim performance assessment has already been reviewed by external groups to ensure its acceptability by peers and stakeholders. The performance objectives and scenarios used in this performance assessment were reviewed by Hanford Site stakeholders. The results of the review were transmitted in a letter report (Murkowski 1995). The dosimetry results presented in this report were reviewed by members of the Hanford Environmental Dose Overview Panel. The results of the review were transmitted in a letter report (Rhodes 1996).

1.2.5 Relationship With Other Parts of the Project

The performance assessment activity is closely connected with other parts of the LLW Disposal Subproject. As shown in Figure 1-2, the schedule for the major events of the LLW Disposal Subproject, the performance assessment activity is iterative, consisting of an interim performance assessment (this document), a preliminary performance assessment, and the final performance assessment. The results from the interim and preliminary performance assessments feed into design activities. Approval of the Preliminary Performance Assessment also allows detailed design of the disposal facility to proceed. The design activities feed back into the preliminary and final performance assessments. The approval of the final performance assessment by the DOE is one of the conditions for the startup of the disposal facility and will be an important input for the full-scale immobilization of Hanford Site tank waste.

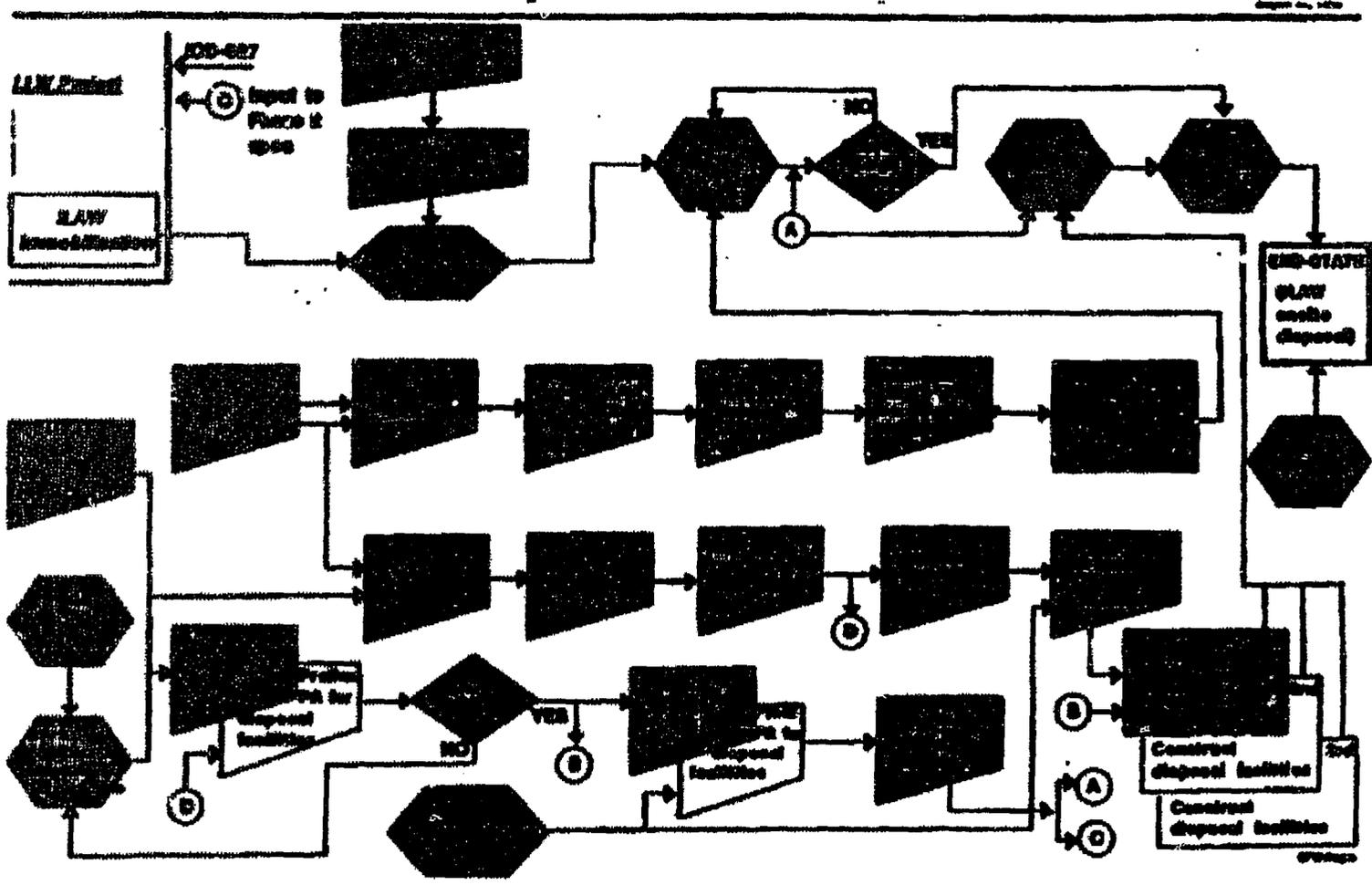
1.3 GENERAL DESCRIPTION OF THE FACILITY

The disposal facility has not yet been designed. However, conceptual ideas (Eiholzer 1995) envision immobilized waste being disposed in metal containers on the scale of 1 to 2 meters in each direction. These containers would be placed into concrete vaults, with 6 vaults forming a row. Sand-gravel capillary barriers would be placed over and along side the vaults to divert water around the vault to minimize infiltration. The disposal facility would be capped by a surface barrier to minimize water, plant, animal, and human intrusion. Two concepts are being considered and evaluated in this performance assessment. The main difference between the concepts is whether soil is present between the vault rows or not. Section 2.4 provides more details on both two concepts.

The DOE is proceeding (DOE-RL 1996) with the process to procure services for treating and immobilizing the tank waste. Depending on the outcome of that process, different waste forms or containers may emerge, which may affect the disposal facility concept.

Figure 1-2. Activities Schedule for the LLW Disposal Subproject.

1-5



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1.4 GUIDANCE DOCUMENTS

The format and content of this document are based on guidance from the Peer Review Panel and on other performance assessments submitted to the Peer Review Panel for their review. The recommendations made in the following documents were used as guidance in preparing this interim performance assessment:

- *Recommended Format and Content for DOE Low-Level Waste Disposal Facility Radiological Performance Assessment Reports, DOE/LLW-81 (Case 1989)*
- *Performance Assessment Review Guide for Low-Level Radioactive Waste Disposal Facility, DOE/LLW-93 (Dodge 1991)*
- *Proceedings of the Department of Energy Performance Assessment Briefing, Denver, Colorado, October 29, 1991, DOE/LLW-138 (NLLWP 1992)*
- *Performance Assessment Task Team Progress Report, Revision 1, DOE/LLW-157 (Wood 1994a)*
- *A Compilation of DOE Performance Assessment Peer Review Panel Review Comments and Recommendations, DOE/LLW-216 (RWSTP 1994).*
- *DOE Headquarters Review of the "Performance Assessment of Grouted Double-Shell Tank Waste at Hanford" (Lytle 1995).*
- *Implementation Plan, Defense Nuclear Facilities Safety Board Recommendation 94-2, Compliance with Safety Standards at Department of Energy Low-Level Nuclear Waste Sites (DOE 1996a).*

1.5 PERFORMANCE OBJECTIVES

1.5.1 Overview

The DOE's requirements for waste disposal (LOE 1988a and DOE-RL 1993) are as follows:

- Protect public health and safety
- Protect the environment.

Most of the requirements are general (for example, the requirement to "protect groundwater resources consistent with Federal, State, and local requirements") or indirectly reference other requirements (for example, the requirement that "releases to the atmosphere shall meet the requirements of 40 CFR 61"). A few of the requirements state quantitative limits such as the limit of 25 area in a year for all exposures.

For this interim performance assessment, the following methods were used to establish the quantitative performance objectives explained in Performance Objectives of the Tank Waste Remediation Systems Low-Level Waste Disposal Program, (PAT 1995):

- Investigating all potentially applicable regulations as well as interpretations made by the Peer Review Panel
- Working with Storage and Disposal Project management to establish their needs
- Working with the Hanford Site stakeholders to understand the values of residents in the Pacific Northwest.

These efforts produced the performance objectives that were used in this interim performance assessment. They are presented in Table 1-1.

Table 1-1. Performance Objectives.^{a,b}

| Protection of General Public and Workers | |
|---|--|
| all-pathways dose from only this facility | 25 mrem in a year ^{c,d,e} |
| all-pathways dose including other Hanford sources | 100 mrem in a year ^{c,d,e} |
| ALARA (treated as an integrated all-pathways dose) | 500 persons-rem/year ^{c,d,e} |
| Protection of an Inadvertent Intruder ^{d,f} | |
| acute exposure | 500 mrem |
| continuous exposure | 100 mrem in a year |
| Protection of Groundwater Resources ^{c,g,h} | |
| alpha emitters ²²⁶ Ra + ²²⁸ Ra | 5 pCi/l |
| all others (total) | 15 pCi/l |
| beta and photon emitters | 4 mrem in a year |
| Protection of Surface Water Resources ^{c,h} | |
| alpha emitters ²²⁶ Ra + ²²⁸ Ra | 0.3 pCi/l ⁱ |
| all others (total) | 15 pCi/l ⁱ |
| beta and photon emitters | 1 mrem in a year ^j |
| Protection of Air Resource ^{c,k,l} | |
| Radon | 20 pCi m ⁻³ a ⁻¹ |
| All other radionuclides | 10 mrem in a year |

- Taken from PAT 1995, except for limit that includes other Hanford sources which is taken from DOE 1996
- All doses are calculated as Effective Dose Equivalents (EDE) all concentrations are in water taken from a well
- Evaluated for 10,000 years, but calculated to the time of peak or 10,000 years, whichever is longer.
- Evaluated for 500 years, but calculated to 1,000 years
- Evaluated at point of maximal exposure, but no closer than 100 meters (328 feet) from the disposal facility
- Evaluated at the 200 East Area fence
- Evaluated at the disposal facility
- Evaluated at the Columbia River, no mixing with the river is assumed
- Main driver is DOE Order 5820.2A, *Radioactive Waste Management* (DOE 1986a)
- Main driver is DOE Order 5400.5, *Radiation Protection of the Public and the Environment* (DOE 1993)
- Main driver is DOE/RL Implementing Directive 5820.2A, *Radioactive Waste Management* (DOE-RL 1993)
- Main driver is National Primary Drinking Water Regulations (40 CFR 141)
- Main driver is Washington State Surface Water Standards (WAC 173-201A)
- Main driver is National Emission Standards for Hazardous Air Pollutants (40 CFR 61H and 40 CFR 61Q).

The following sections summarize how the quantitative performance objectives were established.

1.5.2 Regulations and Other Performance Assessments

1.5.2.1 Introduction. Several federal and state regulations potentially apply to how well the public health and safety and the environment must be protected. These regulations were reviewed for relevance to this proposed disposal action. The following categories of requirements were reviewed:

- Protection of the general public
- Protection for workers
- Protection of the inadvertent intruder
- Protection of groundwater resources
- Protection of surface water resources
- Protection of air resources.

Appendix B of the performance objectives document (PAT 1995) lists the regulations that were reviewed and judged to be potentially relevant to this proposed disposal action. Some regulations and general environmental acts were judged not relevant for one or more of the following reasons:

- Requirements are the responsibility of others of the Disposal Subproject (for example, ensuring compliance with the National Environmental Policy Act (NEPA))

- Requirements are for different environmental actions (for example, the *Comprehensive Environment Response, Compensation, and Liability Act of 1980 (CERCLA)*)
- Requirements deal with general environmental concerns (protection of endangered species) which are thought to be adequately protected for the long-term by regulations presented here
- Requirements are only at a preliminary stage and are likely to change. [e.g., the "Radiation Site Cleanup Regulation" [proposed Title 40 Code of Federal Regulations (CFR) 196] and "Environmental Radiation Standards for Management and Disposal of Low-Level Waste" [proposed 40 CFR 193] from the U.S. Environmental Protection Agency]. The development of these requirements will be closely followed and incorporated as appropriate.

Performance assessments of low-level waste disposal in the DOE complex were also reviewed to identify any regulations relevant to this proposed disposal action. These assessments provide "case law" interpretations. Appendix C of PAT (1995) lists the other performance assessments in the DOE complex, as well as their performance objectives.

1.5.2.2 Protection of the General Public. For the interim performance assessment, the performance objective for the protection of the general public is 25 mrem (EDE) in a year (EDE, Effective Dose Equivalent). The value is consistently used in all the regulations and past performance assessments. Although there are other methods for determining body dose (PAT 1995), the effective dose equivalent method was selected because regulations normally use this method. The location for compliance is at the point of maximal exposure, but not less than 100 meters (328 feet) from the disposal facility (Wood 1992a).

The Defense Nuclear Facilities Safety Board (DNFSB 1994) noted that a member of the public could receive exposures from several sources at a DOE site. Guidance from DOE-Headquarters (DOE 1996a) is that protection of the general public from multiple sources should be based on *Radiation Protection of the Public and the Environment*, DOE Order 5400.5, (DOE 1993-1). This order sets a limit of 100 mrem in a year from all sources. The interpretation of DOE Order 5400.5 places the point of compliance at the fence line of the future site. For the Hanford Site, this is considered to be a fence surrounding the present Hanford 200 Areas. In contrast, DOE Order 5820.2a provides a more restrictive standard (25 mrem in a year at a location not less than 100 meters from the facility) to enable the design of the disposal facility to occur without considering the effect of other facilities.

Little guidance is provided on the interpretation of ALARA (as low as reasonably achievable). For this assessment, the

requirements of DOE, Richland Operations Office (RL) Implementing Directive 5820.2A, Radioactive Waste Management (DOE-RL 1993), were used. This requirement gives ALARA doses as an integrated dose for all pathways of 500 person-rem in a year.

The compliance time for this performance assessment is 10,000 years. (The compliance time is the time starting 100 years from the present over which the predicted dose must remain below the performance objectives.) However, the calculation was carried out to the time of maximum impact if that time is longer than 10,000 years. The compliance time used is consistent with the compliance time used in the Grout Performance Assessment (Kincaid 1995-1) and the 200 West Area Solid Waste Performance Assessment (Wood 1994b-1). Using the 10,000 years compliance time is also consistent with the draft U.S. Nuclear Regulatory Commission (NRC) branch technical position on performance assessment for low-level waste disposal facilities (NRC 1994).

1.5.2.3 Protection for Workers. For this performance assessment as with others performed under 5820.2A, no distinction is made between performance objectives for workers and for the general public. Since the protection requirements are more restrictive for the general public than for the workers, the workers will be adequately protected. Protection for workers during construction and operations will be addressed in the Safety Analysis Report that will be written for the LLW Disposal Subproject.

1.5.2.4 Protection of the Inadvertent Intruder. The exposure limits for protecting a hypothetical inadvertent intruder are consistent with the regulations and with earlier performance assessments. (Appendices Tables B-2 and C-2 in PAT 1995, respectively, give details). These limits are 500 mrem (EDE) for a one-time (acute) exposure and 100 mrem(EDE)/year for a continuous exposure. These limits are used in this performance assessment.

The compliance time for protecting an inadvertent intruder is defined different than the time of compliance for protecting the general public or the environment. For inadvertent intrusion, the compliance time is defined as the time after which the estimated dose is below the performance objective.

The inadvertent intrusion time of compliance time differs slightly between regulations. RL directive 5820.2A (DOE-RL 1993) allows a compliance time of 500 years if passive barriers and markers are used. The current DOE-HQ order (DOE 1988a) does not mention using such barriers or markers and stipulates a compliance time of 100 years. The Hanford Grout Performance Assessment (Kincaid 1995-1) used the 500 years compliance time based on the assumption that passive barriers and markers would be present. The performance assessments for the disposal of Hanford solid waste (Wood 1994b and Wood 1996) have also used a compliance time of 500 years. This is consistent with the NRC requirement for Class C waste (10 CFR 61-1) that inadvertent

intruders be protected for 500 years. Other previous performance assessments have assumed that the disposal facility will be under active control for at least 100 years and have used 100 years as the compliance time.

Following the precedent of the other Hanford performance assessments, the 500-year compliance time was used in this assessment because passive barriers and markers are planned for this proposed disposal action. Therefore, protection of an inadvertent intruder shall be considered met if the exposure limits are met at 500 years after closure. Calculations were run from 100 years after time of disposal to 1,000 years to obtain the doses as a function of time.

1.5.2.5 Protection of Groundwater Resources. This is the most complicated requirement to determine. The protection of groundwater is usually based on its intended use. However, predicting future groundwater use is highly subjective given the long time frames involved in a performance assessment. The quantities being limited (decay rate and dose) differ in the various regulations. Moreover, ~~different regulatory agencies~~ approach the protection of groundwater resources using different methods. In addition, earlier DOE performance assessments have taken different approaches.

Previous performance assessments have generalized the requirements from the *National Primary Drinking Water Regulations* (40 CFR 141) for determining whether the disposal action met the groundwater protection requirement. The scenario used is based on a public drinking water system servicing about 25 people and located not less than 100 meters (328 feet) downstream from the disposal facility. The previous performance assessments set a limit for the total exposure from all radionuclides for an individual drinking the water at less than 4 mrem (EDE) in a year. The *National Primary Drinking Water Regulations*, however, use the limit of 4 mrem in a year not for all radionuclides, but just for beta and gamma emitters. The distance of 100 meters is given in the RL Implementing Directive 5820.2A. Four (4) mrem (EDE) in a year was chosen for two reasons. The value corresponds to the risk-based limit found in the *National Primary Drinking Water Regulations* (40 CFR 141). Also, for most of the radionuclides, the value is more restrictive (see Table B-3 of PAT 1995) than decay rate concentration limits specified in the Washington State regulations (WAC 173-200).

The requirements for alpha emitters are the same in both the Washington State (WAC 173-200) and federal (10 CFR 141) regulations. Both the state and federal regulations limit alpha emitters, not by annual dose, but by decay rate concentration limits. In addition, both sets of requirements limit the same subsets of alpha emitters (^{226}Ra , total radium, and other) and set the same quantitative limits. These decay rate concentration limits (Table 1-2) are used for this performance assessment.

Washington State's requirements for beta emitters are based on a screening level previously used by the U.S. Environmental Protection Agency (EPA). These screening levels were selected because the requirements are easily verified in the field. (The current EPA regulation are based on risk limitation.) The current state screening level ensures that even for beta emitters emitting high-energy gamma radiation, the dose limit will be met. However, for low-energy beta emitters, the state screening level is overly conservative by about a factor of 100. This high degree of conservatism exists for radionuclides, such as ⁹⁹Tc, that are important in this performance assessment.

For this performance assessment, the federal standards are used. This follows the precedent of the Tank Waste Remediation System Environmental Impact Statement (TWRS EIS) (DOE 1996b), a joint publication of the Washington State Department of Ecology and DOE. That is, the current EPA regulation governing drinking water (40 CFR 141) is used to protect groundwater. Thus the performance objective is an effective dose equivalent (EDE) of 4 mrem for beta/photon emitters and a concentration of 15 pCi per liter for alpha emitters. Although uranium is not restricted in the regulations, for this analysis it is included under other alpha emitters. The values are displayed in Table 1-1. A dose of 4 mrem (EDE) in a year for 70 years corresponds to an incremental health risk of 0.0001 (EPA 1989b).

Only the "National Primary Drinking Water Regulations" (40 CFR 141) were used for determining the protection of the groundwater resources. The "National Secondary Drinking Water Standards" (40 CFR 143) were not used because they are stated only as goals.

To ensure compliance with the intent of federal and state groundwater regulations, the limits shown in Table 1-1 are applied to a well 100 meters downgradient from the disposal facility for a time of 10,000 years after closure (the same time of compliance as for protection of the general public). The hypothetical well from which the water is drawn is sized to serve the minimal public drinking water system for 25 people. Further information is given in Section 3.4.8. The effect of placing the well at other locations (including the Hanford 200 Area fence line) are also determined.

1.5.2.6 Protection of Surface Water Resources. The thrust of the federal (10 CFR 141) and state requirements (WAC 173-201A) for surface water resources protection is the same. The point of compliance is where the groundwater is predicted to reach the Columbia River. The concentrations of radionuclides in the groundwater at the point where it enters the Columbia River should meet all of the standards listed in Table 1-1.

The 1.0 mrem (EDE) in a year (one-quarter of the EPA drinking water standard) value is used because it meets the Washington State regulation while minimizing reporting requirements. The Washington State regulation (WAC 173-201A)

mandates a dose limit that is the lesser of the EPA drinking water standard and explicit limits contained in the state regulation. For the major radionuclides of interest, the explicit limits (when converted to dose) are greater than 1.3 mrem in a year. Using 1.0 mrem in a year for the sum of all beta/photon emitters is restrictive.

The time of compliance for the protection of surface water resources is selected as 10,000 years, the same compliance time as for protecting groundwater resources. However, the calculations are carried out to the time of maximum impact, if the peak occurs after 10,000 years.

1.5.2.7 Protection of Air Resources. Air emissions limits were taken from Parts H and Q of the "National Emissions Standards for Hazardous Air Pollutants" (40 CFR 61H and 40 CFR 61Q). These limits are more restrictive than the Washington State requirements (WAC 173-480 and WAC 246-247). Based on these standards, emissions (except radon) are limited to 10 mrem (EDE) in a year with radon emissions limited to 20 pCi/m³.

1.5.3 Programmatic Requirements

The LLW Disposal Subproject has also established other requirements. The project mandated that all waste to be disposed of or stored in the facility shall meet NRC Class C concentration limits (10 CFR 61-2).

1.5.4 Public Involvement

It is important that Hanford Site stakeholders have an opportunity to affect the performance objectives of this proposed disposal action. A summary of the performance objectives and scenarios (WEC 1994b) was written for stakeholders. The summary was sent to each member and alternate of the Hanford Advisory Board, to selected Hanford Site contractor employees, and to selected members of the DOE's Peer Review Panel and Performance Assessment Task Team.

Feedback was received from the stakeholders and we have responded to their concerns. Copies of the performance objectives document (PAT 1994) were sent to all who requested it. All comments received on either the summary or the performance objectives have been documented as an internal file. These comments and corresponding responses are available for review (Murkowski 1995).

1.6 STRUCTURE OF THIS PERFORMANCE ASSESSMENT

This performance assessment is divided into seven chapters and five appendices. The appendices provide additional detailed information about topics presented in the chapters. The contents of each of the following chapters are summarized in this section.

- Chapter 2 describes the Hanford environment, the waste characteristics, and the waste disposal system.
- Chapter 3 covers the methods used to assess performance of the system, including the radionuclide transport pathways and exposure scenarios. It also discusses the assumptions used in modeling system performance, and outlines the quality assurance procedures.
- Chapter 4 presents and integrates results from the transport and exposure models used to estimate the potential consequences of long-term contaminant release from the disposal vaults.
- Chapter 5 interprets disposal facility performance with respect to the performance objectives defined in Chapter 1.
- Chapter 6 contains brief resumes of contributors to the document.
- Chapter 7 lists the cited references.
- Appendix A repeats the specifications for immobilization given in the request for proposal (DOE-RL 1996).
- Appendix B displays the dose factors used in the dosimetry calculations.
- Appendix C describes the computer simulation of the performance of a glass waste form.
- Appendix D describes the computer codes used in moisture flow and contaminant transport simulations.
- Appendix E provides detailed results of the computer simulations.

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2.0 DISPOSAL FACILITY DESCRIPTION

2.1 OVERVIEW

This chapter explains the expected environment within the region and around the low-level tank waste disposal facility, probable waste retrieval and immobilization, and likely design, operating, and closure concepts for the disposal facility. It covers the following topics.

- **Hanford Site Characteristics (Section 2.2).** This topic includes descriptions of regional and local geography, demography (including future land use), climate, geology, hydrology, soils, ecology and biotic conditions, and natural radiation background.
- **Waste Characteristics (Section 2.3).** This topic discusses current waste storage in underground tanks and plans for retrieving the waste, separating it into high- and low-level fractions, and immobilizing the low-level fraction, including packaging and certification.
- **Disposal Technology (Section 2.4).** This topic describes the current concepts on disposal units, waste handling and interim storage operations, waste emplacement, disposal unit closure and stabilization, and site closure.

2.2 HANFORD SITE CHARACTERISTICS

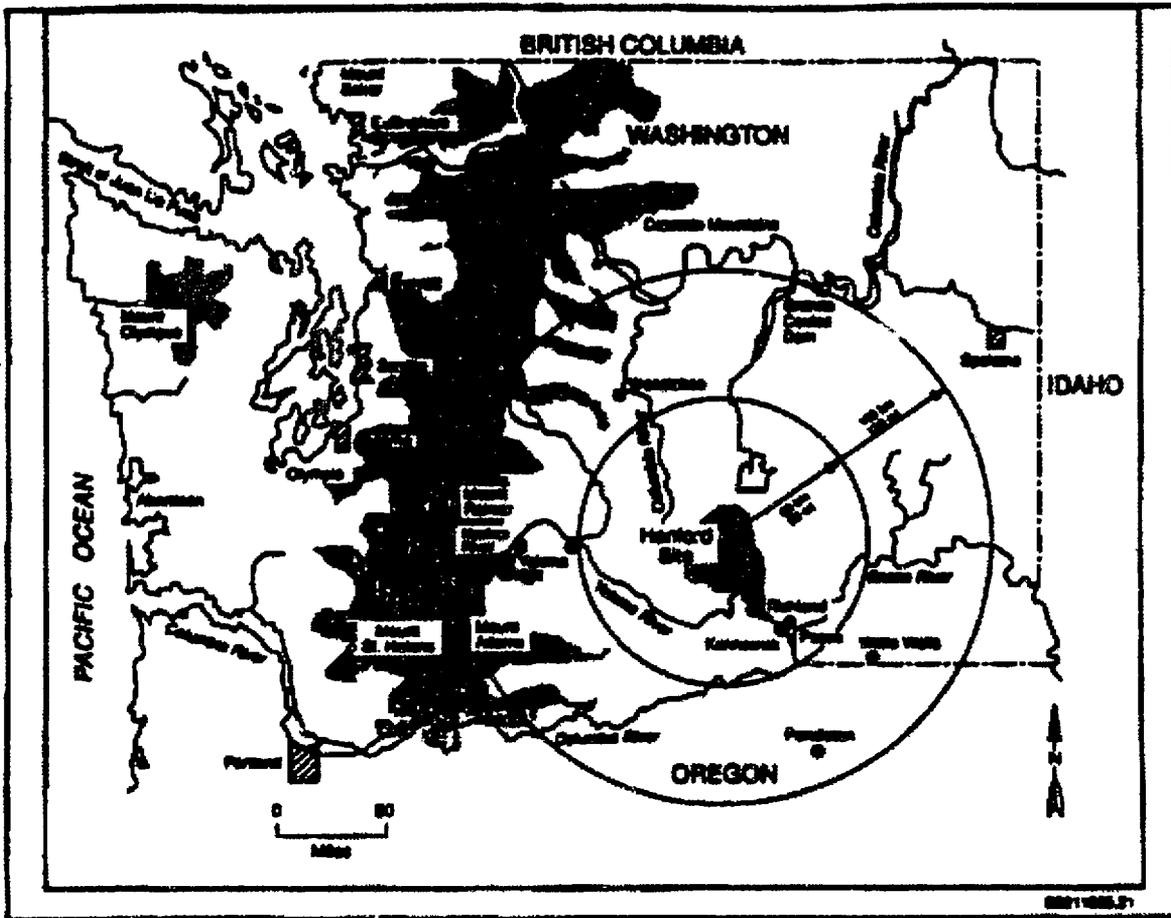
2.2.1 Overview

This section describes the regional and local environment in which the low-level tank waste disposal facility will likely be located. Extensive research has been done on the Hanford Site. However, this section will cover only the characteristics that will be used to model the low-level tank waste disposal facility's long-term performance. More complete descriptions will be referenced whenever possible.

2.2.2 Geography

The Hanford Site is a 1,450-km² (560-mi²) area of semiarid land located in south-central Washington State. The Hanford Site is owned by the U.S. Government and restricted to uses approved by the DOE. Figure 3-1 shows the Hanford Site in relation to the rest of the state. It also identifies the major cities in the region, Seattle, Portland, and Spokane, which are over 160 kilometers (100 miles) from the Hanford Site.

Figure 2-1. Hanford Site in Washington State.



The major features of regional geography are the nearby rivers and mountains. The Columbia River, which forms the eastern boundary of the Hanford Site, is an important source of water and hydroelectric power for the region. Other important rivers near the Hanford Site are the Yakima River to the southwest and the Snake River to the east. The Cascade Mountains, which are about 160 kilometers (100 miles) to the west, have an important effect on the climate of the area as discussed in Section 2.2.4.

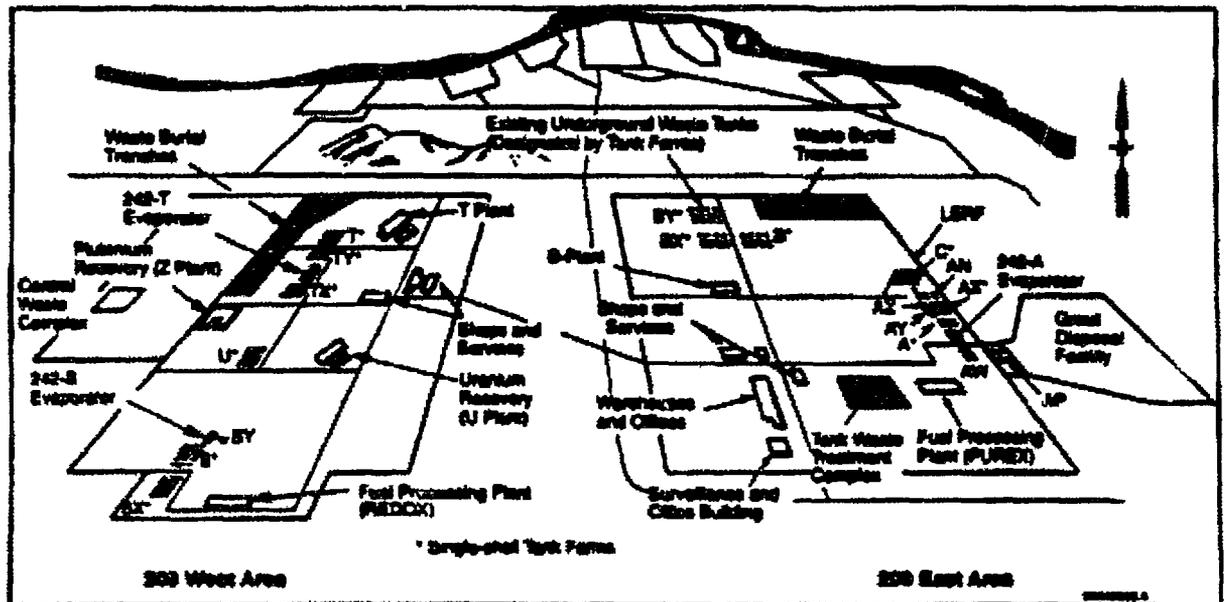
Figure 3-2 shows the Hanford Site. The DOE is planning to release some of the Hanford Site land for public use. The areas planned for release are the area north of the Columbia River and the area to the southwest of State Highway 240 (the Fitzner/Exerhardt Arid Lands Ecology Reserve). The 200 Areas, where the tank waste is currently located, are in the center of the Hanford Site. Just south of the 200 Areas is land used for commercial low-level radioactive waste disposal (US Ecology).

reprocessing facility. Figure 2-3 shows the proposed TWRS complex area. This location was chosen for the following three reasons:

- The location is near existing tank farms
- Unused land is available
- The location is inside the fence line of the 200 Areas.

However, this location still needs to be approved. There is some consideration in using the four existing empty vaults in the Grout Disposal Facility to dispose of the initial part of the waste.

Figure 2-3. Activities in the 200 Areas. The proposed location of the disposal facility is part of the Tank Waste Treatment Complex, located in the south central part of the 200 East Area.



2.2.3 Demography (Including Land and Water Use)

2.2.3.1 Overview. Demographic data are used in a performance assessment to help set the scenarios and select the dosimetry parameters. This section describes the current population database, area socioeconomics, past and planned DOE activities, and the results of an investigation of future uses conducted by the Hanford Future Site Uses Working Group.

2.2.3.2 Population. The major population centers within an 80-kilometer (50-mile) radius of the Hanford Site are illustrated in Figure 2-4, along with populations based on the 1990 U.S. Bureau of Census estimates (DOC 1991). This radius is centered on the Hanford Meteorology Station (EMS), located between the 200

East and 200 West Areas. The Tri-Cities (Richland, Kennewick, and Pasco), southeast of the Site, is the largest population center closest to the Hanford Site. Other major population centers include Yakima and the Yakima Valley towns to the west, Umatilla and Hermiston to the south, and Moses Lake to the north. The cities of Ellensburg and Walla Walla lie just beyond the 80-kilometer (50-mile) radius. Portions of Benton, Franklin, Adams, Grant, Kittitas, Yakima, Klickitat, Walla Walla, Morrow, and Umatilla counties lie within the 80 kilometer radius.

The population estimates for Washington State (OFM 1994) as summarized in Cushing (1995-1) are used. The population in Benton County was approximately 127,000 in 1993. Approximately 35,000 people reside in Richland; 47,000 people reside in Kennewick; and 12,000 people reside in West Richland, Benton City, and Prosser. The approximate population in the unincorporated portions of the county is 32,600. The estimated population of Franklin County was 43,000 in 1993, with 22,000 people living in Pasco, 3,400 people living in other incorporated areas, and 17,600 people living in unincorporated areas. During 1990, Benton and Franklin Counties accounted for approximately 3 percent of Washington State's population.

Based on estimates made during the 1970 and 1980 census years, the population in the area grew approximately 55 percent (Watson 1984). This population growth and the subsequent decline in 1982 were attributed to the creation and loss of several thousand construction jobs at the Washington Public Power Supply System power reactors. Watson et al. (Watson 1984) projected that the populations within a 16-kilometer (10-mile) radius, primarily reflecting the Tri-Cities, would increase by 94 percent between 1980 and 2030 and that the population between 16 and 80 kilometers (10 and 50 miles) would increase by 55 percent.

2.2.3.3 Socioeconomics. The socioeconomics of the area surrounding the Hanford Site are more fully described in Cushing (1995-7). The major employment sectors in the Tri-Cities area since 1970 have been the DOE and the Hanford Site contractors; the Washington Public Power Supply System, which operates a nuclear power plant; agriculture and a large food-processing industry; plus several smaller industrial operations. Other than DOE activities, agriculture and food processing are the dominant industries.

The land use 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's Columbia Basin Project, which uses the 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 a mixture of irrigated agriculture (near the Yakima River) and dry-land farming (at the higher elevations).

2.2.3.4 Past and Future DOE Activities at the Hanford Site. In 1943, the U.S. Army Corps of Engineers created the Hanford Site from small farming areas along the Columbia River and land ceded by local Indian Tribes to locate facilities for producing nuclear weapon materials for fighting World War II. Since then, the major activities on the Hanford Site have been controlled by the DOE and its predecessors, the Atomic Energy Commission (1945-1975) and the Energy and Research Development Administration (1975-6). Current major programs at the Hanford Site are dedicated to waste management, environmental restoration, and research and development.

The DOE nuclear facilities occupy about 6 percent of the Site's total available area. The operating areas, as shown in Figure 2-2, are identified by numbers: 100 Areas, 200 Areas, 300 Area, and 400 Area. The activities in these areas are described in the following paragraphs.

The 100 Areas, directly bordering the Columbia River (Figure 2-2), contain nine graphite-moderated plutonium production reactors, eight of which were shut down by the early 1970's. The ninth is the N Reactor, the first dual-purpose reactor built in the United States. N Reactor began operating in 1963 and ran until it was shut down in 1986.

Fuel reprocessing, plutonium and uranium separation, plutonium finishing, and waste management, including treatment, storage, and disposal activities, were conducted in the 200 Areas. Some waste from research and development activities and fuel fabrication activities in the 300 Area, reactor operation programs conducted in the 100 Areas, and the Fast Flux Test Facility (FFTF) in the 400 Area is sent to the 200 Areas for storage and disposal. Active 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 (Figure 2-2.) The following major facilities are located in the 200 Areas:

- Burial trenches
- Eighteen underground storage tank farms (the A, AN, AP, AW, AX, AY, AZ, B, BX, BY, C, S, SX, SY, T, TX, TY, and U)
- Very large fuel processing and recovery facilities (B, T, U, and E Plants and the REDOX and PUREX facilities)
- Water evaporator facilities (242-A, -S, and -T)
- Office and warehouse buildings.

The locations of these facilities are shown in Figure 2-3.

Between and just south of the 200 East and West Areas is the Environmental Remediation Disposal Facility (ERDF, Figure 2-2).

This trench system will hold most of the contaminated soil and materials from facility decontamination and decommissioning and Hanford Site remediation.

Some sites near the 200 Areas have been leased for disposal of commercial low-level waste. A 3.9-km² (1.5-mi²) parcel located between the 200 West and East Areas is leased to Washington State. A portion of this land is subleased to U.S. Ecology, Inc., a private company, for the disposal of commercially generated low-level radioactive waste.

The Fast Flux Test Facility (FFTF) is located in the 400 Area. This facility contains a liquid-metal cooled fast reactor previously used for testing breeder reactor fuels, materials, and components. The FFTF operated until 1992 and is now shut down.

A 4.4-km² (1.7-mi²) parcel northeast of the 400 Area is leased to the Washington Public Power Supply System for commercial nuclear power reactors. The Washington Nuclear Plant (WNP-2), a boiling-water reactor, is currently the only operating nuclear reactor on the Hanford Site. Construction of WNP-1 and WNP-4 will not be completed; both reactors were to be pressurized-water reactors.

The 300 Area had been dedicated to fabricating fuel for the N Reactor and other reactors on the Hanford Site. Now, the 300 Area is used for research programs performed in laboratories constructed over the last 30 years.

Besides the DOE activities already mentioned, the main future DOE activities will deal with site remediation. The largest addition will be the TWRS Complex, which will include the proposed disposal facility. The TWRS Complex will be used to treat and store the waste now in the underground storage tanks in the 200 Area. It will also be used to dispose of the low-level fraction of that waste.

The proposed TWRS Complex consists of a pretreatment facility, a low-level waste immobilization plant, a high-level waste vitrification plant, and the low-level (or low-activity) tank waste disposal facility. These facilities will be located about 610 meters (2,000 feet) west of the PUREX Plant and about 430 meters (1,400 feet) east of the 200 Area Office Complex (Figure 2-3). Immediately south of the TWRS Complex is the 200 East Area boundary fence and immediately north is unallocated land. Further north are waste burial trenches, the B (B, BX, and BY) tank farms, and the B Plant processing building.

2.2.3.5 Future Hanford Use. In 1992, DOE, EPA, and the Washington State Department of Ecology gathered a group of Hanford stakeholders to study future land-use of the Hanford Site. This Hanford Future Site Uses Working Group issued a summary (HFSUWG 1992a) and a detailed report (HFSUWG 1992b) of its findings.

For nearer term land use planning, as part of the Washington State Growth Management Act of 1991, Benton County is identifying land uses for the Hanford Site. This plan has the 200 Areas treated as industrial areas surrounded by "critical areas." By state law, "critical areas" are defined as land to be protected from use because of wildlife habitat, geologic, or environmental conditions. The only areas found suitable for development are as follows:

- To the northwest of the 200 West Area (a minimum of 6 kilometers [4 miles]), in an area known as the McGee ranch, where farming would be allowed
- to the east of the 200 East Area (a minimum of 5 kilometers [3 miles]) where research and development activities would be allowed.

However, any formal land use planning is not expected to be accurate in the time frame of this analysis (hundreds to hundreds of thousands of years).

2.2.4 Climate and Meteorology

2.2.4.1 Overview. Local and regional climate patterns and projections must be considered when evaluating the amount of water entering the disposal system. Some of the water will enter the disposal facility, react with the waste form, then carry away contaminants. Weather also affects the potential for flooding. Both total precipitation and seasonal frequency are important. Potential long-term climatic conditions must be projected to evaluate future climate changes that might cause higher precipitation rates or glaciation.

The climate of the Pasco Basin (where the Hanford Site is located) can be classified as midlatitude semiarid or midlatitude desert, depending on the climatological classification system being used. Summers are warm and dry with abundant sunshine. Large diurnal temperature variations are common, resulting from intense solar heating and nighttime cooling. Daytime high temperature in June, July, and August can exceed 40 °C (104 °F). Winters are cool with occasional precipitation that makes up about 44 percent 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 °F). Overcast skies and fog do occur during the fall and winter months.

The Cascade Mountain Range greatly affect the temperature, wind, and precipitation in the region. Air masses that reach the Pasco Basin are changed as they pass over the region's relatively complex topography. The mountains limit the Pacific Ocean's maritime influence, making the climate of Eastern Washington drier with greater temperature extremes than the coast. In addition to the rain shadow effect, the Cascades are a source of

cold air drainage, which has a considerable effect on the Site's wind regime.

This rest of this section summarizes the modern climate patterns in the Hanford Site area, the regional climate patterns of the recent past, and the possible future changes.

2.2.4.2 Current Data. Climatological data are available from the Hanford Meteorological Station (HMS), located between the 200 East and 200 West Areas at about 215 meters (705 feet) elevation. Data have been collected at this location since 1945. Temperature and precipitation data also are available from nearby locations for the period from 1912 through 1943. Data from the HMS are representative of the general climatic conditions for the region and describe the specific climate of the 200 Areas. Summaries have been published by Hoitnik (1994) and Stone (1983).

The average monthly temperature at the HMS is 12 °C (54 °F). The unusually cool nights that occur result from cool gravity winds originating from the Cascade Mountains. Seasonal temperature extremes are greater at the Hanford Site than they would be without the Cascade Mountains. The Pasco Basin has milder winters than sites at the same latitude on the Great Plains because mountain ranges to the north and east shield the area from many of the arctic surges that descend from Canada. Half of all winters are free of temperatures of -18 °C (0 °F) or lower.

Precipitation has been measured at the HMS since 1945. Average annual precipitation at the HMS is 16 cm (6.3 in.). The precipitation during November, December, and January accounts for 44 percent of this total, while precipitation from July through September accounts for only 13 percent. On the average, only twice a year do 24-hour amounts of precipitation measure 1.3 cm (0.5 in.) or more. Rainfall intensities of 1.3 cm/h (0.5 in./h) persisting for 1 hour are expected once every 10 years. Occurrences of 24-hour amounts of precipitation of 5.1 cm (2 in.) or more have been recorded only twice from 1946 through 1980. One of these was the record storm of October 1-2, 1957, in which rainfall totaled 2.7 cm (1.08 in.) in 3 hours, 4.3 cm (1.68 in.) in 6 hours, and 4.8 cm (1.88 in.) in 12 hours.

About 38 percent of all precipitation that occurs during December through February is in the form of snow. Winter monthly average snowfall ranges from 0.8 cm (0.3 in.) in March to 13.5 cm (5.3 in.) in January. Only one winter in four is expected to accumulate as much as 15 cm (5.9 in.) of snow on the ground. During these winters, four days, on average, have 15.2 cm (6.0 in.) or more of snow on the ground. However, the 1964-1965 winter had 35 days with snow on the ground, 32 of which were consecutive. That winter also provided one of the deepest accumulations, with 31 cm (12 in.) of snow occurring in December 1964. The record accumulation of snow is 62.2 cm (24.5 in.) in February 1916.

Prevailing wind directions on the Hanford Central Plateau are from the northwest in all months of the year. Secondary maxima occur for southwesterly winds. Monthly average wind speeds are lowest during the winter, averaging about 10 km/h (6 mi/h). The winds are highest during the summer, averaging 15 km/h (9 mi/h). Wind speeds that are well above average are usually associated with southwesterly winds. However, the summertime drainage winds are generally northwesterly and frequently reach 50 km/h (30 mi/h).

This climate profile suggests opportunities for moisture infiltration or recharge (See Section 2.2.6.5 for a discussion of natural recharge rates). This infiltration is centered around the frequency of precipitation events during the winter months when evaporation is less and plant uptake and transpiration are at a minimum.

2.2.4.3 Historical Data. Historical climate data can provide insights into how future and current climate patterns may differ. Information exists on climate for the past few centuries and, in less detail, for the last 10,000 years.

Cropper and Fritts (Cropper 1986) derived a 360-year regional reconstruction of seasonal and annual variations in temperature and precipitation from statistical relationships between meteorological records from Columbia Basin stations and tree-ring data from western North America. They calibrated the relationship between Columbia Basin weather records and a network of 65 tree-ring chronologies. The results suggest that the average temperature of the Columbia Basin for the past 3 centuries was slightly higher by 0.09 °C (0.16°F) and more variable (4 percent higher standard deviation) than in the 20th century. The increase was primarily attributed to warmer winters. This reconstruction also suggests that the past 3 centuries were wetter on the average by 0.8 cm (0.3 in.), primarily in the autumn. Furthermore, droughts were apparently more frequent starting in the second half of the 17th century and lasted longer than droughts of the 20th century.

Gramulich (1987) also used multiple regression models to reconstruct precipitation in the Pacific Northwest. The results indicate that the average precipitation of the 18th and 19th centuries did not differ from the average precipitation of the 20th century.

Chatters (1991) and Chatters and Hoover (Chatters 1992) summarized proxy evidence for climatic change in the Columbia Basin for the past 10,000 to 13,000 years. They identify an environment of about -13,000 years ago that was kept cool and dry by masses of ice and glacial meltwater, supporting a mosaic of isolated plant and animal communities. This was followed between 10,000 and 8,500 years ago by a period of warmer than modern summers, colder than modern winters and low, but spring-dominant, precipitation. This climate supported extensive grasslands and their associated fauna. By 8,000 years ago, summers and winters were both relatively warm, and precipitation was at least

33 percent below current levels. This climate pattern resulted in reduced stream flows, with late spring flow maxima, and extensive development of shrub-steppe vegetation throughout most of the region. Between 4,500 and 3,900 years ago, the climate went through a period of transition to wetter and cooler conditions. Rivers flooded frequently and forests expanded into steppe zones. From 3,900 to 2,400 years ago the climate was cool in the summer and cold in the winter, with winter-dominant precipitation at least 30 percent above current levels. Warmer, drier conditions returned between 2,400 and 2,000 years ago, reducing vegetation density and renewing flooding.

2.2.4.4 Long-Range Forecasts. Future long-range forecasts of climate are uncertain. Climatologists universally accept that global climates have undergone significant variation in the past and that such natural variations are expected to continue into the future. Berger et al. (1991) reviewed 7 models of different complexity developed to predict the global climate for the next 10,000 to 100,000 years. All the models are in relatively good agreement. Without man-made disturbances, the long-term cooling trend that began some 6,000 years ago is expected to continue for the next 5,000 years. This trend should be followed by a stabilization at about 15,000 years, a cold interval centered at approximately 25,000 years, and finally a major glaciation at about 55,000 years. Although man-made distributions (such as the green-house effect) may occur, the main effects are to delay the onset of these trends.

2.2.4.3 Climate Summary. The analyses of present and future climate conditions at the Hanford Site and in the surrounding region suggest that climatic conditions similar to current conditions will prevail for at least 10,000 years and probably considerably beyond. However, considering the uncertainty inherent in any climate analysis, wetter climate conditions and associated higher recharge or infiltration also will be considered. It is generally accepted that, at about 50,000 years or beyond, major glaciation will occur, followed by possible flooding similar to that near the end of the last glacial stage. Although considerable uncertainty is associated with future glaciation, some simulations in this performance assessment will examine human health impacts associated with a resident population following flooding and redeposition after 50,000 years.

2.2.5 Regional Geology

2.2.5.1 Overview. Knowledge of the thickness and lateral distribution of the sediments and other geologic characteristics is required for the following reasons:

- To define a conceptual model for contaminant transport from the disposal facility through the vadose zone (the zone between the surface and the groundwater which is not saturated with water) and from the unconfined

aquifer (the upper most groundwater layer) to the human environment.

- To define hydraulic parameters
- To interpret modeling results.

The geology of the Hanford Site includes thick sequences of water-derived sediments varying in texture from cobbles and coarse gravels to fine silts and clays. These sediments overlay thick basalt flows. The top sequence (surface soil) has been modified by wind. An unconfined aquifer exists in the lower part of the sedimentary sequence overlaying the uppermost basalt flow. This relatively thin aquifer is considered the primary contaminant pathway for evaluating exposure scenarios. The aquifer intercepts infiltration from the vadose (unsaturated) zone above it, providing a pathway for water and contaminant transport to the Columbia River.

The geological and physical settings of the Hanford Site have been extensively characterized during past activities. This section summarizes the physical geology and environmental setting of the Hanford Site and of the proposed disposal site. Emphasis is on the sedimentary sequence which is the pathway to the groundwater. More detailed discussions of the geology of the northwest region and the Hanford Site are found in DOE (1987-1), DOE (1988b), Myers (1979), Myers (1981), Reidel (1989), and Delaney (1991). The related subject of hydrology is summarized in Section 2.2.6.

2.2.5.2 Topography and Physiography. The proposed disposal facility is on the Hanford Central Plateau, a Pleistocene flood bar most commonly referred to as the 200 Areas Plateau, near the center of the Hanford Site. The Hanford Central Plateau is approximately 198 meters (650 feet) to 229 meters (750 feet) above mean sea level. The plateau decreases in elevation to the north, northwest, and east toward the Columbia River. The plateau escarpments have elevation changes of 15 to 30 meters (50 to 100 feet).

The Hanford Site is situated within the Pasco Basin of south-central Washington State (Figure 2-5). The Pasco Basin is one of many topographic depressions located within the Columbia Intermontane Province (Figure 2-6), a broad basin located between the Cascade Range and the Rocky Mountains. The Columbia Intermontane Province is the product of Miocene continental flood, basalt volcanism, and regional deformation that occurred 6 to 17.5 million years ago. The Pasco Basin is bounded on the north by the Saddle Mountains; on the west by Umtanum Ridge, Yakima Ridge, and the Rattlesnake Hills; on the south by the Horse Heaven Hills; and on the east by the Palouse Slope (Figure 2-5).

Figure 2-5. Geologic Structures of the Pasco Basin and the Hanford Site.

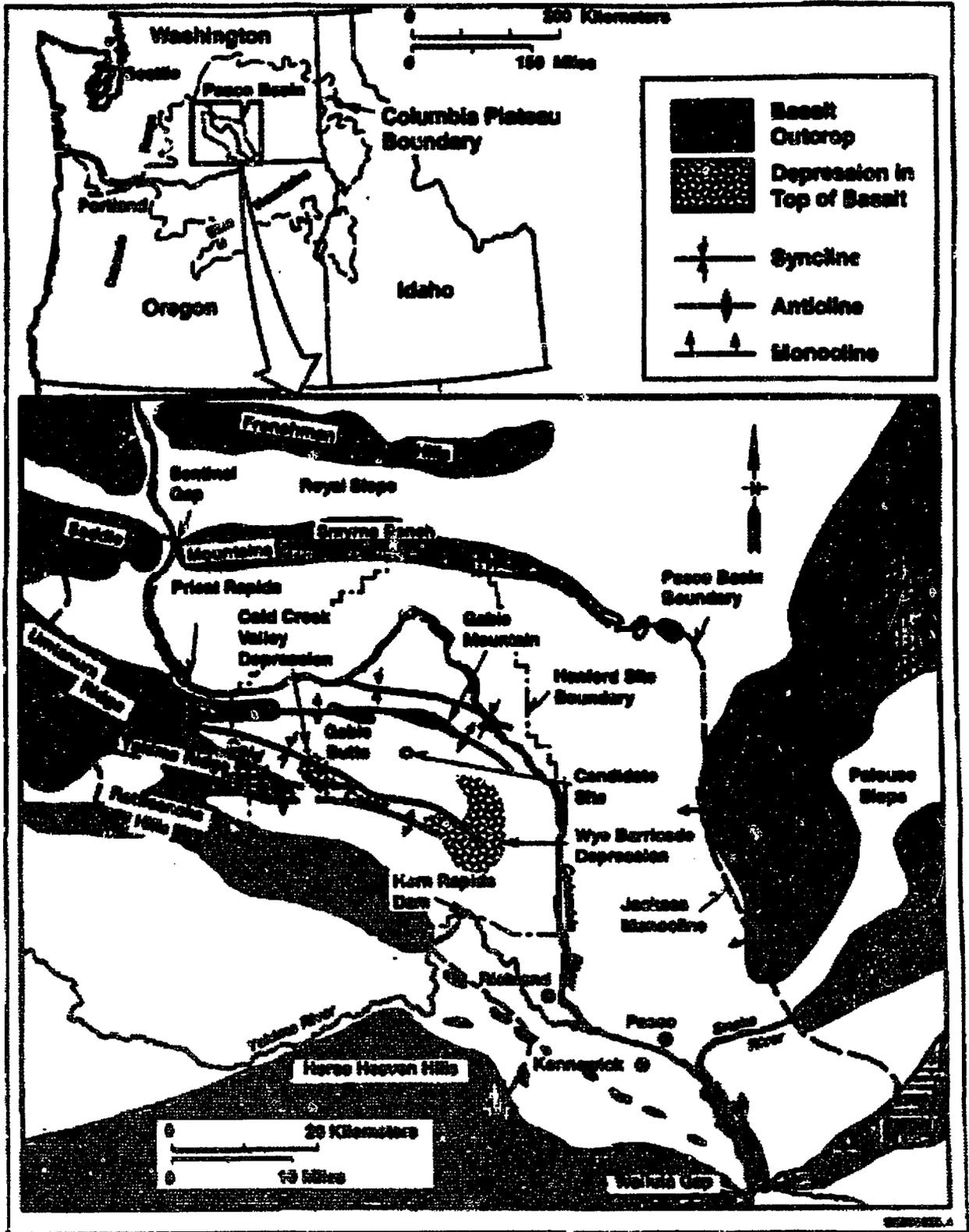
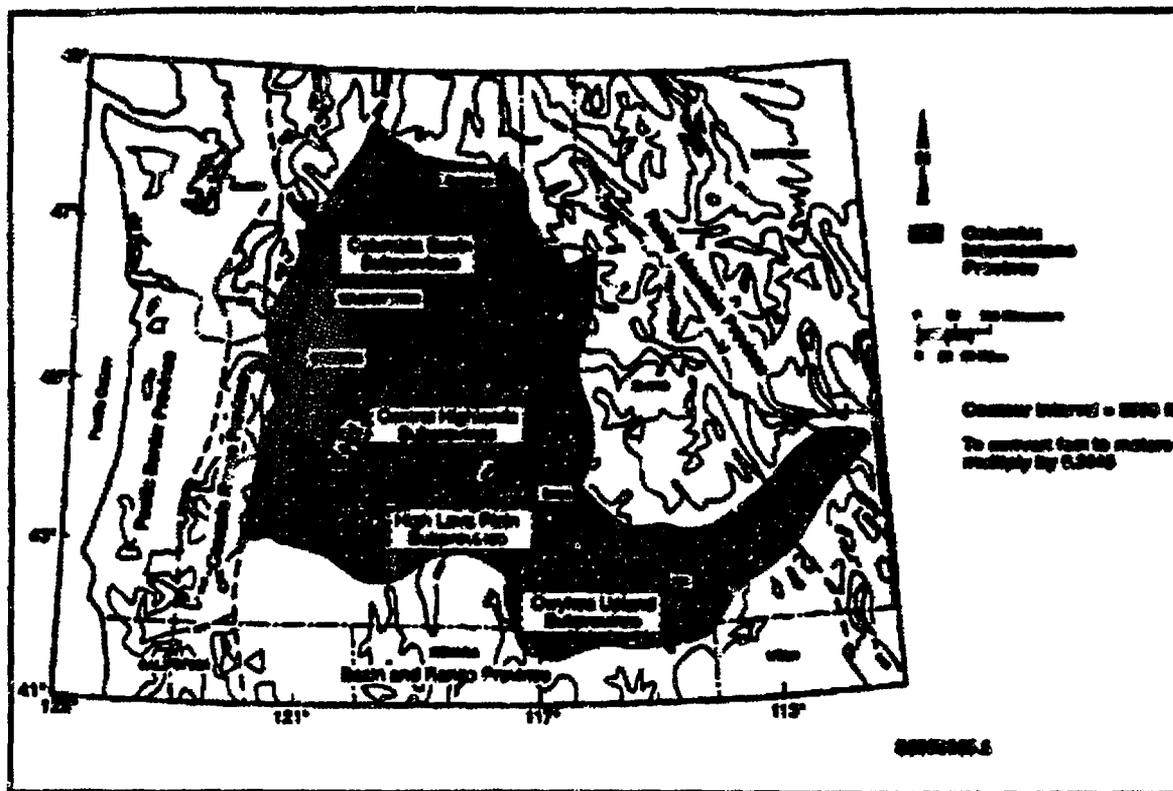


Figure 2-6. Divisions of the Intermontane Physiographic and Adjacent Snake River Plains Provinces.



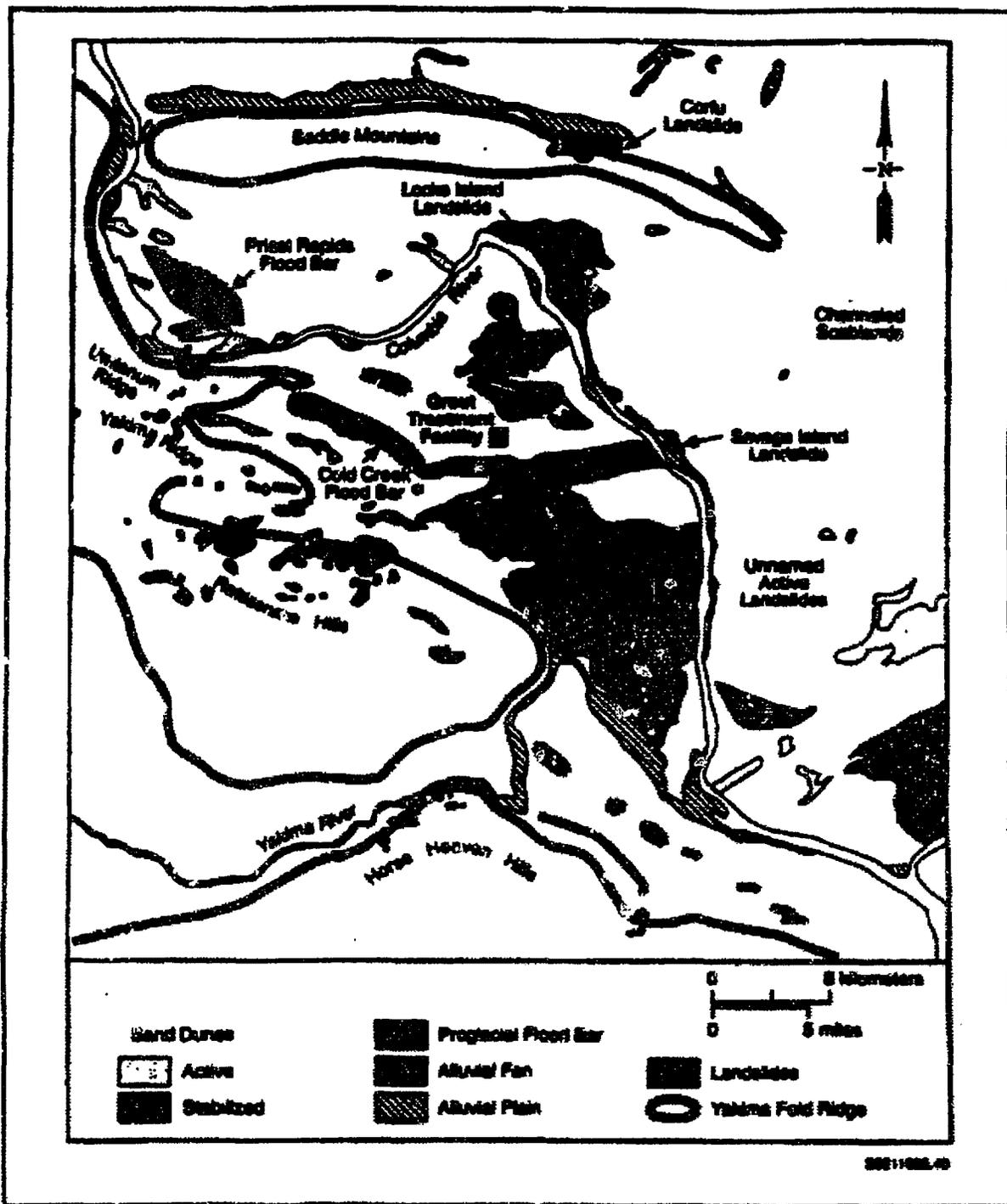
The physical geography of the Hanford Site is dominated by the low-relief plains of the Pasco Basin and anticlinal ridges of the Yakima Folds physiographic region (Figure 2-7). The surface topography of the Hanford Site is the result of the following events:

- Uplift of anticlinal ridges
- Pleistocene cataclysmic flooding
- Holocene eolian activity.

Uplift of the ridges began in the Miocene epoch (starting about 17 million years ago) and continues to the present. This uplift is occurring on geologic time scales (i.e., over tens of millions of years). The uplift is not incorporated into our conceptual model of the low-level tank waste disposal facility, which addresses a time scale of tens of thousands of years.

Glacier-related flooding has had a major impact on the physical geography. Cataclysmic flooding occurred when ice dams in western Montana and northern Idaho were breached, allowing large volumes of water to spill across eastern and central Washington. The last major flood occurred about 13,000 years ago, during the late Pleistocene Epoch. Interconnected flood channels, giant current ripples, and giant flood bars are among the landforms created by the floods. These formations resulted

Figure 2-7. Landforms of the Pasco Basin and the Hanford Site.



in heterogeneous and discontinuous characteristics for sediments ranging in size from silts to coarse gravels. These sediments yield a wide range of vadose zone hydraulic properties.

Landslides have had a limited effect on physical geography. Previous landslide activity in the area is generally limited to the White Bluffs area east of the Hanford Site and the Rattlesnake Hills south of the Site. No landslide activity is observed in the Hanford Central Plateau.

During the Holocene Epoch (the last 11,000 years), winds have locally reworked the flood sediments. The winds deposited dune sands in the lower elevation and loess (very fine wind-blown silts) around the margins of the Pasco Basin. Generally, sand dunes have been stabilized by anchoring vegetation. However, they have been reactivated where vegetation has been disturbed. Most sand dunes on the Hanford Site are located southeast of the 200 East Area and are stabilized by vegetation (Figure 2-7).

The location of the Hanford Site in an intermontane basin helps maintain a semiarid climate with low recharge. Most topographical surface features, such as sand dunes and landslides, that could disturb the near-surface hydraulic characteristics affecting recharge are not found at the proposed location of the low-level tank waste disposal facility. Moreover, sand dunes are indicators of past, cumulative wind directions. Their location approximately downwind of the proposed disposal facility site suggests that future dune formation over the facility is not likely.

2.2.5.3 Stratigraphy

2.2.5.3.1 Overview. The stratigraphy or geologic layering is not extremely complex in the Hanford region. Late Miocene to Pleistocene suprabasalt sediments (2 to 5 million years old) and miocene-aged basalt (16 to 17 million years old) of the Columbia River Basalt Group mostly lie beneath the Hanford Site. Miocene-aged basalt is exposed at some locations, including Gable Mountain and Gable Butte. The basalts and sediments thicken into the Pasco Basin and generally reach maximum thicknesses in the Cold Creek syncline, which is southwest of the proposed site for the disposal facility. Cenozoic (25 to 65 million years old) sedimentary and volcanoclastic rocks underlying the basalts are not exposed at the surface near the Hanford Site.

Figure 2-8 delineates the general stratigraphy of the suprabasalt sedimentation that makes up the vadose zone sediments beneath the proposed location of the disposal facility. This figure illustrates the degree of heterogeneity and discontinuity in the sediments. The sedimentation is composed largely of Ringold Formation and Hanford formation sediments, with the Hanford formation above the Ringold Formation. At the proposed disposal facility site, the Hanford formation makes up most of the vadose zone.

informally defined Plio-Pleistocene unit, early "Palouse" soil, and pre-Missoula gravels compose the remainder of the sequence.

The following sections describe the geology of the Ringold and Hanford formations sediments in some detail. These sediments are the basis for determining vadose zone hydraulic and geochemical properties for contaminant transport modeling.

2.2.5.3.2 Ringold Formation. The Ringold Formation varies in thickness throughout the Hanford Site. It is up to 183 meters (600 feet) thick in the deepest part of the Cold Creek syncline south of the 200 West Area and 170 meters (560 feet) thick in the western Wahiuke syncline near the 100 B Area. It pinches out against the Gable Mountain, Yakima Ridge, Saddle Mountains, and Rattlesnake Mountain anticlines (Figure 2-5). It is mostly absent in the northern and northeastern parts of the 200 East Area and adjacent areas to the north near West Pond.

The Ringold Formation is assigned to a late Miocene to Pliocene age (Fecht 1987, DOE 1988b) and consists of clay, silt, compacted mud, fine- to coarse-grained sand, and granular to cobble gravel. In general, it tends to be finer-grained, or siltier, in the upper parts just below the Hanford formation.

The strata of the Ringold Formation are generally divided as follows (Newcomb 1958; Newcomb 1972; Myers 1979; Bjornstad 1984; DOE 1988b):

- The gravel, sand, and paleosols of the basal unit
- The clay and silt of the lower unit
- The gravel of the middle unit
- The mud and lesser sand of the upper unit
- The basaltic detritus in localized areas.

Ringold strata also have been divided on the basis of facies types (Tallman 1981) and fining upward sequences (PSPL 1982). Recent studies of the Ringold Formation (Lindsey 1989 and 1991) divided the formation on the basis of sediment facies (individual stratigraphic bodies) associations and their distribution. Facies associations in the Ringold Formation (defined on the basis of lithology, petrology, and stratification) include fluvial gravel, fluvial sand, overbank deposits, lacustrine deposits, and basaltic gravel.

2.2.5.3.3 Hanford Formation. The Hanford formation (an informal designation) is up to 64 meters (210 feet) thick in the Cold Creek bar near the 200 areas. It is absent on ridges approximately 360 meters (1,180 feet) above sea level.

The Hanford formation was deposited by the catastrophic ice-age flooding that ended about 13,000 years ago. The formation consists of pebble-to-boulder sized gravel, fine- to coarse-grained sand, and silt. It can be divided into two main facies: coarse-grained or gravelly deposits and fine-grained or sandy and silty deposits. The Hanford formation is also commonly divided into two informal members: the Pasco gravels and the Touchet

Beds (Myers 1979, Tallman 1981, Fecht 1987, DOE 1988b). The Pasco gravels correspond to the gravelly facies, and the Touchet beds to the sandy and silty facies.

The gravelly facies consists of coarse-grained sand and granule-to-boulder sized gravel. These gravels often lack matrix material and have an open framework appearance. The gravelly facies dominates the Hanford formation in the 100 Areas north of Gable Mountain, the northern part of the 200 East Area, and the eastern part of the Hanford Site, including the 300 Area. In the 200 East and 200 West Areas, the facies association generally becomes finer to the south. The gravelly facies was deposited by high-energy flood waters in flood bars and along channelways such as the Ringold Coulee, east of the Hanford Site, and Gable Mountain channel, north of the Central Plateau.

The sand and silt facies consists of silt and fine- to coarse-grained sand that commonly display normally graded rhythmites a few centimeters to several tens of centimeters thick in outcrop (Myers 1979, DOE 1988b). This facies is found throughout the central, southern, and western Cold Creek syncline within and south of the 200 Areas. These sediments were deposited under slackwater conditions and in backflooded areas (DOE 1988b).

Clastic dikes are vertical features occasionally seen in the Hanford formation. In clastic dikes a vertical hexagonal structure of very-fine grained sand is surrounded by coarser Hanford formation materials. The importance of these features will be investigated in future studies.

2.2.5.3.4 Surficial Deposits. Holocene surficial deposits consist of silt, sand, and gravel that form a thin (< 4.9 meters, [16 feet]) veneer atop much of the Hanford Site. These sediments were deposited by wind and flood processes.

2.2.5.4 Seismic

2.2.5.4.1 Overview. Seismic events can accelerate the degradation of the disposal facility and of the waste form.

The Hanford Site lies in the Pasco Basin near the eastern limit of the Yakima Foldbelt. The Site is underlain by basalt of the Columbia River Basalt Group, which is covered by up to 213 meters (700 feet) of relatively stiff sediments. It is in an area of low-magnitude seismicity and is under north-south compressional stress, which is reflected in the deformation of the Yakima folds. The following sources are major contributors to the seismic hazard in and around the Hanford Site:

- Fault sources related to the Yakima fold
- Shallow basalt sources that account for the observed seismicity within the Columbia River Basalt Group and not associated with the Yakima Folds

- Crystalline basement source region
- Cascadia Subduction Zone earthquakes.

The largest historical earthquake in the Columbia Plateau occurred in 1936 near Milton-Freewater, Oregon, approximately 90 kilometers (54 miles) east of the site. The earthquake had a magnitude of 5.75 and was followed by a number of aftershocks. The ground motion from this event is estimated to have been less than 0.03 g at the Hanford Site.

A seismic monitoring network has been operated in and around the site since 1969. The network, operated by DOE, can locate all earthquakes of magnitude 1.5 and larger on or near the Hanford Site, and magnitude 2.0 and larger throughout south-central and south-eastern Washington State. The largest recorded earthquake on the Hanford Site was a magnitude 3.8 near Coyote Rapids in 1971 and was felt in the 100 N Area.

2.2.5.4.2 Seismic Hazard Assessment. This section explains the earthquake ground motions that the facility is expected to experience during the performance period. Elements of the disposal facility that serve as barriers in the overall performance must continue to perform at some level throughout the performance period. Deformation and or cracking from earthquake ground motion is one of the major drivers of physical degradation of the engineered system.

A probabilistic seismic hazard analysis was recently completed for the Hanford Site (Geomatrix 1996). Previous seismic hazard analyses were done for Washington Public Power Supply System's (Supply System) WNP-1/4 and WNP/2, which also are located on the Hanford Site (Power et al. 1981). Woodward Clyde Consultants (WCC 1989) later applied the Supply System study to the Hanford Site areas under DOE control.

The following seismic hazard values are based on the current seismic hazard study by Geomatrix (1996), which incorporates seismo-tectonic data and interpretations included in the Supply System's earlier assessment. The mean seismic hazard curves for the 200 West, 200 East, and 400 Areas are shown in Figure 2.9. The 200 West horizontal ground motion values are shown for the selected time period in Table 2-1. (See Geomatrix [1996] for details including response spectra).

2.2.6 Regional Hydrology (Both Surface and Groundwater)

2.2.6.1 Overview. This section describes the concept of recharge rate for the surface and subsurface hydrology of the Hanford Site region and the proposed site for the disposal facility. The surface hydrology is important in determining possible surface pathways for dissolved or suspended contaminants, as well as for identifying sources of infiltration. The groundwater hydrology helps determine possible flow paths for contaminants released from the disposal facility and provides a

Table 2-1. Approximate Probability of Exceeding Given Ground Motions During Selected Time Periods

| Ground Motion (g) | Return Period (Years) | Annual Probability of Exceedance (P) | Exceedance Probability (EP) ^a over 50 years | EP over 1,000 years | EP over 10,000 years |
|-------------------|-----------------------|--------------------------------------|--|---------------------|----------------------|
| 0.19 | 1,000. | 1 X 10 ⁻¹ | 5.8 | 63% | 100% |
| 0.26 | 2,000. ^b | 5 X 10 ⁻² | 2.8 | 39% | 99% |
| 0.37 | 5,000. | 2 X 10 ⁻² | 1.8 | 18% | 86% |
| 0.48 | 10,000. | 1 X 10 ⁻² | 0.5% | 10% | 63% |

EP = $1 - (1 - p)^n$ where

p = the annual probability of exceedance,

n = the performance life, and

EP = the probability of exceedance over the performance life.

^a Performance Category 3, DOE Order 5480.28.

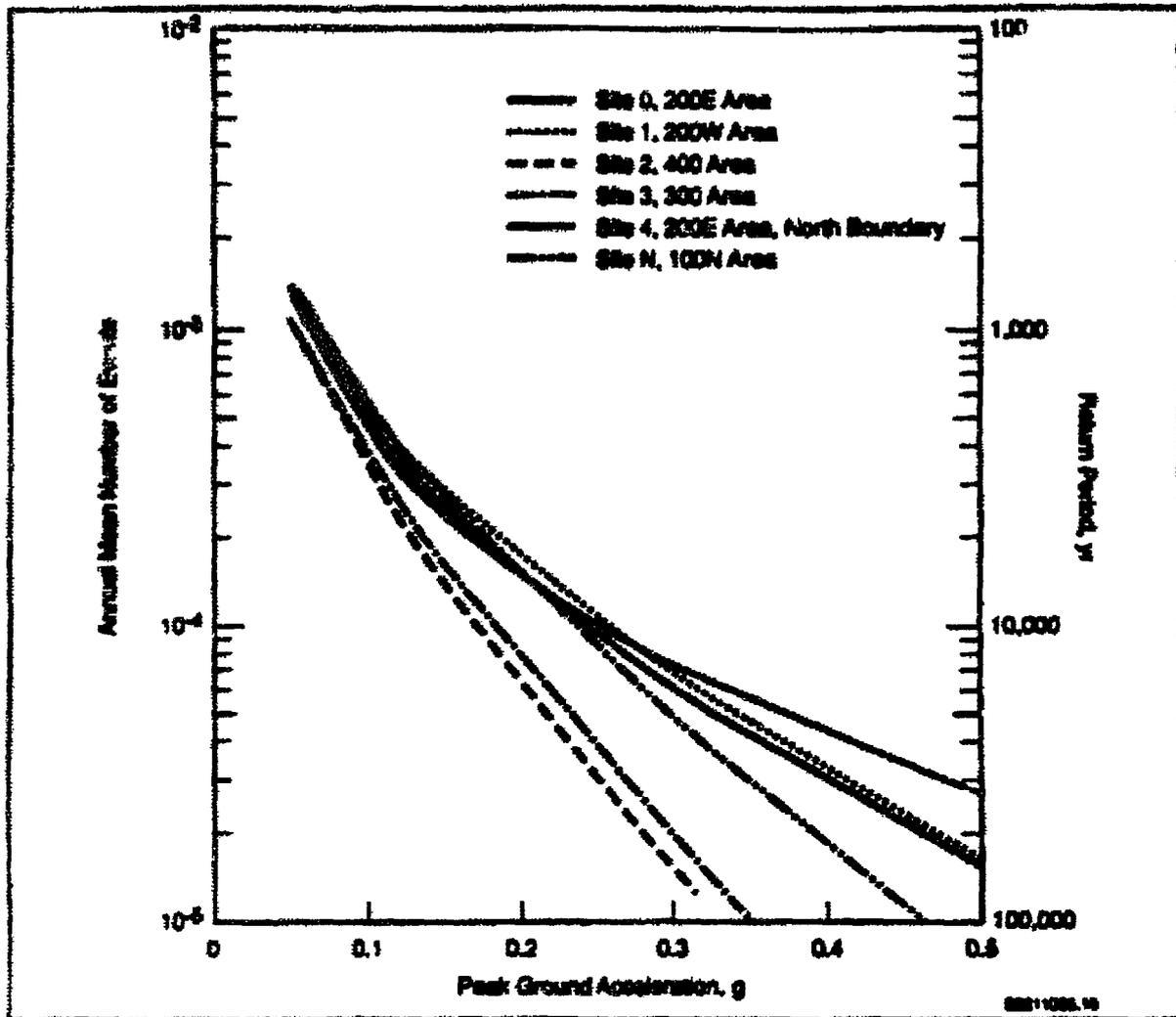
basis for determining vadose zone thickness.

2.2.6.2 Surface Hydrology. The hydrology of the Pasco Basin (Figure 2-10) is characterized by a number of surface sources and aquifers. Surface drainage enters the Pasco Basin from several other basins, including the Yakima River Basin, the Horse Heaven Basin, the Walla Walla River Basin, the Palouse/Snake Basin, and the Big Bend Basin. Within the Pasco Basin, major tributaries, the Yakima, Snake, and Walla Walla Rivers, join the Columbia River. Two intermittent streams, Cold Creek and Dry Creek, cut through the Hanford Site. Water drains through these pathways during wetter winter and spring months. No perennial streams originate within the Pasco Basin.

The total estimated precipitation over the basin averages 16.0 cm/y (6.3 in./y) (Section 2.2.4.2). Mean annual runoff from the basin is estimated to be less than 3.1×10^7 m³/y (2.5×10^6 acre ft/y), or approximately 3 percent of the total precipitation. The remaining precipitation is assumed to be lost through evapotranspiration, with a small component (perhaps a few percent) contributing to the recharging of the groundwater (DOE 1988b).

The Hanford Site has one pond, West Lake, and various water disposal ponds. West Lake, located 2.7 kilometers (1.7 miles) north of the 200 East Area, is a shallow pond with an average depth of about 1 meter (3 feet) and a surface area of 4 hectares (10 acres). While described as a natural lake, the source of recharge to the lake is groundwater that is locally mounded because of infiltration from 200 Area operations. The pond is a topographic depression that intersects the artificially elevated water table (DOE-RL 1993b-1). 200 Area disposal activities are scheduled to halt within a few decades. When this happens, the

Figure 2-9. Comparison of Seismic Hazard for Various Regions of the Hanford Site.

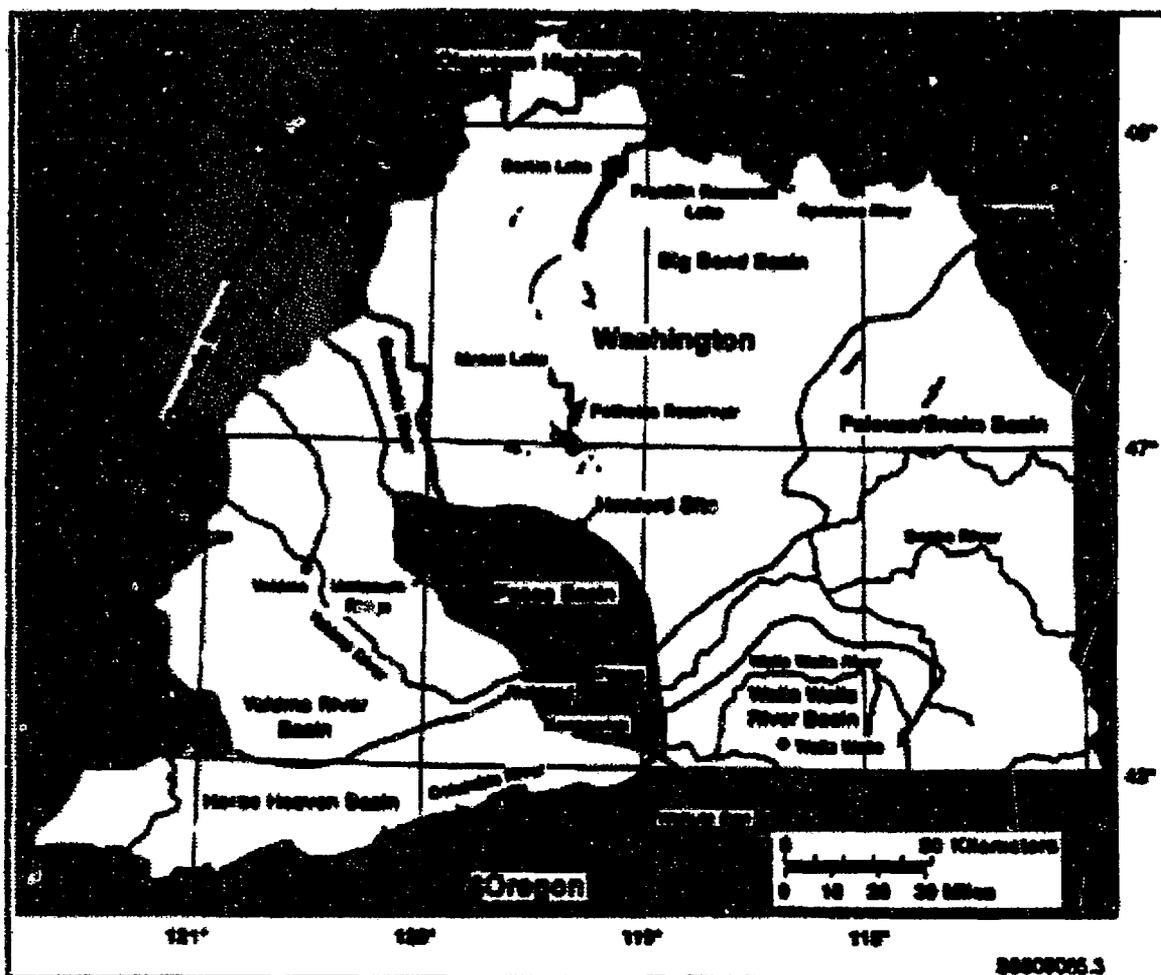


water table will drop and West Lake will become an intermittent seasonal pond (DOE-RL 1993c). Waste water ponds, cribs, and ditches associated with nuclear fuel processing and waste disposal activities, although currently present on the Hanford Site (Figure 2-11), will not be an important source of water in the future.

No surface streams are near the proposed disposal facility, but current disposal ponds have an artificial influence on net contributions to the water table. These disposal ponds and related facilities are not expected to exist after current operations end, so their long-term influence is not considered in this performance assessment.

The surface drainage characteristics of the Hanford Site and regional area indicate that the Columbia River and its

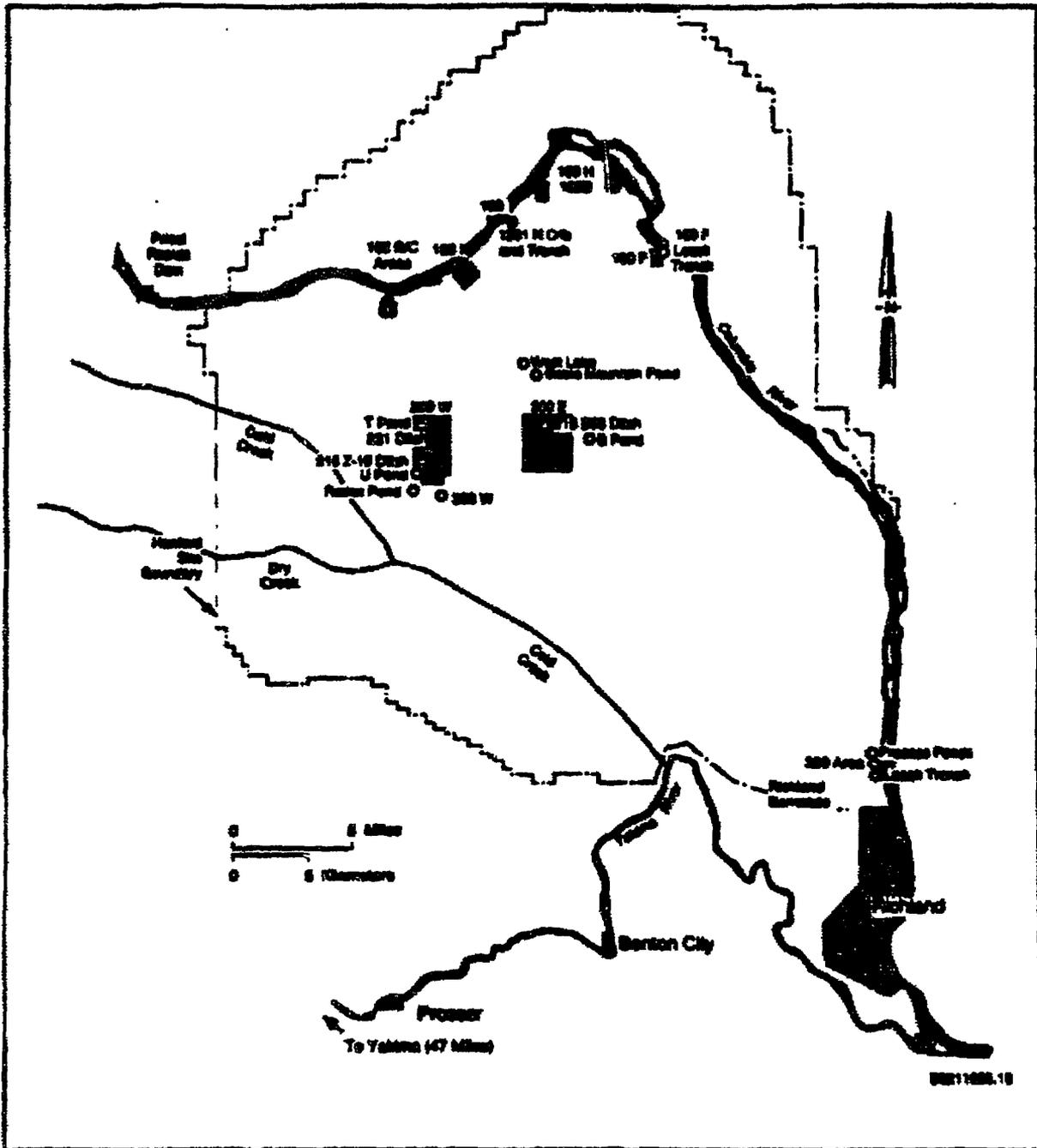
Figure 2-10. Hydrologic Basins Designated for the Washington State Portion of the Columbia Plateau (DOE 1988b).



tributaries are the major surface drainage pathways. The Columbia River is the dominant pathway. The large volume of flow in the Columbia River (typically 1,000 to 3,000 m³/s [Woodruff 1992]) through the Pasco Basin and downstream permits considerable dilution of any contaminants that reach the river.

Routine water-quality monitoring of the Columbia River is conducted by DOE for both radiological and nonradiological parameters. The Pacific Northwest National Laboratory (PNNL) has been reporting the water quality data since 1973. The Washington State Department of Ecology (Ecology 1992) has issued a Class A (excellent) quality designation for Columbia River water from Grand Coulee Dam, through the Pasco Basin, to McNary Dam. This designation requires that all industrial uses of this water be compatible with other uses, including drinking, wildlife habitat, and recreation. The Columbia River water is characterized by a low suspended load, a low nutrient content, and an absence of microbial contaminants (Woodruff 1992).

Figure 2-11. Location of Water Disposal Ponds on the Hanford Site.



2.2.6.3 Flooding. Cushing (1995-3) describes flooding potentials at the Hanford Site. Except for catastrophic glacier flooding, which is not expected for tens of thousands of years, no floods are expected to affect the Hanford Central Plateau.

The flows for the three largest probable Columbia River flood scenarios range from 17,000 to 600,000 m³/s (600,000 to 21 million ft³/s). The probable maximum flood on the Columbia River (DOE 1986), based on natural conditions, has been calculated to be 40,000 m³/s (1.4 million ft³/s). This is greater than the 500-year flood. A landslide resulting in Columbia River blockage, followed by flooding could yield a maximum flow of 17,000 m³/s (600,000 ft³/s). The U.S. Army Corps of Engineers estimated that a 50 percent breach in the Grand Coulee Dam, the largest dam in the region, would yield flows of 600,000 m³/s (21 million ft³/s). None of these flow rates are large enough to cause the waters of the Columbia River to reach the Hanford Central Plateau.

A flood risk analysis of Cold Creek (west of the 200 West Area) was conducted to characterize a basaltic repository for high-level radioactive waste (Skaggs 1981). Based on this evaluation, the probable maximum flood would be 8 kilometers (5 miles) to the west of the TWRS Treatment Complex and its closest approach would be about 6 kilometers (3.6 miles) to the south.

2.2.6.4 Groundwater Hydrology. The groundwater pathway is considered the most likely pathway for contaminants released from the low-level tank waste disposal facility for the following reasons:

- Low precipitation in the Pasco Basin
- Lack of surface transport pathways near the disposal facility
- Subsurface location of the disposal facility
- Near-surface lysimeter measurements showing downward movement of water
- Samples showing the existence of radioactive contaminant plumes in the groundwater due to past Hanford operations.

To evaluate this pathway, information is required about the types of aquifers present, depths to the water table, regional flow paths, and the net recharge rate.

The hydrology of the Pasco Basin is characterized by a multiaquifer system. This system consists of four hydrologic units corresponding to the upper three formations of the Columbia River Basalt Group (Grande Ronde Basalt, Wanapum Basalt, and Saddle Mountains Basalt) and the overlying suprabasalt sediments (the Hanford formation and Ringold Formation). The basalt

aquifers consist of the tholeiitic flood basalts of the Columbia River Basalt Group and relatively minor amounts of intercalated sediments of the Ellensburg formation. Confined zones in the basalt aquifers are present in the sedimentary interbeds and/or interflow zones that occur between dense basalt flows. The main water-bearing portions of the interflow zones are networks of interconnecting vesicles and fractures in the flow tops and flow bottoms (DOE 1988b).

The uppermost aquifer system consists of fluvial, lacustrine, and glaciofluvial sediments. Within the Pasco Basin, this aquifer is regionally unconfined and is contained primarily within the Ringold Formation and the Hanford formation. The main body of the unconfined aquifer usually occurs within the Ringold Formation. The water table in the southwestern Pasco Basin is generally within Ringold fluvial gravels. In the northern and eastern Pasco Basin, the water table is generally within the Hanford formation. Hydraulic conductivities in the Hanford formation are usually greater than in the gravel facies of the Ringold Formation (Graham 1981). However, fine-grained deposits in the Ringold Formation form locally confining layers for Ringold fluvial gravels.

The base of the uppermost aquifer system is defined as the top of the uppermost basalt flow. This aquifer system is bounded laterally by anticlinal basalt ridges and is about 152 meters (500 feet) 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 meter (1 foot) below ground surface near West Lake and the Columbia and Yakima Rivers, to greater than 107 meters (350 feet) in the central portion of the Cold Creek syncline.

Because the uppermost unconfined aquifer is considered the primary pathway for possible contaminant transport from the low-level tank waste disposal facility, it has special importance in this performance assessment. The conceptual model of the unconfined aquifer is discussed in Chapter 3.0. Modeling results are given in Chapter 4.0.

Before the liquid waste disposal systems, such as B Pond, began operating, and before the onset of large regional irrigation projects, the groundwater table for the Hanford Site could be represented by a 1944 water table map (Figure 2-12). This water map includes limited irrigation near the former towns of White Bluff and Hanford but not the irrigation now common in Cold and Dry Creeks. The 1944 water table contours suggest that groundwater flow is easterly toward the Columbia River with a relatively uniform hydraulic gradient (approximately 1.5 m/km [5 ft/mi]). Regional groundwater flow was generally toward the east-northeast, although flow north of Gable Mountain was more to the north.

Effluent disposal at the Hanford Site has altered hydraulic gradients and flow directions of the uppermost aquifer system.

2.2.6.5 Natural Recharge Rates. Recharge is the net amount of total precipitation that infiltrates into the unsaturated zone (vadose zone) after runoff, evaporation, and transpiration by plants have occurred. Recharge from rain and snow melt is a major hydrologic variable affecting contaminant transport from the low-level tank waste disposal facility. Studies conducted over the last 25 years at the Hanford Site (summarized below), indicate that recharge can vary greatly depending on factors such as climate, vegetation, land use, and soil texture. Estimates used for the infiltration rate in the modeling are discussed in Section 3.4.7.

Most recharge rate data at Hanford have been measured directly using a combination of drainage and weighing lysimeters (Rockhold 1995, Gee 1992). These lysimeters are long vertical tubes (some are 5 meters in length) in the ground filled with various type of soils and covered with various types of vegetation. At the bottom of the lysimeters the water which passed through the tube of soil is collected and measured (by volume or weight). From such measurements, the rate at which moisture escapes the near-surface part of the vadose zone can be determined. Because no mechanisms are assumed to exist which act as traps for the moisture, the measured rate from the lysimeters is considered a good approximation to the recharge rate for the conditions (soil, vegetation, and precipitation) tested by the lysimeter.

The recharge rate has been shown to depend on a variety of conditions. The recharge rate depends on the seasonal distribution of precipitation, with maximum recharge events occurring following the wettest winter periods. The effect of a variety of surface soils, vegetation, and climate conditions on recharge have been studied. Under normal conditions, the recharge rate is highest in coarse-textured soils without vegetation and is at the measurement threshold in fine-textured soil with or without vegetation. Coarse soil surfaces that are either vegetated with shallow-rooted species or are bare exhibit recharge on the order of 50 percent of the precipitation.

Routson and Johnson (Routson 1990) reviewed water infiltration data from a 13-year observation period for a closed-bottom lysimeter located in the 200 East Area and ¹³⁷Cs profile data from a solid-waste burial ground trench in the 200 West Area. The recharge rate of the closed-bottom lysimeter was estimated to be 0.0 ± 2.0 mm/y (0.0 ± 0.08 in./y) based on the 13-year record. Gee (1992) reviewed all published lysimeter studies for the Hanford Site. They noted that the main determiners for recharge was the texture of the soil and the amount and type of vegetation on the soil.

The very limited data from environmental tracer techniques are generally consistent with data from the lysimeters. The tracer data indicate that (undisturbed) vegetated sites have experienced as little as 0.01 to 0.1 mm/y (0.0004 to 0.004 in./y) of recharge and up to 3. to 4. mm/y (0.1 to 0.2 in./y) (Prych 1995). However, the tracer techniques, while

powerful, are not applicable to disturbed (or engineered) sites. Also, these techniques have been unable to measure significant rates of recharge at sites with coarse soils and shallow-rooted vegetation, because of deep percolation of natural tracers at these sites.

In addition to studies using lysimeter and tracer techniques, a number of studies have been conducted to estimate recharge on a regional scale. For example, Bauer and Vaccaro (Bauer 1990) estimated groundwater recharge for the Hanford Site as part of their study of recharge affecting the Columbia Plateau regional aquifer. Using estimates of soil type and land use and a water balance model, they estimated recharge rates for most of the Site (including the low-level tank waste disposal facility site) ranging from 0 to 12.7 mm/y (0 to 0.5 in./y). In contrast, in the vicinity of sand dunes in the middle of the Hanford Site, they estimated rates as high as 51. mm/y (2.0 in./y).

More recently, Fayer and Walters (Fayer 1995c) estimated recharge rates based on measurements (of drainage, water contents, tracers) and numerical modeling. Estimates from these methods were assigned to specific soil-vegetation combinations and distributed across the Hanford Site using a soil map and a vegetation/land use map. The long-term average rates varied from 2.6 mm/y (0.1 in./y) for several soil and vegetation combinations in the 200 Areas (including the low-level tank waste disposal facility site) to 127. mm/y (5.0 in./y) for basalt outcrop with no vegetation at the crest of the Rattlesnake Mountain (Fayer 1995c).

Because of the high degree of variability and importance of recharge to the performance assessment, additional work is planned to estimate recharge rates through a combination of computer simulations, lysimeter measurements, and tracer methods (PAG 1995a). These efforts will consider the comments made by outside experts (Honeyman 1995).

2.3.7 Geology and Hydrology of the Proposed Low-Level Tank Waste Disposal Facility Location

2.3.7.1 Overview. The geology and hydrology of the 200 East Area have been the subjects of much study and reports over the past several decades (Myers 1979, Myers 1981, Gephart 1979, Tallman 1979, Graham 1981, Routson 1990). The most recent work on the 200 East Area is by Lindsey (1992) and by Connely (1992a).

The 200 East Area lies on the Cold Creek bar, a geomorphic remnant of the cataclysmic floods of the Pleistocene. As the flood waters raced across the lowlands of the Pasco Basin, they lost energy and began leaving behind deposits of gravels. The Hanford Central Plateau is one of the most prominent of such deposits. The plateau lies just south of one of the major channelways across the Hanford Site that forms the topographic lowland south of Gable Mountain.

The principal source of geologic and hydrologic information for the 200 East Area is boreholes. Numerous boreholes have been drilled in the 200 East Area for groundwater monitoring and waste management studies. However, because few boreholes have been drilled in the area near the TWRS Treatment Complex, data are limited. Most boreholes in the 200 East Area have been drilled using the cable-tool method. Some boreholes were drilled using rotary and wire-line coring methods. Geologic logs based on these boreholes are constructed by examining chips and cuttings, which limits information on all but the broadest stratigraphic units. Chip samples, which are typically taken at 1.5-meter (5-foot) intervals, are routinely archived at the Hanford Geotechnical Sample Library.

To better determine the site-specific properties of the vadose zone and the unconfined aquifer, three new boreholes are planned (PAG 1995-2). Continuous intact core samples are planned. The need for these boreholes and the integrated characterization plan designed around them are described by Reidel et al (Reidel 1995).

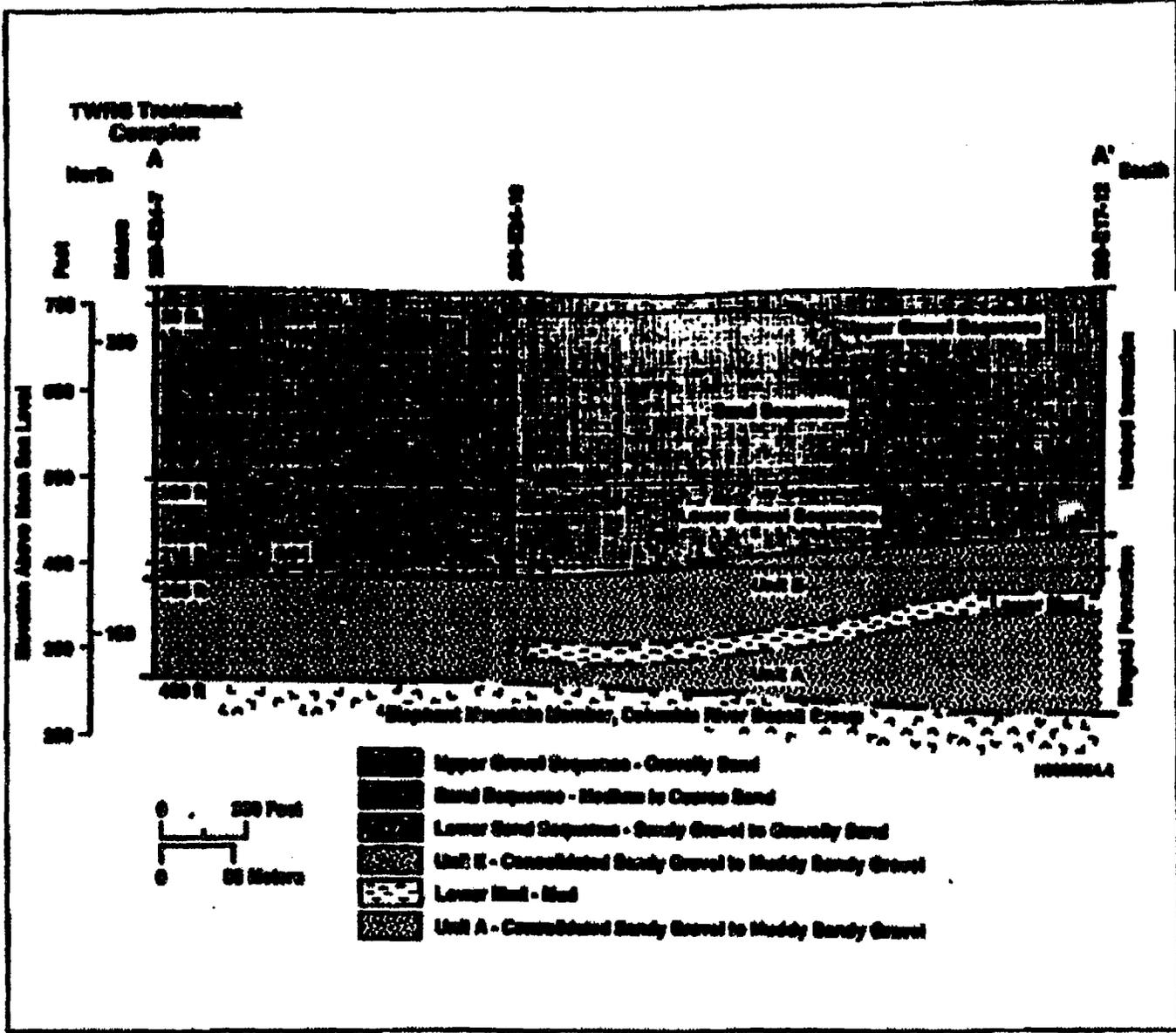
2.2.7.2 Geological Structural Framework. The preferred location of the low-level tank waste disposal facility is south of the Gable Mountain segment of the Umtanum Ridge anticline and north of the Cold Creek syncline (Figure 2-5). The proposed disposal facility lies about 3 kilometers (2 miles) north of the axis of the Cold Creek syncline, which controls the structural grain of the basalt bedrock and Ringold Formation. The basalt surface and Ringold Formation trend roughly southeast-northwest, parallel to the major geologic structures of the Hanford Site. As a result, the Ringold Formation and the underlying Columbia River Basalt Group gently dip to the south off the Umtanum Ridge anticline into the Cold Creek syncline.

Geologic mapping at the Hanford Site has not identified any faults near the proposed disposal facility location (DOE 1988b). The closest faults are along the Umtanum Ridge-Gable Mountain structure to the north and the May Junction fault to the east. Both faults are about 7.2 kilometers (4.5 miles) from the disposal site.

2.2.7.3 Stratigraphy Under Proposed Disposal Site. Borehole 299-E24-7 lies in the northeast corner of the proposed disposal site and 299-E24-18 is located east of the site. The proposed disposal site stratigraphy is estimated from the logs of these boreholes (Figure 2-14). The stratigraphy encountered in the boreholes is summarized in Figure 2-8. Section 2.2.5.3 describes the general stratigraphic units and lithology shown in Figure 2-14. The following sections give details on the stratigraphic units at the proposed disposal site.

2.2.7.3.1 Ringold Formation. The Ringold Formation at the proposed disposal site is about 30 to 38 meters (100 to 125 feet) thick and is dominated by the gravel sequences. The Ringold Formation begins at about 100 meters (330 feet) drilled depth and

Figure 2-14. Stratigraphic Units and Lithology at the Proposed Location of the Tank Waste Remediation System Low-Level Tank Waste Disposal Facility.



continues to the top of the Columbia River Basalt Group at about 137 meters (450 feet).

The primary sediments at the Hanford Site are the Ringold gravel units A and E. Ringold unit A is probably the predominant unit. Both units are a consolidated sandy gravel to muddy sandy gravel. Without an intervening mud unit, the two cannot be easily distinguished from each other.

The Ringold lower mud unit is interpreted to pinch out to the east of the proposed disposal facility or just under it. The lower mud unit is absent in borehole 299-E24-7, but might be present farther south under the site. With the lower mud unit absent, gravel unit E directly overlies gravel unit A. The two units cannot be differentiated in borehole 299-E24-7. Studies in the 200 East Area (e.g., Tallman 1979) show that the lower mud must pinch out somewhere between the eastern boundary of 200 East Area and the proposed disposal facility site.

2.2.7.3.2 Hanford Formation. At the proposed disposal location, the Hanford formation is about 90 to 105 meters (300 to 345 feet) thick and consists predominantly of sands and gravelly sands. The sandy sequence is interpreted to lie between a slightly gravelly sand and a lower sandy gravel to gravelly sand. The Hanford formation thickens both to the north and south of the disposal facility site.

The lower gravel to gravelly sand unit averages about 35 meters (115 feet) thick and probably thins to the east on an irregular Ringold surface. Currently, the water table is probably in this lower gravel sequence. The Hanford formation sandy sequence is about 60 meters (200 feet) thick and is the dominant facies in the proposed disposal facility area. The upper 6 meters (20 feet) is composed of an irregularly distributed gravelly sand sequence.

2.2.7.3.3 Holocene Deposits. The southern 200 meters (656 feet) of the disposal facility site are covered with a stabilized dune sand that is as much as 8 meters (26 feet) high. Mature sagebrush covers much of the proposed disposal facility site and in particular the sand dunes. The age of the sagebrush indicates that the dune field has been stable since before the Hanford Site was established in the 1940's. Because of the relative flat nature of the surface, landslides are not expected to be significant.

2.2.8 Soils

Hajek (1966) lists and describes the 15 different soil types on the Hanford Site, varying from sand to silty and sandy loam. The following soils are found in the south central part of the 200 East Area:

- **Burbank Loamy Sand:** dark-colored, coarse-texture soil underlain by gravel. Surface soil is usually about

40 centimeters (16 inches) thick but can be 76 centimeters (30 inches) thick. Gravel content of subsoil ranges from 20 to 80 percent.

- **Ephrata Sandy Loam:** surface is dark colored and subsoil is dark grayish-brown medium-texture soil underlain by gravelly material, which may continue for many feet.
- **Eupart Sand:** brown-to-grayish brown coarse sand grading to dark grayish-brown at about 90 centimeters (35 inches). Developed under grass, sagebrush, and hopsage in coarse sandy alluvial deposits that were mantled by wind-blown sand.

2.2.3 Ecology and Biotic Conditions

This section summarizes the ecology of the Hanford Site, emphasizing plant and animal activities that may affect exposure pathways. The primary impact would be through root penetration and animal burrowing through barriers into the disposal facility. Secondly, the types of plants and animals and their density can affect net groundwater recharge, which is greatly influenced by surface vegetation and burrowing. Cushing (1995-4) details both the terrestrial and aquatic ecology of the Hanford Site and presents extensive listings of plant and animal species. This section will consider only terrestrial ecological effects because the proposed low-level tank waste disposal facility site is not located near significant aquatic ecological systems.

The Hanford Site consists of mostly undeveloped land. Only about 6 percent of the site is occupied by chemical processing facilities, nuclear reactors that no longer operate, and supporting facilities. Most of the Hanford Site has not experienced tillage or agricultural grazing since the early 1940's.

The Hanford Site is botanically characterized as a shrub-steppe environment. This environment contains numerous plant and animal species adapted to the region's semiarid climate. Because of the aridity and low water-holding capacity of the soils, the productivity of both plants and animals is relatively low.

The dominant plants on the Hanford Site have changed over time. In the early 1800's, before settlement and agricultural activities, the dominant plants were big sagebrush and perennial bunchgrass. Agriculture opened the area to invasion by alien plants, predominantly cheatgrass. Today, cheatgrass dominates fields and rangeland that were cultivated 50 years ago. The dominant plants on the Hanford Central Plateau are big sagebrush, rabbitbrush, cheatgrass, and Sandberg's bluegrass, with cheatgrass providing half the total plant cover. Root penetration to depths of over several meters has not been demonstrated in the 200 Areas. Rabbitbrush roots have been found at a depth of 2.4 meters (8 feet) near the 200 Areas.

A variety of birds and mammals inhabit the Hanford Site. The most abundant nesting birds of the shrub-steppe at the Hanford Site are the horned lark and western meadowlark. Significant populations of chukar and gray partridge also inhabit the Site. Mourning doves also nest throughout the Hanford Site. The most abundant mammals of the Hanford Site are mice, ground squirrels, gophers, voles, and cottontail rabbits. Larger animals include mule deer and elk. The coyote is the principal mammalian predator on the Hanford Site.

2.2.10 Regional Background Contamination and Hanford Site Monitoring

2.2.10.1 Overview. The Hanford Site has an extensive monitoring program. Studies have been directed at determining background levels of possible contaminants in the soil (DOE-RL 1994b and DOE-RL 1995b) and in the groundwater (Johnson 1993). Also, reports are issued annually covering general environmental conditions (Dirkes 1995) and groundwater monitoring (Dresel 1994).

2.2.10.2 Soil Background Levels. Low concentrations of ^{238}U and ^{137}Cs were measured in samples of soil and vegetation during 1994 (Dirkes 1995-1). 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 1995b summarizes all the measurements taken to determine radionuclide background levels at the Hanford Site. Table 2-2 displays the average of the measurements.

Table 2-2. Activity of Radionuclides in Hanford Site-wide Background Data Set (The table is reproduced from DOE-RL 1995b).

| Nuclide | Activity (pCi/g) | Nuclide | Activity (pCi/g) | Nuclide | Activity (pCi/g) |
|---------------------------|------------------|----------------------------|------------------|---------------------------|------------------|
| ^{40}K | 15.4 | ^{60}Co | 0.00132 | ^{90}Sr | 0.0806 |
| ^{137}Cs | 0.417 | ^{154}Eu | 0.0083 | ^{155}Eu | 0.0234 |
| $^{226}\text{Ra}^*$ | 0.686 | $^{232}\text{Th}+\text{D}$ | 0.687 | $^{238}\text{U}+\text{D}$ | 0.0271 |
| $^{238}\text{U}+\text{D}$ | 0.675 | ^{239}Pu | 0.00158 | $^{239/240}\text{Pu}$ | 0.00935 |

*+D^a indicates that daughters are included

^a ^{226}Ra is part of ^{238}U decay chain and is included in that entry.

2.2.10.3 Groundwater Background Levels. Sample results from environmental monitoring can vary depending on local operations, so a regional baseline study was conducted using these and other site wide monitoring results (Johnson 1993). Groundwater background levels are shown in Table 2-3, along with tentative threshold levels.

Table 2-3. Provisional Background Values for Hanford Site Groundwater.^a

| Constituent (Concentration) | PWL Results ^b | Provisional Threshold Values |
|--------------------------------|--------------------------|---------------------------------|
| Aluminum (ppb) | <2 | <200 |
| Ammonium (ppb) | <50 | <120 |
| Arsenic (ppb) | 3.9 ± 2.4 | 10 |
| Barium (ppb) | 42 ± 20 | 68.5 |
| Beryllium (ppb) | <0.3 | <5 |
| Bismuth (ppb) | <0.02 | <5 |
| Boron (ppb) | <50 | <100 |
| Cadmium (ppb) | <0.2 | <10 |
| Calcium (ppb) | 40,400 ± 10,300 | 63,600 |
| Chloride (ppb) | 10,300 ± 6,500 | NC |
| Chromium (ppb) | 4±2 | <30 |
| Copper (ppb) | <1 | <30 |
| Fluoride (ppb) | 370 ± 100 | 1,340, 775 ^c |
| Iron-Mid (ppb) | NA | 291 |
| Lead (ppb) | <0.5 | <5 |
| Magnesium (ppb) | 11,800 ± 3,400 | 16,480 |
| Manganese (ppb) | 7±5 | NC |
| Mercury (ppb) | <0.1 | <0.1 |
| Nickel (ppb) | <4 | <30 |
| Nitrate (ppb) | NA | 12,400 |
| Phosphate (ppb) | <1,000 | <1,000 |
| Potassium (ppb) | 4,950 ± 1,240 | 7,975 |
| Selenium (ppb) | <2 | <5 |
| Silver (ppb) | <10 | <10 |
| Silicon (ppb) | NA | 26,500 |
| Sodium (ppb) | 18,260 ± 10,150 | 33,500 |
| Strontium (ppb) | 236 ± 102 | 264.1 |
| Sulfate (ppb) | 34,300 ± 16,900 | 90,500 |
| Uranium (pCi/l) | 1.7 ± 0.8 | 3.43 |
| Vanadium (ppb) | 17 ± 9 | 15 |

| Constituent (Concentration) | PNL Results ^a | Provisional Threshold Values |
|---------------------------------|--------------------------|---------------------------------|
| Zinc (ppb) | 6 ± 2 | NC |
| Field Alkalinity(ppb) | NA | 215,000 |
| Lab Alkalinity (ppb) | 123,000 ± 21,000 | 210,000 |
| Field pH | NA | (6.90, 8.24) |
| Lab pH | 7.64 ± 0.16 | (7.25, 8.25) |
| Total Organic Carbon (ppb) | 586 ± 347 | 2,610, 1,610 ^c |
| Field Conductivity (µmho/cm) | NA | 539 |
| Lab Conductivity (µmho/cm) | 380 ± 82 | 530 |
| TOX, LDL (ppb) | NA | 60.8, 37.6 ^c |
| Total Carbon (ppb) | NA | 50,100 |
| Gross Alpha (pCi/l) | 2.5 ± 1.4 | 63, 5.79 ^c |
| Gross Beta (pCi/l) | 19 ± 12 | 35.5, 12.62 ^c |
| Radium (pCi/l) | <0.2 | 0.23 |

^a From Tables 5-9 and 5-11 of DOE-RL 1992.

^b Results shown are mean ± one standard deviation, unless only an upper limit is given.

^c Potential outlier observation(s) were removed.

NA = not available.

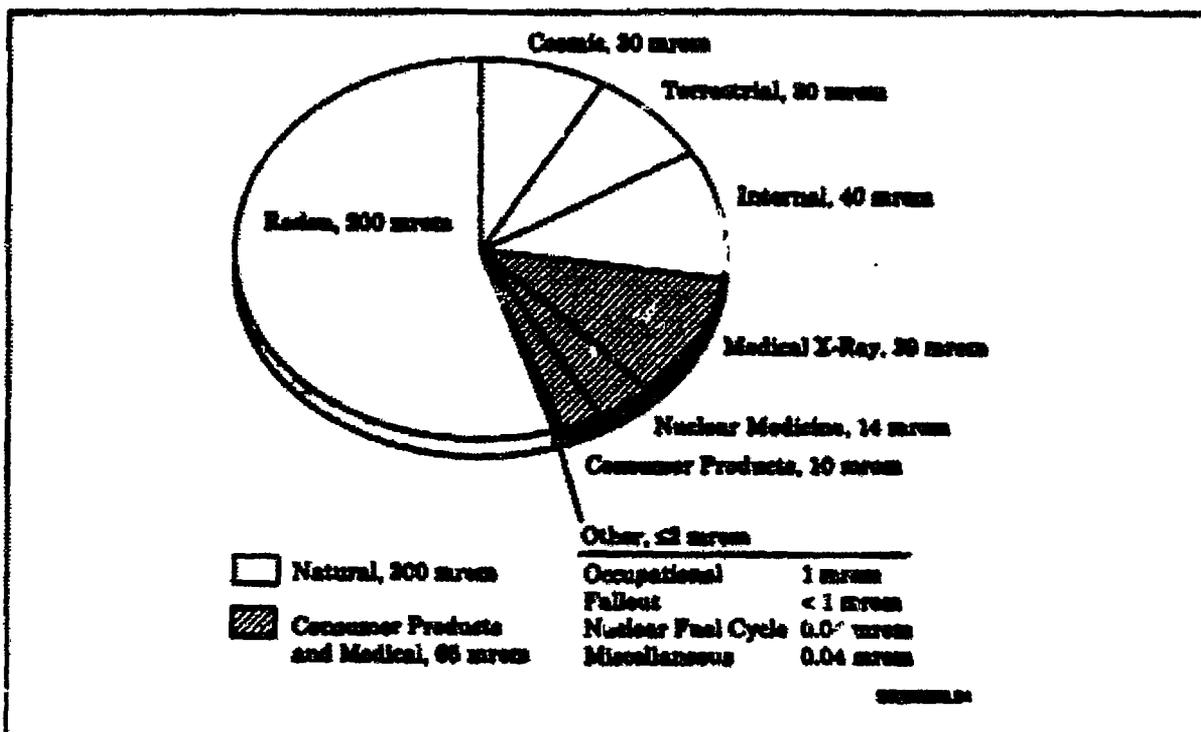
NC = not calculated.

2.2.10.4 Radiation Background Levels. Various natural and human-produced sources contribute to radiation doses. These sources include natural terrestrial and cosmic background radiation, medical treatment and x-rays, natural internal body radioactivity, and inhalation of naturally occurring radon. Figure 2-15 shows the national average dose from each of these sources to an individual. Of the contributions shown in Figure 2-15, natural background contributes 300 mrem to the estimated per capita annual dose to individuals living near the Hanford Site. Human-produced sources contribute an additional 65 mrem. In contrast, annual Hanford Site environmental reports such as Dirkes and Hanf (Dirkes 1995-2) estimate that the maximum annual dose to an individual from Hanford Site operations in 1994 was about 0.05 mrem. This value is similar to values seen in the last 4 years.

Other non-DOE industrial sources of public radiation exposure exist at or near the Hanford Site. These include the low-level radioactive waste burial site operated by U.S. Ecology, the nuclear generating station operated by the Supply System, the

nuclear fuel production plant operated by Siemens Nuclear Power Corporation, the low-level waste compacting facility operated by Allied Technology Corporation, and a decontamination facility operated by Pacific Nuclear Services. Based on information gathered from these companies, Dirkes and Hanf (Dirkes 1995-2) conservatively determined that the total 1994 annual dose for the hypothetical maximally exposed individual from those activities was also 0.05 mrem.

Figure 2-15. Averages for Natural and Human-Produced Sources of Radiation (NCRP 1987).



2.3 WASTE CHARACTERISTICS

2.3.1 Overview

The source of the waste material to be incorporated into a solidified waste form is the waste currently stored in the Hanford Site's single- and double-shell tanks.

Processes used to recover plutonium and uranium from irradiated fuel and radionuclides from tank waste plus miscellaneous sources (e.g., laboratory waste and reactor decontamination solutions) generated over 209,000 m³ (55.3 Mgal) [Hanlon 1996-1] of waste at the Hanford Site. This waste is currently stored in 177 underground tanks in the

200 Areas. The consistency of the tank waste ranges from dilute aqueous solutions to thick paste to hard rock.

The waste will be retrieved from the tanks and pretreated to form the high-level and low-level radioactive waste streams. The high-level radioactive waste stream will contain 90% of the radionuclides. This waste stream will be vitrified, and the product stored until it can be transferred to a licensed repository. The low-level radioactive waste stream contains the bulk of the non-radioactive chemicals, and is predominantly made up of the soluble components of the waste in the tanks. This waste stream will be solidified in a glass or other form that meets the DOE specifications (DOE-RL 1996, reproduced in Appendix A). It is proposed to dispose of the low-level waste form on site in a manner that allows the waste to be retrievable for at least 50 years, although this time period has not been officially adopted.

This overall strategy for the Hanford Tank Waste Remediation System is shown in Figure 2-16 (DOE-RL 1995a-1).

2.3.2 Underground Tank Storage

To store the liquid radioactive waste generated by Hanford Site operations since 1944, 149 single-shell tanks and 28 double-shell underground tanks were built. The tanks are grouped into 18 tank farms.

Four basic chemical processing operations generated the radioactive waste solutions. These operations were the Bismuth Phosphate process, the REDOX process, the PUREX process, and the Tributyl Phosphate process. The first three processes recovered plutonium from irradiated reactor fuels. The last process recovered uranium waste generated in the bismuth phosphate process. Other specialized campaigns recovered ^{137}Cs , ^{90}Sr , and other special nuclear materials. To make it less corrosive, the aqueous waste was made alkaline for storage in the underground tanks. Anderson (1990) provides a history of the liquid waste generation and its subsequent handling and storage in the tank farms.

The single-shell tanks, built between 1943 and 1964, are made of reinforced concrete with carbon steel liners (Figure 2-17). Their nominal capacities range from 208 m³ (55,000 gal) to 3,785 m³ (1 Mgal). No new waste has been added to any of these tanks since 1980. Most of the pumpable liquids have been transferred to double-shell tanks for safer storage. The remaining waste is in the following forms:

- Insoluble sludge with interstitial liquids
- Crystalline, water-soluble solids (salt cake)
- Supernatant liquids.

and nitrite, sodium hydroxide, sodium aluminate, sodium phosphate, various insoluble hydroxides and phosphates, significant quantities of organic materials, and approximately 250 MCi of many different radionuclides. The main effect of the treatment steps other than neutralization was to alter the water content of the waste.

2.3.3 Tank Waste Retrieval

According to the Tri-Party Agreement (Ecology 1996-3), as much waste as is technically possible must be removed from the tanks. Unless limited by waste retrieval technology, the single-shell tank waste residues must not exceed -10 m³ (360 ft³) in each 100-series tank, which can hold 208 m³ (55,000 gallons) of waste. For the 200-series tanks, which have volumes above 2,000 m³ (530,000 gallons), the limit is 30 ft³ (-1 m³). On a tank-by-tank basis, the DOE can request the EPA and Ecology to approve a higher residue limit.

2.3.4 Separations

The purpose of the separations step is to separate the retrieved tank waste into the following two radioactive waste streams:

- A low-level stream containing the bulk of the material
- A much smaller high-level stream containing most of the radionuclides.

TWRS plans to use the following three-step approach to accomplish this task.

1. Separate the soluble fraction from the insoluble fraction of the in-tank waste by means of in-tank "sludge washing" followed by settle-decant of the supernate.
2. Pretreat the soluble fraction to provide a feed to the low-level waste immobilization facility that is in accordance with the U.S. Nuclear Regulatory Commission's "incidental waste" classification for Hanford Site waste (Berneo 1993).
 - The waste has been processed (or will further be processed) to remove key radionuclides to the maximum extent possible that is technically and economically practical.
 - The waste will be incorporated in a solid physical form at a concentration level that does not exceed the applicable concentration limits for Class C low-level waste as set out in 10 CFR Part 61 (10 CFR 61-2).

- The waste is to be managed, pursuant to the Atomic Energy Act (AEA 1954), so that safety requirements comparable to the performance objectives set out in 10 CFR Part 61 (10 CFR 61 - 3) are satisfied.
- 3. Wash the insoluble fraction in-tank and then use enhanced in-tank sludge washing (alkaline leaching) to remove more soluble non-radioactive material from the feed going to the high-level waste vitrification facility. Any additional pretreatment required will be performed in the proposed high-level waste pretreatment facility.

2.3.5 Immobilization of the Low-Level Waste

After separation, the waste will be immobilized. The nature of the resulting waste form has not yet been determined. Only some external properties (size, shape), including the maximum contaminant release rate, have been set (DOE-RL 1996). However, there is a high probability that some or all of the low-level waste will be vitrified. None of the secondary waste streams from immobilization are expected to go into the proposed low-level tank waste disposal facility.

2.3.6 Privatization

The DOE is proceeding to privatize the immobilization functions of the TWRS. Under privatization, DOE would supply material retrieved from the tanks to private companies. DOE would then receive back the high-level waste, the low-level solidified waste, and various other waste streams. Specifications for the separation and immobilization of the first 6 to 13 percent of the retrieved waste are included in Appendix 2-A. Specifications for the remainder of the waste are not expected until 2004. In the specifications, the phrase "low-activity" is used instead of "low-level."

2.3.7 Packaging and Certification

The physical, chemical, and radiological properties of the waste at the time of disposal have not been completely determined. The waste form is expected to be contained in metal containers having external dimensions of 1.8 by 1.2 by 1.2 meters (about 6 by 4 by 4 feet) (DOE-RL 1996).

Since the contract for privatization is about to be awarded, no certification procedure has been established. Because of the time and associated facilities necessary to test the product, most of the certification procedure will probably address monitoring the waste immobilization process rather than testing the product itself.

2.4 DISPOSAL TECHNOLOGY

2.4.1 Overview

The design process for the disposal facilities has not yet begun. In the absence of a design, two disposal facility concepts were developed for the interim performance assessment. Both concepts are based on a vault disposal concept developed for estimating costs for a disposal options configuration study (Mitchell 1995). The vault concept was enhanced by adding physical barriers to inhibit water from entering the vault and a chemical barrier to reduce glass corrosion (Eibolzer 1995). The concepts were based on the assumption that the waste would be in glass form. The difference between the two facility concepts is the approach taken to incorporate the enhancements. Figures 2-19 and 2-20 show Concepts 1 and 2, respectively.

The following sections outline the current concepts and thinking for disposal technology for the low-level tank waste disposal facility. The disposal units, waste handling and interim storage operations, waste emplacement, disposal unit closure and stabilization, and site closure are addressed. For some of the areas covered, planning work has not started. In other areas, the only ideas available now are related to the vault concept given in Mitchell 1995.

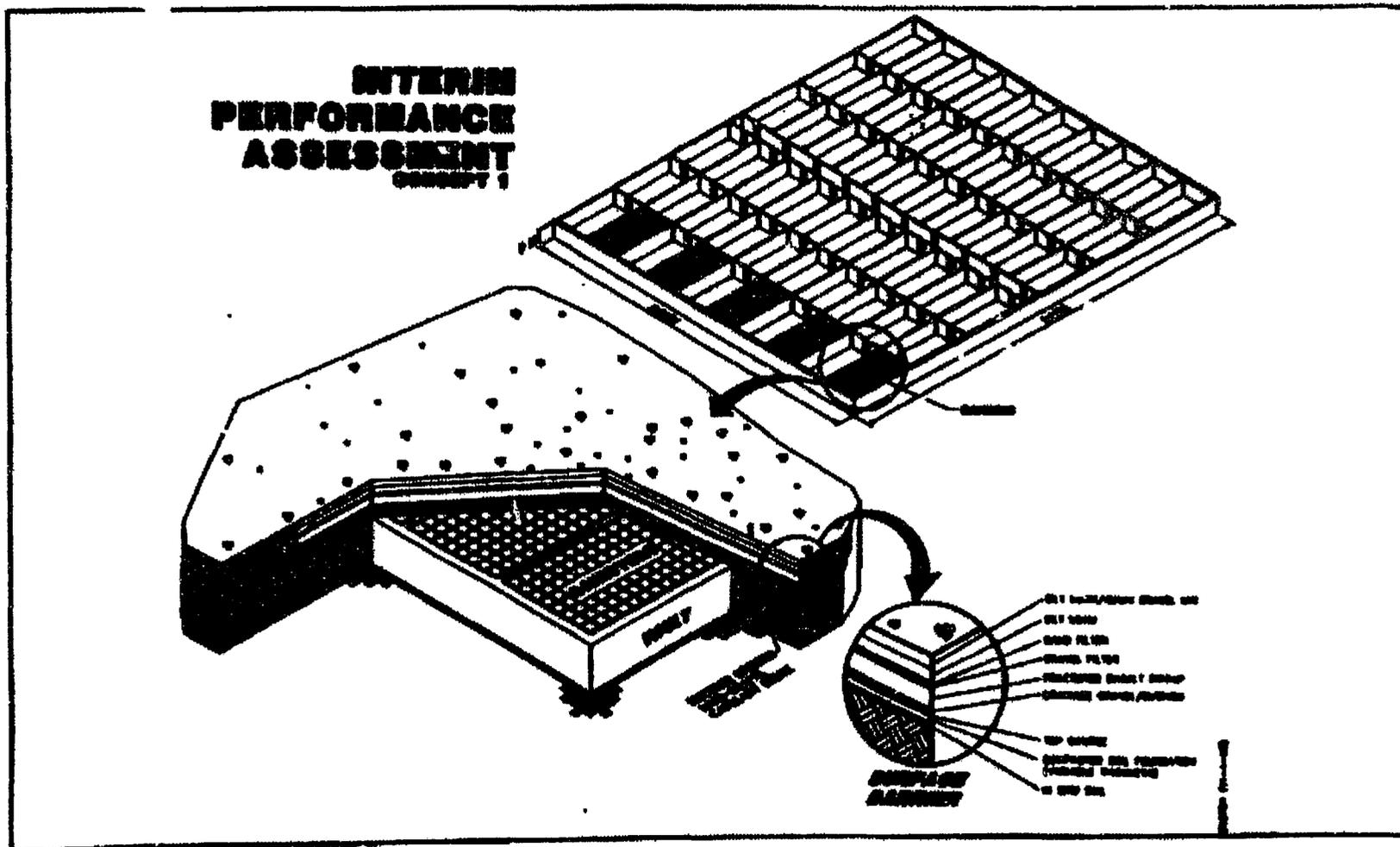
2.4.2 Disposal Units

The vault bay is the basic unit for both disposal facility concepts. The overall concrete facility is divided into several sections called vault bays. Each vault bay is 38 by 19.5 by 9 meters high (125 by 64 by 29.5 feet). The number of vault bays depends on the size of the canisters and the spacing between canisters. The vault bays have concrete walls, floors, and ceilings. Six vault bays form a vault row.

Concept 1 consists of 10 adjacent vault rows, all of which are covered by continuous water barriers and a water-conditioning layer (Figure 2-19). The uppermost barrier is the surface barrier which is designed to minimize intrusion and recharge. Beneath the surface barrier, a sand-gravel capillary break will divert any moisture that may come through the surface barrier away from the vault. These two barriers implement the goal of minimizing the amount of water that enters the vault.

Beneath the capillary break is a water-conditioning layer of crushed glass. This layer will increase the silica content of any moisture that penetrates the first two barriers. It has been well documented in water saturated tests with a wide variety of glass compositions that corrosion rates are much lower in water that is near saturation with respect to amorphous silica. However, as yet, there is no theoretical or direct laboratory evidence that such preconditioning will be effective in reducing glass corrosion rates under low moisture conditions, as are expected in the disposal vault.

Figure 2-19. Facility Concept 1.



Concept 2 consists of 13 vault rows each having its own capillary break and water-conditioning layer (Figures 2-20 and 2-21). The rows containing waste canisters are separated by rows of backfilled soil. The reason for alternating rows of vault bays and rows of soil was to reduce the width of the capillary break. The stability of the long capillary break in Concept 1 is a concern. The soil between vault rows allows each capillary break to drain into soil instead of another vault bay. Each row containing canisters is covered by a water-conditioning layer similar to the one described for Concept 1. The entire engineered region of Concept 2 is capped with a surface barrier.

2.4.3 Waste Handling and Interim Storage Operations

Currently, conceptual plans for waste handling or storage are beginning to be studied. How the waste containers will be handled and transported to interim storage will depend on the size of the containers and the proximity of the storage area to the waste immobilization processing area. The proposed privatization effort will determine or influence these factors.

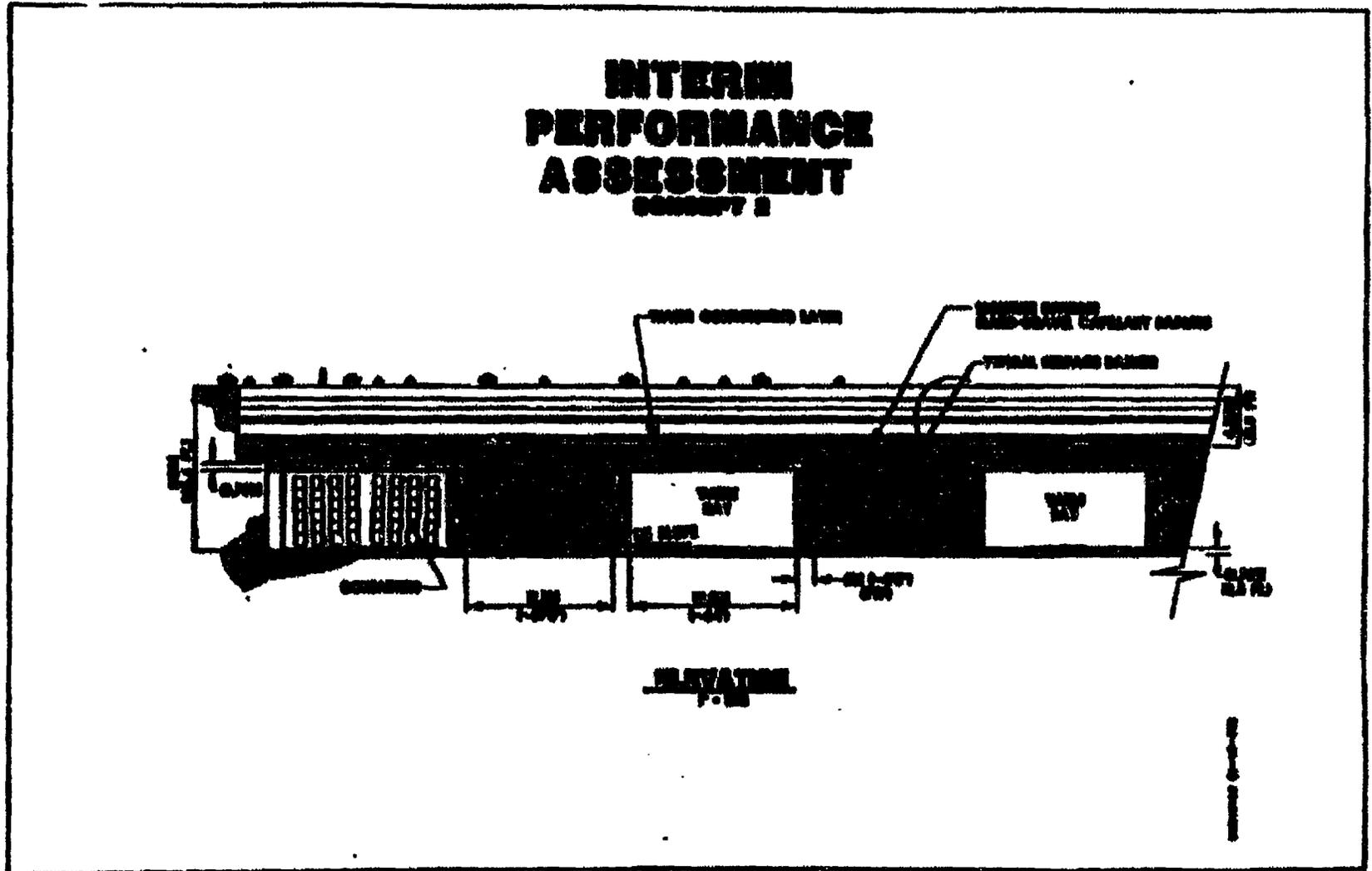
2.4.4 Waste Emplacement

Mitchell (1995) provides an idea on how the waste packages might be placed in the disposal facility. This concept was developed for the vault facility described in Mitchell (1995) and used as the basis for disposal facility Concepts 1 and 2. The filled containers would be brought into the disposal facility and moved within the facility remotely. A cart on a track would bring the waste container into the facility. A remotely operated crane in the facility would remove the waste container from the cart and place the container in one of the vault bays. This emplacement method did not consider the placement of backfilled soil between the containers because filler material was not considered in Mitchell (1995).

Both Concepts 1 and 2 include backfilled soil around and on top of the waste containers in the facility. The soil was included in these concepts for the following three reasons:

- Structural support. The initial Mitchell 1995 design had void space between the canisters and between the canisters and the ceiling. The soil would help prevent significant subsidence of the physical barriers when the concrete components of the system fail and collapse into the void space.
- To wick moisture away from the waste canisters.
- To provide radiation shielding for the facility workers.

Figure 2-21. Facility Concept 2, Cross Section of Concept.



2.4.5 Disposal Unit Closure and Stabilization

Plans for the disposal unit closure and stabilization have not been developed yet. For this analysis, the unit is assumed to be closed so that the amount of water inside the disposal unit is minimized.

2.4.6 Disposal Site Closure

Disposal site closure is presumed to consist of applying the surface barrier and placing passive controls on the surface. The surface barrier envision is based on the Hanford Barrier (Myers 1994). The intent of the surface barrier is to use evaporation and plant transpiration to minimize the effect of precipitation on the disposal system. The surface barrier includes a sand/gravel layer to work as another capillary break and a layer of basalt riprap to deter burrowing animals, plant root intrusion, and inadvertent intruders.

The original Hanford Barrier included an asphalt layer to help prevent moisture for going toward the vault. This layer has been eliminated for the current disposal concepts for two reasons. First, another capillary break is being used for the second defense to prevent moisture for reaching the vault. Second, the asphalt layer is organic. Organic mixtures are being avoided because they may enhance colloid transport.

Passive controls are assumed to be used to deter inadvertent intrusion. However, the type of passive controls have not yet been selected.

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3.0 ANALYSIS OF PERFORMANCE

3.1 OVERVIEW

This chapter defines the models, computer codes, and input data used to analyze the long-term performance of the proposed disposal facility. The information from Chapter 2 is translated into a conceptual model, then into a numerical model. The data for the conceptual and numerical models are described and justified to the extent practicable. Stronger justification is expected in the preliminary and final performance assessments. For this assessment, the justification is mostly based on engineering judgment; for the preliminary and final assessments it will be based on experimental evidence that is specific to the site, waste form, and facility design as well as from calculational evidence.

The analysis strategy for this assessment was to define and perform an analysis of a base analysis case and sensitivity cases bracketing the base analysis case. The base analysis case was developed using our best estimates of the environmental, the waste form, and the disposal facility parameters and how they will change with time. Following the recommendations of the Peer Review Panel (Case 1989), assumptions were "conservative but reasonable."

Most of the information in this chapter comes from previously released documents related to the interim performance assessment. Most of the data are from *Data Packages for the Hanford Low-Level Tank Waste Interim Performance Assessment* (Mann 1995a). The base analysis case was defined in *Definition of the Base Analysis Case of the Interim Performance Assessment* (Mann 1995b), which also contains a list of sensitivity cases.

This chapter shows in the following manner how the physical systems presented in Chapter 2 are translated into the numerical models which produce the results presented in Chapter 4.

1. The source term radionuclide inventories are described (Section 3.2).
2. The pathways and scenarios analyzed are explained (Section 3.3).
3. The assumptions (Section 3.4) and methodology (Section 3.5) used in the analyses, including the actual data used are presented.
4. The quality assurance measures used in the project are described (Section 3.6).

3.2 SOURCE TERMS

3.2.1 Relevant Isotopes

The anticipated tank waste inventories were prescreened (Schmittroth 1995a) to determine which radionuclides are potential problems for the inadvertent intruder and groundwater pathway scenarios. The study indicated that the following radionuclides are the potentially most important ones for each scenario:

- ^{90}Sr , ^{99}Tc , ^{137}Cs , ^{126}Sn , ^{237}Ac , ^{239}Pu , and ^{241}Am for the inadvertent intruder scenario
- ^{90}Sr , ^{99}Tc (from ^{90}Sr and ^{99}Mo), ^{137}Cs , ^{131}I , and uranium isotopes and their daughters for the groundwater scenario
- Uranium, plutonium, neptunium, and americium isotopes and their daughters for the groundwater scenario in which geochemical retardation effects are ignored.

For this analysis, the top 10 contributors from the inadvertent intruder scenario, the top 12 contributors from the groundwater scenario, and the top 14 contributors from the unretarded groundwater scenario were used. These 26 isotopes contribute over 99% of the dose for the scenarios.

3.2.2 Inventory Values

The inventory for this study is from Schmittroth 1995b except where noted. Inventory values were not taken from the Grout Performance Assessment (Kincaid 1995), because those estimates were only the waste from double-shell tanks and because those estimates have been superseded. As the TWRS Characterization Program proceeds, new and better estimates are expected and will be used in the preliminary and final performance assessments.

Table 3-1 gives the inventories for the year 2010, which is halfway through the treatment, immobilization, and disposal operations. The column labeled "Percent to LLW from Tanks" provides the current estimate of the fractional amount of material that will go into the waste form. This estimate comes primarily from the Process Design Group of the Disposal Engineering Section of the Westinghouse Hanford Company (Attachment 1 of Schmittroth 1995b). However, noted changes in Table 3-1 are from Petersen 1995. Inventories for years other than 2010 and for all the radionuclides are given in Schmittroth 1995b. The following paragraphs summarize how the inventory was developed.

Table 3-1. Inventories for Interim Performance Assessment.^a
Inventory is decayed to 2010.

| Radionuclide | Percent to LLW from Tanks ^b | Inventory in LLW Decayed to 2010 (Curies) |
|-------------------------------|--|---|
| ³ H | 100 | 8.94 E+4 |
| ¹⁴ C | 1 | 7.73 E+0 |
| ⁷⁵ Se | 100 ^c | 1.03 E+3 |
| ⁹⁰ Sr | 3 ^e | 1.61 E+6 ^e |
| ⁹² Zr | 1 ^f | 4.87 E+1 |
| ⁹³ Nb ^g | 1 ^f | 4.20 E+1 |
| ⁹⁹ Tc | 82 | 2.23 E+4 |
| ¹¹⁰ Sn | 100 ^h | 1.58 E+3 |
| ¹²⁹ I | 10 ⁱ | 6.62 E+0 |
| ¹³⁷ Cs | 1 ^g | 4.51 E+5 ^e |
| ¹⁵¹ Sm | 1 ^f | 3.16 E+4 |
| ²²⁶ Ra | 50 ^{f,h} | 2.35 E-3 |
| ²²⁸ Ra | 50 ^{f,h} | 1.38 E+0 |
| ²²⁷ Ac | 1 ^{f,h} | 1.08 E+0 |
| ²²⁹ Th | 1 ^{f,h} | 9.79 E-3 |
| ²³² Th | 1 ^{f,h} | 2.68 E-2 |
| ²³¹ Pa | 100 ^{g,h} | 1.45 E+2 |
| ²³³ U | 6 | 2.58 E+1 |
| ²³⁴ U | 6 | 1.80 E+1 |
| ²³⁵ U | 6 | 7.36 E-1 |
| ²³⁶ U | 6 | 4.47 E-1 |
| ²³⁸ U | 6 | 1.78 E+1 |
| ²³⁷ Np | 5 | 3.74 E+0 |
| ²³⁹ Pu | 6 | 2.23 E+3 |
| ²⁴⁰ Pu | 6 | 4.31 E+2 |
| ²⁴¹ Am | 8 | 4.25 E+3 |
| ²⁴³ Am | 8 | 2.70 E+0 |
| ²⁴⁵ Cm | 100 ^c | 1.03 E-1 |

- * Data are taken from Schmittroth 1995b except as indicated by superscript "f".
- * The fraction of tank waste going into the waste form was taken from Shelton 1995.
- * Because of the absence of defensible data, no credit is taken for a reduction in the amount going to the low-level fraction.
- * 23 percent of ^{90}Sr produced went into capsules rather than tanks.
- * The daughters (^{90}Y and ^{210}Pb) are in secular equilibrium with their parents and their inventories are not included.
- * These values are based on the more recent work of Petersen (1995). Schmittroth 1995b used values of 100 percent because of the lack of data.
- * 45 percent of ^{137}Cs produced went into capsules rather than tanks.
- * Also a decay product of other actinides.
- * Assumed in order to track significance. Most of ^{131}I is assumed to be trapped in off-gas stream and disposed elsewhere.

3.2.3 General Description of the Development of Current Inventory

3.2.3.1 Introduction. Tank-by-tank inventories of the radionuclides are generally not currently well known. However, reactor production records are accurate enough to establish accurate total tank waste inventory values for most of the fission products and uranium. The actinide inventory is more uncertain because actinide production is sensitive to the time dependence of the neutron function and to processing transfers and losses. The estimated loss of fission products (particularly technetium and iodine) during processing or from tank leaks or discharges was used in adjusting the inventories.

Schmittroth et al. (Schmittroth 1995b) developed an inventory for this interim performance assessment. This inventory is based on the production of various radionuclides and the losses of the same radionuclides from processing and other factors. The strategy used started by calculating radionuclide production values with the ORIGEN2 code (Croff 1980). (The detailed ORIGEN2 model is documented in Schmittroth 1995b.) Then, the calculated production values were corrected for known losses. Next, the reduction factors (splits) from the pretreated waste to an assumed glass waste form (Shelton 1995) are incorporated. Sections 3.2.3.2 through 3.2.3.5 summarize this strategy. Schmittroth (1995b) gives the details.

3.2.3.2 Calculated Radionuclide Production. The irradiation histories of Hanford's production reactors are modeled as two conceptual reactors. The ORIGEN2 computer code (Croff 1980) is used for this modeling. One conceptual reactor is representative

of all the single-pass irradiations. The other conceptual reactor explicitly models the N reactor, the last production reactor at the Hanford Site. In both cases, detailed fuel types and irradiation histories are simplified, but still accurate. For example, although some enriched fuel was used in the single-pass irradiations, it was assumed that all the single-pass fuel was natural uranium. Likewise, although N reactor produced some weapons-grade plutonium, a burnup of 2,000 MWd/MTU, more typical of fuels-grade production, was used for the entire operating history. The consequences of these assumptions are more fully reported in Schmittroth 1995b.

Schmittroth et al. (1995b) modified an earlier radionuclide production calculation to obtain the current inventory. Two thorium campaigns were added to the model to account for ^{233}U production. N reactor fuel discharged to the K Basins was deleted from the production history because this fuel will not be processed. Cross section modifications were also included. The $^{235}\text{U}(n,2n)$ cross section was adjusted to better account for ^{237}Np production. The thorium capture cross section was changed to account for ^{233}U production.

The uncertainties of the ORIGEN2 results vary for different nuclides. For some, including the important fission products ^{99}Tc , ^{90}Sr , and ^{137}Cs , and ^{129}I , these uncertainties are expected to be less than 10 percent. The results in these instances depend primarily on fission-product yields and the production reactor operating histories. Both these areas are well known. The inventories of ^{235}U and ^{239}Pu before reprocessing are also well-known. However, reprocessing efficiencies and other losses introduce significant uncertainties in the estimated tank waste inventories for these isotopes. These uncertainties are less than a factor of 2 and based on conservative reprocessing efficiencies; i.e., losses to waste were overestimated. Uncertainties for uranium, neptunium, and plutonium may also be significant. Calculations for ^3H and ^{14}C require special care, and current results are only rough estimates.

3.2.3.3 Hanford Production Processing and Storage. Recovery fractions from the processing of material from the Hanford Site production reactors were included in the ORIGEN2 model. These fractions were deducted from the reprocessed waste. The assumed uranium recovery value from reprocessing was 0.99 to give a more conservative (larger) value for the amount of uranium waste. While efficiencies were higher for much of the reprocessing history, considerable uncertainty is associated with early operations. In the early operations, the uranium was discarded, then later extracted in U plant recovery operations.

The separation fractions for technetium and neptunium were also large. Evidence is good that 20 percent or more of the technetium produced was lost to the waste stream, mainly co-processed with the UO₂ and sent off site. Small amounts of technetium were lost to the environment as well. For most of the Hanford processing history, about 70 percent of the neptunium was

recovered. Support for these values is provided in Section 4 of Schmittroth (1995b).

3.2.3.4 Pretreatment and Vitrification Losses. The fractions of radionuclides that go to the low-level waste depend on evolving pretreatment evaluations. The amount of separation is uncertain because the separation process has not yet been determined. Preliminary values were recently updated (Shelton 1995) with mainly minor changes from the 1994 estimate (Boldt 1994). The most significant change was an increase from 60 to 82 percent for the fraction of technetium that becomes part of the low-level glass waste. The estimate of the fraction of uranium going to the low-level waste stream (6 percent) was unchanged. However, a somewhat higher value is possible. All the tin was assumed to follow the low-level waste, although there is some indication that the amount may be less than 100 percent. In recognition of the potential importance of ^{129}I , the fraction going to the low-level waste was given as 10 percent in a 1994 memo (Boldt 1994). In the most recent memo (Shelton 1995), this value was reduced to zero reflecting the expected volatilization of iodine in the melter. To ensure that ^{129}I continues to be monitored in the interim performance assessment, the earlier value of 10 percent was maintained. Table 3-1 shows the specific values for separation fractions used in the present analyses.

Much of the total cesium and strontium produced in the reactors was separated in earlier chemical processing campaigns at the Hanford Site. This separated inventory, which currently resides in capsules, is not included in this low-level waste inventory. This assumption is consistent with the revised Tri-Party Agreement (Ecology 1996-2), which assumes that cesium and strontium in capsules will be disposed of as high-level waste.

Following pretreatment of the tank waste, immobilization of the low-level waste stream is expected to volatilize some species, notably iodine, cesium, and potentially technetium. The present plan is to trap the volatile radionuclides and to dispose of them in a separate facility.

3.2.3.5 Modeling of Decay Chains. In general, the ORIGEN2 model represents the complete production history as well as the reprocessing operations and losses. Thus, the ORIGEN2 results provide total radionuclide inventories for both the single-shell and double-shell tanks. For the most part, recovery fractions and losses expected during pretreatment of the tank waste going to the low-level waste stream are treated separately. An exception was made for the uranium pretreatment recovery fraction, assumed to be 6 percent, that was explicitly included in the ORIGEN2 calculation. The long half-lives associated with uranium and its daughters make it necessary to explicitly follow the decay chains after the pretreatment split.

3.2.4 Tank-to-Tank Variations

Only the estimate for the total inventory is used for the interim performance assessment. Presently, a good estimate of tank-to-tank variations is not available. Large differences in concentrations are known to exist among the tanks. For example, ^{99}Tc concentrations vary from less than $0.01 \mu\text{Ci}/\text{ml}$ to $1 \mu\text{Ci}/\text{ml}$ with a mean of about $0.09 \mu\text{Ci}/\text{ml}$ (Schmittroth 1995b). Because waste from various tanks is expected to be mixed, the extremes will not be this severe. However, accurate variations cannot be estimated now because the mixing sequence is not known. Variations in the amount of other radionuclides are also expected but at the present are not well known.

3.2.5 Release Rate from Waste Form

The radionuclide source term used in the transport calculations is not only based on the inventory discussed but also on the release rate of the radionuclides. The release rate is a function of the waste form, the disposal facility design, and the resulting chemical environment.

For an accurate determination of the source term, the chemical and physical models for contaminant release from the waste form must be explicitly modelled. However, because the waste form has not yet been determined and only specifications for its short-term release rate are known (DOE-RL 1996), simplified models are used in this analysis. More complete computer simulations of waste form corrosion and contaminant release are planned similar to the simulations found in some of the sensitivity studies.

The scenario for radionuclide release is described in Section 3.3.4 (Contaminant Release Scenario). The release rates of radionuclides from the waste form actually used in the calculations are described in Section 3.4.5.4 (Waste Form Radionuclide Release Rate).

3.3 Pathways and Scenarios

3.3.1 Overview

This section discusses the selection criteria, the pathways considered and not considered, and the exposure pathways considered and not considered. Special emphasis is given to the justification of the choices made. In this discussion pathways refer to the various environmental paths (for example, groundwater) by which contaminants move in order to go from the waste form to the human environment. Scenarios are the environmental and human-made events (for example, human intrusion or irrigation) which influence how contaminants move or affect humans.

3.3.2 Selection Criteria

The selection of relevant pathways and scenarios for these analyses was mainly based on pathways and scenarios used in earlier Hanford Site long-term environmental analysis documents. Previous long-term environmental analyses have included performance assessments written to satisfy the requirements of DOE Order 5820.2a as well as environmental impact statements. As noted in Section 1.2.1, four Hanford Site performance assessments for the disposal of low-level waste have already been done (Kincaid 1995, Wood 1994b, Wood 1995, and Wood 1996). The most important environmental impact statements (EIS) have been the Hanford Defense Waste EIS (DOE 1987) and the Tank Waste Remediation System EIS (DOE 1996b). These documents have been fairly consistent in their choice of pathways and scenarios.

After reviewing the relevant documents, reviews, and guidance, pathways and scenarios were selected for this interim performance assessment. Selection was based on the relevance of the pathway or scenarios to the current disposal action and performance objectives. Sections 3.3.3 and 3.3.4 contain summaries of the selections and justifications.

3.3.3 Pathways

3.3.3.1 Introduction. The selection of pathways for this performance assessment is covered more fully in Scenarios of the TWRS Low-Level Waste Disposal Program (WMC 1995). Possible scenarios were suggested by analyzing the performance objectives from Chapter 1 and determining which pathways could lead to a level of exposure represented by the specified performance objective. Postulated land use was also studied to determine possible additional pathways. Finally, likely natural events were identified.

In previous Hanford Site performance assessments (Wood 1994b, Kincaid 1995, Wood 1995, Wood 1996), the dominant pathway involved the groundwater pathway. Infiltration of moisture from precipitation entered the engineered system, where the moisture may cause release of the contaminants (for example in a water-glass interaction) or may simply carry away already released contaminants. The moisture and released contaminants travel downward through the vadose zone until the contaminants reach the unconfined aquifer where humans can encounter the radioisotopes through recovery of the groundwater resource for uses in residential and agricultural settings. From previous analyses (Rawlins 1994, Mann 1995b) supporting the Hanford Low-Level Tank Waste Program, this pathway again is expected to be dominant.

The rest of this discussion on pathways is divided into four subsections. First, the future land use of the Central Plateau is discussed. Based on the future land use, the second subsection gives land-use-driven scenarios. Then the inadvertent

intruder scenarios are discussed. These intruder scenarios provide additional pathways to consider. Finally possible natural event scenarios are identified.

3.3.3.2 Future Land Use. In 1992 the Hanford Future Site Uses Working Group (HFSUWG) was charged to determine potential future uses of the various parts of the Hanford Site. This group consisted of local, state, and federal officials, representatives of affected Indian tribes, and people from agriculture and labor, as well as members of environmental and other special interest groups. Their summary report (HFSUWG 1992a-2) states

"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 the disposal areas."

The following four general land uses can be envisioned for the Central Plateau over the time of interest to a performance assessment.

- Industrial/commercial
- Dry-land farming
- Irrigated farming
- Natural.

The present land use is heavy industrial. If this use is maintained, records of past activities (particularly the disposal of nuclear materials) are likely to be kept. In addition, in an industrial area, liquid discharges to the ground would be highly regulated and be kept small.

Dry-land farming occurs on the Horse Heaven Hills which are south of the Hanford Site. Like the Central Plateau, the Horse Heaven Hills are near, but at a significantly higher elevation than, the Columbia River. Little irrigation occurs in the Horse Heaven Hills because of the relatively high energy cost (hence economic cost) of bringing water to the surface. Groundwater is used, however, for household and other small-scale uses.

East of the Central Plateau, across the Columbia River, irrigated farming is extremely common. The water, however, does not come from the nearby stretches of the Columbia River. The water comes from the Columbia Basin Project, which derives its water from the Grand Coulee Dam, over 322 kilometers (200 miles) upstream of the Hanford Site. The water is gravity-fed to the farms. The regional geography makes such a water delivery system unlikely for the Central Plateau.

Finally, west of the Central Plateau is the Fitzner/Eberhardt Arid Lands Ecology Reserve, a nature preserve area.

For the base analysis case, the assumptions used related to how land would be used in the future where that knowledge of the disposal activities has been retained and that water discharges to the ground are minimized. These assumptions are consistent with the assumptions of HFSWG, the DOE, and the local planning authorities which are all using a short term (50-100 year) planning horizon.

3.3.3.3 Land-Use-Driven Scenarios

3.3.3.3.1 Introduction. The pathways described here assume that some controls remain in place to prevent public intrusion into the disposal site. That is, the barriers and markers that are to be left will be effective in preventing open use of the land over the disposal site. The land surrounding the marked area, however, could be farmed and could contain wells.

Based on previous analyses at the Hanford Site, the main exposure pathway is expected to be the contamination of the underground aquifer leading to various exposure scenarios. Other pathways include the upward diffusion through the engineered system into the air. The scenario for contaminant release from the engineered system is given Section 3.3.4. Exposure scenarios are described in Section 3.3.6.

3.3.3.3.2 Unconfined Aquifer Contamination. Contamination of the unconfined aquifer is caused by water (natural or human-caused) penetrating through the ground surface layer, interacting with the engineered structure (including the waste), and then transporting contaminants down through the unsaturated sediments to the unconfined aquifer.

The main effects of landuse on the analyses presented in this performance assessment are as follows:

- The amount of water penetrating through the ground surface layer above the disposal facility
- The direction and magnitude of flow of the unconfined aquifer from regional irrigation
- The amount of well water pumped to the surface.

Because the site of the disposal facility is assumed to be known to the surrounding population, it was assumed that the surface immediately above the disposal facility will not be used. Thus the only source of water would be natural rain or snowfall. The infiltration rate, the rate at which water actually penetrates through the surface layer and enters the sand-gravel capillary barrier, is described in Section 3.4.7. However, based on earlier Hanford Site environmental assessments, the amount of water entering the disposal facility will be small (less than 10. mm/y (0.4 in./y)).

The second major consequence of land use is on the flow of groundwater in the unconfined aquifer. Analysis (ERDA 1975) of groundwater flow before the start of Hanford Site operations shows a predominantly west-to-east flow (Figure 2-12). Current calculations for post-Hanford operation conditions predict a similar flow (Figure 3-1). These groundwater calculations form an important part in this analysis and are described below (the model in Section 3.5.3.4, the data in Section 3.5.4.4, and the results in Section 4.3.3). However, the creation of ponds and the large amount of water discharged to the ground have altered the groundwater flow (Dirkes 1995) (Figure 2-13). The use of irrigation on the Central Plateau that will also affect groundwater must be considered. No irrigation was assumed for the base analysis case because the energy requirements for irrigation in the Central Plateau are significantly higher than for other nearby regions. However, irrigation on the plateau was considered in sensitivity cases to see the effects of selected irrigation on the regional flow of the groundwater in the unconfined aquifer. Irrigation on the 200 Areas was considered as this area will be dedicated to waste disposal and hence irrigation would be considered an inadvertent intrusion. Each of the following sensitivity cases was considered separately:

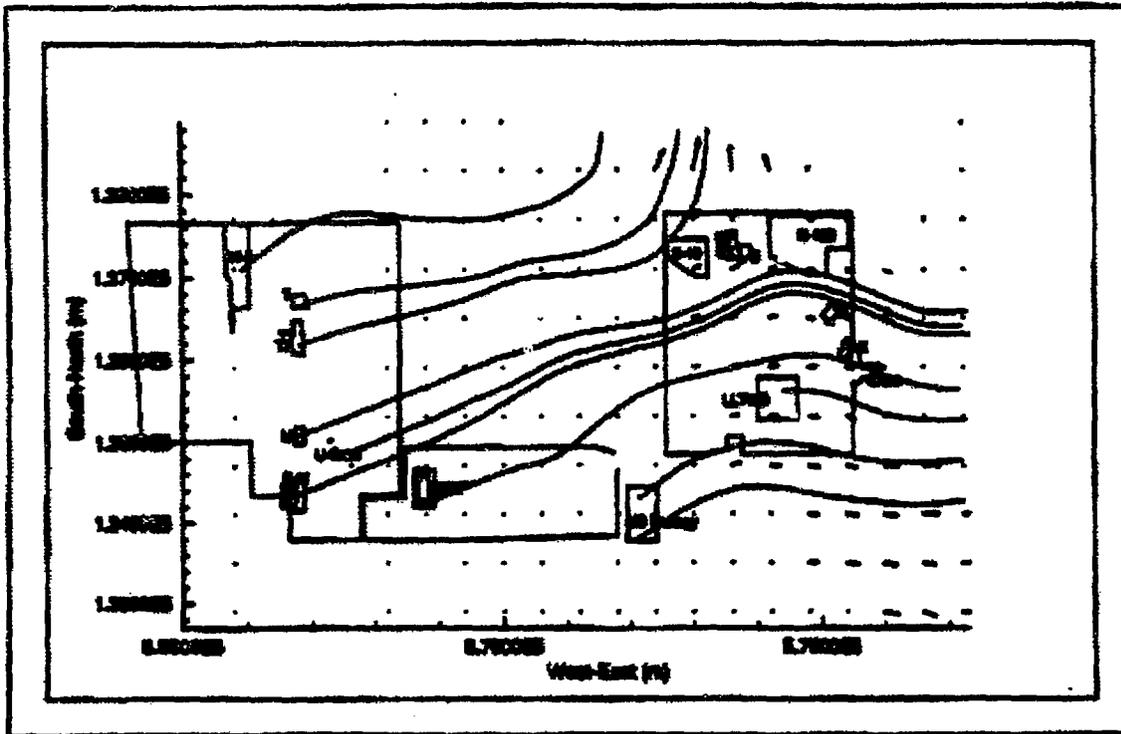
- Irrigated farming in the area north of the 200 Areas
- Irrigated farming in the area west of the 200 Areas.
- Irrigated farming in all areas on the plateau except the 200 West Area, the 200 East Area, and the region between these two areas

The last major effect is the amount of water being taken from a well. At the location of the proposed disposal facility, there is a very limited amount of water available in the unconfined aquifer. Because the amount of water is so limited, either only a small amount would be pumped from the unconfined aquifer or the well would extend much deeper and tap the confined aquifer instead of the unconfined aquifer. Thus, minimum distortion of the groundwater flow field in the unconfined aquifer was assumed for the base analysis case. Sensitivity cases were considered, however, to determine the effect of the amount of pumping on the calculated doses.

3.3.3.3.3 Surface Water. The major surface water in the region is the Columbia River. Here the main impact of land-use is possible irrigation of land near the river. The Columbia River is a more likely source of water than the unconfined aquifer for farm land near the river because of the low elevation and nearness to the river. However, as part of the Washington State Growth Management Act, Benton County is planning to use the land downgradient from the Central Plateau for research and development purposes or for uses not affecting the groundwater.

For the base analysis case, the assumption was that no irrigation would occur downgradient from the plateau.

Figure 3-1. Predicted Groundwater Flowlines for Post Hanford Conditions.



3.3.3.3.4 Air Resources. Gases and vapors could travel upward from the facility through the soil to the ground surface. This pathway is maximized with minimum downward water movement. No water flow is considered in the calculations for the protection of air resources.

3.3.3.4 Inadvertent Intruder Scenarios

3.3.3.4.1 Introduction. The pathways described here assume that no memory of the disposal facility remains. Two principal cases of intruders were considered:

- The disposal facility is compromised by irrigation for commercial farming. A large amount of water enters the disposal facility, causing increased contaminant release from the facility and increased transport to the unconfined aquifer.
- An inadvertent intruder digs or drills into the disposal site and brings some of the waste to the surface, receiving an acute dose. Another intruder tills the waste into the soil and grows vegetables, receiving a continuous dose while engaged in various activities.

3.3.3.4.2 Irrigated Farming on the Disposal Site. This pathway is basically the same as the base analysis case. The difference is that instead of a small amount of water naturally infiltrating the disposal facility, a much larger amount of water enters the disposal facility. The larger amount of water may increase the contaminant release rate from the engineered facility. The increased amount of water certainly speeds the transport of the contaminants through the vadose zone into the unconfined aquifer.

3.3.3.4.3 Inadvertent Breach of Disposal Facility. Three intruder scenarios that involve bringing waste from the disposal facility to the surface are usually considered in a performance assessment.

1. Excavating for a basement or building foundation
2. Drilling for groundwater or minerals
3. Living where waste has been exhumed and scattered over the surface.

Scenario 1 is not considered credible because the top of the waste is over 10 meters (32.8 feet) below the surface. Neither basements for home residence nor foundations for commercial structures are likely to extend this far below surface level. This scenario was not evaluated in these analyses.

Scenario 2, the construction of small water wells, is quite possible. The driller scenario begins with the assumption that some time after the disposal practices have ended a well is drilled through the waste. Drilling at the disposal site is unintentional, and the waste is not recognized as a potential hazard, even though it is assumed to be in the form of glass chunks. The waste, along with uncontaminated soil taken from the well, is spread over a work area near the well. The dose to the worker is the sum of the contributions from inhalation of resuspended dust, ingestion of trace amounts of soil, and external exposure at the center of a slab of contaminated soil.

The remaining scenario considers a family planting a garden using the material taken from the well. Each individual of concern receives dose by direct exposure to the radiation field in the garden, by inhaling resuspended dust, by ingesting trace amounts of soil, and by consuming garden produce.

Values for the parameters important for these intruder scenarios are given in Section 3.4.8.

3.3.3.5 Natural Event Scenarios. The main natural events to be expected are as follows:

- Wind erosion of the surface above the disposal facility
- Earthquakes
- Flooding caused by post-glacial events.

Wind erosion and earthquakes are considered as drivers for changes in the engineered structure as a function of time. They are described in Section 3.4.6.7. Massive regional flooding has occurred many times during the past 50,000 years (see Section 2.2.5.2). The flood in the scenario (caused by the release of water during glacial retreat from a receding ice dam) removes 30 or more meters of ground (including the disposal units). In this scenario, the waste is uniformly redeposited over the Hanford Site. Seasonal flooding or flooding caused by collapsed dams would not affect the disposal site (see Section 2.2.6.3).

3.3.4 Contaminant Release Scenario

The actual waste form that will contain the contaminant is not yet known. Before the final request for proposal (RFP) for the privatization effort was released (DOE-RL 1996), the reference waste form was silicate glass. Until the privatization contract is awarded, the waste form will be uncertain.

The following subsections discuss different aspects of contaminant release. Section 3.3.4.1 gives a general overall description of the contaminant release scenario. Section 3.3.4.2 focuses on what occurs during the water/waste form interaction if the waste form is a silicate glass. This more detailed scenario was developed in the acknowledgement of the maturity of silicate glass waste forms. The scenario is based on experience with silicate glass.

The contaminant release rate used in the calculations is described in Section 3.5.4.2.

3.3.4.1 General Description. The contaminant release scenario is based on a water/waste form interaction. Initially, the disposal facility design (Section 2.4) delays moisture from entering the vault bays. Eventually, water enters the vault bays and moves downward to the waste packages. Once at a waste package, the water first interacts with the container, aiding its corrosion. Once the container is breached, water is assumed to reach the waste form. The water starts interacting with and breaking down the waste form. The waste form then releases the contaminants into the available water. The release rate will depend on the material, temperature, and the local chemical environment. Then available water transports the contaminant from the waste package and through the disposal facility. If the vault bay contains a getter material that sorbs the contaminant, the contaminant takes longer to move through the disposal facility. Finally, the moisture and contaminants migrate to the vadose zone through cracks in the bottom of the disposal facility.

3.3.4.2 Contaminant Release Based on Glass Corrosion. If the waste form is a silicate glass, glass corrosion processes would control the initial release of the contaminants. Studies have shown (Cunnane 1994) that silicate glasses corrode in three stages.

The first stage occurs under dilute solution conditions. Under these conditions, the water does not contain significant concentrations of many elements released from the glass. The glass reacts at a characteristic initial rate (known as the "forward rate") that depends only on glass composition, temperature, and solution pH. During this time the water/glass reaction releases components of the glass into the water.

The second stage occurs as the concentration of elements released from the glass in the contacting water increases. The rate of glass corrosion continually slows as the solution becomes more concentrated with glass components. The reaction may reach a point where the glass corrosion rate cannot be distinguished from zero. This rate has been called the saturation rate where apparent saturation occurs with respect to the glass phase. The solution is not saturated in a thermodynamic sense because glass is metastable. The solution is saturated in a kinetic sense in that the corrosion rate approaches a very low constant value.

The third stage of glass corrosion may occur if secondary mineral phases begin to precipitate from the "saturated" fluid. Precipitation of many of these mineral phases will cause the solution to become undersaturated with respect to the glass. This undersaturation affects the glass corrosion rate. Mass transfer between the solution and the mineral secondary phases will maintain undersaturation. The resulting glass corrosion rate will depend on the specific chemistry of the secondary mineral phases that are formed. Depending on the secondary mineral phase formed, glass corrosion could remain near the low rate attained during the second stage or could accelerate to a rate near the forward rate. The mineral phases that consume silicon from the solution could accelerate the corrosion rate to near the forward rate.

The glass corrosion process releases contaminants into the moisture in contact with the glass. However, the contaminant release rate is not necessarily proportionally to the glass corrosion rate. Rather each contaminant is subject to a variety of chemical reactions that can significantly alter the concentration of the contaminants in the moisture that eventually exits the disposal vault. These reactions include oxidation/reduction, dissolution/precipitation, and adsorption. Experiments and numerical analysis are proceeding to better understand the actual contaminant release. Testing is continuing on selected silicate glasses while testing on waste forms chosen by the TWRS privatization effort will start as soon as possible.

3.3.5 Contaminant Transport

3.3.5.1 Overview. Previous analyses (Kincaid 1995, Mann 1995b, Wood 1994b, Wood 1995, Wood 1996) have shown that contaminants are transported mainly by their movement in the aqueous phase. Contaminant movement can occur by moving with the water and by diffusing through water. Other mechanisms involved vapor phase

transport of the gaseous contaminants or massive movements caused by catastrophic events such as glacial-age flooding. Sections 3.3.5.2 through 3.3.5.5 describe how contaminant transport mechanisms were modeled. Appendix D contains the equations actually used in the models.

3.3.5.2 Moisture Movement. Two distinct moisture content regimes are present during contaminant transport: (1) the unconfined aquifer and (2) the vadose zone. In the unconfined aquifer, all the pore space of the porous sediment matrix is filled with water; that is, the matrix is water saturated. In the vadose zone, the pore space is only partially filled with water; that is, the vadose zone is unsaturated.

Water flow through a saturated porous medium, such as the unconfined aquifer, is governed by the empirical relationship known as Darcy's Law (Freeze 1979) and by the conservation of mass. Darcy's law defines the discharge of water through a cross section of a porous medium. However, in contamination transport, the average velocity of water flowing through the medium is needed. This is because contaminants that are not geochemically retarded move with the water. The average velocity of the pore water is determined by dividing the discharge or Darcy velocity of the water by the water-filled porosity of the medium. Total porosity is defined as the ratio of void space to total volume.

In an unsaturated medium, the pores are not completely filled with water. For such a medium, moisture content is defined as the ratio of water filled void space to the total volume and the average velocity of the pore water is determined by dividing the Darcy velocity by the moisture content. Additional effects (capillary forces, the dependence of hydraulic conductivity on moisture content) must be considered when analyzing an unsaturated medium. Richards equation (Richards 1931) becomes the governing equation (see Appendix D).

The important parameters in these equations are the following:

- Matric potential (or pressure head) as a function of moisture content (water retention function)
- Hydraulic conductivity as a function of moisture content (relative permeability function)
- The source or sink of moisture.

Under extremely dry conditions, water vapor diffusion may be important. Water vapor diffuses through porous media along vapor pressure gradients. The presence of water-soluble components (for example, in the waste form) acts to depress the water vapor potential and causes the water vapor to diffuse from the surrounding soils. This water could then condense at the location of the water-soluble material and leach contamination from that surface. Important factors in this process are the

level of water vapor pressure depression and the effective diffusion coefficient of water vapor.

3.3.5.3 Advective, Dispersive, and Diffusive Transport. The equation for the advective, dispersive, and diffusive transport of contaminants can be viewed as a mass balance on a differential volume.

The parameters important in this equation are

- The pore water velocity
- The dispersion coefficient
- The effective porosity of the soil layer
- The retardation factor that depends on the soil's density and wetted porosity and chemical distribution coefficient
- The effective diffusion coefficient
- The half-life for decay.

An increase in the retardation factor increases the time for the contaminant to reach the aquifer. In the absence of an advective component, the diffusion process could bring water soluble contaminants to the land surface via diffusion in a continuous liquid pathway.

Because of the very dry conditions in Hanford soils and expected in the disposal facility, diffusive transport may be more important than advective movement in some conditions. Because of the large storage capacity of the surface soils, the effect of large transient rainstorms is confined to the top few feet of soil.

3.3.5.4 Vapor Transport. Some contaminants may move upward from the disposal facility to the surface in the vapor phase. Such movement is governed by Fick's law.

3.3.5.5 Solid Transport. When another glacial-age catastrophic flood (such as the previous Missoula floods) occurs, the contaminants will be widely dispersed. For this case, the entire inventory is assumed to be mixed with soil to a depth of 20 meters (66 feet) (the depth of the disposal facility) over the Hanford Site south of the Columbia River [an area of 906 km² (350 mi²). Past glacial-age catastrophic floods have deposited soils over a far greater area (even to the extent of carrying most of the soil all the way to the Pacific Ocean) and mixed the soil to greater depths. The all-pathways scenario (described in Section 3.3.6) is then used to estimate the dose.

3.3.6 Exposure Scenarios

Two major exposure scenarios are considered: drinking contaminated water and living on a small farm. The details of these scenarios and the justification for all the parameters used in them are in Rittmann (1995). Values for the parameters in these scenarios are discussed in Section 3.4.8 and are given in Appendix B.

The simplest case is exposure to contaminated drinking water pumped from a well. This well is assumed to be no closer to the disposal facility than 100 meters (328 feet) and to be located to provide the maximal exposure. This location is the one recommended by the Performance Assessment Task Team (Wood 1994a) and required by the RL implementation directive (DOE-RL 1993) for DOE Order 5820.2A (DOE 1988b). The two major exposure parameters in this scenario are the amount of water consumed and the suite of dose conversion factors used.

The more complex scenario has a person not only drinking the well water, but also using it to irrigate a small farm. Exposure comes from drinking contaminated water, ingesting contaminated food, ingesting and inhaling contaminated soil, and from direct irradiation from the contaminated soil. The total exposure results in the all-pathways dose.

3.4 VALUES/ASSUMPTIONS

3.4.1 Overview

This section provides and justifies the conceptual models and data for those models that were used in the analyses. The section covers the selection criteria and key assumptions for the conceptual models; describes the models and their associated data, the waste form, release rate, disposal facility, and moisture and moisture infiltration rate. The dosimetry parameters are also discussed. The models actually used in the computer simulations were derived from these conceptual models and are described in Section 3.5.

3.4.2 Selection Criteria

The following criteria are used to select among the alternatives:

- The ability to justify the choice.
- The availability of experimental evidence
- The use of best calculational methods.

The overriding criterion was the ability to justify the data and calculational methods selected. Justification required that

all data, assumptions, and processes were questioned for applicability. Does each selection realistically portray probable situations? The justification process quickly identifies errors, misunderstandings, and false assumptions that can be corrected. This process provides insight into the true requirements for methods and the true need for data.

Whenever possible, direct experimental evidence is the basis for selecting data or approaches for the conceptual models. However, in most cases, collecting direct experimental evidence is not possible. Sometimes collecting all the evidence could take too long such as observing the behavior of glass for 10,000 years. Sometimes the amount of data is too large to obtain such as determining hydrologic parameters for the entire vadose zone.

When direct experimental evidence is limited, the available data are used to support analytical simplifications. This approach has two major examples. The first is extrapolating laboratory-measured data to field conditions, as in the case of hydrologic parameters. The second is measuring various effects of the total process to form a complete picture, as was done to determine the infiltration rate. The infiltration rate was determined by combining short-term lysimetry with mid- and long-term tracer and moisture measurements.

Because this analysis is being performed before key decisions on waste form, location, and disposal facility design have been made, relatively little experimental data are available to directly support this interim performance assessment. However, significant amounts of experimental data should be available to support the preliminary and final performance assessments. The statements of work (PAG 1994 and PAG 1995) outline the experiments that will be performed in geology, hydrology, glass performance, other material performance, and infiltration rate.

Analytic and calculational studies must be performed to provide data for processes, such as glass corrosion, that will be evolving over thousands of years. Analytical and computational tools were selected with the intention of using them to provide the most insight and accurate simulations of these processes.

3.4.3 Key Assumptions

Most of the data needed for a performance assessment have not yet been obtained. However, enough is known about the proposed disposal action that necessary assumptions can be made. The key assumptions are as follows:

- Location (which dictates geology, stratigraphy, infiltration rate, and associated parameters)

- Waste form (which influences the release rate of contaminants)
- Inventory
- Disposal facility design.

As noted in Section 2.2.2, a preferred location for the disposal action has been recommended by the technical staff (Shord 1995). For this interim performance assessment, the preferred location was assumed to be the site of this disposal action. However, as part of this work a sensitivity study is performed on a site east of the recommended site to determine the impact if part of the waste is disposed in existing TWRS disposal facilities. Only limited characterization has been performed at either site. However, the central plateau area in which the preferred site rests has been well characterized. Therefore, rather good assumptions can be made about parameters that describe the proposed disposal site. Extensive characterization of the disposal site is planned (Reidel 1995).

As noted in Section 2.3.5, the waste form has not been determined. However, the final specifications for the waste form are outlined in the RFP for privatization (DOE-RL 1996). The original waste stabilization program focused on silicate glass. Because of the knowledge and experience base that has been established for silicate glass, many believe that it will be the waste form. In any event, the selected waste form is likely to have release properties similar to those of silicate glass to meet performance criteria. This assumption is based on the requested release rates given in the specifications for the waste form (DOE-RL 1996). For the base case of this interim performance assessment, the specified release rates from the waste form given in the privatization specifications was used. No other credit was taken. For some sensitivity cases, computer simulations of contaminant release rates under disposal conditions for a silicate glass were performed. When the actual waste form is defined, short- and long-term experiments and analyses are planned for understanding the release behavior as a function of time and environmental conditions.

The actual composition of the waste form (both radioactive and nonradioactive) is not known. For these analyses, only the mean composition based on the estimated total radionuclide inventory was used. As retrieval scenarios are better defined and individual tank contents become better known, composition variations in the waste form will be determined. These variations will then be used in the analyses.

Finally, only conceptual ideas exist for the facility design (See Section 2.4). Important features have been identified and preliminary investigations have been done (Mann 1995b). Thus, certain design features can be included with some confidence. Much more work remains to be done as the conceptual design ideas are translated into preliminary and then final designs. An

important part of such work will be experimental and analytical studies of how the various features behave over time.

3.4.4 Site

3.4.4.1 Introduction. This section translates the geology, hydrogeology, and geochemistry found in Chapter 2 into a conceptual model and values that can be used in the analyses supporting this interim performance assessment. The location and stratigraphy of the disposal site are discussed first. Next, the hydrologic and geochemical properties of the vadose zone are addressed. Finally, the properties of the unconfined aquifer are examined.

3.4.4.2 Location and Stratigraphy. As noted in Section 2.2.2, the location of the disposal facility has not been determined. However, a preferred location in the south central part of the 200 East Area has been recommended by the technical staff (Shord 1995). The main strata at this location are the Hanford formation and the Ringold Formation.

The Hanford formation beneath the disposal area consists of three layers. The upper 6 meters (20 feet) is the Upper Gravel Sequence. The next 60 meters (197 feet) consists of the Sand Sequence. The bottom, the Lower Gravel Sequence, is 25 to 40 meters (82 to 131 feet) thick. For modeling purposes (Table 3-2) a mean thickness of this bottom sequence was taken as 35 meters (115 feet) making the Hanford formation 101 meters (331 feet) thick in the model.

Table 3-2. Geology Used for the Base Analysis Case. (Reidel 1995-1)

| Formation | Thickness/Location |
|-----------------------|--|
| Hanford formation | starts at surface |
| Upper Gravel Sequence | 6 meters (20 feet) (on surface) |
| Sand Sequence | 60 meters (197 feet) |
| Lower Gravel Sequence | 35 meters (115 feet) (bottom) |
| Ringold Formation | starts just below Hanford formation, |
| Unit E | 101 meters below the surface 30 meters (98 feet) |
| Unconfined aquifer | 103 meters (338 feet) below surface, 118 meters (387 feet) above mean sea level |

Below the Hanford formation lies the Ringold Formation. Only Unit E is of concern for these analyses. Unit E is consolidated sandy gravel to muddy sandy gravel 30 meters (98 feet) thick.

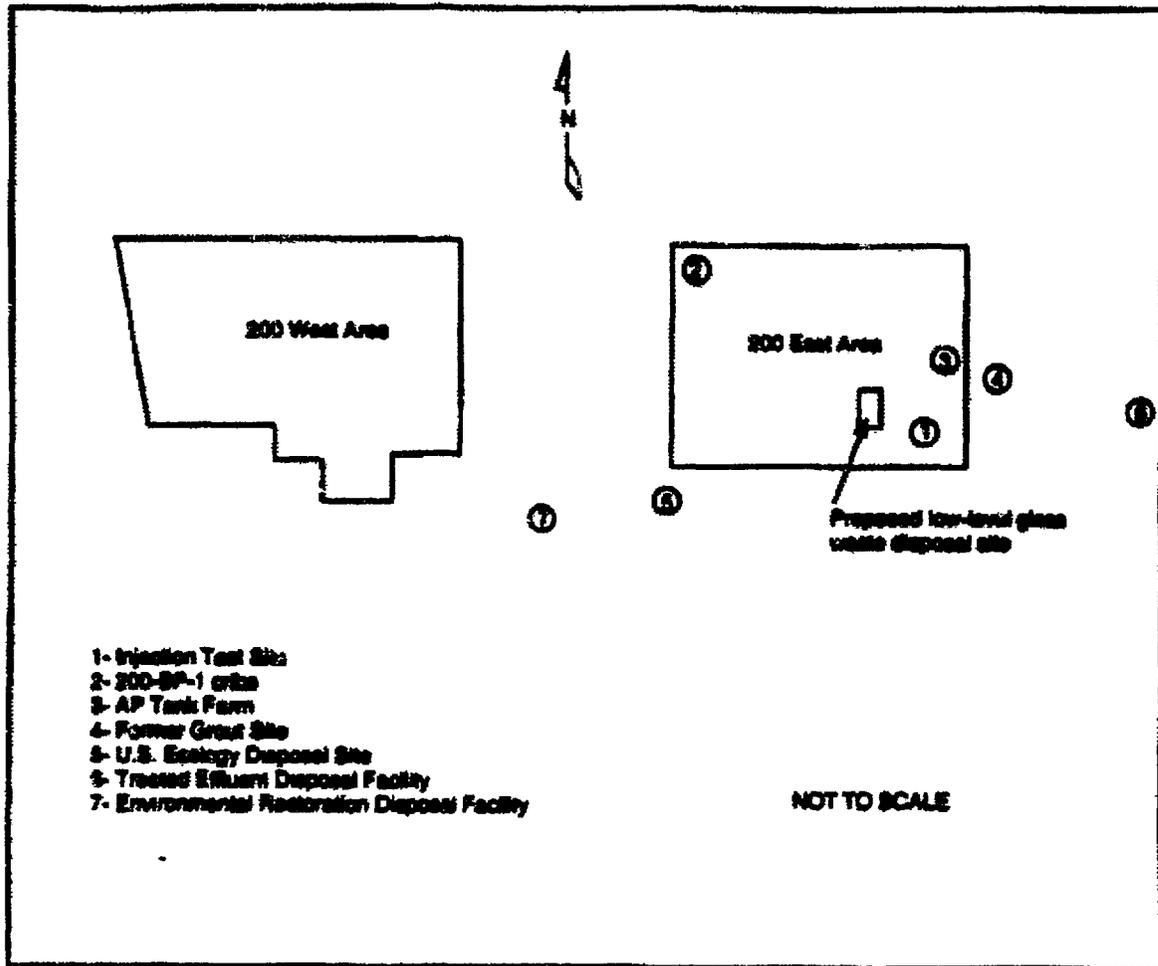
The large discharge of water from Hanford Site operations has significantly affected the level and flow of the unconfined aquifer. However, DOE has agreed to severely limit such discharges; and at the time of this analysis there will be no discharges. Based on calculations using the Environmental Restoration Contractor (ERC) Hanford Sitewide groundwater model (Law 1996), the present location of the aquifer at the disposal site is 96 meters (315 feet) below the surface level or 125 meters (410 feet) above mean sea level which is in good agreement with measurements. Computer simulations were used to define the level of the unconfined aquifer after Hanford Site operations cease. Current estimates of the post-Hanford water table (Law 1996) suggest this level as 103 meters (338 feet) below the surface level or 118 meters (387 feet) above the mean sea level. This level was used for the base analysis case. The post-Hanford unconfined aquifer is expected to be in the Ringold Formation.

Two sensitivity cases were produced to determine the importance of the hydrologic parameters of each layer. The first sensitivity case considers that all, rather than most, of the Hanford formation consists of the Sand Sequence. The second sensitivity case assumes that the Lower Gravel Sequence starts at 50 meters (164 feet) below the surface rather than at 66 meters (216 feet).

Two sensitivity cases will be studied to determine the importance of which formation contains the unconfined aquifer. In one sensitivity case, the top of the unconfined aquifer is at its present location, 96 meters (315 feet) below the surface (that is, the top of the aquifer is 7 meters above the position of the base analysis case). In the other case, the top of the aquifer is lowered from the base analysis case by the same amount as it was raised in the first sensitivity case. Thus for the second sensitivity case the top of the aquifer is at 110 meters (361 feet) below the surface. In both cases the bottom of the aquifer remains at the same elevation below the surface.

3.4.4.3 Vadose Zone Hydrologic Parameters. Vadose zone hydrologic parameters for these analyses come from laboratory analyses of samples from the various strata found at the disposal site. Samples were taken from several locations near the disposal site (Figure 3-2). Corrections were made for the gravel content and for primary drainage. This resulted in moisture retention data. A detailed discussion of the data and methods used to derive them can be found in the work of Khaleel and Freeman (Khaleel 1995). The following paragraphs summarize the methods and data.

Figure 3-2. Hydrologic-Conductivity Sample Locations.



The moisture retention data can be described in an empirical relationship following the methods of van Genuchten (1980). The moisture retention function is

$$\theta(\psi) = \theta_r + (\theta_s - \theta_r) \cdot (1 + |\alpha \psi|^n)^{-m}$$

- where
- $\theta(\psi)$ is the volumetric moisture content [dimensionless]
 - ψ is the matric potential or pressure head [f]
 - θ_r is the residual moisture content [dimensionless]
 - θ_s is the saturated moisture content [dimensionless]
 - α is a fitting parameter [f⁻¹]
 - n is a fitting parameter [dimensionless]
 - m is $1 - 1/n$.

Using the Mualem (1976) model and the above form for moisture retention, the hydraulic conductivity is

$$K(S_e) = K_s \cdot S_e^l \cdot [1 - (1 - S_e^{1/n})^2]^2$$

where $K(S_e)$ is the unsaturated hydraulic conductivity [length/time]
 K_s is the saturated hydraulic conductivity (l/t)
 S_e is effective saturation = $(\theta - \theta_r) / (\theta_s - \theta_r)$
 l is the pore-connectivity parameter, estimated by Mualem to be about 0.5 for many soils. In this work, l is taken to be 0.5 (a dimensionless quantity).

The RETC code (van Genuchten 1991) was used to determine values for θ_r , θ_s , α , and n . Values for K_s were determined by fitting laboratory data to a log-normal distribution. The resulting values are shown in Table 3-3.

Table 3-3. Values for Hydrologic Parameters for the Vadose Zone for the Base Analysis Case.*

| Material | Number of Samples | van Genuchten Curve Fitting Parameters for Moisture Retention | | | | Saturated Hydraulic Conductivity (cm/s) |
|-------------------|-------------------|---|--|--------------------------------|--------|---|
| | | $\theta_r^{* *}$ (cm ³ /cm ³) | $\theta_s^{* *}$ (cm ³ /cm ³) | α^* (cm ⁻¹) | n^* | |
| Hanford sands | 60 | 0.3578 | 0.0246 | 0.1566 | 2.1768 | 1.17x10 ⁻³ |
| Hanford gravel | 8 | 0.1312 | 0.0126 | 0.0125 | 1.530 | 1.32x10 ⁻³ |
| Ringold Formation | 15 | 0.1342 | 0.0220 | 0.0122 | 1.5865 | 8.74x10 ⁻³ |

* Parameters (from Khaleel 1995) are used to determine unsaturated hydraulic conductivity, see text.
 ** The saturated volumetric moisture content.
 * The residual volumetric moisture content.
 * A van Genuchten curve fitting parameter.

The grout performance assessment (Kincaid 1995-2) relied on the work of Rockhold et al. (Rockhold 1993) to determine the unsaturated hydraulic conductivity in the vadose zone. Their procedure was similar to the Khaleel and Freeman approach. However, their data set was slightly smaller and did not include samples from near the proposed disposal site. The samples used by Rockhold et al. were mainly from the Grout Disposal Facility with some samples from the AP tank farm, the U.S. Ecology Site, and the 200-WP-1 site. The residual moisture content ($\theta_r = 0.0234$ cm³/cm³) that Rockhold et al. determined for their 57 samples from the sandy sequence of the Hanford formation is very similar to that found by Khaleel and Freeman ($\theta_r = 0.0246$ cm³/cm³). The residual moisture contents found by Rockhold et al. for the Hanford formation lower gravel sequence (14 samples yielding $\theta_r = 0.0213$ cm³/cm³) and the Ringold

Formation (5 samples yielding $\theta_r = 0.0283 \text{ cm}^3/\text{cm}^3$) are slightly higher than the values from the Khaleel and Freeman analysis ($\theta_r = 0.0126$ and $0.0220 \text{ cm}^3/\text{cm}^3$, respectively). In general, the two analyses are in close agreement.

The hydraulic properties for construction materials are taken from the work of Rockhold et al. (Rockhold 1993). The values are displayed in Table 3-4. Hydrologic parameters for sand (which is used in the sand-gravel capillary barrier and in sensitivity cases) are assumed to be the same as for the sandy sequence of the Manford formation. The hydrologic parameters for the water conditioning layer are assumed to be the same as for gravel.

Table 3-4. Values for Hydrologic Parameters for Construction Materials for the Base Analysis Case^a

| Material | van Genuchten Curve Fitting Parameters for Moisture Retention | | | | Saturated Hydraulic Conductivity (cm/s) |
|-------------------|---|--|---------------------------------|-------|---|
| | $\theta_r^{b,c}$ (cm^3/cm^3) | $\theta_r^{d,e}$ (cm^3/cm^3) | α^d (cm^{-1}) | n^d | |
| Back-filled soil | 0.3710 | 0.0450 | 0.0683 | 2.080 | 3.00×10^{-3} |
| Gravel | 0.5180 | 0.0140 | 3.5366 | 2.661 | 1.85 |
| Portland Concrete | 0.2258 | 0.0000 | 7.6×10^{-4} | 1.393 | 3.75×10^{-10} |

^a Parameters (from Rockhold 1993) are used to determine unsaturated hydraulic conductivity, see text.
^b The saturated volumetric moisture content.
^c The residual volumetric moisture content.
^d A van Genuchten curve fitting parameter.

For the calculations, the bulk density of the soil was taken to be 2.72 g/cm^3 . The dispersion coefficient of the contaminations was taken to be $0.1 \times$ travel length in the direction of travel. The dispersion in the vadose zone in the horizontal direction was taken to be one tenth of the value in the direction of travel. For aquifer transport, the dispersion in the horizontal direction (not in the direction of flow) was also taken to be $0.1 \times$ travel length in the direction of flow and in the vertical direction $0.01 \times$ travel length.

The value of the diffusion coefficient in unsaturated sediments of the vadose zone is taken from the grout performance assessment (Kincaid 1995-3), using the model of Kemper and van Schaik (1966).

$$D = 1.25 \times 10^{-7} \exp(-10 \theta) \text{ cm}^2/\text{s},$$

where θ is the volumetric moisture content of the sediment.

To estimate the release of radon from the soil, radon's diffusivity must be estimated. Harris et al. (1992) summarized

the measurements of gaseous diffusion performance on concrete materials. They concluded that, for dry materials, diffusivities ranged from 10^{-5} to 10^{-3} cm^2/s (10^{-6} to 10^{-4} $\text{in.}^2/\text{s}$). The presence of moisture reduces the diffusivity value. Therefore, for these analyses, a value (corresponding to dry conditions) of 1.0×10^{-3} cm^2/s (1.6×10^{-4} $\text{in.}^2/\text{s}$) was used. A value 10 times larger, based on diffusion in air corrected for moisture and tortuosity, was used in the Hanford Solid Waste Performance Assessments (Wood 1994b and Wood 1996).

Sensitivity cases center around altering the presumed strata and hence their hydrologic properties. The strata changes (sensitivity) investigated in this interim performance assessment are given in Section 3.4.4.2.

3.4.4.4 Vadose Zone Geochemical Retardation Factors. Chemical interactions with the soil in the vadose zone can greatly slow the transport of contaminants. The amount of slowing is described by a multiplicative factor known as the geochemical retardation factor (see Section 3.3.5.3). Geochemical retardation factors for these analyses are based on extensive laboratory work performed at the Hanford Site. This work is summarized in Kaplan (1995).

Geochemical retardation in unsaturated conditions is predicted to be

$$R_r = 1 + \rho K_d / \theta$$

where R_r is the geochemical retardation factor (dimensionless)
 ρ is the bulk density of the material (M/L^3)
 K_d is the chemical distribution coefficient (L^3/M).
 θ is the volumetric moisture content (dimensionless).

A derivation from the general contaminant transport equation is given in Appendix D, Section D.2.3. The chemical distribution coefficient (K_d) is measured in the laboratory by comparing the amount of material entrapped in or on the soil matrix compared to the amount in the water phase.

The chemical distribution coefficients used in these analyses are based on the reports of Kaplan et al. (Kaplan 1995a and Kaplan 1995b). In particular, Kaplan (1995a) investigates in detail best estimate K_d values for the most important contaminants for our disposal conditions. For other contaminants, the "low K_d " values for neutral-to-high pH, low salt, low organic, and oxic solutions from Table 6.1 of Kaplan 1995b are the bases for the values used. The values are based on experiments using saturated Hanford soils (mainly the sandy sequence). Until planned experiments are completed, the chemical distribution coefficients are assumed independent of moisture and geologic layer.

For convenience in modeling, a subset of K_d values from Kaplan (1995) and Kaplan (1995a) were used in these analyses. The computer code PORFLOW (see Section 3.5.2.3) treats the chemical distribution coefficients as point-estimate values, not as probability functions. The code calculates the contaminant transport for only 4 K_d values at a time.

To reduce the number of computer simulations made, only eight values are used for the distribution coefficients. Five of the values chosen are based on the K_d values of the most important elements in these analyses. These elements (and the corresponding K_d values) are technetium and selenium ($K_d = 0$ for both), uranium ($K_d = 0.6$ ml/g), iodine ($K_d = 3$ ml/g), carbon ($K_d = 6$ ml/g), and neptunium ($K_d = 15$ ml/g). Two higher K_d values, 40 and 100 ml/g, were chosen to represent more retarded elements. Elements with such high K_d values have very little significance for vadose zone transport within the Hanford Site soils. These higher values used for the chemical distribution coefficients for the less important elements in the computer simulations were selected to be conservative. These values are lower than the recommended values given in Kaplan (1995). Table 3-5 shows the values recommended by Kaplan (1995) and Kaplan (1995a) and the values actually used in these analyses.

Table 3-5. Chemical Distribution Coefficients (K_d) for the Base Analysis Case^a

| Element | K_d (ml/g) | Element | K_d (ml/g) | Element | K_d (ml/g) |
|---------|------------------|---------|----------------|---------|-----------------|
| Ac | 67 -> 40 | Am | 67 -> 40 | C | 6 |
| Ce | 100 | Cm | 106 ->100 | Co | 1200 ->100 |
| Cs | 540 ->100 | Eu | 100 | I | 3 ^b |
| Nb | 50 -> 40 | Ni | 50 -> 40 | Np | 15 ^b |
| Pa | 10 -> 6 | Pb | 13000 ->100 | Pu | 80 -> 40 |
| Ra | 24 -> 15 | Se | 0 ^b | Sn | 100 |
| Sr | 5 -> 3 | Tc | 0 ^b | Th | 40 |
| U | 0.6 ^b | Zr | 90 -> 40 | others | 0 |

^a The number to the left of the arrow is the best estimate of the K_d value, the number to the right of the arrow is a conservative estimate to minimize the number of computer simulations since the code only uses 4 K_d values at a time.
^b Data taken from Kaplan (1995a), others from Kaplan (1995).

Because radionuclides spend significantly shorter time in the unconfined aquifer than in the vadose zone, no credit for increased travel time in the unconfined aquifer due to geochemical retardation was taken.

Sensitivity cases were used to judge the effects of different K_f values. Two cases used different K_f s for uranium. One case used a K_f value of zero for uranium. This was the conservative value used in earlier environmental assessments. The other used a K_f value of 100 ml/g for uranium in concrete (Krupka 1995) and K_f value of 0 for uranium everywhere else in the system. Another sensitivity case used $K_f = 0.1$ ml/g for technetium and selenium.

3.4.4.5 Unconfined Aquifer Properties. No data are available on the hydraulic parameters for the immediate vicinity of the proposed disposal site. The hydraulic parameters to be used are from the Environmental Restoration Contractor (ERC) sitewide model of the Hanford unconfined aquifer (Law 1996). This model was created for the DOE's remedial restoration effort at the Hanford Site. Table 3-6 gives the hydraulic parameters immediately around the disposal site and their values used for these analyses. Measured data are planned for the preliminary performance assessment.

Table 3-6. Hydraulic Parameters for Unconfined Aquifer Immediately Around the Disposal Site (Law 1996)

| Parameter | Value |
|---|-------|
| Saturated hydraulic conductivity (cm/s) | |
| Ringold Formation | 0.095 |
| Hanford formation | 3.6 |
| Effective porosity | 0.1 |
| Ringold aquifer thickness (m) | 20. |

For calculations involving a larger region of the Hanford Site, the ERC Hanford Sitewide Groundwater Model was used. This model contains 18 hydrogeologic material types. The material identification numbers for the upper and lower layers are shown in Figures 3-3 and 3-4, respectively. The hydrologic parameters are displayed in Table 3-7. Hydraulic conductivities for the 200 East and West Areas were obtained from Connelly et al. (1992a and 1992b) while those for other areas were obtained from Thorne and Newcomer (1992). Because almost all the aquifer tests used to infer data contained in these compilations were single well tests, no information is available for estimating the storage parameters. The aquifer test results were interpolated from point measurements to areal values with the application of the software program EarthVision¹.

¹ EarthVision is a registered trademark of Dynamic Graphics, Inc.

Figure 3-3. Zone Map for the Upper Layers of the EAC Hanford Nitride Groundwater Model. See Table 3-7 for corresponding hydraulic parameters.

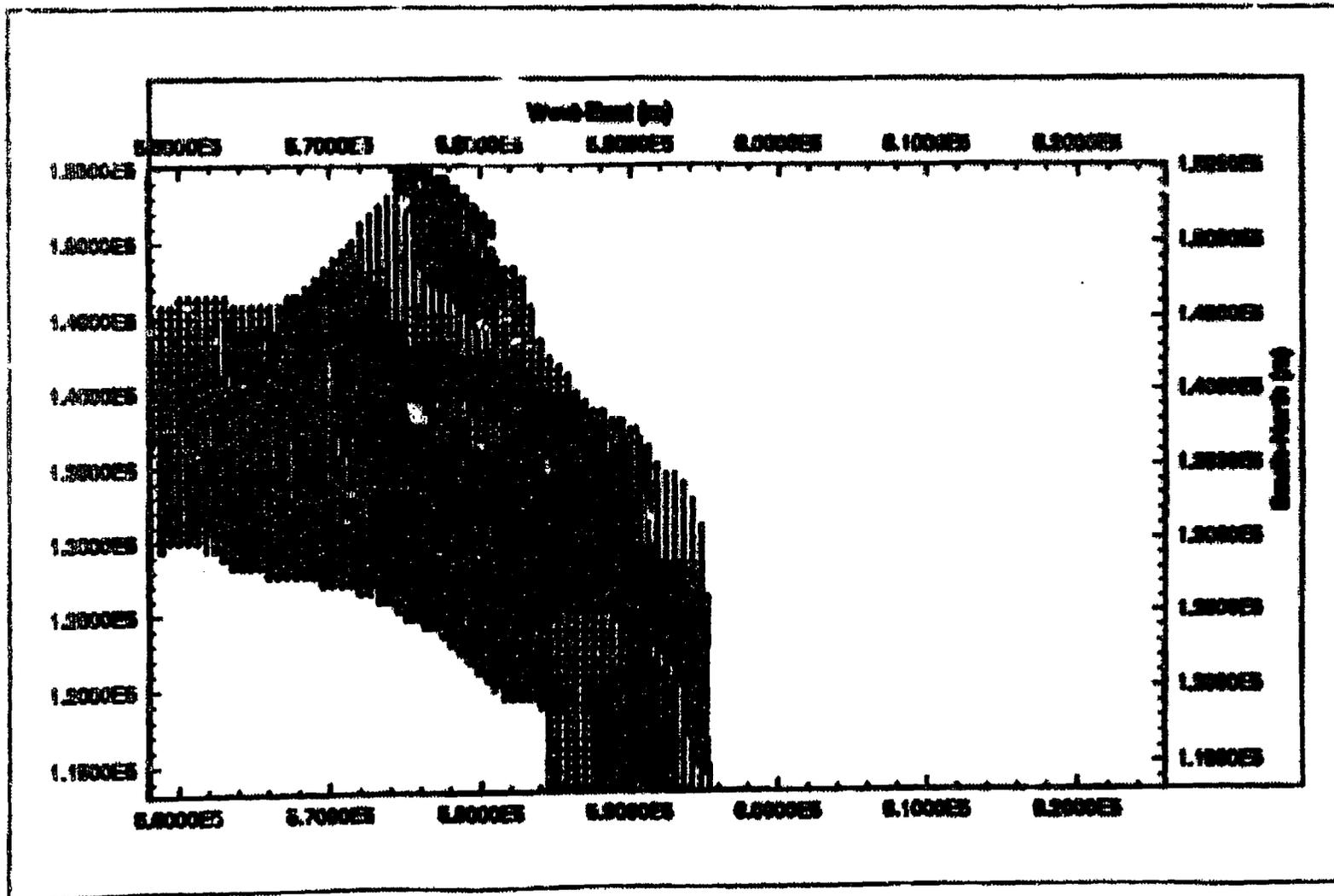
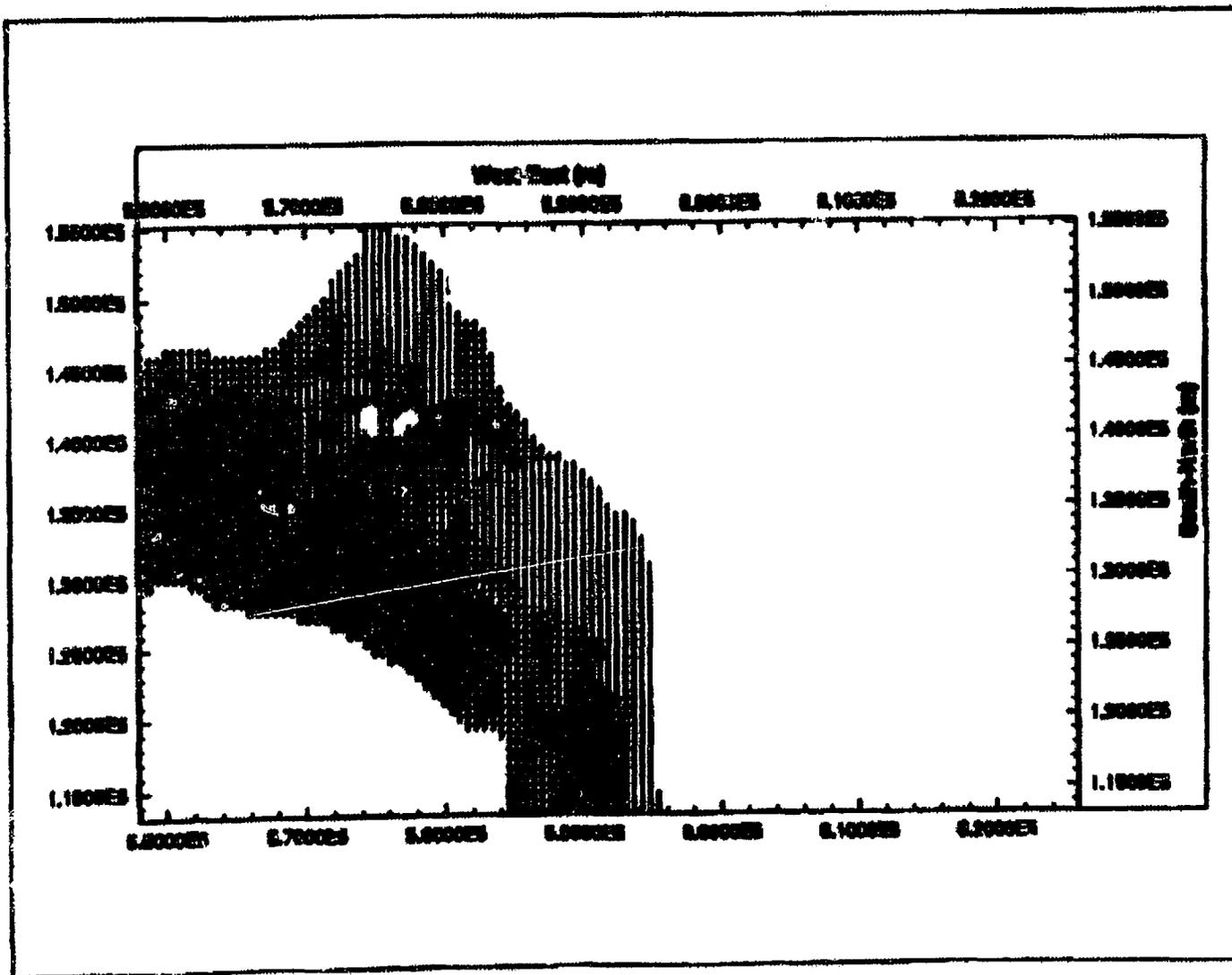


Figure 3-6. Zone Map for the Lower Layers of the NRC Hanford Sitewide Groundwater Model. See Table 3-7 for corresponding hydraulic parameters.



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Table 3-7. Element Material-Zone Flow Properties. (Law 1996)

| Zone | Horizontal Saturated Conductivity (cm/s) | Storage | Effective Porosity |
|------|---|---------|--------------------|
| | $K_{Hx} = K_y$ $K_{Hz} = 0.1 \cdot K_{Hx}$ | | |
| 1 | 2.53 e-3 | 1.0 e-4 | 0.10 |
| 2 | 6.03 e-3 | 1.0 e-4 | 0.25 |
| 3 | 1.59 e-2 | 1.0 e-4 | 0.10 |
| 4 | 2.06 e-2 | 1.0 e-4 | 0.10 |
| 5 | 4.44 e-2 | 1.0 e-4 | 0.25 |
| 6 | 2.29 e-1 | 1.0 e-4 | 0.25 |
| 7 | 8.25 e-2 | 1.0 e-4 | 0.10 |
| 8 | 9.52 e-2 | 1.0 e-4 | 0.25 |
| 9 | 1.37 e-1 | 1.0 e-4 | 0.25 |
| 10 | 1.75 e-1 | 1.0 e-4 | 0.25 |
| 11 | 2.44 e-1 | 1.0 e-4 | 0.25 |
| 12 | 2.85 e-1 | 1.0 e-4 | 0.25 |
| 13 | 4.44 e-1 | 1.0 e-4 | 0.25 |
| 14 | 9.52 e-1 | 1.0 e-4 | 0.25 |
| 15 | 2.38 | 1.0 e-4 | 0.25 |
| 16 | 3.59 | 1.0 e-4 | 0.25 |
| 17 | 5.81 | 1.0 e-4 | 0.25 |
| 18 | 6.76 | 1.0 e-4 | 0.25 |

3.4.5 Waste Package

3.4.5.1 Introduction. This section describes the conceptual model for the waste package, which consists of the container and the waste form. The contents of the waste package are currently unknown because an effort is under way to privatize the immobilized waste function of (TWRS) (Section 2.3.5). Sections 3.4.5.2 through 3.4.5.5 describe what is known about the waste package components. This description includes the release rate from the waste form. Alternative waste forms and release rates that were used in sensitivity cases are also discussed.

3.4.5.2 Container. The final TWRS privatization Request for Proposal (RFP) (DOE-RL 1996) outlines the type of container that would be acceptable. The aspects of the container that affect the performance assessment are summarized here. The container would be an unspecified metal. The nominal outside dimensions of the package are 1.8 by 1.2 by 1.2 meters (about 6 by 4 by 4 feet). The thickness depends on the type of metal used. It must be thick enough to meet the shielding requirement for a maximum contact dose rate of 1 rem/hr. The stacking height of containers was assumed to be 7.2 meters (23.6 feet), which is 6 containers high, consistent with the RFP.

The conceptual model for the performance and degradation of the waste package ignores the presence of the container. The RFP (DOE-RL 1996) only specifies that the container be made out of metal. Thus the content and durability of the container is not yet known. For these analyses, the container material was assumed to have no effect on hydraulics, chemical retardation, or waste form performance. Once the container has been selected, testing on the container material and container-waste form interactions will be planned to determine the effect of the container degradation on waste form performance.

3.4.5.3 Waste Form. The TWRS privatization RFP (DOE-RL 1996) does not specify a waste form. The waste form will be based on maximum package volume related to gram-mole of waste sodium content and on release rates. For the base analysis case, the waste form is not defined. Only a release rate is prescribed (Section 3.4.5.4). The shape of the waste form is assumed to be nearly cubical. The inventory is also assumed to be evenly distributed among the waste packages produced. Because the waste form will control the release rate of the radionuclide contaminants, related sensitivity cases are described in the next section.

3.4.5.4 Waste Form Radionuclide Release Rate. Although the final TWRS privatization RFP does not specify a waste form, the request does specify initial (the first 7 days) fractional radionuclide release rates (DOE-RL 1996). The initial fractional radionuclide release rate from the waste form averaged over all the containers shall not be greater than:

- $1.4 \text{ E-13}(\text{s}^{-1})$ [4.4 ppm/y] for ^{76}Se , ^{129}I , ^{237}Np , and uranium isotopes
- $2.8 \text{ E-14}(\text{s}^{-1})$ [0.88 ppm/y] for ^{99}Tc .

For the hypothetical waste form used in the base analysis case, the time dependence of the radionuclide release rate was calculated using the non-technetium initial fractional release rate and the following assumptions:

1. The waste form corrosion rate is constant in time and does not vary with location in the vault.

2. The radionuclide release rate is proportional to the waste form corrosion rate and the inventory density at the surface.
3. The waste form corrosion rate is proportional to the instantaneous surface area.
4. The radionuclides are uniformly spatially distributed in each waste form.
5. Each linear dimension of the waste form decreases at a constant rate.
6. The waste form has similar lengths in each dimension (for example, a sphere or a cube).

Assumption 2 is perhaps the most questionable assumption. Waste form corrosion rates and, more importantly, contaminant release rates are strong nonlinear functions of the local physical and chemical environment. It is certain that these properties will vary as a function of time and space in the disposal facility. However, to account for these effects in computer simulations requires detailed physical and chemical process models for waste form corrosion. Because the waste form and other details of the disposal facility design have not yet been specified, assumption 2 was used as an enabling assumption. Computer simulations of the physical and chemical processes for the corrosion and contaminant release for a silicate waste form are performed as sensitivity cases.

Using these assumptions, the time-dependent release rate is derived as follows. See Mann (1995b) for details. The first four assumptions yield:

$$RRR(t) = C * S(t) * I(t) / V(t)$$

where:

| | |
|--------|--|
| RRR(t) | is the radionuclide release rate [Ci/t] |
| t | is the time [t] |
| C | is the corrosion rate [l/t], taken to be independent of time and chosen so that the non-Tc rate given in the request for proposal is met |
| S(t) | is the surface area of the waste form [l ²] |
| I | is the inventory in the waste form [Ci] |
| V(t) | is the volume of the waste form. [l ³] |

Assumption 4 applies at the initial time (t=0). Thus

$$I(t) / V(t) = I(0) / V(0).$$

Then

$$RRR(t) = C * S(t) * I(0) / V(0).$$

The shape of the waste form and Assumption 5 determine the rate at which the surface area decreases. For the base analysis case, the waste form was assumed to be nearly cubical. The surface area then becomes:

$$S(t) = K1 * x(t)^2 = K1 * [K2 * (T - t)]^2 \\ = K3 * (T - t)^2$$

where,

x is the time-dependent length [ft]
 T is the time for all the radionuclides to be released from the waste form [t]
 K1, K2, K3 are constants [various units].

The radionuclide release rate for a cubical waste form then becomes

$$RRR(t) = C * K3 * (T - t)^2 * I(0) / V(0) \\ = K4 * (T - t)^2 * I(0).$$

The constant K4 is determined by the integral over time of the radionuclide release rate from 0 to T. The result of the integral is the total inventory, I(0). Thus,

$$K4 = 3/T^3.$$

The radionuclide release rate becomes:

$$RRR(t) = 3 * I(0) * (T - t)^2 / T^3.$$

The value of T can be determined at t=0. At t = 0, RRR(0)/I(0) is the initial fractional radionuclide release rate {FRRR(0)}. This rate is given in the RFP. Thus, the time for the waste form to release all the radionuclides is:

$$T = 3 / FRRR(0).$$

The last two equations were used in the base analysis case for the time-dependent radionuclide release rate from the waste form. Table 3-8 displays their simplified form.

Table 3-8. Relative Radionuclide Release Rate from the Waste Form for the Base Analysis Case

Relative Radionuclide Release Rate from the Waste Form
 (ppm/year) =

$$4.4 * [T - \text{time}(\text{years})]^2 / T^3, \text{ where } T = 6.8 \times 10^3 \text{ years}$$

Calculations show that the temperature rise from decay in the waste form in the disposal facility is less than 1°C. The soil above the disposal facility will provide a thermal shield. Thus although the glass corrosion rate is temperature-dependent, the release rate is assumed not to change because of temperature effects.

Several sensitivity calculations on contaminant release were performed because the release rate is important to the performance assessment. Some of the sensitivity cases are variations of the RFP specifications. Others involve a mechanistic estimation of the release rate as a function of space and time based on experimental data. Still others investigate the effects of different release rates caused by relatively small pieces of waste form.

Two sensitivity cases focused on variations of the RFP specifications. The base analysis case was based on a waste form that releases all radionuclides at a rate proportional to the inventory. However, the RFP specifies that the rate for technetium release be a factor of 5 slower based on initial inventories. Such a reduction can occur if the technetium is trapped or if 80 percent of the technetium is removed during pretreatment. One sensitivity case based on the RFP analyzes the effect of trapping the technetium. The case of removing 80 percent of technetium from the inventory is treated as an inventory sensitivity case (Section 3.2.5). The other variation on the RFP was to assume that the waste form shape is not nearly cubical, but plate-like. This leads to a constant non-technetium release rate of 4.4 ppm per year for 227,000 years.

The base analysis case is built on a contract specification. Some sensitivity cases were built on how the waste form is expected to behave. In these cases, the waste form was assumed to be silicate glass. This waste form was the leading candidate before privatization and is the only waste form for which the RFP provides an acceptable performance test. The waste form probably will be a silicate glass. The release rate for these sensitivity cases results from the model discussed in Section 3.3.4.2 and implemented in the AREST-CT computer code (Section 3.5.2.2).

3.4.5.5 Getter or Filler Material. The TWRS privatization RFP (DOE-RL 1996) states that the container may not have void space greater than 1 percent of the volume. This means that a getter or filler material may be part of the waste form. A getter material is a material that chemically combines or traps selected radionuclides. This "trapping" restricts the radionuclides movement downward. Because the form of the waste package is not known, the base analysis case assumed that the canister was completely filled with the stabilized waste form. No getter or special filler materials are used, only backfill soil is between the canisters.

3.4.6 Waste Disposal Facility

3.4.6.1 Introduction. The disposal facility concepts summarized in Section 2.4 and given in Eiholzer (1995) are used for the conceptual model. Concept 1 (see Figure 2-19) was used for the base analysis case. Specific aspects of Concept 2 (see Figures 2-20 and 2-21) were used for sensitivity studies. These concepts were used because the actual disposal facility has not been designed, but these concepts are thought to feature the components thought likely to be in the final design.

Sections 3.4.6.2 through 3.4.6.6 cover the specific key components of the disposal concepts. These components are the surface barrier, the capillary barrier, the water conditioning layer, and the vault layout. Values used for each component and any related sensitivity studies are discussed. Section 3.4.6.7 covers the degradation of the man-made portion of the disposal facility.

3.4.6.2 Surface Barrier. The surface barrier is designed to store water from precipitation long enough for most of the water to evaporate or transpire through plants in the Hanford Site's arid climate. The surface barrier in the disposal facility concepts is expected to be a Hanford-type surface barrier (Myers 1994) without the asphalt layer. The top of the surface barrier will be flush with the soil surface, which is 221 meters (725 feet) above sea level. The barrier covers the entire disposal facility. The barrier extends 1 meter (3.3 feet) beyond the outside edge of the over all facility and 8.75 meters (28.7 feet) beyond each vault row for Concepts 1 and 2, respectively. This is the distance that the sand-gravel capillary barrier (next subsection) extends beyond the edge.

The surface barrier is not explicitly modeled in the computer simulations. Rather, the rate of moisture moving through the surface barrier (or the degraded barrier) and passing into the soil beneath it is considered the top boundary condition for the computer simulation. The value for this rate of moisture movement (known as the infiltration rate) is discussed in Section 3.4.7.

3.4.6.3 Sand-Gravel Capillary Barrier. The disposal facility concepts include a sand-gravel capillary barrier beneath the surface barrier. The capillary barrier is designed to divert water away from the disposal vaults. The barrier is a pyramid with 1 meter (3.3 feet) of sand on top of gravel (Figure 2-21). The pyramids for Facility Concepts 1 and 2 have -2° and -5° slopes, respectively. The pyramids are 4 and 2 meters (about 14 and 6.5 feet) high for Concepts 1 and 2, respectively. The barriers will extend laterally beyond the vaults to mirror the surface barrier. Based on University of Washington experiments for the grout program (Kramer 1989), the sand is not expected to migrate into the gravel even under seismic shaking.

Disposal Facility Concept 1 includes a 1-meter (3.3-foot)-thick gravel wall along the outside vertical concrete walls. This gravel wall is a side capillary barrier which encourages the moisture to remain in the soil and not pass through the gravel into the disposal facility. Mann (1995) indicates that a gravel wall will improve the moisture movement around the facility.

Three sensitivity cases looked at the effects of the capillary barrier. The first case included the large capillary barrier over the top of the vault, but no side capillary barrier. The second case did not contain any sand-gravel capillary barriers. The last case looked at the influence of the size of the capillary barrier. In this case, the effects of the capillary barrier for Concept 2 were compared to the effects of the capillary barrier for Concept 1. The widths of the capillary barriers for Concepts 1 and 2 are 208 and 41 meters (682 and 134.5 feet), respectively.

3.4.6.4 Water Conditioning Layer. Each disposal facility concept includes a water conditioning layer. This layer, which is above the roof of the concrete disposal vaults, is designed to add silicon to any moisture that reaches the layer. If the waste form is a glass, silicon enriched moisture could slow down glass corrosion. For the conceptual model, this water conditioning layer (1 meter [3.3 feet] thick.) was considered only as back-filled soil. The efficiency of such a water conditioning layer to change the chemical environment inside the disposal vault will be investigated in future analyses.

3.4.6.5 Vault. The concrete structure containing the waste packages is generically called the vault.

As described in Section 2.4.2, the basic unit of the vault is the vault bay. A vault bay consists of four walls, a roof, and a floor (sometimes call a pad) made from concrete. For the conceptual design the concrete structure is assumed to be made from Portland cement. While steel structural reinforcement of the walls is likely to be used in the design, the impacts of the presence of steel were not included in this study because an actual design is not available. The bottom of the vault bay floor is 20.75 meters (68 feet) below grade (200 meters [656 feet] above mean sea level). The dimensions of the vault bay are given in Table 3-9.

Six vault bays placed end to end make a vault row. For Concept 1, the vault rows are next to each other, sharing a common wall. For Concept 2, the vault rows are separated by a row width of soil. Such a row of dirt would allow greater radiation protection for workers and a more robust sand-gravel capillary barrier would use more land and cost more. Section 2.4.2 describes and shows the vault layouts. These are summarized in Table 3-10 and displayed in Figures 2-19 (Concept 1) and 2-20 (Concept 2).

Table 3-9. Dimension of a Vault Bay for Base Analysis Case*

| Part of Vault Bay | height | length | width | thickness |
|-------------------------------------|------------------|------------------------------------|---------------------|--------------------|
| roof (ceiling) | --- | 40 m (131 ft) | 21.5 m (70.5 ft) | 0.76 m (2.5 ft) |
| internal walls | 9 m (29.5 ft) | dependent on floor length or width | --- | 1 m (3.3 ft) |
| external walls (walls next to soil) | 9 m (29.5 ft) | dependent on floor length or width | --- | 2 m (6.6 ft) |
| floor (pad) | --- | 40 m (131 ft) | 21.5 m (70.5 ft) | 0.76 m (2.5 ft) |

Data from Eiholzer (1995). Figures of the facility concepts are in Section 2.4.2.

Table 3-10. Vault Layout for Base Analysis Case*

1. Six (6) vault bays are laid out forming a vault row so that short sides are next to each other, resulting in a length of 246 meters (807 feet). A vault row is oriented in the east-west direction.
2. Concept 1 (base analysis case)
 - a. Ten (10) vault rows are placed parallel to each other, having a common internal wall. Total width is 208 meters (682 ft), resulting in an area of 51,000 m² (12.6 acres). (Eiholzer 1996)
3. Concept 2 (sensitivity)
 - a. Thirteen (13) vault rows are placed parallel to each other. (Eiholzer 1996)
 - b. Vault rows are separated by 17.5 meters (57.4 ft), with walls on long side being exterior walls. Separations filled with compacted backfill soil created during excavation. The facility (vault rows plus separations) is 515.5 meters (1,691.3 ft) wide, resulting in an area of 127,000 m² (31 acres).

Data from Eiholzer (1995) except where noted. Section 2.4.2 contains figures (2-19 through 2-21) on the facility concepts.

Section 3.5.5.6 describes the sensitivity cases analyzed. These cases focused on the different impacts of design features, including vault layout and orientation as well as the effectiveness of various facility components.

3.4.6.6 Filler Material. The disposal facility concepts include filler material between and above the stacks of waste packages inside the vault bays. Section 2.4.5.5 discusses the purposes of the filler material.

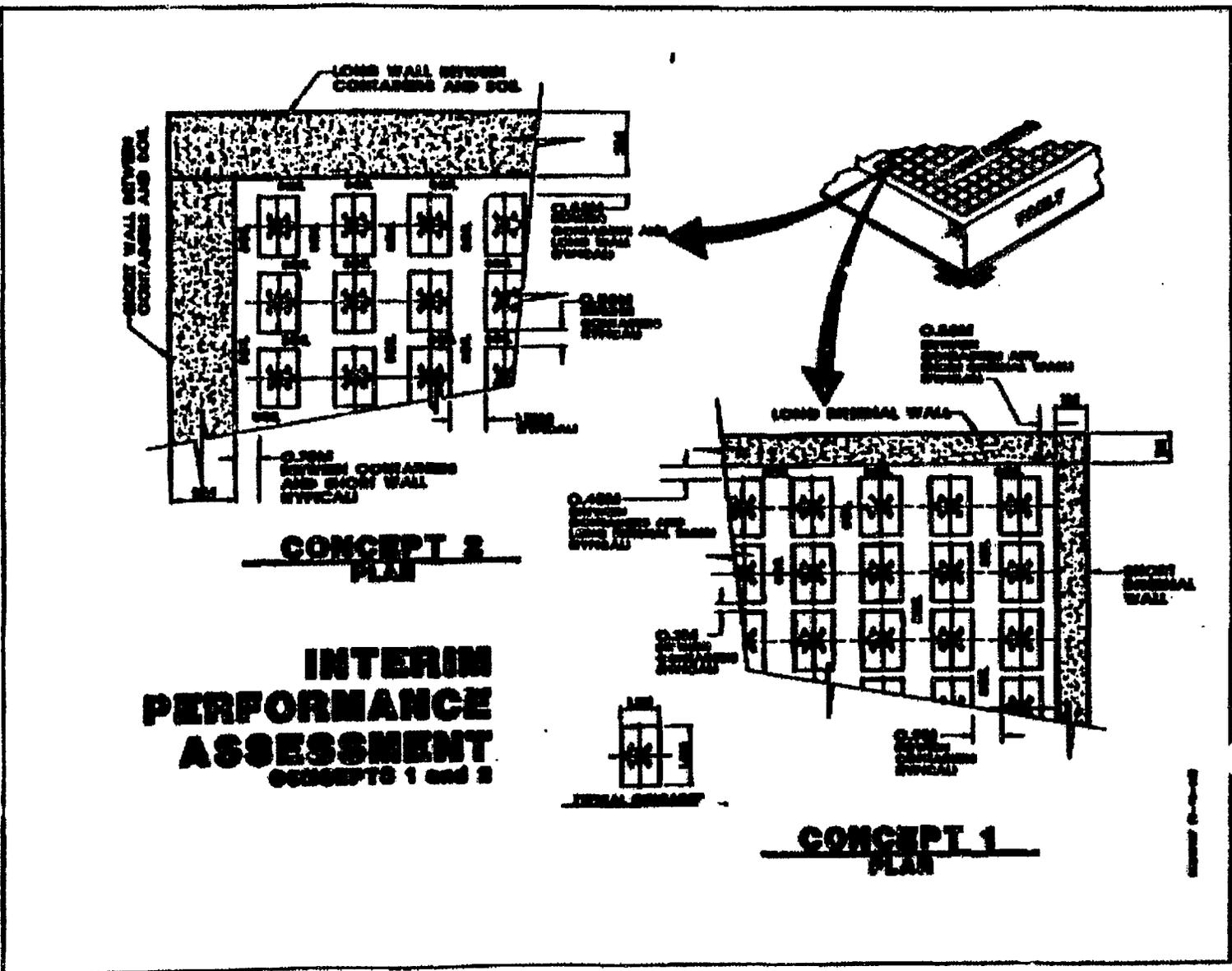
The amount of filler material will depend on the stacking arrangement and number of waste packages. Because the actual arrangement is not known, an arrangement was developed for each concept. Figure 3-5 shows the spacing of the waste packages in the vault bays for Concepts 1 and 2, respectively (Eiholzer 1996). The arrangement for Concept 1 was used for the base analysis case. The arrangement for Concept 2 was used as a sensitivity case. The sensitivity case that used the arrangement for Concept 2 determined the effect of a lower radionuclide concentration throughout the disposal facility. The arrangements differ for each concept to examine if the spacing between canisters affects the overall environmental outcome.

3.4.6.7 Existing TWRS Disposal Facilities Sensitivity Study. Using the four existing TWRS disposal vaults as part of the disposal action is being considered. These vaults, described in *Performance Assessment of Grouted Double-Shell Tank Waste Disposal at Hanford* (Kincaid 1995-4), are located about one kilometer east of the proposed disposal site. They could hold about 6 percent of the projected waste volume. Because the vaults are so close to the preferred location, the geology and associated data are very similar. The design for the grout vaults is similar to the presumed facility design, except that the grout vaults have .5 to 1.0 meter of asphalt surrounding the concrete structure. No credit is taken for this asphalt, even though, as shown by Kincaid 1995, the asphalt greatly slowed the release of moisture and contaminants from the disposal facility.

3.4.6.8 Degradation of the Waste Disposal Facility. Parts of the disposal facility will degrade during the first 10,000 years. These analyses are based on the assumption that natural materials such as sand and gravel will not degrade, but that manufactured materials such as concrete and glass will. This section discusses components of the waste disposal facility and how they may degrade.

The Hanford surface barrier has a design life of at least 1,000 years (Myers 1994), with deterioration thought to come mainly from the effects of wind and animal intrusion. Although the actual lifetime of the surface barrier is not known, 1,000 years was used for these analyses. The infiltration rate through the barrier will change at the end of the lifetime of the barrier (Section 3.4.7). Because the top of the Hanford-type surface barrier is at ground level, erosion should not pose the problem that it would if the barrier were above ground. Also, the facility's location is not in an area of sand dune formation (Section 2.2.5.2).

Figure 3-5. Waste Package Spacing for Disposal Facility Concepts 1 and 2 (from Ilhobser 1996).



Because the capillary barrier is constructed of natural materials, it is assumed not to change as a result of its own degradation. Studies (Kramer 1989) have shown that the mixing of the sand and gravel should not significantly affect performance. However, the capillary barrier could fail if such subsidence occurs within the disposal facility. Large drops or gaps in the barrier would cause a discontinuity and possible functional failure. However, calculations (Mann 1995b) indicate that large subsidence is required for the capillary barrier to fail. The subsidence aspect of the capillary barrier was examined in a sensitivity study.

The waste packages will degrade over time from the water-waste form interaction described in Section 3.4.5.4. The effect of the degradation of the waste containers is ignored in these 10,000-year analyses because these materials will degrade so quickly in comparison that the container is assumed to have never existed. The possible effect of changed waste form release rates caused by chemical interactions of the waste form and container await the specifications for these materials.

All concrete structures are considered to be degraded at 500 years. Five hundred years was chosen because of a Nuclear Regulatory Commission staff's draft branch technical position (NRC 1994) recommending that no credit be taken for engineered physical components after at most 500 years. It is expected that future analysis will show that because of the design specifications and conditions on the Hanford Site that the design life of the concrete structures in the disposal facility will be longer than 500 years.

Earthquakes could accelerate the facility's degradation, particularly that of the concrete structures. However, earthquake analyses will not be performed for these analyses because not enough is known about the design of the disposal facility. As the facility design develops, the influence of earthquakes will be incorporated in future low-level tank waste performance assessments.

Besides the influence of subsidence on the capillary barrier, the following sensitivity cases related to facility degradation were investigated:

- All the concrete was considered degraded at closure. This case indicates how important the concrete structure is to the disposal system.
- The concrete structure degrades at 2,000 years. This case examined the "bathtub" effect that occurs when water collects in the bottom of the disposal facility for a long time and is then immediately released.

3.4.7 Infiltration Rate

The infiltration rate is the rate at which water leaves the near-surface zone (the zone affected by plant development, animal intrusion, and evaporation) and enters the sand-gravel capillary barrier. For the first 1,000 years, the near-surface zone is the Hanford-type barrier. That part of the infiltration rate not diverted by the sand-gravel capillary barrier provides the moisture that drives the corrosion of the waste form and carries the contaminants from the facility. This moisture and (starting at some depth into the vadose zone) the diverted water carry the contaminants into the aquifer. Table 3-11 displays the infiltration rates for the base analysis case.

Table 3-11. Infiltration Rates for Base Analysis Case.
(Rockhold 1995)

| Parameter | Recharge Rate Value |
|--------------------------|-----------------------|
| At the Disposal Facility | |
| First 1,000 years | 0.5 mm/y (0.02 in./y) |
| Thereafter | 3.0 mm/y (0.12 in./y) |

Normally, the infiltration rate is assumed to be equal to the recharge rate, the rate at which water enters the aquifer. This assumption is based on the separate assumption that little water is stored or converted in the vadose zone. Because of the equality of values, recharge rate and infiltration rate are often used interchangeably in performance assessments. In future performance assessments, the removal of water from the system during the corrosion processes will be explicitly included.

Rockhold et al. (Rockhold 1995) estimated the short-term and long-term recharge rates for the proposed disposal site. The short-term recharge rate (0.5 mm/y [0.02 in./y]) was based on the design specifications of the Hanford surface barrier (Myers 1994 and described in Section 3.4.6.). The long-term recharge rate (3 mm/y [0.12 in./y]) was based on the data for the disposal site from Fayer and Walters (Fayer 1995a). Fayer and Walters estimated recharge rates at locations throughout the Hanford Site based on vegetation cover and soil type. Site-specific measurements will be performed once the location of the disposal facility is decided.

Because the specifications for the surface barrier cite 1,000 years for the design life, the base analysis case used the infiltration rate of 0.5 mm/y for the first 1,000 years. Then the infiltration rate was immediately increased to 3 mm/y. The infiltration through the surface barrier is not expected to increase this quickly. However, no data exist on which to base a slower rate of increase. The infiltration rate outside the region of the surface barrier for the first 1,000 years is

expected to be the natural rate (3 mm/y). However, this effect is ignored because the barrier covers most of the surface area important for contaminant transport.

The following three sensitivity cases, based on natural conditions were selected to bracket the selected infiltration rates for the disposal facility:

- The first does not consider the surface barrier. The 3 mm/y recharge rate was used throughout the calculation.
- The second used the rate that was used in the grout performance assessment (Kincaid 1995). For the grout performance assessment, the surface barrier was assumed to be effective forever. However the recharge rate was slightly higher, 1 mm/y (0.04 in./y).
- The third used a very low recharge rate. The recharge rate of 0.1 mm/y (0.004 in./y) was used. Preliminary tracer measurements indicate that if sagebrush persists at the disposal site, this recharge rate may be appropriate.

The infiltration rate used for the land-use sensitivity cases given in Sections 3.3.3.3.2 and 3.3.3.4.2 was 100 mm/y (3.9 in./y) to simulate irrigated farming.

3.4.8 Exposure Parameters

3.4.8.1 Overview. Data are needed to convert radionuclide concentrations into human dose equivalent. The first step is to decide which of several internal and external dose conversion libraries to use. The next step is to calculate dose conversion factors based on the various exposure scenario pathways (Sections 3.3.3 and 3.3.6). Finally, significant data need to be determined for the inadvertent intrusion scenarios. The values for all the exposure parameters are those recommended in Rittmann 1995.

3.4.8.2 Internal and External Dose Conversion Factors. Both the Department of Energy and the Environmental Protection Agency have published libraries of values to be used in converting radionuclide concentrations into human dose equivalent. In addition, the Hanford Site has developed its own library. This section describes the choice of libraries used for internal and external dose conversion.

The internal dose conversion factors specify the effective dose equivalent (EDE) from a unit intake (ingested or inhaled). These dose factors reflect the committed dose over a period of 50 years of a radionuclide over 50 years. This period was established by the International Commission for Radiological

Protection (ICRP 1977) for determining internal dose and relating it to whole body exposure.

The three internal dose conversion libraries considered for this performance assessment were the ones developed by the DOE (DOE 1988d), the EPA (EPA 1988), and the Hanford Site. The Hanford Site values were based on the GENII computer code system (Napier 1988), which was last revised in 1993 (Rittmann 1993). In most cases, the three libraries have similar values. However, for technetium, a key radionuclide the values greatly differ. The GENII value for ^{99}Tc is 70 percent higher than the DOE value. The EPA value is 12 percent higher than the DOE value. The DOE library (DOE 1988d) was chosen for this performance assessment because of its widespread use in other DOE performance assessments.

External dose conversion factors give the expected dose equivalent to an individual standing in the center of a large contaminated area. The three sources of external dose factors used at the Hanford Site are from the DOE (DOE 1988c) and EPA (EPA 1993), and from the revised values based on GENII (Rittmann 1993). The values in the external dose factors libraries differ more than the values in the internal dose factors libraries. The DOE external dose factors library assumes that all radionuclides are at the surface and that no soil mixing has occurred. Thus, the values of the DOE library lead to larger dose estimates. The GENII and EPA models are similar to each other, but the EPA implementation uses a Monte Carlo approach while GENII uses a deterministic approach. For the key radionuclides important in external exposure, ^{137}Cs and ^{134}Cs , the DOE dose factor is about four times larger than the EPA value. The GENII value is about 20 percent larger than the EPA value. Because of its modern database and methods, the EPA library was used in these analyses for external doses.

Although not the intent, the effect of these choices is to choose libraries with the lowest dose factors for the important radionuclides. Sensitivity cases were performed using each of the dose factor libraries.

3.4.8.3 Drinking Water and All-Pathways Dose Conversion Factors. Parameters other than the dose conversion factors are important in converting radionuclide concentrations into doses. This section covers the values needed for the drinking water exposure pathway and the all-pathways scenario, the two exposure scenarios considered in this performance assessment.

Pumping water up from the unconfined aquifer can distort the groundwater flow at high pumping rates and hence lower the concentration of radionuclides in the well water. A minimal pumping rate of 10 liters/day (10.6 quarts/day) [2 liters/day (2.1 quarts/day) per person for a family of 5] is assumed. To maximize the exposure at the 200 East Area boundary and make the calculations simpler, the position of the vaults is assumed to be in the northeast quarter of the disposal area.

For the drinking water scenario, the dosimetry parameter needed is the amount of water consumed. The value commonly used in performance assessments, 2 liters/day, is the value used in these analyses. This value is 35 percent higher than the 1.48 liters/day (1.56 qt/day) measured for the western United States by the EPA (Yang 1986). The resulting drinking water dose factors used for this performance assessment are displayed in Table B-1 in Appendix B.

As its name implies, the all-pathways scenario is more inclusive. This scenario includes drinking water, ingesting and inhaling soil, ingesting food, and receiving external radiation. Rittmann (1995) provides a complete description of all the parameters and the justification for the selected values. The resulting dose factors are displayed in Table B-2 in Appendix B. The following paragraphs summarize these pathways and the values used in this performance assessment.

Soil is taken into the body by ingestion and by inhalation. Soil ingestion is assumed to occur through hand-mouth contact, licking the lips, and similar motions at the rate of 100 milligrams per day (0.0035 ounce/day) (EPA 1989a). Soil inhalation is based on the methods found in NUREG/CR-5512 (Kennedy 1992) and results in 2.3 mg/day (0.00008 oz/day) being inhaled.

Food ingestion exposure is based on the EPA's Exposure Factors Handbook (EPA 1989a), daily consumption factors for the western United States (Yang 1986), and animal, dairy, and plant intake rates (Kennedy 1992). However, water consumption is taken as 2 liters per day. For this calculation it is assumed that half of the person's meat is raised on irrigated fodder and 25 percent of the person's vegetables come from the garden.

Finally, the individual is exposed daily to radiation emitted by the contaminated soil. For these analyses, the time for external exposure was assumed to be 4,120 hours per year (Rittmann 1995).

The all-pathways dose factors found in Table B-2 are nearly the same as the drinking water dose factors found in Table B-1. The drinking water pathway is the largest contributor for most nuclides. Table B-2 shows the ratios between the all-pathways dose factors and the drinking water dose factors.

3.4.3.4 Inadvertent Intruder Parameters. Selecting values for parameters important in inadvertent intruder scenarios is very difficult. Such intrusion is postulated to be in the future so that the nature of the intrusion is ill-defined. Moreover, uncertainty abounds about the proper values to be used in a given scenario. This performance assessment looks at the driller and homesteader scenarios (Section 3.3.3.4).

For the driller scenario the most important parameters are the amount of waste taken from the site, the size of the area over which the waste is spread, and the physical integrity of the waste.

The amount of waste material taken from the disposal site is assumed to be the stack height of the waste (7.2 meters [23.6 feet] from Section 3.4.5.2) times the area of the bore hole for the well. For this performance assessment, the diameter of the well is assumed to be 0.3 meter (1 foot). Although consistent with the diameters used in earlier Hanford Site performance assessments, this value is larger than the range of diameters (10.2 to 25.4 centimeters [4 to 10 inches]) commonly found in local communities. In future performance assessments, an estimate of the well diameter based on actual experience will be used.

The area over which the waste is spread is initially 100 m² (about 1,100 ft²). This value has been historically used in Hanford performance assessments.

The integrity of the waste form becomes important in determining the amount of radionuclides available for inhalation or uptake by plants and animals. For the base case analysis, 90 percent of the waste exhumed is assumed to stay within the waste form. The importance of this assumption was investigated by sensitivity cases.

The worker at the well drilling site is exposed for 5 days (8 hours per day). The dose to the worker is the sum of the contributions from inhalation of resuspended dust (0.1 mg/m³), ingestion of trace amounts of soil (100 mg/day), and external exposure at the center of a slab of contaminated soil for 40 hours. The dose factors for this drilling scenario can be found in Table B-3 in Appendix B.

The most important parameters in the second phase of the inadvertent intruder scenario, the homesteader scenario, are the volume of waste exhumed, the area over which it is spread, and the integrity of the waste form. For this scenario, the depth over which the waste is mixed with the soil and the parameters from the all-pathways scenario are also important.

The same amount of waste is exhumed as in the driller scenario, but now the waste is assumed to be spread over a larger area. The area over which the waste is spread is assumed to be 500 m² (0.124 acre). In all earlier Hanford Site performance assessments, the garden area has been 2,500 m² (0.62 acre). The 500-m² garden was chosen for this performance assessment because the size represents an area large enough to supply a significant portion of a person's vegetable and fruit diet. Household gardens in the vicinity of the Hanford Site range in size from 10 m² to 1,000 m² (107 ft² to 0.25 acre) (Napier 1984).

The value taken for the depth of the soil mixing is 15 cm (5.9 in.). This value has been used in other onsite performance assessments and is typical for root systems of garden vegetables.

The values for other parameters for this scenario are taken from the driller scenario (immediately above) and from the all-pathways exposure scenario (Section 3.4.8.3). The resulting dose factors are displayed in Table B-4 in Appendix B.

A sensitivity case for the 2,500-m² garden was run. The change in garden size proportionally changes the soil concentration and internal doses, but only slightly changes the external dose. The larger garden area is five times larger than the smaller garden size. The larger garden has soil concentrations that are a factor of five smaller than the soil concentration in the small garden. The same relationship is found with the internal doses. However, the external doses from the larger garden are only 10 to 25 percent less than the external dose from the smaller garden. The smaller garden is occupied less (900 hr/year) than the larger garden (4,120 hr/year). Part of the reduction in effective exposure time is caused by the rapid decrease in dose rate as one moves away from the garden. The ratio of effective dose rates for each radionuclide for the 500 m² (5,382 ft²) garden to the 2,500 m² (26,910 ft²) is shown in Table B-5 in Appendix B.

3.4.8.5 Other Scenarios. Two other scenarios (integrated dose estimate and the glacial-age catastrophic flood) have additional parameters. For the cases where integrated doses are calculated, populations of 25 for a public drinking water system (40 CFR 141) and 5,000,000 for the number of people living on the Columbia River (Kincaid 1995-5) were used. The flow rate in the Columbia River was taken to be 1000 m³/s (the lower end of typical values, 1,000 - 3,000 m³/s, cited by Woodruff 1992). For the catastrophic flood scenario, the waste is conservatively assumed to be redeposited uniformly to a depth of 20 meters (65.6 feet, the depth of the bottom of the disposal facility) over an area equivalent to the Hanford Site (1,450 km² [560 mi²]).

It is realized that the exposure parameters chosen for the base analysis case may not be appropriate for Native American communities. Future performance assessments will treat these communities.

3.4.8.6 Half-lives. The half-lives and decay chain branching ratios are taken from *Radioactive Decay Data Tables* (Kocher 1981). The half-lives and other decay data used in this analysis are presented in Table 3-12. Normally these data have very small uncertainties. However, for two key nuclides in this study (¹³⁷Se and ¹³⁷Sr), the half-lives are based on a single measurement from the 1940's. Unpublished data from the Pacific Northwest National Laboratory (PNL) (Jenquin 1995) indicates that the calculated values of reactor fuel yield in terms of curies/gram of fuel are a factor of 7 higher than measured values for ¹³⁷Se and a factor of 4.5 higher for ¹³⁷Sr. Because the fission yield is well known

and burnout cross sections are insignificant, these more recent results indicate that the half-life values for ^{76}Se and ^{126}Sn given in most standard references are about a factor of five too small. An increase in the half-lives would imply a decrease in the inventories used in this analysis.

Table 3-12. Half-life and Other Decay Information

| Parent | Half-life (y) | End of Decay Chain | Number of Alpha Emitters | Branching Ratio |
|---------------------|-----------------------|--------------------|--------------------------|-----------------|
| ^3H | 12.28 | | 0.0 | 1.0 |
| ^{10}Be | 1.60×10^6 | | 0.0 | 1.0 |
| ^{14}C | 5,730. | | 0.0 | 1.0 |
| ^{22}Na | 2.602 | | 0.0 | 1.0 |
| ^{36}Cl | 301,000. | | 0.0 | 1.0 |
| ^{40}K | 1.277×10^9 | | 0.0 | 1.0 |
| ^{54}Mn | 0.8561 | | 0.0 | 1.0 |
| ^{55}Fe | 2.7 | | 0.0 | 1.0 |
| ^{60}Co | 5.271 | | 0.0 | 1.0 |
| ^{63}Ni | 75,000. | | 0.0 | 1.0 |
| ^{65}Ni | 100.1 | | 0.0 | 1.0 |
| ^{76}Se | 65,000. | | 0.0 | 1.0 |
| ^{87}Rb | 4.73×10^{10} | | 0.0 | 1.0 |
| ^{90}Sr | 28.6 | | 0.0 | 1.0 |
| ^{93}Zr | 1.53×10^6 | $^{93}\text{Nb}^a$ | 0.0 | 1.0 |
| $^{93}\text{Nb}^a$ | 14.6 | | 0.0 | 1.0 |
| ^{94}Nb | 20,300. | | 0.0 | 1.0 |
| ^{93}Mo | 3,500. | | 0.0 | 1.0 |
| ^{99}Tc | 213,000. | | 0.0 | 1.0 |
| ^{100}Ru | 1.0081 | | 0.0 | 1.0 |
| ^{107}Pd | 6.50×10^6 | | 0.0 | 1.0 |
| $^{108}\text{Ag}^b$ | 127. | | 0.0 | 1.0 |
| ^{109}Cd | 1.2704 | | 0.0 | 1.0 |
| $^{113}\text{Cd}^b$ | 13.7 | | 0.0 | 1.0 |
| ^{115}In | 4.6×10^{13} | | 0.0 | 1.0 |
| $^{121}\text{Sn}^b$ | 55. | | 0.0 | 1.0 |

| Parent | Half-live (y) | End of Decay Chain | Number of Alpha Emitters | Branching Ratio |
|--------------------------------|------------------------|--------------------|--------------------------|-----------------|
| ¹²⁴ Sb | 100,000. | | 0.0 | 1.0 |
| ¹²⁵ Sb | 2.77 | | 0.0 | 1.0 |
| ¹²⁹ I | 1.57x10 ⁷ | | 0.0 | 1.0 |
| ¹³⁴ Cs | 2.062 | | 0.0 | 1.0 |
| ¹³⁵ Cs | 2.30x10 ⁵ | | 0.0 | 1.0 |
| ¹³⁷ Cs | 30.17 | | 0.0 | 1.0 |
| ¹³⁸ Ba | 10.5 | | 0.0 | 1.0 |
| ¹⁴⁷ Pm | 2.6234 | | 0.0 | 1.0 |
| ¹⁴⁷ Sm | 1.06x10 ¹¹ | | 1.0 | 1.0 |
| ¹⁵¹ Sm | 90. | | 0.0 | 1.0 |
| ¹⁵² Eu | 36. | | 0.0 | 1.0 |
| ¹⁵³ Eu | 13.6 | | 0.0 | 1.0 |
| ¹⁵⁴ Eu | 8.6 | | 0.0 | 1.0 |
| ¹⁵⁵ Eu | 4.96 | | 0.0 | 1.0 |
| ¹⁵⁷ Gd | 1.10x10 ¹⁴ | | 1.0 | 1.0 |
| ¹⁶⁰ Ho ^o | 1,200. | | 0.0 | 1.0 |
| ¹⁶⁷ Re | 4.7x10 ¹⁰ | | 0.0 | 1.0 |
| ²⁰⁴ Tl | 3.779 | | 0.0 | 1.0 |
| ²¹⁰ Pb | 22.26 | | 1.0 | 1.0 |
| ²²⁶ Ra | 1,600. | ²¹⁰ Pb | 4.0 | 1.0 |
| ²²⁸ Ra | 5.75 | ²¹² Th | 0.0 | 1.0 |
| ²²⁷ Ac | 21.773 | | 5.0 | 1.0 |
| ²¹⁰ Th | 1.9132 | ²⁰⁶ Pb | 5.0 | 1.0 |
| ²²⁹ Th | 7340. | | 5.0 | 1.0 |
| ²³⁰ Th | 77000. | ²¹⁰ Pb | 1.0 | 1.0 |
| ²³² Th | 1.405x10 ¹⁰ | ²⁰⁶ Pb | 1.0 | 1.0 |
| ²³¹ Pa | 32,764. | ²²⁷ Ac | 1.0 | 1.0 |
| ²³³ U | 72. | ²²⁸ Th | 1.0 | 1.0 |
| ²³⁵ U | 159200. | ²²⁹ Th | 1.0 | 1.0 |
| ²³⁸ U | 244,500. | ²¹⁰ Pb | 1.0 | 1.0 |

| Parent | Half-life (y) | End of Decay Chain | Number of Alpha Emitters | Branching Ratio |
|--------------------------------|-----------------------|--------------------|--------------------------|----------------------|
| ²³⁵ U | 7.038x10 ⁸ | ²¹¹ Pb | 1.0 | 1.0 |
| ²³⁶ U | 2.34 x10 ⁷ | ²²² Rn | 1.0 | 1.0 |
| ²³⁸ U | 4.468x10 ⁹ | ²²⁶ Ra | 1.0 | 1.0 |
| ²³⁷ Np | 2.14 x10 ⁶ | ²²³ Rn | 1.0 | 1.0 |
| ²³⁸ Pu | 2.851 | ²²² Rn | 1.0 | 1.0 |
| ²³⁹ Pu | 87.75 | ²²⁶ Ra | 1.0 | 1.0 |
| ²³⁹ Pu | 24,131. | ²²³ Rn | 1.0 | 1.0 |
| ²⁴⁰ Pu | 6,569. | ²²⁶ U | 1.0 | 1.0 |
| ²⁴¹ Pu | 14.4 | ²⁴¹ Am | 0.0 | 1.0 |
| ²⁴² Pu | 375,800. | ²²⁶ Rn | 1.0 | 1.0 |
| ²⁴⁴ Pu | 8.26x10 ⁷ | ²⁴⁰ Pu | 1.0 | 1.0 |
| ²⁴¹ Am | 432.2 | ²³⁷ Np | 1.0 | 1.0 |
| ²⁴² Am ^a | 152. | ²³⁸ Pu | 1.0 | 0.82782 ^b |
| ²⁴³ Am | 7,380. | ²³⁹ Pu | 1.0 | 1.0 |
| ²⁴³ Cm | 28.5 | ²³⁹ Pu | 1.0 | 1.0 |
| ²⁴⁴ Cm | 18.11 | ²⁴⁰ Pu | 1.0 | 1.0 |
| ²⁴⁵ Cm | 8,500. | ²⁴¹ Pu | 1.0 | 1.0 |
| ²⁴⁶ Cm | 4,750. | ²⁴² Pu | 1.0 | 1.0 |
| ²⁴⁷ Cm | 1.56x10 ⁷ | ²⁴³ Am | 1.0 | 1.0 |
| ²⁴⁸ Cm | 339,000. | ²⁴⁴ Pu | 1.0 | 0.9174 ^b |

Remainder goes to ²⁴⁴Cm

^a Remainder undergoes spontaneous fission

3.5 Performance Analysis Methodology

This section describes how the performance of the system was determined. That is, this section explains how the data and conceptual models presented in Sections 3.2 through 3.4 are translated into a numerical model suitable for computer simulation. First the strategy of the computer simulation is introduced. Then the computer code selection criteria are summarized. The codes used are then described with their selection justified. Next the description of how the disposal facility concepts and the natural system are translated into computer models is presented. Finally the parameters used in the computer simulations are given.

Calculations of relatively simple equations (for example, gaseous diffusion or glacial-age catastrophic flood consequences) were done by hand. These equations will be treated in Chapter 4, where the results are discussed.

3.5.1 Integration

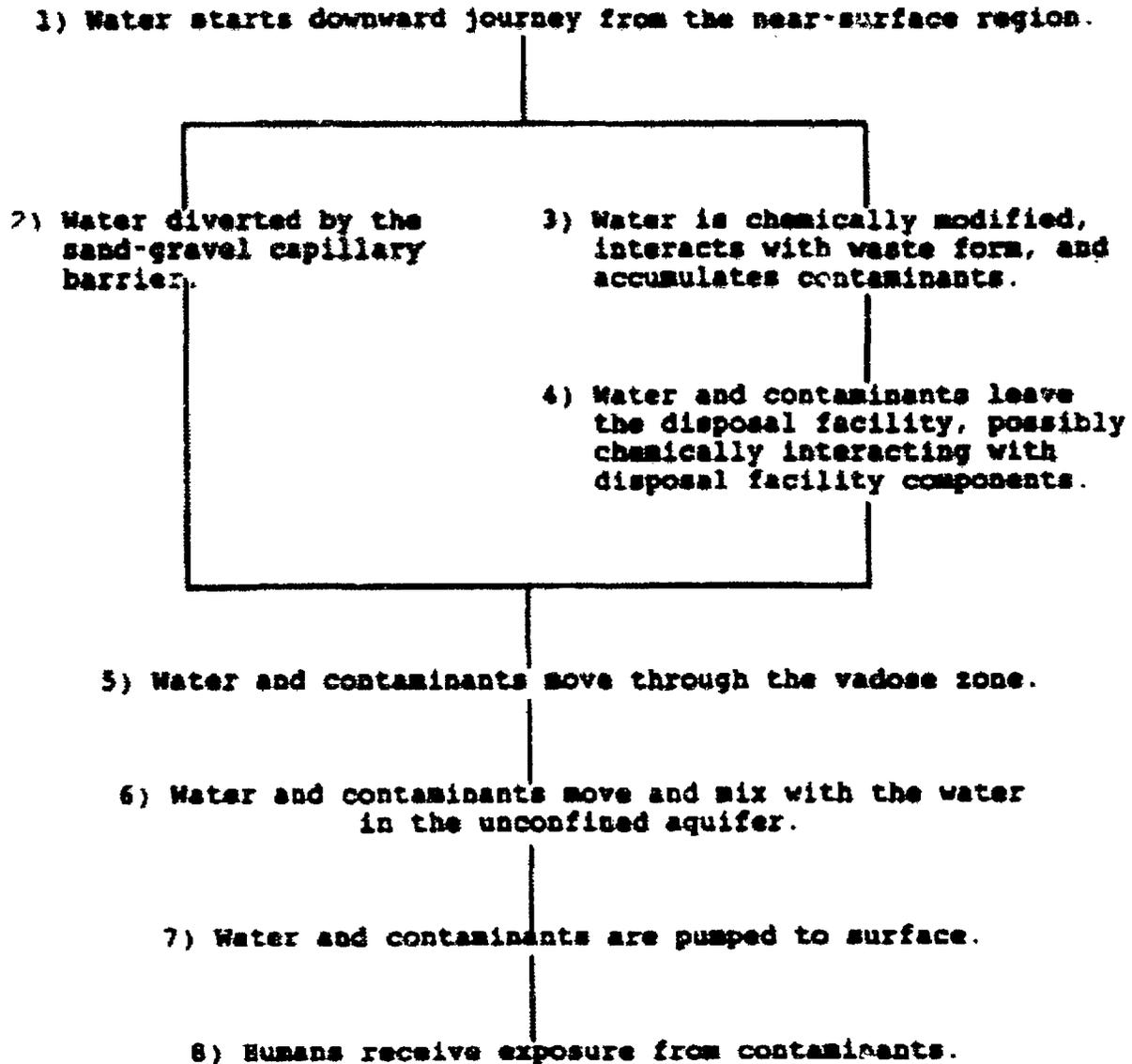
3.5.1.1 Strategy. Previous long-term environmental assessments at the Hanford Site have consistently shown that the groundwater pathway is the most important. This pathway also requires the most calculations. The conceptual model used for this and earlier Hanford Site performance assessments takes eight steps:

1. The water leaves the very near-surface soil region at the infiltration rate.
2. The water moves toward the waste form, most of which is diverted by any intact capillary barrier.
3. The water that is not diverted is chemically modified by the local environment, interacts with the waste form, accumulates contaminants, and again is chemically modified by the local environment.
4. The water (possibly a reduced amount) leaves the disposal facility carrying contaminants with it. Some contaminants may interact with the material in the disposal facility, slowing the release of the contaminants to the surrounding natural environment.
5. The water moves through the undisturbed, unsaturated zone (vadose zone) below the disposal facility down to the unconfined aquifer. The contaminants also are transported through the vadose zone, again possibly undergoing some geochemical sorption.
6. The water and contaminants move and mix with the water in the unconfined aquifer until they are extracted from the aquifer and brought to the surface or until they reach the Columbia River.
7. Contaminants are normally extracted by being carried to the surface with groundwater being pumped through a well.
8. The radionuclide contaminants then result in human exposure through a variety of pathways (ingestion, inhalation, and external radiation).

These eight steps are shown in Figure 3-6 as a flow chart.

The results for each step are computed separately and used in the next step so that computations can be made more easily. Such an approach is taken to maximize computational efficiency. Some of the computer simulations take 100 hours of computer time;

Figure 3-6. Eight Sequential Steps for the Groundwater Pathway



some take a few minutes. Each is a highly specialized calculation. However, the overall model is always considered at each step and consistent data are used throughout.

The strategy for the current computations is to define a base analysis case, then develop sensitivity cases derived from that base analysis case. In some instances the sensitivity cases are built on an alternative case (such as the one describing Concept 2). The results for the base analysis case and the sensitivity cases are presented in Chapter 4. Chapter 5 combines the results of the computer simulations, the results of simpler calculations, and the results of other analyses to integrate and interpret how the contaminants will affect the environment in the long term.

3.5.1.2 Base Analysis Case. The base analysis case provides the best estimate of how the system may evolve given the information available. The base analysis case is not necessarily the way that the system will behave. As more information concerning the waste form, the disposal facility design, and disposal site location are gathered, it is expected that the definition of the base analysis case will evolve. The approach used in the base analysis case is conservative, but reasonable. This approach is required by the DOE's Peer Review Panel.

The major features of the base analysis case are as follows:

- The location of the facility is as recommended by Shord (1995)
- The future land-use is as a protected area, without artificial recharge
- The design of the disposal facility is based on Concept 1 (Section 3.4.6)
- The contaminant release rate from the waste form is that given in the TWRS Privatization Specifications (DOE 1996a)
- The data for the natural system are those collected and interpreted for this performance assessment (Section 3.4.4).

Mann (1995b) describes the base analysis case in detail. The details of the models and related data for the base analysis case are presented in Sections 3.5.3 and 3.5.4, respectively.

3.5.2 Computer Codes

This section discusses the computer codes used for this performance assessment and justifies their technical adequacy. The general selection criteria used to select the major computer codes are first summarized. Succeeding subsections describe each major computer code used and the reason for their selection.

3.5.2.1 General Selection Criteria for Computer Codes. The large computer codes used for this assessment were selected based on meeting general code selection criteria and functional criteria related to the simulation being done. Large computer codes were needed for computing in the following two functional areas:

- Calculation of the contaminant release rate from glass (used only for sensitivity cases in this analysis) and
- Calculation of water flow and contaminant transport.

The codes considered had to first meet the general code selection criteria.

The general code selection criteria were based on government code selection documents and the experience of others. The waste management code selection criteria of the DOE (Case 1988) and of the NRC (Kozak 1989) were used to develop these selection criteria. The criteria were also shaped by the experience gained from other DOE performance assessments (WSRC 1992, Kincaid 1995-6) and on codes selected for earlier Hanford Site risk assessments (DOE-RL 1991a). The general required selection criteria included the following:

- Having the appropriate scientific framework
- Having documentation covering the underlying theory, use, and verification
- Being under configuration control.

General desirable criteria included the following:

- Suitable hardware requirements
- Suitable complexity
- Flexible interfaces with other codes
- A bias against proprietary codes
- Familiarity of the users with the code.

Mann 1995c details the development of the general selection criteria and the complete criteria.

The actual codes selected also had to meet criteria related to the function being simulated. Sections 3.5.5.2 through 3.5.2.6 summarize the codes chosen and the reasons for their selection. References to specific functional criteria will be given in their sections or related appendices.

3.5.2.2 AREST-CT

3.5.2.2.1 Overview. The analyzer for Radionuclide Source-Term with Chemical Transport (AREST-CT) code is the source-term code used for some of the sensitivity cases in the interim performance assessment. The base analysis case and many of the sensitivity cases assumes the release rate is that specified in the request for proposal for the waste form (DOE-RL 1996) which was not derived from a simulation of how a waste form would perform. AREST-CT calculates the time-dependent flux of radionuclides released from the waste form. AREST-CT contains two important factors that allow the code to simulate the processes in the disposal facility. First, the code is based on basic principles of physics, chemistry, and thermodynamics which provides the best estimate of contaminant release over the spatial and long time periods of interest. Second, the model for the disposal facility can be coupled with a model for

radionuclide release, thus providing the ability to couple the effects of facility design with waste form performance.

Using chemical reaction rates (including the glass corrosion rates) and moisture values in the vaults from PORFLOW (Section 3.5.2.3), AREST-CT provides the source term for the vadose zone calculations. AREST-CT calculates the following:

- The degradation of the waste form with corresponding release of radionuclides
- The chemical reactions that depend on time and space (including the formation of secondary mineral phases and the consumption of water)
- The transport of the water and contaminants through a vertical slice of the disposal facility.

3.5.2.2.2 Selection. AREST-CT was selected because it meets the criteria and requirements for the disposal system release model (McGrail 1994) and the general code requirements (Mann 1995c). Ten possible source codes were considered. AREST-CT was chosen because it had the highest score: 361. The next code had a total score of 264. The scoring methods, the other codes considered, and their scores are presented in Appendix C.3.

3.5.2.2.3 Code Description. AREST-CT calculates the total mass flux of radionuclides leaving the disposal facility by solving a coupled set of equations. The set describes the radionuclide release from the waste form and the mass transport from the waste form through the disposal facility, constrained by chemical reactions. This coupled set of equations is commonly known as the reaction-transport equation. The value for radionuclide release from the waste form is taken from either an assumed constant release rate or a simulation using a mechanistic glass corrosion model. More detailed documentation of the design or models used in the AREST-CT code are found in Engel (1995) and Engel (1995a), respectively.

The governing equations are given in Appendix C.2.

3.5.2.2.4 Code History. The AREST-CT code was developed at PNNL to analyze the engineered barrier system of a subsurface disposal site for storing nuclear waste. The engineered barrier system is the constructed or human-altered components of the disposal system. In this case, it is the disposal facility design starting with the water conditioning layer.

The code was originally developed to support the engineered-system performance analyses for the proposed high-level waste repository at Yucca Mountain, Nevada. Specific capabilities that address the low-level waste disposal action have been included in AREST-CT.

3.5.2.3.5 Verification. A two-part verification test of AREST-CT, Version 1, was done to ensure that modules of the program were correctly implemented and worked together (Chen 1995). A summary is given here; more details are given in Appendix C.4.

First, specific portions or modules of AREST-CT were unit tested to verify that the modules performed correctly. Individual code modules were evaluated against hand calculations, analytical solutions, or other existing numerical codes. Each module was unit tested before being incorporated into AREST-CT. All modules were considered acceptable for current use.

Second, the entire integrated computer code was tested. At the time of verification, no analytical solutions existed for the reaction-transport problems designed for AREST-CT. The code was benchmarked against simulation results other similar reaction-transport codes.

A one-dimensional idealization of a low-level-waste engineering system was run as a benchmark test case. The system consisted of 7 solids and 12 aqueous species. Two types of reactions were considered, equilibrium aqueous reactions and solid dissolution/precipitation reactions. The results of the test showed that AREST-CT simulations were of similar quality to the other codes. More details are given in Chen (1995).

Additional testing and verification will be conducted as the AREST-CT code develops. Future testing will include integration testing for mechanisms of radioactive decay and decay chain ingrowth, and for two-dimensional simulation. Plans for code development call for coupling with a multiphase flow solver so that it can model infiltration velocity changes with time-dependent porosity and permeability changes that result from solid dissolution/precipitation reactions and from the consumption of water that occurs during the hydrolysis of the glass waste form. Now, the program uses the water velocity from the separate moisture flow code.

3.5.2.3 PORFLOW.

3.5.2.3.1 Overview. The PORFLOW code (ACRI 1994) was used to calculate the transport of contaminants from the waste packages in the disposal facility to the unconfined aquifer. PORFLOW was also used to calculate the effect of possible disposal facility components on the amount of water that goes into the vaulted area then to the vadose zone.

PORFLOW interfaces with the two other major codes, AREST-CT (Section 3.5.3.2) and VAN3D-CG (Section 3.5.2.4), used in the analyses. PORFLOW supplies AREST-CT with the moisture movement velocities into the vault, which drives the glass corrosion process. AREST-CT supplies PORFLOW with the contaminant source term at the bottom of the waste disposal facility. PORFLOW

supplies VAM3D-CG, the code used for the unconfined aquifer, with the amount of moisture and contaminants entering the aquifer.

3.5.2.3.2 Selection. The process used to select PORFLOW (Piepho 1995) is summarized here. PORFLOW was given first consideration for use as a flow and transport code because it was used in the *Performance Assessment of Grouted Double-Shell Tank Waste Disposal at Hanford* (Kincaid 1995) and in earlier analyses of this disposal action (Rawlins 1994 and Mann 1995b). The capabilities of PORFLOW were compared to the capabilities of the VAM3D-CG (Buyakola 1994) and TRAC3D (Birdsell 1991) codes. All three codes met the flow and transport code requirements for this performance assessment (Mann 1995c).

Other codes, such as CPEST (Gupta 1987), MODFLOW (McDonald 1987), and SLAEMS (Strack 1989), were considered. However, they are aquifer codes and hence can not be used for vadose zone transport. Code selection documents from the Yucca Mountain Project (Reeves 1994) and the Savannah River Saltstone effort (WSRC 1992) were also consulted for alternative codes.

PORFLOW was selected to simulate flow and transport in the vadose zone for the following reasons:

- It met all the requirements established for this performance assessment
- It had desired features that the other codes lacked
- It was used in the earlier phases of this project
- The analysts were familiar with PORFLOW

As Section 3.5.2.4.2 describes, VAM3D-CG was used for the unconfined aquifer simulations because it is used in the Hanford sitewide groundwater model.

Versions of the PORFLOW and VAM3D-CG codes available in 1990 were approved by Hanford regulators to support Waste Management and Environmental Remediation activities (DOE-RL 1991a and 1991b).

3.5.2.3.3 Code Description. PORFLOW (ACRi 1994) calculates multi-phase fluid flow, heat transfer, and mass transport in unsaturated and saturated porous or fractured media. The code can simulate transient or steady state problems in Cartesian or cylindrical geometry in two or three dimensions. The material, i.e., soil or concrete, that PORFLOW models can be either uniform or a mixture. The material can contain distinct elements such as discrete fractures or boreholes within a porous matrix.

In this interim performance assessment, PORFLOW is used to simulate the following:

- The moisture content distribution from the bottom of the surface barrier into and through the vault region
- The contaminant concentration distribution from the vault area down into the unconfined aquifer.

For the first simulation, the source rate of the moisture is the infiltration rate given in Section 3.4.7. PORFLOW tracks the moisture front through and around the sand-gravel capillary barrier, through the water conditioning layer, through the concrete structure, and into the vault bay with containers and filler material. PORFLOW simulates the moisture content distribution at the surface of the waste package. This distribution is an input used by AREST-CT.

Tracking the contaminants from the vault region down into the unconfined aquifer is a more complicated task. Again PORFLOW uses the infiltration rate from Section 3.4.7 and the various features of the disposal facility to establish moisture movement. For this problem, the vadose zone region below the disposal facility is also considered. The moisture content distribution within the vadose zone is predicted. Then PORFLOW tracks the movement of the radioactive contaminants down into the groundwater. The contaminants are assumed to be released from the surface of the waste package at the rate established in Section 3.4.5.4. Each PORFLOW run follows four sets of radionuclides, each set corresponding to a different K_d value (Section 3.4.4.4). All the geologic layers (Section 3.4.4.2) with their different properties (Section 3.4.4.3) are treated in the same run.

3.5.2.3.4 Verification and Benchmarking. PORFLOW Version 2.394gr, used in this analysis, has been extensively verified and benchmarked (Piepho 1994). Verification and benchmarking efforts were based on the following:

- Comparing the results of the Version 2.394gr with earlier versions of PORFLOW
- Reproducing the results of analytical solutions from verification problems
- Comparing the results with other codes used to solve complex problems.

Additional details are given in Appendix D.4.1

3.5.2.3.6 Field Testing. As this document is being written PORFLOW is being used to simulate the Sisson/Lu Injection Experiment and previous leaks from Tank T-106. The Sisson/Lu experiment (Sisson 1984) injected a known amount of water and radioactive tracers into a well just east of the proposed disposal site. The methods, tools, and boreholes have been recently reevaluated (Fayer 1995c). The unintended leak from

Tank T-106 is the best characterized of the Hanford Site tank leaks.

3.5.2.4 VAM3D-CG

3.5.2.4.1 Overview. VAM3D-CG (Variably Saturated Analysis Model in 3-Dimensions with Preconditioned Conjugate Gradient Matrix Solvers) (Huyakorn 1994) is used to calculate flow and contaminant transport in the unconfined aquifer from unit moisture flow and contaminant amounts at the bottom of the vadose zone.

3.5.2.4.2 Selection. Although PORFLOW was selected to be the flow and transport code in both the vadose zone and the unconfined aquifer (Piepho 1995), VAM3D-CG was chosen to calculate results in the aquifer because of the need for a model to treat not just the area near the disposal facility but the entire Hanford Site.

Recommendation 94-2 of the Defense Nuclear Facilities Safety Board (DNFSB 1994) stressed the importance of calculating the environmental impact of all previous DOE actions on the points of compliance. This means that at the point where performance objectives must be met, the actions of all disposal and ground discharges besides the current proposed action must be included in the evaluation. Fortunately, the ERC Hanford Sitewide Groundwater Model (Law 1996) based on VAM3D-CG had been developed. Although other groundwater models of the Hanford Site (for example, Wurster 1995) exist, this model has had boundary conditions optimized for future land uses.

VAM3D-CG was selected for the Hanford Sitewide Groundwater Model (Law 1996) for the following reasons:

- The solution algorithms were robust
- The original developer, an internationally known expert, was available
- The VAM3D-CG code is capable of dealing with partially and fully saturated flow, thus efficiently simulating a fluctuating free water surface
- The VAM3D-CG code supports the use of special grid shapes (transitional elements) for detailed simulation of small areas, thereby making computations more efficient
- The version of the VAM3D-CG code available in 1990 was approved by Hanford Site regulators to support Waste Management and Environmental Remediation activities (DOE-RL 1991a and DOE-RL 1991b).

The VAM3D-CG code is preferred over the PORFLOW code for Hanford sitewide groundwater modeling applications because it offers a curvilinear grid. A curvilinear grid can be set up to follow layering or other characteristic patterns. For example, the thickness of the aquifer at the Hanford Site varies from over 100 meters (328 feet) to a few meters. A curvilinear grid was set up for the varying aquifer thickness, which allows faster input data preparations and faster code execution. The rectangular grid representations for varying formation thicknesses can lead to erroneous results when coarse grids are used or to prohibitively large matrices and computational times when fine grids are used.

3.5.2.4.3 Code Description. VAM3D-CG (Huyakorn 1994) calculates saturated-unsaturated groundwater flow and solute transport with variable water table positions and highly non-linear soil moisture conditions. The code can simulate transient or steady state problems in one, two, or three dimensions using a finite element model. Special grid elements (in the shape of hexahedrals) are used to define discrete volumes with irregular geometry. The size of these elements can vary. Many "fine" elements can be used in places where the geometry varies quickly. Such finer elements allow a better description of regions in which the values of parameters and variables are rapidly changing. An orthogonal curvilinear grid can also be used to represent flow domains.

In this interim performance assessment, VAM3D-CG was used to forecast the contaminant movement in the groundwater. VAM3D-CG used the values for the hydrologic parameters from the ERC Hanford Sitewide Groundwater Model (Section 3.4.4.5). A normalized contaminant source term was used for the amount of contaminant entering the unconfined aquifer. Water flow and contaminant transport patterns were then distorted by stress of pumping the water in the well. Thus VAM3D-CG calculated the contaminant concentration in the well relative to the normalized contaminant source term.

3.5.2.4.5 Verification and Benchmarking. Versions 2.4b (Lu 1994) and 3.1 (Lu 1995) of VAM3D-CG were tested in the following manner:

- Results of the installed version were compared to those published by the vendor (Huyakorn 1993)
- These versions were benchmarked against the results from PORFLO-3 Version 1.2 (Sagar 1990) for Hanford Site-relevant problems.

More details are given in Appendix D.4.2.

3.5.2.4.6 Calibration and Validation. Calibration and validation tests were run for both Versions 2.4b and 3.1. The calibration/validation effort for Version 2.4b (Lu 1993) used data from the Hanford Injection Test experiment (Sisson 1984).

The calibration/validation effort for Version 3.1 used data from the reevaluation of the Hanford Injection Test Experiment and from new experiments (Fayer 1995b). The Hanford Site-wide Groundwater Flow and Transport Calibration Report (Law 1996) describes in detail the various comparisons made with Hanford Site data.

3.5.2.5 INTEG. INTEG (Mann 1996) calculates a specific impact (whether dose rate or concentration level) based on the inventory, vadose zone transport, aquifer transport, and the dosimetry factors. The dose rate calculated depends on the type of dosimetry factor (i.e., all-pathways, drinking water). The program solves the following equation for each year under consideration.

$$\text{Response} = \sum_i \frac{I_i(t) \Gamma_i(t) w_i D_i}{r A}$$

where

- I_i is the amount (or inventory) of radionuclide i (Ci). The time-dependent value is calculated by INTEG based on the initial inventory and on decay and the ingrowth from other radionuclides.
- Γ_i is the flux of contaminants at the bottom of the vadose zone normalized to an unit inventory for radionuclide i ((Ci/y)/Ci). The time-dependent value is calculated by PORFLOW.
- w_i is the ratio of the concentration of radionuclide i at the well location to the contaminant concentration at the bottom of the vadose zone (Dimensionless). This quantity was called the well intercept factor in earlier Hanford performance assessments. The peak value as calculated by VAM3D-CG is used.
- D_i is the dose rate factor (mrem/y per Ci/m³). The values are taken from the tables in Appendix B. D_i is unity when the response that is calculated is a concentration.
- r is the recharge rate (m/y). The value at 10,000 years is used at all times.
- A is the area over which the contaminant flux enters the aquifer (m²). The value used is the area of the disposal facility being modelled.

The program is modeled after GRTPA (Rittmann 1993), which served a similar function in earlier work (Rawlins 1994 and Mann 1995b). INTEG allows greater freedom in specifying data used in the integration. The code has been benchmarked against the results of GRTPA (Mann 1996).

3.5.2.6 Spreadsheets. Commercial spreadsheets were used in determining inadvertent intrusion doses. The Quattro² Pro spreadsheet was used for developing the spreadsheet cells, while the Wingz³ spreadsheet was used for the actual runs. The spreadsheet calculations were compared with answers from the GENII computer program (Rittmann 1994). The verification of the spreadsheet formulas was done as part of the review by the Hanford Environmental Dose Oversight Panel (HEDOP) (Rhoads 1996).

3.5.3 Computer Models

3.5.3.1 Overview. This section describes the numerical models used in the PORFLOW and VAM3D-CG computer simulations. Because the ARFST-CT simulations of contaminant release rate are only used in sensitivity studies, the discussion of its numerical models is given only in Appendix C.

For both the vadose zone and groundwater calculations, two slightly different models are used. These models are described in the following sections. Each case has a computational complex model that describes the effect of many interacting features. These are the disposal facility models for the vadose zone calculations and the sitewide models for the groundwater calculations, respectively. Each case also has a much simpler calculational model that comprises the major features of the more complex models, but allows quicker runs. These simpler models are the unit cell model for the vadose zone calculations and the pumping model for the groundwater calculations. The base analysis case was run using all the models. Most of the sensitivity cases were run using the simpler models.

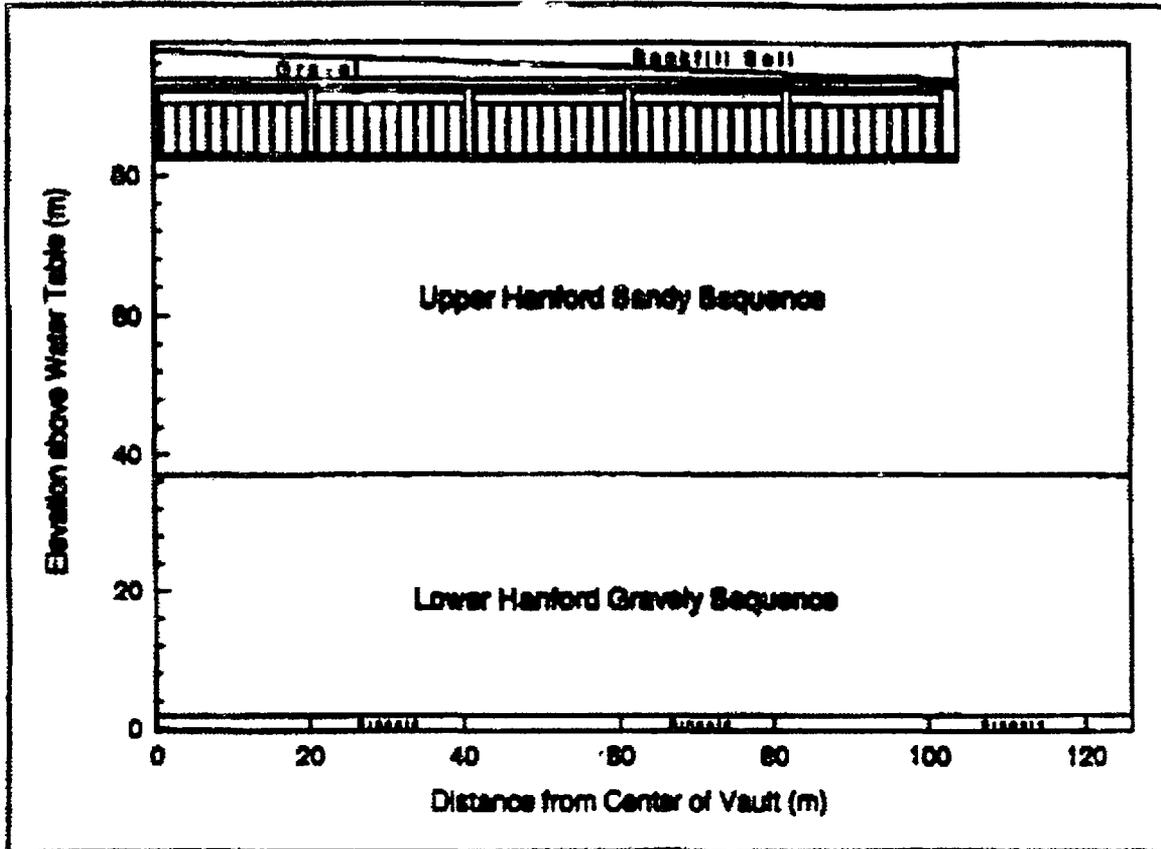
3.5.3.2 Disposal Facility Model. This two-dimensional model, shown in Figure 3-7, treats an entire vault row (see Section 3.4.6). See Piepho 1996 for more details. The model includes the sand-gravel capillary barrier, the water conditioning layer, the vault row, the waste packages, the filler material, and the vadose zone. The surface barrier is not treated. The water flux at the bottom of the surface barrier is considered a boundary condition. Source terms for contaminant release are considered to be at the surfaces of the waste containers.

Appendix D.6.1 has the input file for the base analysis case. A two-dimensional model (165 columns with 133 layers) is used. The sand-gravel capillary barrier is modelled with 28 layers, the water conditioning layer with 3, the vault roof, walls, and floor with 3. In each of the five vault bays modelled, there are 9 sets of canisters (each canister being modelled by a 2 x 9 grid) separated by a 1 x 9 grid for the

² Quattro is a registered trademark of Corel Corporation

³ Wingz is a trademark of Investment Intelligence Systems Incorporated

Figure 3-7. Zone Map for Disposal Facility Model



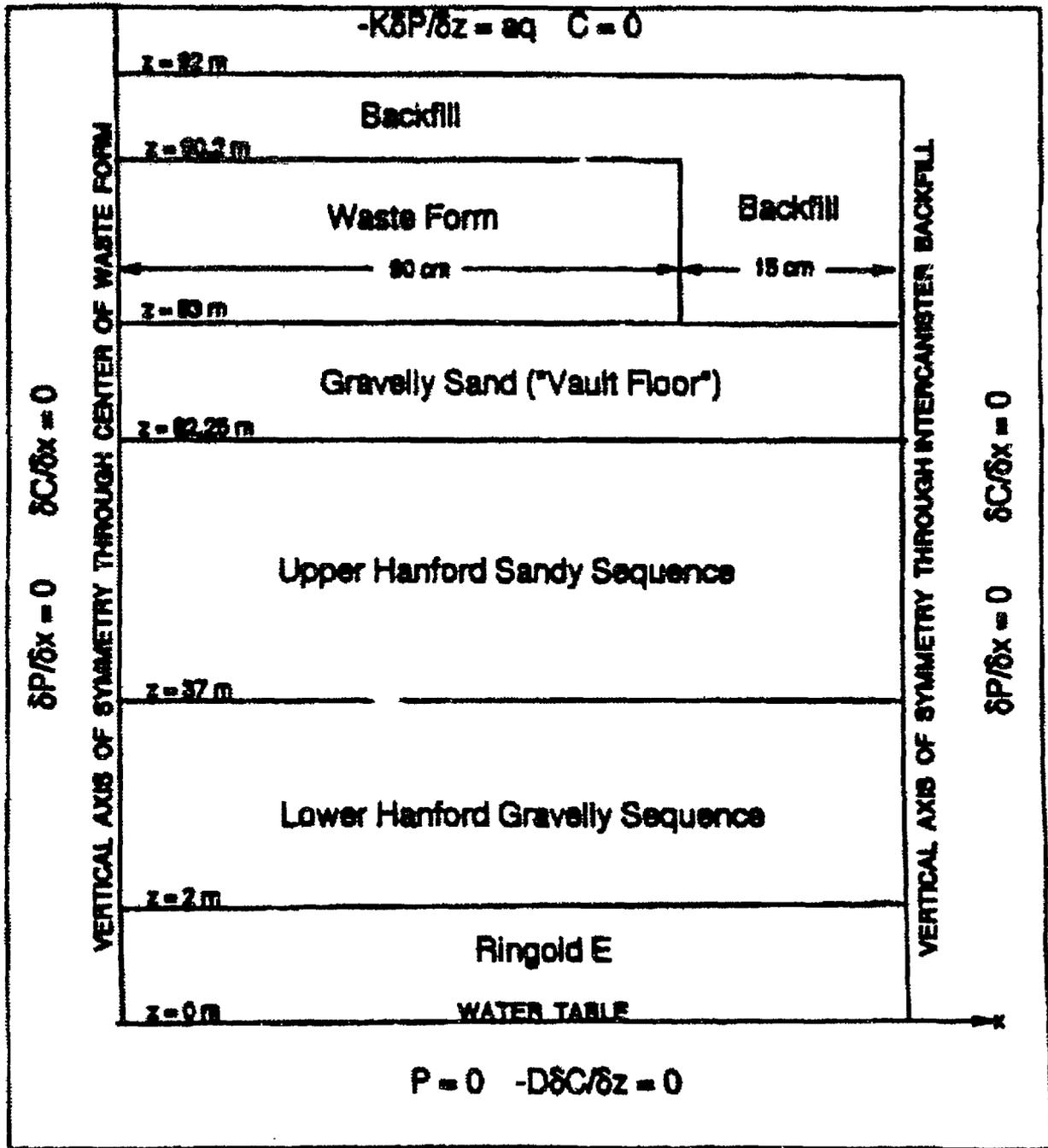
filler material. The vadose zone was modeled using 46 layers for the sandy sequence, 36 for the gravel sequence, and the bottom 4 modeled for the unconfined aquifer. Symmetry is assumed about the center of the disposal facility with the last 10 columns separating adjacent vaults.

Earlier versions of this model were used in determining the effect of various disposal facility design options on long-term environmental performance (Mann 1995b).

The diffusion coefficient specified in Section 3.4.4.3 is based on the Kemper diffusion model (Kemper 1966). However, if the Kemper model is used in PORFLOW, then dispersion cannot be calculated. Therefore the Scheidegger (1961) model was used and the parameters adjusted to obtain the same diffusion value for the moisture content expected in the problem.

3.5.3.3 Unit Cell Model. This two-dimensional model treats a vertical slice one container (1.8 meter) wide and six containers high of the disposal facility model. Kline 1996 gives full details. Figure 3-8 displays the geometry. The top of the model is the filler material atop the canisters. The sand-gravel

Figure 3-8. Zone Map for Unit Cell Model. P = head, C = concentration, sq = infiltration rate, and x and z are spatial directions.



capillary barrier and concrete roof are not modeled. The model continues with the canisters and lateral filler material and with a degraded concrete floor. The vadose zone is below the engineered system with the unconfined aquifer at the very bottom of the model.

The grid spacing is 10 by 50, resulting in Peclet numbers near unity. Nonuniform spacing that includes more detail in the disposal facility is used to minimize the number of nodes. The contaminant source terms ($6.92 \times 10^{-7} \text{ y}^{-1} \text{ m}^3$) are given as a volumetric source within the waste containers. Both vertical sides of the model are assumed to be reflective. The boundary condition at the top is the specified infiltration rate. The boundary condition at the water table is fully saturated.

An earlier use of this model (Kline 1995b) showed very good agreement with full disposal models (Mann 1995b).

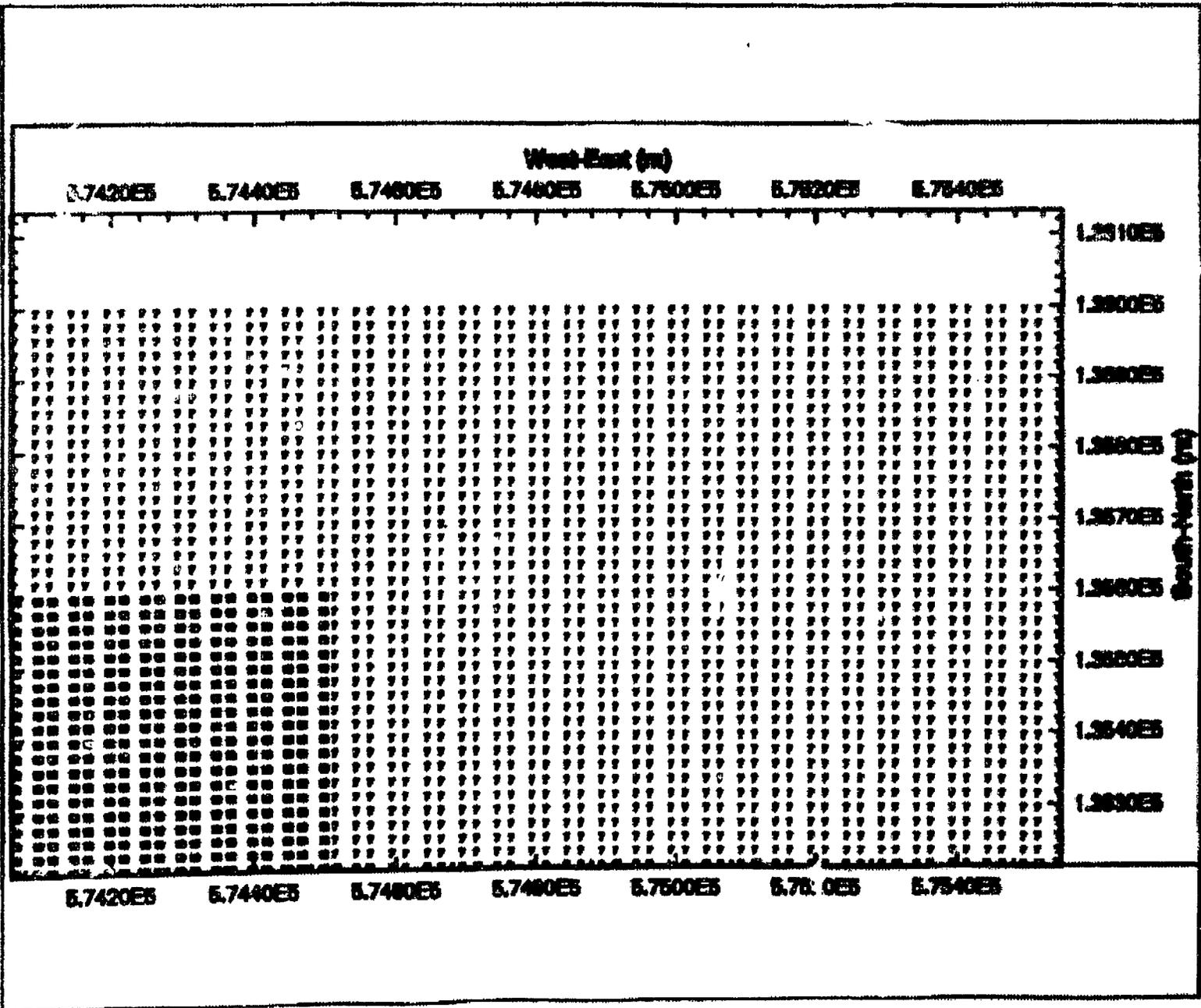
3.5.3.4 Sitewide Model. The aquifer was analyzed using the ERC Hanford Sitewide Groundwater Model (Law 1996). A horizontal finite-element grid size of 600 m by 600 meters (1,962.5 by 1,962.5 feet) was selected. Element heights varied depending on the thickness of the aquifer and the thickness of the high-conductivity Hanford formation. The model grid consists of 6 layers each with 2,474 elements and 2,611 nodes. Vertical discretization was performed using six layers; the top three are in the Hanford formation, the bottom three, the underlying Ringold Formation.

Boundary conditions reflect an arid environment with a few streams and rivers as water sources. Inflow along Cold Creek and Dry Creek are prescribed as hydraulic head conditions for model calibrations under 1979 conditions. For these calculations influx representing the recharge from the Cold Creek and Dry Creek was used as flux boundary conditions, replacing the fixed head condition. Influx from the Yakima River is treated as a prescribed head. The recharge from the front of Rattlesnake Mountain or from precipitation is not included in the present model. The model treats the Columbia River as a boundary that is held constant in time but variable in distance along the river, with numerical values obtained by five river stage ganges over a 1-year period (1992-3). The data are undocumented, but were collected using the protocol described by Campell (1994). No flow is allowed into basalt outcrops or into the bottom of the model (corresponding to the top of the underlying basalt unit or to the lower mud unit of the Ringold Formation).

As noted in Section 3.5.2.4.4, versions of this Hanford sitewide groundwater model have been used for earlier Hanford Site performance assessments.

3.5.3.5 Pumping Model. This model is similar to the ERC Hanford Sitewide Groundwater Model, but on a smaller scale. This model calculates the effect of various pumping rates at the well on the groundwater flow. The element size is 25 by 20 meters (82 by 66 feet) and consists of four layers (Figure 3-9). Each layer has 2,400 elements and 2,501 nodes. The bottom of the model is flat, using an average value for the top of the basalt zone. Values of the hydraulic head from the sitewide model were used as boundary conditions.

Figure 3-9. Zone Map for Pumping Model (Material types 7 and 13 from Table 1-7 are used).



3.5.4 Input Data

3.5.4.1 Overview. This section specifies the data actually used in the computer models for the base analysis case. The intent is to follow the data given in Sections 3.2, 3.3, and 3.4 as closely as possible. Data used in the sensitivity cases are given in Section 3.5.5.

Input files for each computer model related to the base analysis case are given in Appendices C.5 and D.5.

3.5.4.2 Contaminant Release Modeling. The contaminant release rate from the waste package is based on the request for proposal and on a time dependence derived in Section 3.4.5.

3.5.4.3 Vadose Zone Modeling. The same input data are used for both the disposal facility and unit cell models. The input data used by both models for the base analysis case are summarized in Table 3-13. The actual input files for the base analysis case calculations are presented in Appendix D.5.

3.5.4.4 Aquifer Modeling. The aquifer models are based on a Hanford Site groundwater model (Law 1996). The hydrologic parameter data for the base analysis case are from Table 3-7 (Section 3.4.4.5). For the pump model, only material types 7 and 12 of the 18 types shown in Figures 3-3 and 3-4 were used.

The data set for the site model was calibrated/validated in three ways. The 1979 Hanford Site water tables were simulated using the known Hanford Site-related artificial recharges and assuming steady-state conditions. Second, the difference between the 1993 water table and the 1979 water table was calculated using a transient simulation. Finally, the movement of tritium plumes from 1979 to 1993 was simulated in a transient contaminant transport calculation. In all cases (Law 1996), good agreement was found between measured and simulated values.

3.5.4.5 Integration of Results. In addition to data already discussed, the input data for INTEG were taken from the output of the vadose zone and the aquifer models. Inventories were taken from Section 3.2.3. Dose conversion factors were taken from Section 3.3.6.

Table 3-13. Base Analysis Case Input Data for the Disposal Facility and Unit Cell Models.

| Parameter | Value | Location with Justification for Using Value |
|--|---|--|
| Soil Layering | | |
| Hanford formation Upper Gravel Sequence Sand Sequence Lower Gravel Sequence | 6 meters (20 ft) (on surface) 60 meters (197 ft) 35 meters (98 ft) (bottom) | Section 3.4.4.2 |
| Ringold Formation Unit E | 3 meters (98 ft), below Hanford formation | Section 3.4.4.2 |
| Hydrologic Parameters | | |
| Vadose Zone Soil Layer | Calculated based on curve-fitting parameters and saturated hydraulic conductivity. See reference section. | Section 3.4.4.3 (Values given in Table 3-3) |
| Construction Material | Calculated based on curve-fitting parameters and saturated hydraulic conductivity. See reference section. | Section 3.4.4.3 (Values given in Table 3-4) |

| Parameter | Value | Section with Justification for Using Value |
|--|--|---|
| Geochemical Parameters | | |
| Chemical Distribution Coefficients (K_d) | | Section 3.4.4.4 |
| Se, Tc, Others | 0.0 ml/g | |
| U | 0.6 ml/g | |
| Sr, I | 3.0 ml/g | |
| Pa, C | 6.0 ml/g | |
| Na, Np | 15. ml/g | |
| Ac, Nb, Am, Ni, Zr, Pu, Th | 40. ml/g | |
| Ce, Cs, Cm, Eu, Pb, Co, Sn | 100 ml/g | |
| Infiltration Rate | | |
| At the Disposal Facility | | Section 3.4.7 |
| First 1000 years | 0.5 mm/y (0.02 in./y) | |
| After 1000 years | 3.0 mm/y (0.12 in./y) | |
| Contaminant Release Rate | | |
| Relative Radionuclide Release Rate | Calculated release based on initial release rate and time-dependent surface area. See reference section. | Section 3.4.5.4 (Values given in Table 3-8) |
| Disposal Facility Degradation | | |
| Concrete | degraded at 500 years | Section 3.4.6.7 |
| Natural materials | do not degrade | Section 3.4.6.7 |

3.5.4.6 Inadvertent Intrusion. The base analysis case evaluates the two relevant parts of the inadvertent intrusion scenario: drilling for groundwater or minerals and homesteading where waste has been exhumed and spread around the surface. The input data values related to the scenarios were taken from Section 3.3.3.4.3. These values are summarized in Table 3-14. The dose conversion factors used were taken from Section 3.4.8.

Table 3-14. Important Input Parameters for the Base Analysis Case Inadvertent Intrusion Analysis.

| Parameter | Value | Section with Justification |
|--------------------------|--|----------------------------|
| Diameter of well drilled | 0.3 m (12 in.) | Section 3.3.3.4.3 |
| Garden size | acute exposure: 100 m ² (1,071 ft ²) chronic exposure: 500 m ² (5,374 ft ²) | Section 3.3.3.4.3 |
| Waste Form Size | Calculated by linear release rate based on initial release rate and time | Section 3.4.5.4 |

3.5.5 Sensitivity Cases

3.5.5.1 Overview. Sensitivity cases were run to determine the effect of various assumptions and data values. For most sensitivity cases, only one parameter or one set of parameters differs from the base analysis case or another sensitivity case. Thus, the change, if any, in the final answer will indicate the effect of that parameter on the overall answer. Table 3-15 summarizes the sensitivity cases. Sections 3.5.3.2 through 3.5.5.12 discuss the sensitivity cases and explain why each case was run.

Table 3-15. List of Sensitivity Cases

| Discussion Section | Sensitivity Case | Results Presented in Section |
|--------------------|---|------------------------------|
| Scenario | | |
| 3.5.5.2 | Assume different parameters for intrusion scenario: Cases include garden size = 2,500 m ² (26,910 ft ²) rather than 500 m ² (5,382 ft ²) and diameter of the well = 0.2 m (8 in) rather than 0.3 m (12 in.). | 4.2.3 |
| 3.5.5.2 | Irrigated farming over the disposal facility, implying an infiltration rate of 100 mm/y (3.9 in./y) forever, rather than base analysis case of 0.5 mm/y (0.02 in./y) for first 1,000 years and 3.0 mm/y (0.12 in./y) thereafter. | 4.7.4.3 |
| 3.5.5.2 | Assume irrigation occurs on Hanford Plateau. Cases studied are irrigation in all areas except 200 Areas and region between 200 East and 200 West Areas, irrigation only north of 200 Areas, and irrigation only west of 200 Areas. In base analysis case, no irrigation is assumed. | 4.8.3.3 |
| 3.5.5.2 | Assume industry in 200 Areas (recharge reduced in 200 Areas by a factor of 2). | 4.8.3.3 |
| 3.5.5.2 | Assume different well locations, ranging from 100 m (328 ft) downgradient from the disposal facility to the Columbia River. Base analysis case assumes well is 100 m (328 ft) downgradient. | 4.8.3.5 |
| 3.5.5.2 | Assume different pumping rates at the well (10 m ³ /d [2,640 gal/day], 50 m ³ /d [13,200 gal/d], 100 m ³ /d [26,400 gal/d], and 150 m ³ /d [39,600 gal/d]) instead of the rate of 0.01 m ³ /d [10 l/d = 2.6 gal/day] used in the base analysis case. | 4.8.3.6 |
| 3.5.5.2 | Treat natural events, such as glacial-age flooding. | 4.11 |

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| Discussion Section | Sensitivity Case | Results Presented in Section |
|--------------------|--|------------------------------|
| Inventory | | |
| 3.5.5.3 | Changes in inventory caused by TWRs Privatization Effort. Cases assumes that only 20% of the ⁹⁹ Tc inventory of the base analysis case is disposed in facility. | 4.8.2 |
| 3.5.5.3 | Arbitrary changes in inventory to determine sensitivity (I, Se, U). | 4.8.2 |
| Recharge | | |
| 3.5.5.4 | Recharge rate = 3.0 mm/y (0.12 in./y) forever. The base analysis case used 0.5 mm/y (0.042 in./y) for the first 1,000 years, and 3.0 mm/y thereafter. | 4.7.4.2 |
| 3.5.5.4 | Recharge rate = 1.0 mm/y (0.04 in./y) forever. | 4.7.4.2 |
| 3.5.5.4 | Recharge rate = 0.1 mm/y (0.004 in./y) forever. | 4.7.4.2 |
| Geology | | |
| 3.5.5.5 | Top of unconfined aquifer is at 96 m (315 ft) below the surface. In the base analysis case, the top of the aquifer is at 103 m (338 ft) below the surface. | 4.7.2.3 |
| 3.5.5.5 | Top of unconfined aquifer is at 110 m (360 ft) below the surface. | 4.7.2.3 |

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| Discussion Section | Sensitivity Case | Results Presented in Section |
|--------------------|--|------------------------------|
| Facility | | |
| 3.5.5.6 | Reduce radionuclide density in disposal facility by a factor of 2 by increasing the number of vault rows by a factor of 2. | 4.6.2.2 |
| 3.5.5.6 | Rotate the disposal facility 90°. Long side now being north-south. | 4.6.2.3 |
| 3.5.5.6 | Shorter sand-gravel capillary barrier (Concept 2 layout). Base analysis case used Concept 1 layout. | 4.6.2.4 |
| 3.5.5.6 | Sand-gravel capillary barrier in facility design replaced with back-filled soil. | 4.6.3.2 |
| 3.5.5.6 | Side sand-gravel capillary barrier in facility design replaced with back-filled soil. | 4.6.3.3 |
| 3.5.5.6 | Sand used as filler material inside the disposal facility instead of back-filled soil. | 4.6.3.4 |
| Degradation | | |
| 3.5.5.7 | Concrete floors, walls, and ceiling degrade at 2,000 years in order to test "bath tub effect". Base analysis case has all concrete degrading at 500 years. | 4.6.4 |
| 3.5.5.7 | Degraded sand-gravel capillary barrier. (The degradation point is at 2/3*1 from the apex of the barrier where 1 is half the width of the barrier.) | 4.6.4 |

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| Discussion Section | Sensitivity Case | Results Presented in Section |
|------------------------------|--|------------------------------|
| Hydrologic Parameters | | |
| 3.5.5.8 | Change hydrologic parameters in vadose zone so that the entire zone has parameters corresponding to the Hanford formation sandy sequence instead of the varying sequences. | 4.7.2.3 |
| 3.5.5.8 | Change hydrologic parameters in vadose zone so that the bottom half of the zone has parameters corresponding to the Hanford formation gravelly sand sequence instead of the Ringold Formation. | 4.7.2.3 |
| 3.5.5.8 | Change diffusion constant for the vadose zone to 1.00×10^{-6} cm ² /sec from 1.25×10^{-7} cm ² /sec. | 4.7.2.3 |
| Waste Form | | |
| 3.5.5.9 | Waste form is a thin plate, implying a time-independent radionuclide release rate. | 4.4.3.2 |
| 3.5.5.9 | ⁹⁹ Tc release rate reduced by a factor of 5 from the base analysis case. | 4.4.3.3 |
| 3.5.5.9 | All $K_d = 0$ elements release rate reduced by factor of 5. | 4.4.3.3 |
| 3.5.5.9 | Release rate for all elements reduced by factor of 5. | 4.4.3.3 |
| 3.5.5.9 | Contaminant release rate from glass as calculated by mechanistic models, including sodium ion exchange. Contaminants transported to floor of vault. | 4.4.3.4 |
| 3.5.5.9 | ⁹⁹ Tc release determined by mechanistic models, but with sodium ion exchange. Contaminants transported to floor of vault. | 4.4.3.4 |

| Discussion Section | Sensitivity Case | Results Presented in Section |
|-----------------------------|---|------------------------------|
| 3.5.5.9 | ⁹⁹ Tc release determined by mechanistic model, with sodium ion exchange. Contaminants transported to floor of vault with pore velocity of 10 cm/y. | 4.4.3.4 |
| Geochemical | | |
| 3.5.5.10 | For uranium: $K_d = 0$ instead of 0.6 ml/g as was used in the base analysis case. | 4.7.3 |
| 3.5.5.10 | For uranium: $K_d = 0$ in vadose zone and $K_d = 100$ ml/g in concrete. | 4.7.3 |
| 3.5.5.10 | For major elements (Se and Tc): $K_d = 0.1$ ml/g instead of 0. | 4.7.3 |
| Exposure | | |
| 3.5.5.11 | Different dose factor sets. The dose factor libraries from DOE, EPA, and GENII computer analyses were used instead of taking internal dose factors from DOE and external dose factors from EPA. | 4.8.4 |
| 3.5.5.11 | Use different ingestion, inhalation, and time of exposure values from base analysis case. | 4.6.4 |
| Location of Facility | | |
| 3.5.5.11 | Location of facility at existing TWRS disposal (grout) vaults which are east of the PUREX Facility, rather than at the proposed location which is west of PUREX. | 4.8.5 |

| Discussion Section | Sensitivity Case | Results Presented in Section |
|--------------------|---|------------------------------|
| Calculations | | |
| 3.5.5.13 | Halved dispersion of base analysis case for vadose zone contaminant transport. | 4.7.2.3 |
| 3.5.5.13 | Twice dispersion of base analysis case for vadose zone contaminant transport. | 4.7.2.3 |
| 3.5.5.13 | Twice number of grid points from base analysis case for vadose zone flow and transport. | 4.8.6 |
| 3.5.5.13 | Initial volumetric moisture content in the disposal facility = residual moisture content of material, rather than 10% as in the base analysis case. | 4.8.6 |
| 3.5.5.13 | Initial volumetric moisture content in disposal facility = 20%. | 4.8.6 |

3.3.3.3 Scenario-Dependent Sensitivity Cases. The scenario-dependent sensitivity cases are selected analyses to determine if results related to a scenario depend on selected values or assumptions. Several scenario-dependent cases were developed (Table 3-15). Land-use, drinking water, inadvertent intruder, and catastrophic natural scenarios were considered (Section 3.3).

Predicting the land use at the Hanford Site for the next 10,000 years is impossible. Natural conditions were assumed for the base analysis case (Section 3.3.3.2). For land-use sensitivity cases, the effect of various land uses were calculated. The following uses were examined:

- Irrigated farming on top of the disposal facility with an infiltration rate of 100 mm/y (3.9 in./y). Such irrigation is considered as an inadvertent intrusion. However, in this analysis such irrigation is calculated as part of the groundwater scenario.
- Irrigated farming in other parts of the Hanford Central Plateau with recharge rates of 100 mm/y (3.9 in./y). Such irrigation will distort the groundwater flow and change the water table height.
- Industrial use of the 200 Area, which is assumed to decrease the infiltration rate over the entire 200 Area by a factor of 2, since water would be collected and then discharged at a point off the 200 area plateau.

The real value for the infiltration rate for irrigated farming is unknown. However, the value of 100 mm/y (3.9 in./y) is the lower value used in the Hanford grout performance assessment (Kincaid 1995) (the other value was 250 mm/year) and twice that used in the Hanford solid waste performance assessments (Wood 1994b and Wood 1996). These sensitivity cases treat only the effect of infiltration on the unconfined aquifer; the effect of changed vadose zone distance is examined separately (See Section 3.5.5.5)

The drinking water scenario is based on the pumping rate and the location of the well. Minimal pumping (0.01 m³/day = 10 liters/day [2.6 gallons/day], corresponding to a family of five using the well only to obtain drinking water) is assumed for the base analysis case. As pumping is increased, water is taken from a wider area, resulting eventually in drawing in water that is uncontaminated. Pumping rates of 10 to 150 m³/day (2,640 to 39,600 gallons/day) were used to determine the effect of the pumping rate on the overall drinking water dose.

In the base analysis case, the well is assumed to be 100 meters (328 feet) downgradient from the disposal facility. To determine the effect of the position of the well, the well was located as near as 50 meters (164 feet) and at various other distances (including the 200 Area fence line) along flow lines down to the Columbia River.

For the intrusion scenario, the parameters are quite uncertain. For one sensitivity case, the well diameter was decreased from 0.3 meters (12 inches) to 0.2 meters (8 inches). In another sensitivity case, the garden area was increased from 500 m² to 2,500 m² (0.124 acre to 0.618 acre). The values used in the sensitivity cases were the values used in the base case of the grout performance assessment (Kincaid 1995).

Finally, the effects of catastrophic natural events were evaluated. The base analysis case does not evaluate a catastrophic natural event. Neither seasonal flooding nor even the collapse of the region's largest dam would cause water to reach the disposal facility. However, a catastrophic ice-age flood similar to those that have occurred in the past, would affect the disposal facility and is analyzed.

3.5.5.3 Inventory-Dependent Sensitivity Cases. The inventory of radionuclides that will be in the waste form is uncertain. The inventory in the waste form depends on the amount and type of waste presently being stored in the Hanford Site tanks, the process used to separate tank waste into low-activity and high-activity waste streams, and the method of immobilization. At present, the separation process that the private vendors will use is unknown, as is the method of immobilization. These sensitivity cases are designed to evaluate the effect of different amounts of key radioisotopes.

One sensitivity case was based on a possible strategy for reducing technetium release rates. In the request for proposal, the total ⁹⁹Tc release rate is specified at a level 5 times lower than that for other radionuclides. One strategy for achieving this reduced release rate is to reduce the amount of technetium by 80 percent. Such a sensitivity case was run.

The degree to which iodine will be volatilized in the immobilization operation (and hence not be in the final waste form) is unknown. For the base analysis case, it was assumed that 90 percent of the iodine will be volatilized. A sensitivity case of 50 percent of the iodine being volatilized was performed.

In the supporting document (WNC 1996) for the DOE petition to the NRC for the separated waste to be considered as non-high-level waste, various uncertainty bands are given. The amount of Cs separation may be different from what is assumed in the base analysis case. A sensitivity case increasing the amount of ¹³⁷Cs from 0.451 MCi to 5.0 MCi was performed.

3.5.5.4 Infiltration-Dependent Sensitivity Cases. The infiltration rate is one of the most important parameters of the calculation (Section 3.4.7). Besides the sensitivity case of 100 mm/y (3.9 in./y) mentioned in Section 3.5.5.2, three additional cases involving different recharge rates were run. The base analysis case used 0.5 mm/y (0.02 in./y) for the first 1,000 years, followed by a rate of 3.0 mm/y (0.12 in./y). The first sensitivity case models the case of extremely low recharge

(0.1 mm/y) [0.004 in./y]. The second case uses the same rate as the Hanford Grout Performance Assessment (Kincaid 1995), (1.0 mm/y) [0.04 in./y], allowing comparisons to be made with that analysis. The final case used a recharge rate of (3.0 mm/y) [0.12 in./y]. This case shows the effectiveness of the surface barrier, because the difference between this sensitivity case and the base analysis case is the recharge rate for the first 1,000 years. The recharge rate in the latter case was based on the presence of the surface barrier.

3.5.5.9 Geology-Dependent Sensitivity Cases. An understanding of the geologic strata is the starting point for the vadose zone simulations. Most of the sensitivity studies that are partially derived from geologic considerations are described in Sections 3.5.5.8 and 3.5.5.10. The sensitivity cases considered in this section deal with the location of the top of the unconfined aquifer. The effects of contaminant transport in both the vadose zone and in the unconfined aquifer were calculated.

Two sensitivity cases were developed that place the top of the unconfined aquifer above and below the position given in the base analysis case, 103 meters (338 feet) below the surface. One case located the top of the aquifer at 96 meters (315 feet) below the surface, its present location. This location is in the Hanford formation; the base analysis case had the aquifer in the Ringold Formation. This is an indirect way to study the influence of the hydrologic parameters.

The other sensitivity case located the top of the aquifer at 110 meters (360 feet) below the surface. This was deeper than the location used in the base analysis case by the same amount as the previous case was above the value of the base analysis case. The deeper location results in a larger vadose zone. The case also accounts for the effect of longer contaminant travel time through the vadose zone.

3.5.5.f Facility-Dependent Sensitivity Cases. The design of the disposal facility has not yet started, so the model used in the base analysis case has significant uncertainties. Several sensitivity cases were studied to determine the importance of various design features.

Three sensitivity cases deal with the sand-gravel capillary barrier proposed for the top and sides of the disposal facility. The first case has no capillary barrier at all. The second case has the barrier only at the top of the facility. The third case used the Concept 2 layout (Section 3.4.6.3), which has a much shorter barrier.

Another case replaces the soil between the stacks of containers with sand to examine the effect of the hydrologic properties of the filler material. The hydrologic properties determine the "wicking" action of a

Two additional sensitivity cases deal with the geometry of the disposal facility. In one case, the facility is rotated to determine the effect of facility orientation on contaminant concentration in the well compared to contaminant concentration at the bottom of the vadose zone. The second case doubles the area of the facility, while keeping the total inventory of radionuclides constant. This simulates a decrease in radionuclide density, which could result from lower waste loadings, different spacing between the containers, or other reasons.

3.3.5.7 Facility Degradation-Dependent Sensitivity Cases. Four sensitivity cases test the importance of assumptions made about facility degradation for the base analysis case. These assumptions were that natural materials do not degrade but that man-made materials, such as concrete, degrade at 500 years (Section 3.4.6.7).

Two cases deal with the degradation of the concrete walls, floors, and ceilings. In the first case, the concrete degrades to gravelly sand at the time of closure. No credit is taken for concrete as a physical barrier. The second case determines the effect of the concrete structure trapping water and then releasing it all at once. This so-called "bathtub effect" is modeled by having the concrete ceiling and the upper parts of the concrete walls degrade at 500 years but the concrete floor degrades at 2,000 years.

A group of sensitivity cases focuses on the effects of a degrading sand-gravel capillary barrier. The degradation of the capillary barrier is modeled by having the capillary barrier subside at a point 2/3 down the length of the barrier. The cases run were based on different amounts of subsidence.

3.3.5.8 Hydrologic Parameter-Dependent Sensitivity Cases. Hydrologic properties are expected to vary spatially. To determine the importance of different hydrologic parameters, large changes in these parameters were made in the vadose zone calculation. For the base analysis case, the Hanford formation was assumed to have the hydrologic properties of gravelly sand for the top 6 percent, sand for the middle 50 percent, and gravelly sand for the bottom portion. The first sensitivity case assumes that the entire formation has the properties of sand. The second assumes that the hydrologic properties correspond to gravelly sand for the top 6 percent, sand for the next 44 percent, and gravelly sand for the bottom 50 percent.

A separate sensitivity case looked at the importance of diffusion. The diffusion constant was changed from $1.27 \times 10^{-7} \text{ cm}^2/\text{s}$ to $1 \times 10^{-6} \text{ cm}^2/\text{s}$.

3.3.5.9 Waste Form-Dependent Sensitivity Cases. Waste form-dependent sensitivity cases were made to relate the effects assumptions about the waste form have on the overall source term component of the analysis. For the base analysis case, the

contaminant release rate was based on the initial fractional radionuclide release rate (Section 3.4.5.4) given in the TWRB privatization specification (DOE-RL 1996). Also, because the waste form was unspecified, it was assumed to be a large cube that fits in the container. The related sensitivity cases focus on changes in the contaminant release rate and the waste form.

Two main sensitivity cases dealt with alternative interpretations of the waste form performance in the request for proposal (DOE-RL 1996). The first assumed the release rates were independent of time. This is equivalent to assuming that corrosion is only important in one dimension (for example if the waste form were a series of plates). The second sensitivity case assumes that, for some reason, the release rate for technetium was a factor of five less than for the other elements. The effect of a reduced release rate for all elements or for just $K_d=0$ elements was also calculated.

The final sensitivity cases used a mechanistic approach to determine the contaminant release rate, rather than using the specifications in the RFP. The AREST-CT computer code (Section 3.5.2.2) simulated the corrosion of LD6-5412 glass, the release of contaminants into the water, the formation of secondary mineral phases, and then the transport of contaminants out of the waste package. For these calculations (see Appendix C for details), spheres 1 centimeter in diameter surrounded by a sand matrix were used. The glass made up 70 percent of the volume. Such assumptions led to a surface area that is 27 times larger than the surface area of a non-fractured monolithic 1.2 x 1.2 x 1.8 meter cube. An average pore velocity of 1 cm/y was used for the transport calculations. Two sensitivity cases were performed around this case. The first case assumed that the only reaction involving glass was the glass corrosion reaction (and that the sodium in the glass was not preferentially leached out). The second involved a pore velocity of 10 cm/y. The results of these calculations (which yield time- and spatial-dependent release rates) are presented in Section 4.4.2.

3.5.5.10 Geochemical-Dependent Sensitivity Cases. The values for chemical distribution coefficients, K_d , can vary with environmental conditions (Kaplan 1995a). This means that as a contaminant moves from the disposal facility environment to the vadose zone, the K_d value for the contaminant will change. However, in the base analysis case, the K_d values were assumed not to vary as the contaminants move through the disposal system and the vadose zone. To determine the sensitivity to different K_d values, a series of sensitivity cases for the most important elements was defined.

Two cases involve the K_d for uranium. The first used a reduced value for the K_d value for uranium. The value was reduced from 0.6 ml/g to 0 throughout the system. A uranium K_d value of 0 has been used in other Hanford Site performance assessments (Wood 1994b, Kincaid 1995, Wood 1995, and Wood 1996). The other case used 0 as the K_d value of uranium everywhere.

except in concrete, where the K_d value was 100 ml/g (Krupka 1995).

The best present knowledge for the chemical distribution coefficients for technetium and selenium is that these elements do not sorb on sediments present on the Hanford Site. This is why the K_d value used in the base analysis case for each element was 0. However, a sensitivity case using 0.1 ml/g was created to quantify the effect of a small amount of retardation to determine the value of on-going experiments to determine non-zero K_d values for very mobile contaminants.

3.5.5.11 Exposure Parameter-Dependent Cases. Many dosimetry parameters have been proposed. To determine the sensitivity to the parameters chosen for the base analysis case, different parameter sets were used in sensitivity cases. Separate sensitivity runs were made with the dose factor sets from the DOE, EPA, and GENII computer analyses. The dose factor values are given in Rittmann (1995). In addition, the sensitivity to ingestion rates, inhalation rates, and time of exposure was calculated.

3.5.5.12 Location of the Facility. The base analysis case assumed that a single disposal facility would exist in the south central part of the 200 East Area. However, some of the immobilized waste could be placed in the existing vaults at the eastern edge of the 200 East Area, which were built to hold grouted waste from the double-shell tanks. Sensitivity studies were made to determine the long-term impacts from placing part of the waste in these vaults.

3.5.5.13 Calculational Assumption-Dependent Sensitivity Cases. The previous sections addressed uncertainties related to data about natural and man-made materials. However, uncertainties based on the calculational methods used must be addressed. Sensitivity cases were defined to address steady-state versus transient calculations, the effect of the number of grid points, the effect of dispersion, and the effect of initial moisture content.

In any computer representation, a finite number of points must represent an infinite number of positions. A sensitivity case using double the number of grid points shows the effect of grid size and spacing.

Dispersion of contaminants, especially on the large scales represented in these analyses, is quite uncertain. A series of dispersion values was used to determine the sensitivity of the calculations to this parameter.

Finally, the initial moisture content in the disposal facility was varied to determine the importance of this initial condition. The base analysis case used 10-percent moisture content as the initial value. One sensitivity case used the residual moisture content (θ_r , from Section 3.4.4.3) as the

initial moisture content for each soil type. The other sensitivity case used a value of 20 percent, twice that used in the base analysis case.

3.6 Quality Assurance

3.6.1 Overview

This section describes the quality assurance activities associated with the performance assessment activity. Three separate areas are covered: 1) experimental data collection, 2) computer code use, and 3) analysis. The following sections are arranged according to which organization performing the activity.

3.6.2 Pacific Northwest National Laboratory (PNNL).

The work for the performance assessment activity conducted by PNNL was performed according to the appropriate portions of PNNL's Quality Assurance (QA) Program Plan. This program conforms to NQA-1, *Quality Assurance Standard Requirements for Nuclear Facilities* (ANSI/ASME 1989), as interpreted in Parts 1 and 3 of PNNL's *Quality Assurance Manual* (PNL 1994). Part 3 of this manual is a set of administrative procedures that define how the various requirements of NQA-1 are implemented. The administrative procedures define controls, policies, and established methods for managing and conducting all aspects of work that affect quality. For experimental studies at PNNL supporting this performance assessment, all phases of the work were performed according to the QA program.

Computer codes used for the performance assessment are documented, tested, and reviewed following the software control procedures established as part of the overall QA program. These software control procedures have been structured to address requirements of NQA-1, Basic Requirements 3, and Supplement 3S-1, *Supplemental Requirements for Design Control*. The procedures cover all aspects of code development and use.

A key aspect of the QA program involves technical and peer reviews of procedures, test plans, data, calculations, and test results. The reviews range from verifying that calculations or data reduction have been performed correctly to evaluating test methodology as described in a proposed test plan.

No audits were performed for the interim performance assessment. However, comprehensive audits are expected for the preliminary and final performance assessments.

Records generated from all activities are indexed and managed according to QA program requirements. Record holding facilities are used for long-term records retention and storage.

3.6.3 Westinghouse Hanford Company (WHC)

The quality assurance activities at WHC are similar to those at PNNL. The disposal project does not yet have a QA plan, so the requirements of the Hanford Site Grount Facilities Quality Assurance Program Plan (Wood 1992) are being used temporarily. Further requirements are established in WHC's Quality Assurance Manual (WHC 1992); the requirements are indexed corresponding to NQA-1.

For this performance assessment, Basic Item 19 of the WHC Quality Assurance Program (software quality assurance) was implemented by using the document *Software Practices* (WHC 1993) and Section 2.1 of *Standard Engineering Practices* (WHC 1994a). All codes used in these analyses are under configuration control and have been verified.

3.6.4 Other Contractors

Other organizations, such as Argonne National Laboratory and D.B. Stevens, Inc., worked on this activity. Their work was performed under either the PNNL or WHC QA plan.

3.6.5 Hanford Environmental Dose Overview Panel

The Richland Operations Office of DOE established the Hanford Environmental Dose Oversight Panel (Schreckhise 1993) to

- Ensure that appropriate radiological and nonradiological environmental and health dose assessment methods are used at the Hanford Site
- Ensure that all Hanford Site-related environmental and health dose assessments are technically consistent
- Foster communications among Hanford Site contractors regarding environmental and health dose assessments.

All dose calculations used in this performance assessment have been reviewed and approved for publication by a HEDOP reviewer (Rhoads).

3.6.6 Technical Reviews of Supporting Efforts

External technical reviews by outside experts are being held on specialized topics because of the large amount of technical data used in performance assessments. The purpose of these reviews is to ensure that the proper methods, techniques, and resources are used in obtaining the data.

The only review held so far concerned the recharge rate (Honsyman 1995). The panel consisted of Mr. William E. Kennedy,

Dr. Fred M. Phillips, Dr. Bridget Scanlon, Dr. Martius Th. van Geuchten, and Dr. Peter J. Wierenga. They concluded that the recharge research performed at the Hanford Site over the past several decades was adequate for the preliminary performance assessment. However, additional effort would add credibility to the final performance assessment.

Additional focused panel reviews are expected to occur in the future for the preliminary and final performance assessments.

1.3.7 External Review of the Performance Assessment

An advisory board to Disposal Project Management will be created during fall 1996. This panel reviewed the interim performance assessment as part of their duties, and this document was revised to address their concerns.

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4. RESULTS OF ANALYSES

4.1 OVERVIEW

This chapter presents the results of the analyses described in Chapter 3. Further it discusses the data and methods affecting those results. The emphasis of this chapter is not on the computational results per se, but rather on understanding the suite of analyses. Thus many of the numerical results will be found in Appendix E, "Detailed Results".

This chapter is divided into four parts:

1. The results from the inadvertent intruder scenarios (Section 4.2)
2. The results from the groundwater scenarios (Sections 4.3 - 4.10)
3. The results from the releases to air (Section 4.11)
4. The results of catastrophic events (Section 4.12).

4.2 RESULTS FOR INADVERTENT INTRUDER SCENARIO

4.2.1 Overview

Based on the discussion presented in Section 3.3.3.4, only two scenarios are considered:

1. A person drills through the disposal facility in the process of creating a well to obtain water
2. A homesteader lives on the land contaminated by the drill tailings.

As noted in Section 1.5.2.4, the time of compliance is 500 years after closure. Results will be presented, however, for the time period of 100 years after closure to 1000 years after closure. The exposure limit for the driller scenario is 500 mrem (EDE) for a one-time exposure, while for the homesteader scenario the performance objective is 100 mrem (EDE) per year for a continuous exposure.

The time of closure is taken to be 2020, although the final closure of all the vaults is not expected until 2028.

4.2.2 Driller Scenario

This scenario is described in Section 3.3.3.4; the parameters used are presented in section 3.4.8.3. This scenario is less restrictive than the homesteader scenario, which is

described in Section 4.2.3. Therefore, only a brief summary of the driller scenario will be presented.

The results for the driller scenario are presented in Table 4-1 and displayed in Figure 4-1. The effect of waste form dissolution can be seen for the long-lived radionuclides. For these radionuclides, the estimated dose increases as a function of time because more of the radionuclides are available for ingestion.

At all times calculated, the predicted dose is at least one order of magnitude less than 500 mrem, the performance objective at 500 years. The main radionuclide contributing to the dose initially is ^{137}Cs . After about 180 years, ^{129}I becomes the most important nuclide.

None of the sensitivity cases affect the conclusion that the driller scenario meets the performance objective. Even increasing the ^{137}Cs content to 5 MCi (WEC 1996) only results in increasing the predicted total driller dose to 493 mrem at 100 years and has no significant effect after 300 years. Changing other parameters (inventory of other radionuclides, waste density, size of the well, area over which the waste form is spread, the integrity of the waste form) modified the predicted exposures by at most a factor of two.

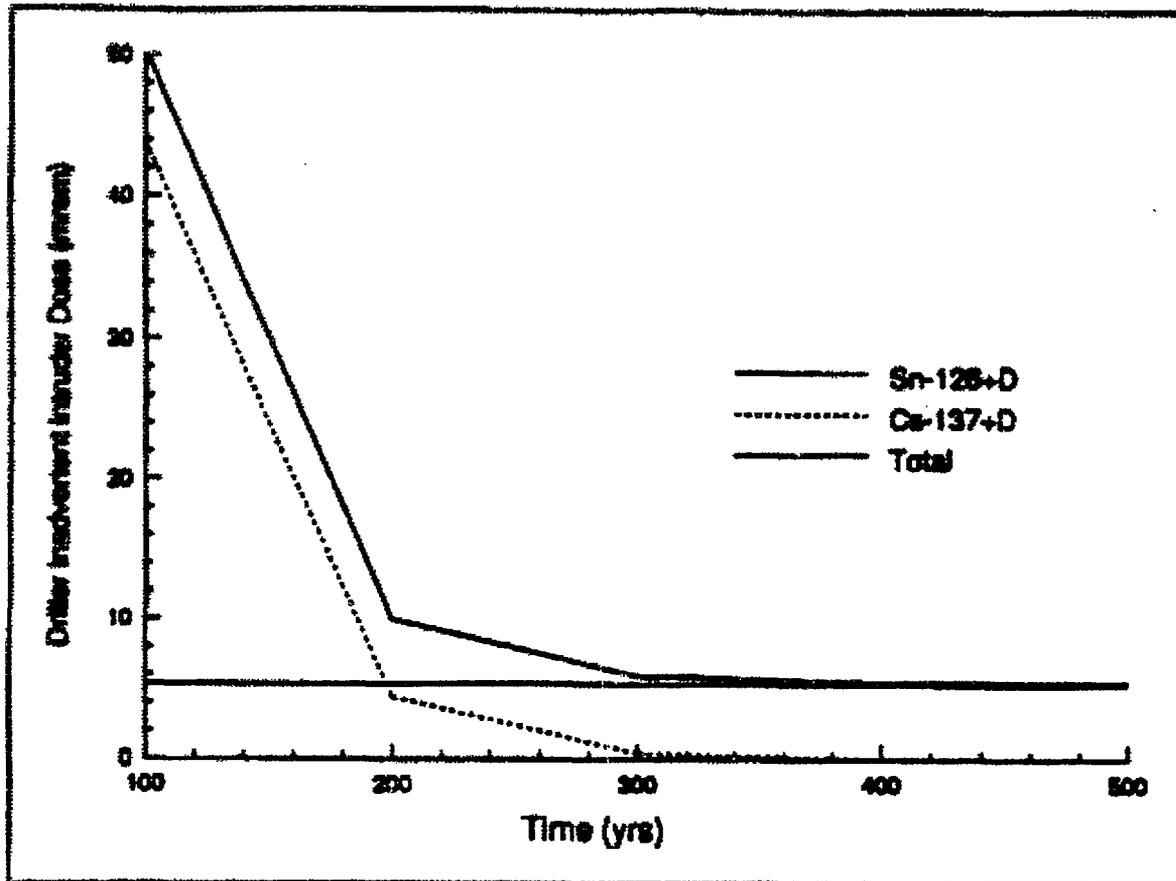
4.2.3 Homesteader Scenario

4.2.3.1 Results. This scenario is described in Section 3.3.3.4; the parameters used are presented in Sections 3.4.8.3 and 3.4.8.4. The waste is assumed to be 7.2 meters (24 feet) thick and uniformly distributed in the disposal facility. The well is 0.30 meters (12 inches) in diameter. Thus, the drilling operation brings 0.509 cubic meters of waste to the surface. This waste is spread over an area of 500 m^2 (5382 ft^2) and mixed by tilling to a depth of 0.15 meters (5.9 inches). Since the garden volume is 75 m^3 (2649 ft^3), the waste is diluted by a factor of 133. For dose factor generation, if the waste has an unit concentration of 1 Ci/ m^3 , then the final concentration in the garden soil is 4.52 $\mu\text{Ci}/\text{kg}$.

The predicted doses for a hypothetical homesteader are presented in Table 4-2 and displayed in Figure 4-2. As in the driller scenario, estimated doses for long-lived radionuclides increase as a function of time because more of the waste is available for ingestion and inhalation as the waste form degrades.

The main radionuclide contributing to the dose initially is ^{137}Cs . After 180 years, ^{129}I becomes the most important radionuclide. Because the radionuclides are assumed to be trapped in the glass and hence unavailable for ingestion or inhalation, the dominant dose pathway is external radiation. Using the many (mostly conservative assumptions) of the base

Figure 4-1. Inadvertent Intruder Results for the Driller Scenario - Base Analysis Case. The D in the legend represents "daughters."



analysis case, the predicted dose is 27.5 mrem in a year, over a factor of 3 lower than the performance objective of 100 mrem/y at 500 years. The estimated dose exceeds 100 mrem/y for times less than 150 years after closure of the facility. The major parameters driving these results are the following:

- The initial inventory of ^{137}Cs
- The initial inventory of ^{126}Sn
- The assumption that the glass does not shatter into extremely small fines after the drilling episode
- The area over which the waste is spread
- The size of the hole drilled
- The areal density of the waste.

Table 4-1. Driller Intruder Dose (mrem) at Various Intrusion Times (years)^a

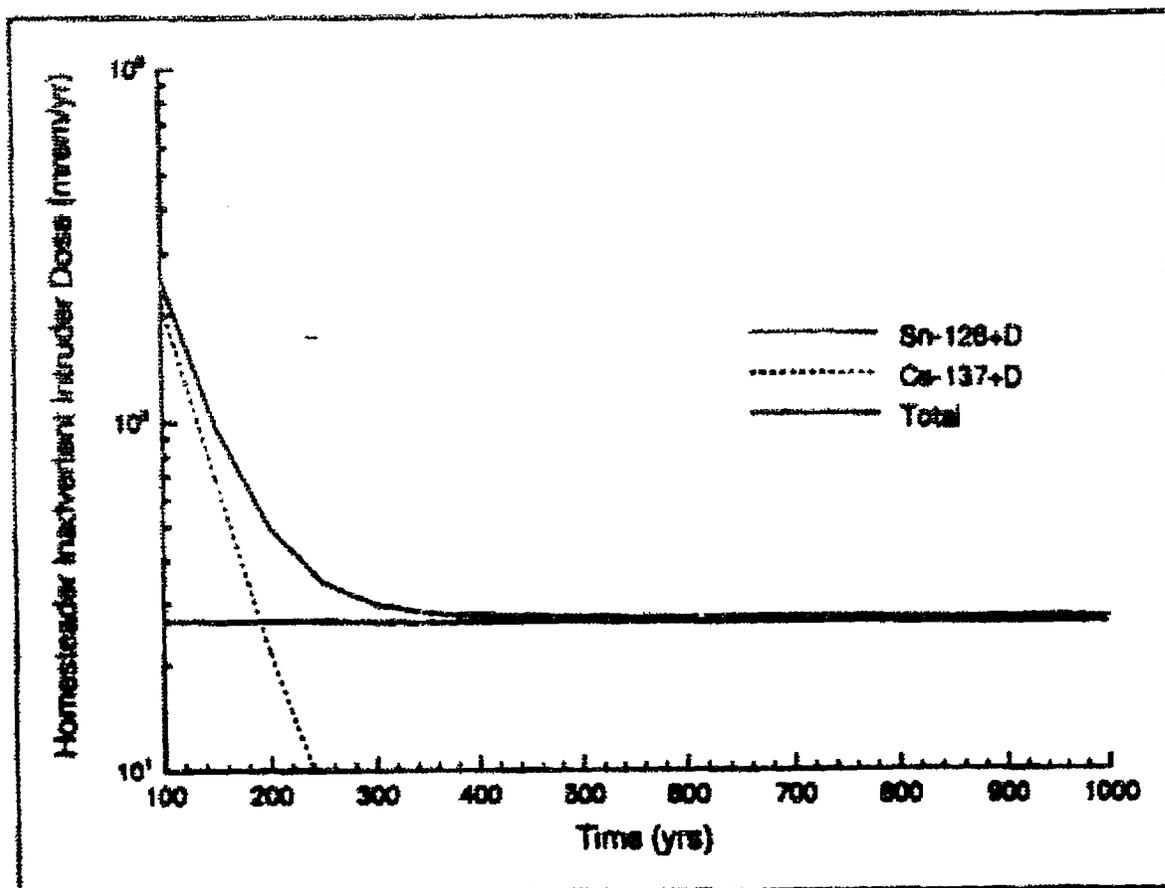
| Nuclide ^b | 100 | 200 | 300 | 400 | 500 | 600 | 800 | 1000 |
|----------------------|----------|----------|----------|----------|----------|----------|-----------|-----------|
| C-14 | 3.36E-08 | 3.39E-08 | 3.41E-08 | 3.44E-08 | 3.46E-08 | 3.49E-08 | 3.53E-08 | 3.57E-08 |
| Sr-90 | 6.50E-06 | 6.86E-06 | 7.21E-06 | 7.57E-06 | 7.93E-06 | 8.28E-06 | 8.98E-06 | 9.68E-06 |
| Sr-90+D | 1.06E+00 | 9.38E-02 | 8.32E-03 | 7.30E-04 | 6.54E-05 | 5.80E-06 | 4.56E-08 | 3.59E-10 |
| Zr-90 | 1.62E-06 | 1.65E-06 | 1.66E-06 | 1.67E-06 | 1.68E-06 | 1.69E-06 | 1.71E-06 | 1.74E-06 |
| Nb-93m | 1.22E-08 | 1.06E-10 | 9.16E-13 | 7.95E-15 | 6.91E-17 | 5.99E-19 | 4.52E-23 | 3.61E-27 |
| Tc-99 | 8.97E-04 | 8.98E-04 | 8.99E-04 | 9.00E-04 | 9.01E-04 | 9.02E-04 | 9.04E-04 | 9.06E-04 |
| Sr-136+D | 5.35E+00 | 5.35E+00 | 5.34E+00 | 5.34E+00 | 5.33E+00 | 5.33E+00 | 5.32E+00 | 5.32E+00 |
| I-129 | 2.75E-05 | 2.76E-05 | 2.77E-05 | 2.78E-05 | 2.79E-05 | 2.79E-05 | 2.81E-05 | 2.82E-05 |
| Ce-134 | 1.36E-20 | 3.43E-35 | 8.64E-50 | 2.17E-64 | 5.48E-79 | 1.38E-93 | 8.74E-123 | 5.54E-152 |
| Ce-137+D | 4.38E+01 | 4.41E+00 | 4.44E-01 | 4.46E-02 | 4.48E-03 | 4.50E-04 | 4.55E-05 | 4.60E-06 |
| Sm-151 | 5.00E-06 | 2.49E-06 | 1.24E-06 | 6.10E-07 | 3.06E-07 | 1.47E-07 | 7.50E-08 | 8.24E-09 |
| Ra-226+D | 6.81E-06 | 6.52E-06 | 6.24E-06 | 5.98E-06 | 5.73E-06 | 5.48E-06 | 5.03E-06 | 4.61E-06 |
| Ra-228+D | 4.47E-08 | 2.60E-13 | 1.51E-18 | 8.81E-24 | 5.12E-29 | 2.98E-34 | 1.01E-44 | 3.41E-55 |
| Ac-227+D | 2.73E-05 | 1.14E-06 | 4.74E-08 | 1.98E-09 | 8.24E-11 | 3.43E-12 | 5.95E-15 | 1.03E-17 |
| Th-229+D | 4.59E-06 | 4.56E-06 | 4.53E-06 | 4.49E-06 | 4.46E-06 | 4.43E-06 | 4.36E-06 | 4.30E-06 |
| Th-232 | 1.14E-04 | 1.14E-04 |
| Pa-231 | 9.32E-02 | 9.72E-02 | 9.78E-02 | 9.82E-02 | 9.86E-02 | 9.90E-02 | 9.98E-02 | 1.01E-01 |
| U-233 | 1.28E-04 | 2.44E-04 | 3.59E-04 | 4.73E-04 | 5.87E-04 | 7.01E-04 | 9.25E-04 | 1.15E-03 |
| U-234 | 3.47E-06 | 4.64E-06 | 5.82E-06 | 7.00E-06 | 8.18E-06 | 9.38E-06 | 1.18E-05 | 1.42E-05 |

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| Nuclide* | 100 | 200 | 300 | 400 | 500 | 600 | 800 | 1000 |
|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| U-235+D | 1.75E-04 | 1.76E-04 | 1.77E-04 | 1.78E-04 | 1.79E-04 | 1.80E-04 | 1.82E-04 | 1.85E-04 |
| U-236 | 5.71E-08 | 8.37E-08 | 1.10E-07 | 1.37E-07 | 1.63E-07 | 1.90E-07 | 2.43E-07 | 2.95E-07 |
| U-238+D | 6.77E-04 | 6.78E-04 | 6.79E-04 | 6.80E-04 | 6.81E-04 | 6.82E-04 | 6.84E-04 | 6.86E-04 |
| Th-232+D | 1.25E-03 | 1.25E-03 | 1.25E-03 | 1.25E-03 | 1.26E-03 | 1.26E-03 | 1.26E-03 | 1.26E-03 |
| Pu-239 | 1.07E-03 | 1.93E-03 | 2.78E-03 | 3.63E-03 | 4.48E-03 | 5.31E-03 | 6.5 E-03 | 8.61E-03 |
| Pu-240 | 1.86E-04 | 3.49E-04 | 5.07E-04 | 6.63E-04 | 8.15E-04 | 9.63E-04 | 1.25E-03 | 1.52E-03 |
| Am-241 | 5.12E-02 | 4.58E-02 | 4.01E-02 | 3.51E-02 | 3.07E-02 | 2.68E-02 | 2.05E-02 | 1.56E-02 |
| Am-243+D | 7.47E-04 | 7.41E-04 | 7.35E-04 | 7.30E-04 | 7.24E-04 | 7.18E-04 | 7.07E-04 | 6.96E-04 |
| Cm-245 | 1.12E-05 | 1.14E-05 | 1.15E-05 | 1.16E-05 | 1.17E-05 | 1.18E-05 | 1.19E-05 | 1.20E-05 |
| Total | 58.46 | 10.00 | 5.96 | 5.53 | 5.42 | 5.47 | 5.46 | 5.45 |

Values in bold indicate highest contributor to dose
 * Nuclides with "+D" added to their name include the contributions from short-lived progeny, which are assumed to be in equilibrium at all times

Figure 4-2. Inadvertent Intruder Results for the Homesteader Scenario - Base Analysis Case. The D in the legend represents "daughters."



The sensitivity of the results to these and other parameters is discussed in sections 4.2.3.2 through 4.2.3.8.

4.2.3.2 ¹³⁷Cs. At 100 years after closure, ¹³⁷Cs makes up over 88 percent of the predicted dose. Thus if the amount of ¹³⁷Cs is changed, the change in the predicted dose at 100 years follows the change in ¹³⁷Cs. However, the amount of ¹³⁷Cs will not affect the predicted dose at the time of compliance (500 years after closure), because of its short half-life (30 years). The predicted dose decreases about an order of magnitude for every 100 years, thus the predicted dose at 500 years is 10⁻⁴ of the value at 100 years.

As part of the effort to determine the radioactive classification of the material taken from the single shell tanks (whether it is high-level waste or incidental waste after it has been pretreated) (WNC 1996), an inventory as high as 5 MCi of ¹³⁷Cs in the disposal facility has been proposed. This increase of 11, implies the predicted dose of 9.8 rem 100 years after closure.

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Table 4-2. Nonsteady Intruder Dose (mrem in a year) at Various Intrusion Times (years)^a

| Isotclide ^a | 100 | 150 | 200 | 250 | 300 | 350 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 |
|------------------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| H-3 | 3.34E-07 | 3.04E-06 | 1.65E-09 | 1.25E-10 | 8.76E-12 | 6.86E-13 | 4.33E-14 | 1.83E-16 | 7.75E-19 | 3.30E-21 | 1.29E-23 | 5.14E-26 | 1.63E-28 |
| C-14 | 3.99E-06 | 4.30E-06 | 5.76E-06 | 7.11E-06 | 8.45E-06 | 9.77E-06 | 1.11E-05 | 1.26E-05 | 1.61E-05 | 1.84E-05 | 2.09E-05 | 2.37E-05 | 2.65E-05 |
| Co-60 | 9.27E-05 | 1.24E-04 | 1.55E-04 | 1.86E-04 | 2.16E-04 | 2.47E-04 | 2.78E-04 | 3.19E-04 | 4.01E-04 | 4.83E-04 | 5.65E-04 | 6.47E-04 | 7.29E-04 |
| Cr-51 | 6.50E+00 | 2.13E+00 | 6.94E-01 | 2.24E-01 | 7.20E-02 | 2.50E-02 | 7.31E-03 | 2.10E-04 | 7.30E-05 | 2.50E-05 | 7.62E-06 | 2.40E-06 | 7.62E-07 |
| Cr-51 | 8.20E-06 | 8.47E-06 | 8.60E-06 | 8.72E-06 | 8.85E-06 | 8.97E-06 | 9.10E-06 | 9.14E-06 | 9.59E-06 | 9.64E-06 | 1.01E-05 | 1.02E-05 | 1.06E-05 |
| Mo-99 | 5.90E-08 | 5.53E-08 | 5.23E-10 | 4.89E-11 | 4.57E-12 | 4.27E-13 | 3.99E-14 | 3.49E-16 | 3.05E-18 | 2.67E-20 | 2.33E-22 | 2.00E-24 | 1.70E-26 |
| Mo-99 | 1.94E-02 | 1.46E-02 | 1.24E-02 | 1.07E-02 | 9.26E-03 | 8.04E-03 | 7.06E-03 | 6.32E-03 | 5.65E-03 | 5.04E-03 | 4.48E-03 | 3.97E-03 | 3.50E-03 |
| Sm-126 | 2.67E+01 | 2.67E+01 | 2.47E+01 | 2.67E+01 | 2.66E+01 | 2.64E+01 | 2.60E+01 | 2.60E+01 | 2.60E+01 | 2.64E+01 | 2.76E+01 | 2.89E+01 | 2.95E+01 |
| Zr-90 | 1.43E-04 | 1.54E-04 | 1.64E-04 | 1.77E-04 | 1.89E-04 | 2.00E-04 | 2.12E-04 | 2.25E-04 | 2.50E-04 | 2.81E-04 | 3.18E-04 | 3.57E-04 | 3.98E-04 |
| Ca-137 | 2.17E+02 | 6.87E+01 | 2.10E+01 | 6.91E+00 | 2.19E+00 | 6.95E-01 | 2.20E-01 | 2.21E-02 | 2.23E-03 | 2.24E-04 | 2.25E-05 | 2.26E-06 | 2.27E-07 |
| Co-151 | 3.54E-05 | 3.83E-05 | 3.71E-05 | 3.70E-05 | 3.29E-05 | 3.69E-05 | 7.21E-05 | 3.91E-05 | 2.07E-05 | 1.09E-05 | 5.57E-06 | 2.80E-06 | 1.44E-06 |
| Mo-226 | 5.40E-05 | 3.33E-05 | 3.26E-05 | 3.19E-05 | 3.13E-05 | 3.06E-05 | 3.00E-05 | 3.07E-05 | 3.75E-05 | 2.64E-05 | 2.53E-05 | 2.43E-05 | 2.33E-05 |
| Mo-229 | 3.11E-07 | 5.00E-10 | 1.23E-12 | 3.06E-15 | 7.13E-18 | 1.72E-20 | 4.19E-23 | 3.62E-26 | 1.01E-28 | 6.10E-31 | 4.74E-34 | 3.57E-37 | 1.01E-40 |
| Ac-227 | 1.36E-04 | 2.60E-05 | 5.76E-06 | 1.10E-06 | 2.63E-07 | 4.99E-08 | 1.01E-08 | 4.32E-10 | 1.02E-11 | 7.69E-12 | 3.20E-14 | 1.57E-15 | 5.75E-17 |
| Th-229 | 2.31E-05 | 2.31E-05 | 2.30E-05 | 2.30E-05 | 2.30E-05 | 2.29E-05 | 2.29E-05 | 2.29E-05 | 2.29E-05 | 2.27E-05 | 2.27E-05 | 2.26E-05 | 2.26E-05 |
| Th-232 | 5.70E-04 | 5.71E-04 | 5.71E-04 | 5.71E-04 | 5.71E-04 | 5.72E-04 |
| Pu-231 | 4.74E-01 | 4.94E-01 | 5.02E-01 | 5.06E-01 | 5.13E-01 | 5.16E-01 | 5.23E-01 | 5.33E-01 | 5.47E-01 | 5.53E-01 | 5.63E-01 | 5.73E-01 | 5.83E-01 |
| Pu-233 | 6.70E-04 | 9.76E-04 | 1.20E-03 | 1.59E-03 | 1.90E-03 | 2.21E-03 | 2.52E-03 | 3.14E-03 | 3.76E-03 | 4.39E-03 | 5.01E-03 | 5.64E-03 | 6.26E-03 |
| Pu-238 | 3.54E-05 | 4.74E-05 | 5.95E-05 | 7.16E-05 | 8.37E-05 | 9.59E-05 | 1.08E-04 | 1.33E-04 | 1.58E-04 | 1.83E-04 | 2.08E-04 | 2.34E-04 | 2.61E-04 |
| U-235 | 6.53E-04 | 6.67E-04 | 6.70E-04 | 6.73E-04 | 6.76E-04 | 6.80E-04 | 6.83E-04 | 6.90E-04 | 6.97E-04 | 6.95E-04 | 6.93E-04 | 6.91E-04 | 6.89E-04 |
| U-238 | 7.04E-07 | 9.83E-07 | 1.26E-06 | 1.54E-06 | 1.81E-06 | 2.09E-06 | 2.37E-06 | 2.92E-06 | 3.61E-06 | 4.03E-06 | 4.30E-06 | 5.13E-06 | 5.69E-06 |
| U-238 | 3.36E-03 | 3.57E-03 | 3.30E-03 | 3.39E-03 | 3.40E-03 | 3.42E-03 | 3.43E-03 | 3.45E-03 | 3.47E-03 | 3.49E-03 | 3.51E-03 | 3.54E-03 | 3.56E-03 |

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| nuclide* | 100 | 150 | 200 | 250 | 300 | 350 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 |
|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| Am-241 | 6.99E-02 | 6.11E-02 | 6.19E-02 | 6.25E-02 | 6.27E-02 | 6.19E-02 | 4.72E-02 | 1.25E-02 | 6.29E-02 | 6.24E-02 | 6.27E-02 | 6.21E-02 | 4.09E-02 |
| Pu-239 | 1.72E-02 | 2.53E-02 | 3.33E-02 | 6.13E-02 | 6.92E-02 | 1.73E-02 | 6.52E-02 | 6.09E-02 | 6.66E-02 | 1.12E-02 | 2.28E-02 | 1.62E-02 | 1.59E-02 |
| Pu-240 | 1.21E-02 | 6.74E-02 | 6.28E-02 | 7.75E-02 | 6.23E-02 | 1.07E-02 | 1.15E-02 | 1.58E-02 | 1.78E-02 | 3.02E-02 | 2.43E-02 | 2.59E-02 | 2.62E-02 |
| Am-241 | 2.83E-02 | 3.72E-02 | 2.69E-02 | 2.94E-02 | 2.44E-02 | 2.39E-02 | 2.36E-02 | 2.07E-02 | 1.09E-02 | 1.72E-02 | 1.55E-02 | 1.40E-02 | 1.28E-02 |
| Am-243 | 2.79E-02 | 2.75E-02 | 3.74E-02 | 3.78E-02 | 3.73E-02 | 2.72E-02 | 1.71E-02 | 1.70E-02 | 1.68E-02 | 1.67E-02 | 3.05E-02 | 3.44E-02 | 3.42E-02 |
| Am-245 | 5.64E-02 | 3.74E-02 | 5.02E-02 | 5.90E-02 | 5.96E-02 | 6.25E-02 | 6.12E-02 | 6.28E-02 | 6.41E-02 | 6.57E-02 | 6.71E-02 | 6.64E-02 | 6.97E-02 |
| Total | 2.61E+02 | 6.96E+02 | 5.88E+02 | 3.47E+02 | 2.98E+02 | 2.02E+02 | 2.77E+02 | 2.72E+02 | 2.32E+02 | 2.75E+02 | 2.75E+02 | 3.75E+02 | 2.72E+02 |

* Values in bold indicate highest contributor to dose
 * Nuclides with *D* added to their name include the contributions from short-lived progeny, which are assumed to be in equilibrium at all times

The predicted dose from ^{137}Cs falls below that from ^{136}Sn at about 300 years.

4.2.3.3 ^{136}Sn . Similarly the dose at 500 years (the compliance time) is so dominated by ^{136}Sn (over 95 percent of the dose), that the change in the predicted dose is proportional to the change in the initial inventory of ^{136}Sn . Because of the long half-life of ^{136}Sn (100,000 years), the predicted dose is relatively insensitive to the amount of time since closure.

It should be noted that the amount of ^{136}Sn to be placed in the waste form is highly uncertain. For these calculations (as was explained in Section 3.2.3), all of the ^{136}Sn from the Hanford Site production reactors is assumed to go into the waste form. No credit is taken in this analysis for any separation that may have been done during the initial processing of the fuel or in the pretreatment of the waste following their retrieval from the Hanford Site tanks. Future efforts will use less conservative assumptions.

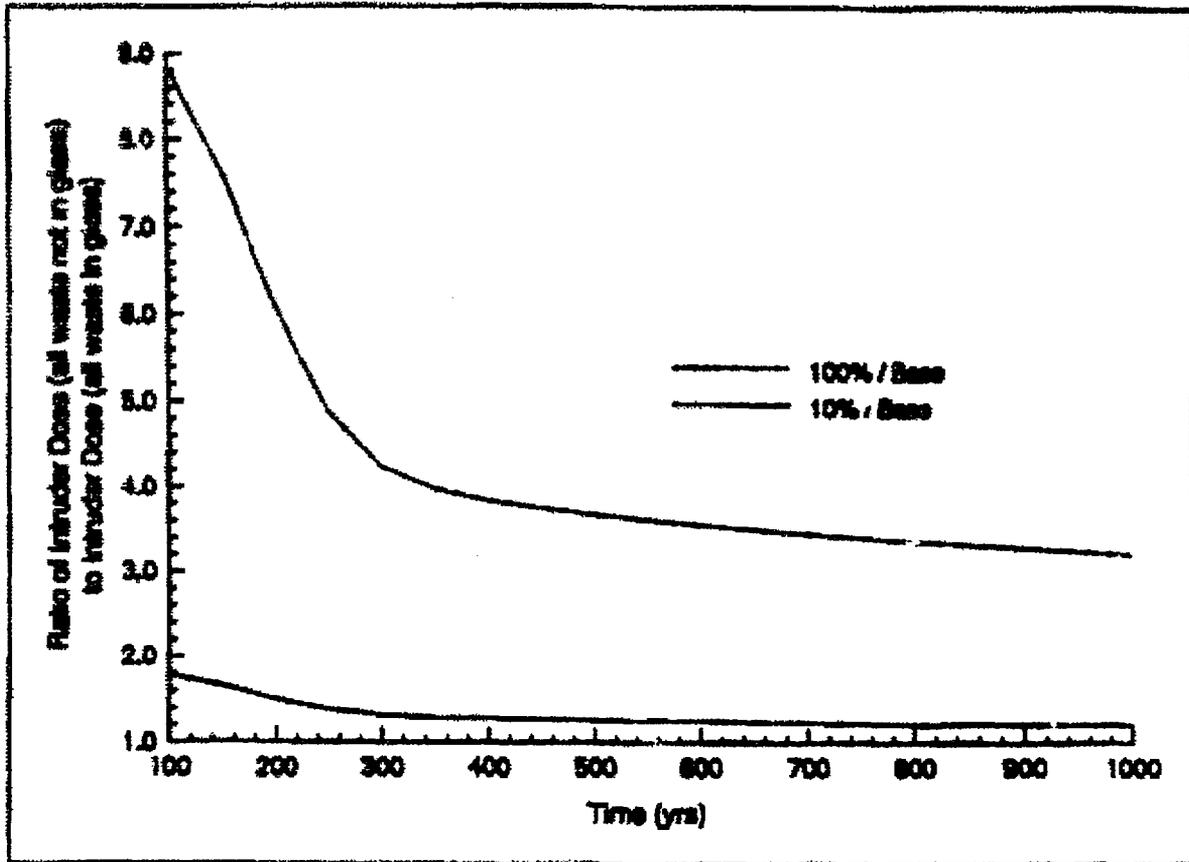
4.2.3.4 Stability of Waste Form. It is assumed that the waste form will not completely shatter into fine grains that could then be either ingested or inhaled. Rather, the waste form would retain most of its radionuclides. Sensitivity cases assuming that 10 and 100 percent of the radionuclides are available for ingestion or inhalation show that the predicted dose is relatively insensitive to this assumption.

Figure 4-3 displays the ratio of the case assuming 10 percent of the waste available for ingestion to the case where none of the waste is available as well as the ratio for the case of 100 percent availability to the case of 0 percent availability. Both ratios are displayed as a function of time since closure.

Figure 4-4 shows the radionuclides predicted to contribute to the dose at 100 years and at 500 years for the base analysis case where the amount of glass available is the amount of glass that has dissolved (< 1 percent) and for 100 percent availability. It can be seen that at 100 years, ^{90}Sr becomes significant when ingestion is allowed. However, ^{137}Cs still contributes over two-thirds of the predicted dose. At 500 years, even with ingestion, ^{136}Sn still contributes two-thirds of the predicted dose. However, ^{99}Tc , ^{239}Pa , ^{239}Pu , and ^{241}Am contribute noticeable amounts when ingestion is possible. In no case is inhalation a major exposure path.

4.2.3.5 Area of Homesteader Garden. The predicted dose depends on the area of the homesteader garden and the time during which the homesteader spends in the garden. The homesteader receives dose from external radiation when he is in the garden or dose from internal exposure when he ingests produce from the garden. A homesteader is assumed to remain in a smaller garden a shorter amount of time.

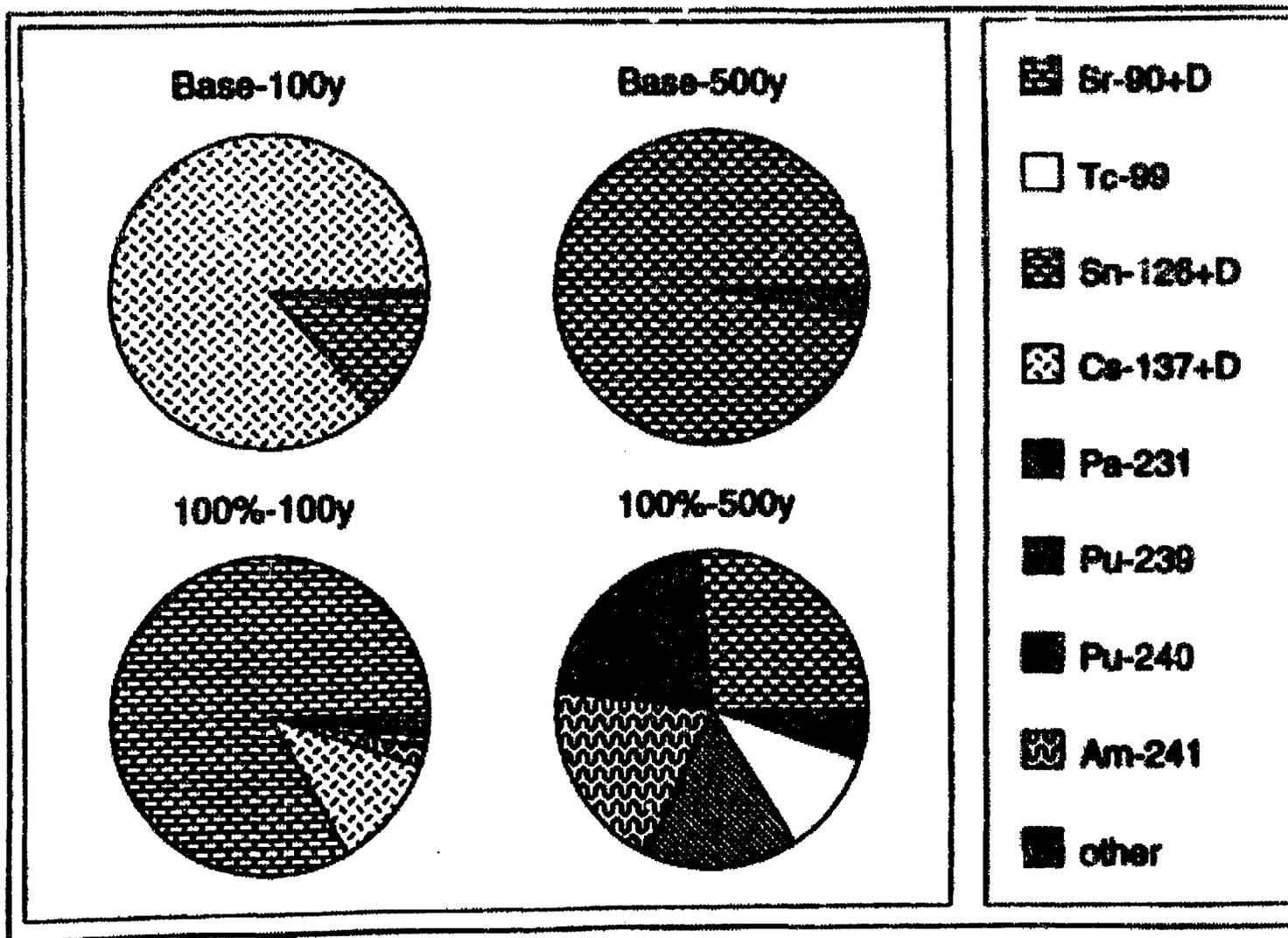
Figure 4-3. Ratio of Predicted Homesteader Doses for Different Availability of Radionuclides for Ingestion and Inhalation.



The base analysis case assumes a much smaller area (500 square meters) than previous Hanford performance assessments (2500 square meters). However, the smaller garden only increases the predicted homesteader dose a small amount because a homesteader spends less time in a small garden than a large one (see Section 3.4.8.4). Thus, relative to the larger garden, the smaller garden gives only a 10% increase in the predicted dose for ^{135}Sn and only a 24% increase for ^{137}Cs . For those radionuclides where ingestion is the main exposure pathway (for example ^{90}Sr , ^{99}Tc , Pu isotopes, ^{241}Am), then the ratio of the predicted dose is, in fact, nearly inversely proportional to the ratio of the garden areas.

4.2.3.6 Size of the Hole Drilled. The predicted dose is proportional to the amount of waste brought up from the disposal facility. For the base analysis case, the hole was conservatively estimated as 0.3 meters (12 inches). However, a more likely maximum diameter is 0.2 meters (8 inches). Such a smaller diameter hole would bring up only 42% of the waste when compared to the 0.3 meter (12 inch) hole. Thus the predicted dose is reduced by 42%.

Figure 4-4. Contribution of Major Radionuclides for the Base Analysis Case and When Ingestion is Allowed.



4.2.3.7 **Areal Density of the Waste.** Because the predicted dose depends linearly on the amount of waste material brought to the surface, the predicted dose depends on the waste concentration. However, because the hole is assumed to go through the entire height of the disposal facility, the vertical dimension becomes unimportant. Thus, it is not the normal volumetric density but the areal density (the volumetric density times the height) that is important.

The areal density can differ from the base analysis case for a number of reasons. The area of the disposal facility could differ because of any of the following:

- A different design of the disposal facility (for example, the use of airt spacers between vault rows)
- Different amounts of waste material to filler material in a vault
- Different assumption of the total height of waste, causing a change in the area occupied by the waste itself
- Different waste loading (because of sodium content or other reasons).

If Concept 2 (Section 3.4.6.5) is used for the design of the disposal facility, then the area of the disposal facility increases by a factor of 2.5 and the predicted dose decreases by 60%. If the sodium loading of the waste form decreases from 20% to 15%, then the area increases by four-thirds (1.333) (assuming no change in facility height) and the predicted dose decreases by 25%.

4.2.3.8 **Other Factors.** Other factors are less important in determining the predicted dose. Such factors include the use of dose conversion factors and estimates of the amount of radionuclides other than ^{129}Sn and ^{137}Cs .

The dose conversion factors important to the homesteader scenario are the external dose conversion factors. The factors used in the base analysis case are the ones from the EPA (EPA 1993). For ^{129}Sn , the DOE external dose conversion factor (DOE 1988c) is a factor of 4.45 larger than the EPA factor. The DOE value is larger because it assumes all the radionuclides are on the surface of the soil and hence there is no shielding of the photon radiation. The EPA factor, on the other hand, is based on the more realistic assumption of mixing (over a 15 centimeter layer). Previous Hanford performance assessments have used dose factors based on GENII (Napier 1988) which uses models similar to that of the EPA. For ^{129}Sn , the external dose conversion factor is 20 percent higher than the EPA value. For ^{137}Cs , the ratios of the external dose conversion factors are similar to those for ^{129}Sn .

Because of the dominance of ^{135}Sn and ^{137}Cs in the dose calculations, changes in the amount of other radionuclides is relatively unimportant. Because of different processing strategies, the amount of ^{90}Sr might be as much as twice the amount assumed in the base analysis case (3.4 MCi versus 1.6 MCi) (NRC 1996). Even using the maximum amount of ^{90}Sr would increase the total predicted dose at 100 years by less than 0.3% because ^{90}Sr does not significantly contribute to the estimated dose unless it is ingested. Changes in the amount of other isotopes are predicted to be less significant to the intruder dose.

4.2.4 Summary

The estimated exposures of the driller scenario easily meet the performance objectives by two orders of magnitude. The estimated exposures for the homesteader scenario are a factor of three lower than performance objectives.

Conservative values were taken for most of the parameters. Further analysis is expected to show that the diameter of the borehole should be smaller, that the area over which it is spread will be larger, and that the amount of ^{135}Sn (the dominant isotope) will be smaller. Each of these will lead to smaller estimated doses. Also, once experiments on the half-life of ^{135}Sn are documented, it is likely the value taken for its half-life will increase over the value used in this analysis, leading to lower estimated inventory values (when expressed in Ci) and hence lower estimated dose values.

This analysis assumed that the inventory in the Hanford Site tanks was uniformly spread among the vaults. Because the amount of ^{135}Sn is likely to vary among the tanks, the estimated maximum exposure will be higher than calculated here. Such a calculation awaits a better definition of the contents of each tank and a strategy for mixing tank contents during the retrieval and separations processes. Given the conservatism of the rest of the calculations and the gap between the estimated doses and the performance objectives, it is likely that the maximum exposure will also easily meet the performance objective.

4.3 RESULTS OF GROUNDWATER SCENARIOS - BASE ANALYSIS CASE

4.3.1 Overview

This section presents the results of the analyses for the base analysis groundwater contamination case. The groundwater analysis is by far the most complex of the various scenarios. This section provides the results for the base analysis case. Later sections in this chapter provide the sensitivity analyses:

- Section 4.4 (Base Case Sensitivity)

- Section 4.5 (Waste Form Sensitivity)
- Section 4.6 (Facility Design Sensitivity)
- Section 4.7 (Contaminant Transport Sensitivity)
- Section 4.8 (Other Factors).

Section 4.9 describes the effect of other Hanford Site actions on the groundwater affected by this study. Section 4.10 puts into context the information given in Sections 4.3 through 4.9.

The various parts of Section 3.3 described the scenarios considered in the groundwater scenario. Section 3.4 presented the values used for the parameters.

Each analysis case depends on three key calculations:

- The release rate of contaminants from the waste form
- The transport of those contaminants to the aquifer
- The transport through the aquifer to man.

For the base analysis case, the release rate of contaminants from the waste form is derived from the TWRS Privatization Specifications (DOE-RL 1996). This section presents numerical simulation results for the transport of the contaminants through the vadose zone, the transport through the unconfined aquifer, and the integration of those simulation results.

4.3.2 Vadose Zone Transport

4.3.2.1 Overview. Once the contaminants are released from the waste form and the disposal facility, they slowly move downward through the unsaturated soil (the "vadose zone") beneath the disposal facility. At the Hanford Site this zone is characterized by very low moisture content.

To separate the inventory contained in the waste form from the travel in the vadose zone, vadose zone calculations were performed for a waste form containing an unit inventory. The results of the vadose zone transport calculations are a normalized contaminant flux through the vadose zone to the groundwater.

Because the radionuclide release from the waste form extends over many hundreds of thousands of years, the normalized contaminant flux appears to be a step function with a fairly sharp rise (see Figure 4-5). Such a curve can be characterized by three numbers:

- The maximum value
- The time at which the curve reaches half the maximum value
- The first time at which the curve has a non-zero value (taken here as 10^{-6} times the maximum value).

These three values, along with the value for the compliance time of 10,000 years will be tabulated for each calculation. When a graphical comparison of different calculations yields insight, figures will also be displayed. Appendix E contains tables and figures that provide more information.

This type of shape results from the contaminant release time from the disposal facility being much longer than the travel time in the vadose zone. Appendix E.1 contains a mathematical justification of this effect. This "step" shape is different from the quickly rising, slowly decaying peaked shapes often seen in performance assessments.

4.3.2.2 Comments on Computer Simulations. As noted in chapter 3, two separate sets of analyses were performed for contaminant transport in the vadose zone. The results from the full facility model are documented in Piepho (1996). The results from the Unit Cell Model are documented in Kline (1996).

Because of the large size of the disposal facility and the significant depth of the vadose zone, the model for vadose zone transport is quite complex. Because of the large number of spatial nodes and the small timesteps needed, the model strains computer resources. For the base analysis case, 4 K_d bins were solved for over 70,000 time steps at 22,000 nodes. This run took about 100 hours on an IBM RS 6000 Model 580 UNIX computer. For the cases modelling Concept 2, where far fewer nodes are used, runs were made on a Pentium-based processor and took 10 hours. Simulations of the Unit Cell Model, which used fewer nodes still, were run on the UNIX computer and took about 1 hour.

The fractional mass balance errors for Concept 1 simulations (the largest ones experienced in the modeling) are shown in Table 4-3. Simulations for Concept 2 and the Unit Cell Model yielded fractional mass balance errors of less than 1 percent for all times. In addition, for the simulations of Concept 1 cases having a reduced release rate, the solution became unstable after 50,000 years. In such cases, values for times greater than 50,000 years were replaced by the maximum value at 50,000 years. This instability is thought to be due to terminating the transient flow calculation before an equilibrium flow condition was reached. The value at 50,000 years is near the rate of contaminant release from the waste form and is a good approximation for later times.

The Unit Cell Model calculations focused on the calculations of sensitivity cases. Thus to simplify the model and to conserve computer resources and, the model did not include a hydraulic diverter above the vaults. Because of the assumed instantaneous step change in infiltration rate at 1,000 years and the step change in properties of the man-made materials at 2,000 years, a pulse of unretarded contaminants occurs shortly after 2,000 years. Only unretarded contaminants ($K_d = 0.0$) showed this effect. Since the $K_d = 0.1$ ml/g group had nearly the same time dependence as the $K_d = 0.0$ group (except for this pulse), all dose

calculations reported for the Unit Cell Model use the $K_d=0.1$ ml/g results for the unretarded group.

Figure 4-3. General Characteristics of Vadose Zone Transport. The normalized contaminant flux to the aquifer is shown for the simulation of Concept 2, constant release rate from waste form, full facility model.

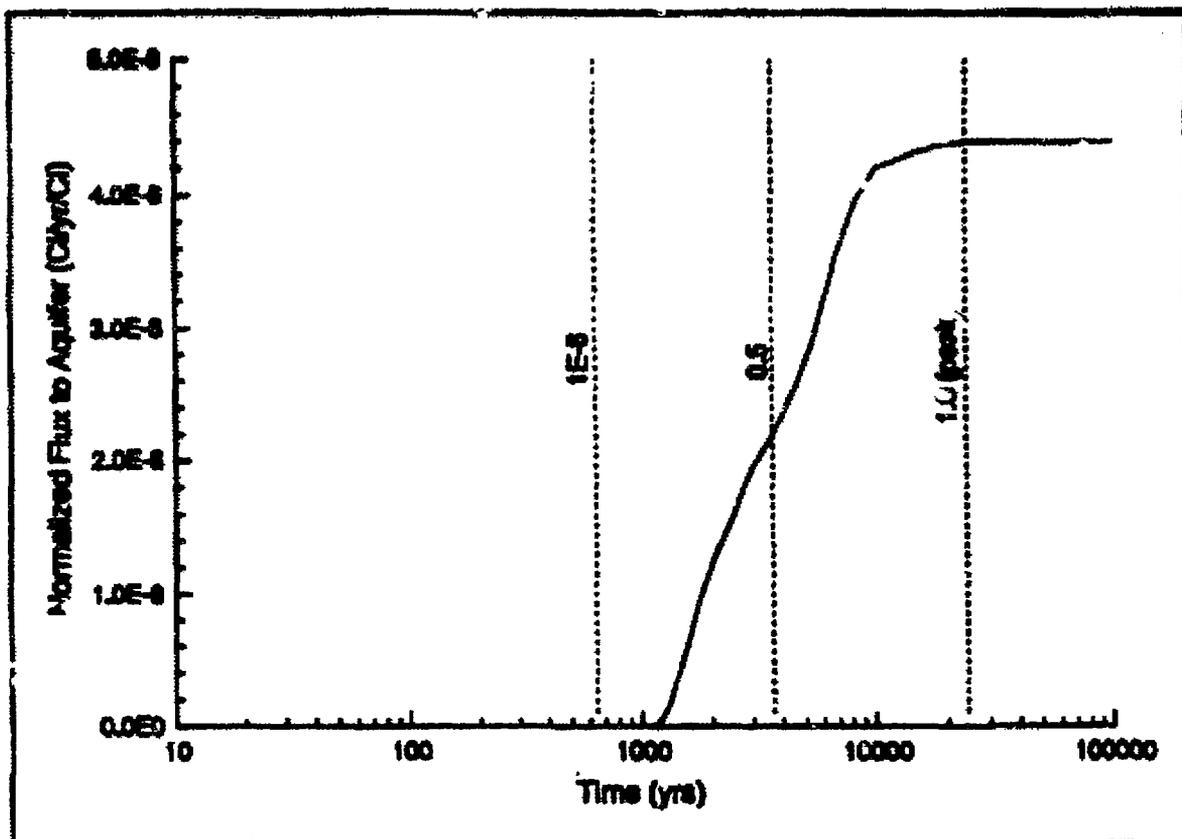


Table 4-3. Fractional Mass Balance Error as a Function of Time for Modeling Concept 1 Simulations (Base Analysis Case).

| Time (years) | Fractional Mass Balance Error (%) |
|--------------|-----------------------------------|
| 21,500 | 0.5 |
| 37,500 | 2.1 |
| 53,500 | 3.5 |

4.3.2.3 Base Analysis Case Simulation Overview. This section describes the simulation of the moisture flow and contaminant transport in the vadose zone for the base analysis case. The following paragraphs discuss the simulated moisture content distribution within the disposal facility and the vadose zone as a function of time, the simulated flow paths within the vadose zone, and the contaminant transport within the vadose zone and the unconfined aquifer.

4.3.2.4 Base Analysis Case Simulation of Moisture Flow in Vadose Zone. Contaminant transport depends strongly on the moisture content and flow in the vadose zone. Figure 4-6 shows the moisture content and a few flow lines at 1,000 years for the entire vadose zone. Figure 4-7 shows that information in more detail around the edge of the disposal facility. Figures 4-8 and 4-9 show similar information at 4,000 years (the time at which steady state flow occurs).

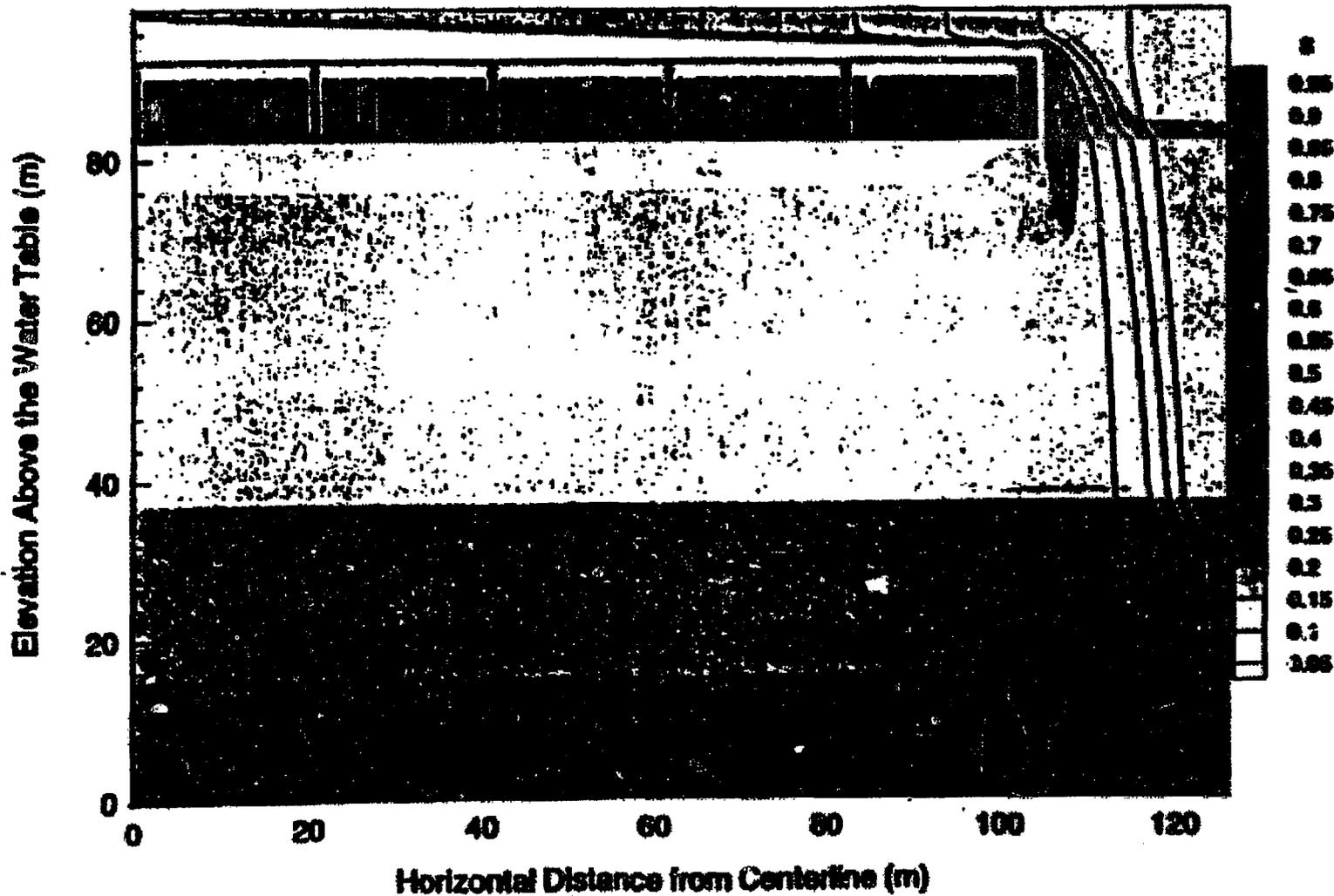
The effectiveness of the sand-gravel capillary barrier is clearly seen in the figures. The flow lines go around the hydraulic diverter, leaving a moisture shadow underneath. At 500 years, the moisture content [$\text{volume}_{\text{water}} / \text{volume}_{\text{soil}}$] beneath the facility is $0.035 \text{ cm}^3/\text{cm}^3$. In the path of the diverted flow, the moisture content increases to $0.050 \text{ cm}^3/\text{cm}^3$, then declines to $0.042 \text{ cm}^3/\text{cm}^3$ moving away from the facility. Most of the shadowing effect disappears by the time the moisture reaches the bottom of the sandy sequence of the Hanford formation.

At 500 years, the simulation shows no indication of significant flow through the barrier. The moisture content in the backfill soil separating the canisters is $0.050 \text{ cm}^3/\text{cm}^3$ at the top of the canisters, increasing to only $0.053 \text{ cm}^3/\text{cm}^3$ at the bottom. These results remain almost constant (the relative change being less than 3 percent) moving horizontally outward from the center of the facility.

At longer times, the shadow remains intact but is not quite as extensive. At 4,000 years, the moisture content directly beneath the facility has increased slightly (to $0.038 \text{ cm}^3/\text{cm}^3$ at the edge of the facility). More significantly the large flow around the barrier has increased the moisture content just outside of the facility to $0.078 \text{ cm}^3/\text{cm}^3$. The moisture content of the soil most distant from the facility also increases (to $0.050 \text{ cm}^3/\text{cm}^3$, reflecting the 3 mm/y recharge that occurs beginning at 1,000 years caused by the presumed return of the surface soil and vegetation to natural conditions.

At these longer times, the computer simulation shows somewhat poorer performance of the hydraulic diverter. Isolated set of nodes show higher moisture contents (0.016 to $0.028 \text{ cm}^3/\text{cm}^3$) than the remainder of the nodes ($0.014 \text{ cm}^3/\text{cm}^3$). However, the moisture content of the filler material between the canisters still remains at about $0.05 \text{ cm}^3/\text{cm}^3$ with the bottom of the filler material again being slightly moister than the top.

Figure 4-6. Moisture Content and Flow Lines for the Base Analysis Case at 1,000 Years. The moisture content is given as saturation which is volumetric moisture content divided by the porosity of the material. The waste forms are shown as 100% saturated to improve readability.



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Figure 4-7. Moisture Content and Flow Lines at 1,000 Years with Emphasis on the Edge of the Disposal Facility.

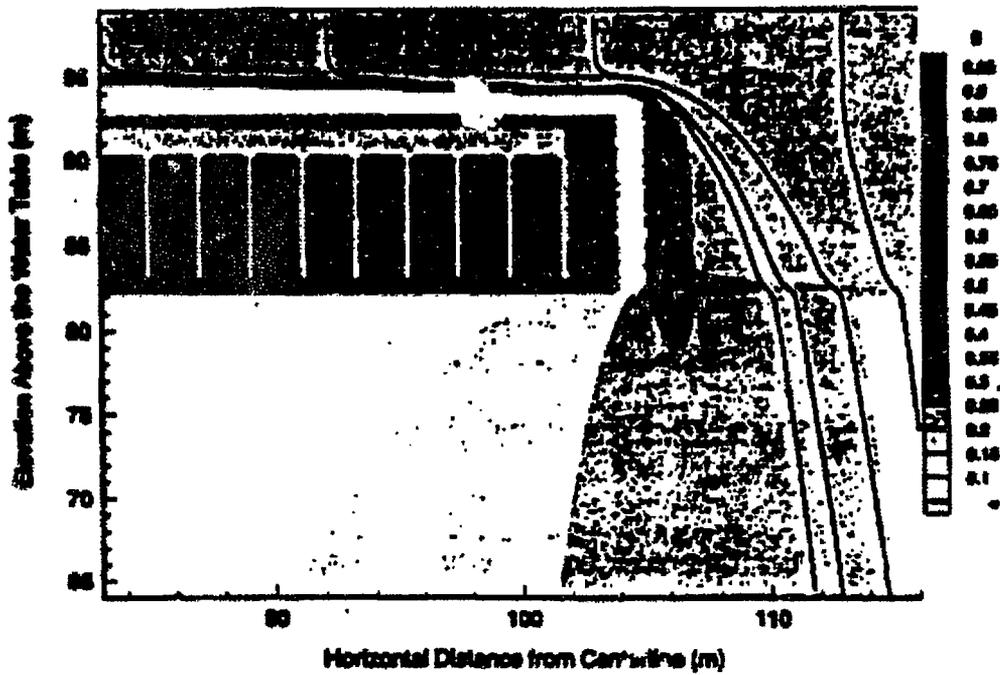


Figure 4-8. Moisture Content and Flow Lines at 4,000 Years (Steady State) with Emphasis on the Edge of the Disposal Facility

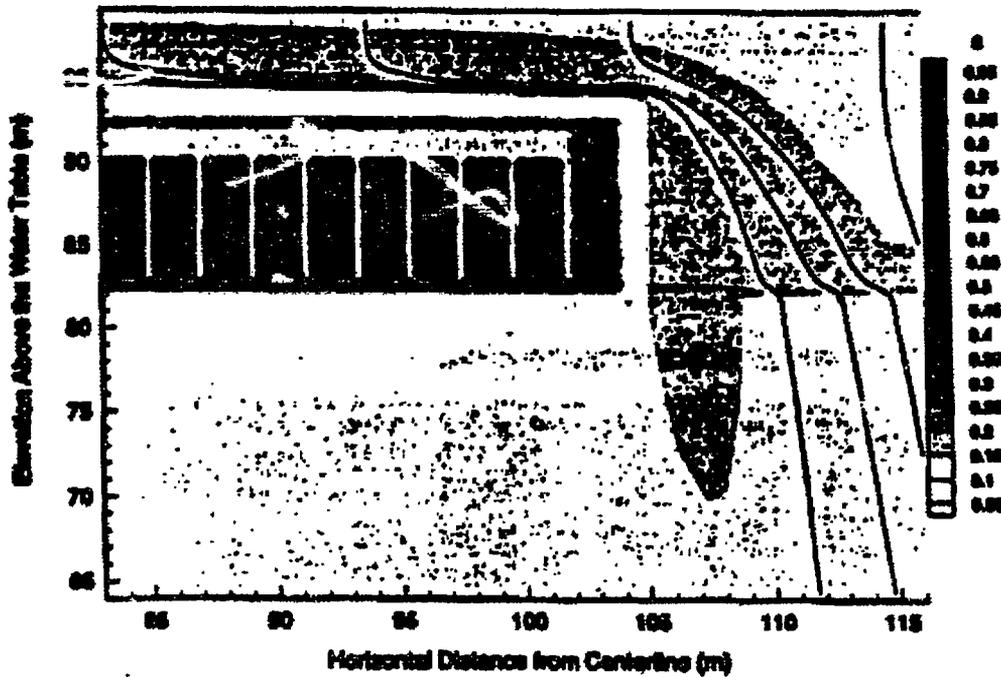
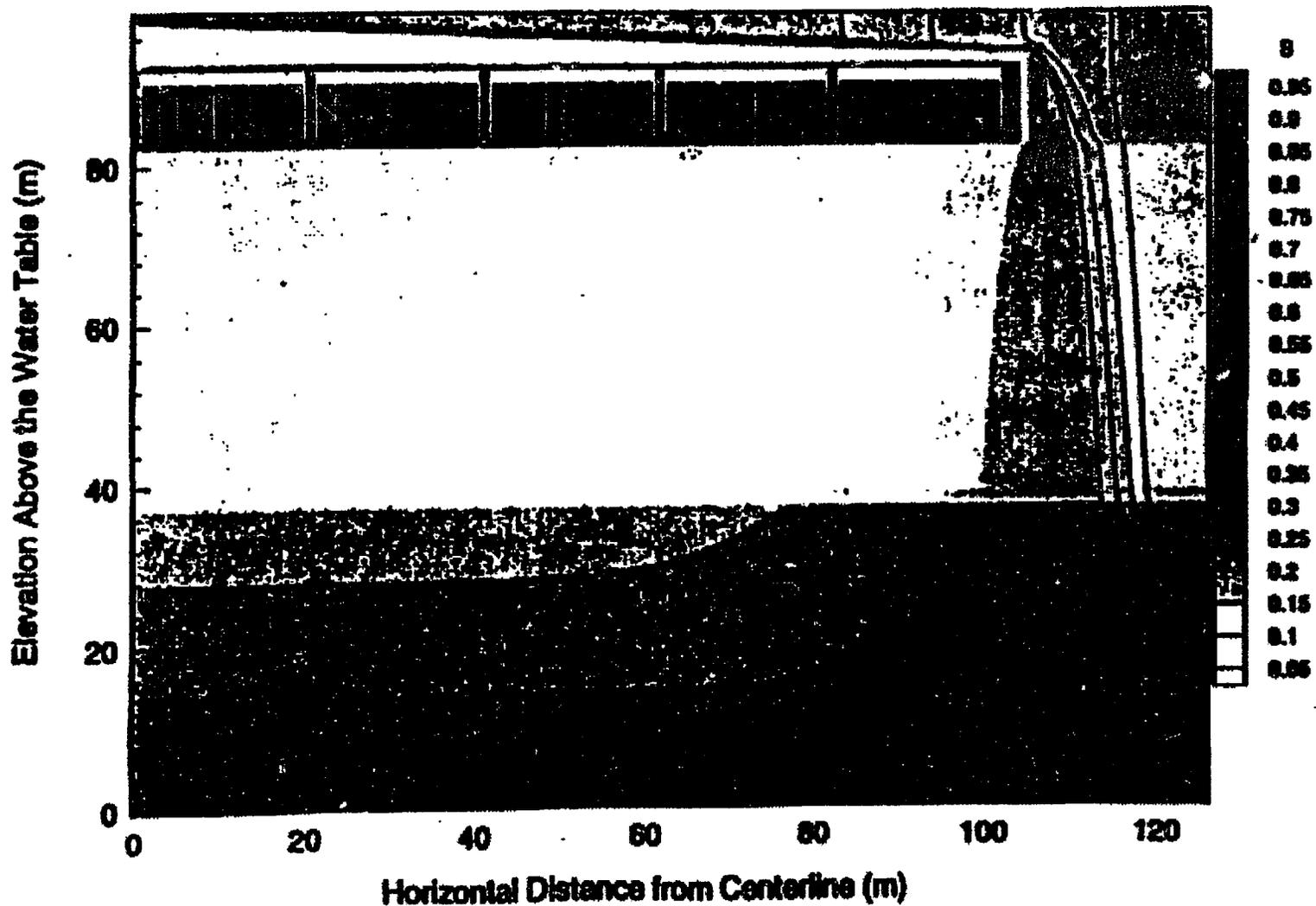


Figure 4-9. Moisture Content and Flow Lines for the Base Analysis Case at 4,000 Years (Steady State). The moisture content is given as saturation which is volumetric moisture content divided by the porosity of the material. The waste forms are shown as 100% saturated to improve readability.

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4.3.2.5 Base Analysis Case Simulation of Contaminant Transport in Vadose Zone. Normalized contaminant fluxes to the aquifer [that is, contaminant fluxes normalized to 1 Curie of inventory] were calculated using PORFLOW for 7 different K_d values ($K_d = 0, 0.1, 0.6, 1.0, 15., 40.,$ and $100. \text{ ml/g}$) for times up to 100,000 years. The functions are normalized to 1 unit of contaminant in the waste form.

Figure 4-10 shows the normalized contaminant flux to the aquifer for $K_d = 0, 0.1,$ and 0.6 ml/g . Table 4-4 shows the major parameters describing the normalized contaminant flux for each K_d group calculated.

At 10,000 years, only the first 3 K_d groups are significant, having normalized flux values greater than 10^{-6} per year. In fact, the calculations indicate that those radionuclides with $K_d = 100. \text{ ml/g}$ do not even reach the aquifer in 10,000 years. Because of the large value used for dispersion, an extremely small amount of the $K_d = 0$ group reaches the aquifer before 500 years.

Figure 4-10. Normalized Contaminant Flux to the Aquifer for $K_d = 0, 0.1,$ and 0.6 ml/g - Base Analysis Case.

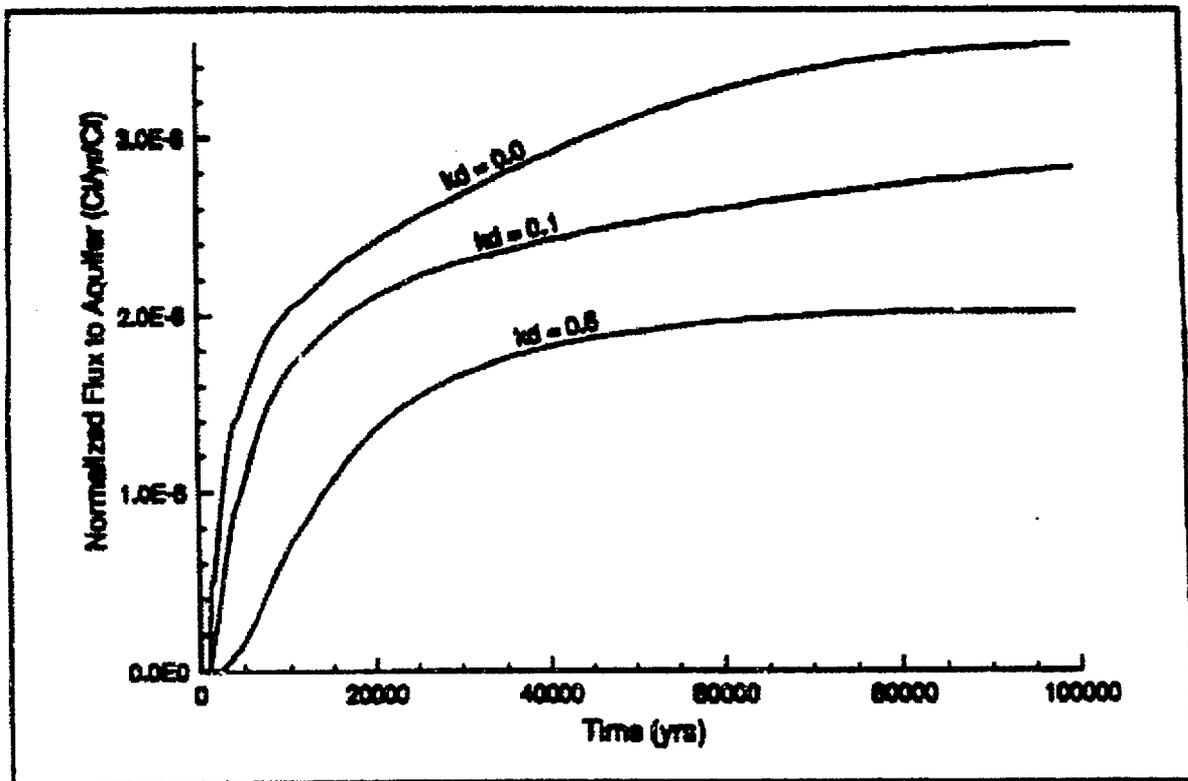


Table 4-4. Major Parameters Describing the Normalized Contaminant Flux to the Aquifer for the Base Analysis Case. Decay is included later in the analysis.

| K_d (ml/g) | Value at 10K Years (Ci/y/Ci) | Peak Value ^(a) in First 100K Years (Ci/y/Ci) | Time of True Peak Value (y) | Time of 0.5*True Peak Value ^(a) (y) | Time of 10 ⁻⁶ *True Peak Value ^(a) (y) |
|-----------------|------------------------------------|---|--------------------------------------|--|--|
| 0. | 2.04 e-6 | 3.53 e-6 | >100,000 | 12,000 | 450 |
| 0.1 | 1.71 e-6 | 2.84 e-6 | >100,000 | 12,000 | 650 |
| 0.6 | 0.72 e-6 | 2.02 e-6 | >100,000 | >100,000 | 1,300 |
| 3. | 1.3 e-09 | 1.37 e-6 | >100,000 | >100,000 | 3,400 |
| 15. | 9.3 e-15 | 0.20 e-6 | >100,000 | >100,000 | 17,000 |
| 40. | 2.4 e-23 | 4.0 e-09 | >100,000 | >100,000 | 44,000 |
| 100. | 0.0 | 2.1 e-12 | >100,000 | >100,000 | >100,000 |

The value given is for the peak value in the first 100,000 years.

- ^a Unless a peak value was obtained in the first 100,000 years, the true peak value was taken as 4×10^{-6} Ci/y/Ci.

For none of the K_d groups does the normalized flux to the unconfined aquifer reach its maximum before the computer simulations end at 100,000 years. However, the $K_d=0$ group is expected to be very near its peak (based on the shape of the curve in Figure 4-10 and the contaminant release rate). Because the contaminant flux to the aquifer is expected to stay high (due to the slow release of contaminants from the waste form), calculations to longer times are needed to demonstrate the character of the full release and the magnitude of peak concentration and dose. The normalized flux to the aquifer can be approximately estimated based on the $K_d=0$ group. By assuming that the release rate continues indefinitely and that the waste form release controls the temporal shape, the normalized flux to the aquifer can be approximated by

$$\Gamma(K_d, t \cdot [1 + \alpha K_d]) = \Gamma(K_d=0, t). \quad (1)$$

By comparing the time of occurrence for $\Gamma = 10^{-6}$ per year for $K_d=0$ and $K_d = 3$ ml/g, α is found to be 6.6 g/ml. Larger values are found in the Unit Cell Model (-35 g/ml) where the effect of the moisture shadow of the facility is absent. A comparison between the two methods is shown in Appendix E.2.2. Using equation 1, normalized fluxes were estimated out to 66 million years assuming that the flux never decreases from its maximum value. The value of 67 million years results the endpoint of the

explicit calculation (100,00 y), α (6.6 g/m³), and the maximum K_d value (100 ml/g).

This is a conservative assumption, because the flux for groups with small K_d values will show decreases in the range of a few million years as the release rate from the waste form goes to zero in this time frame.

4.3.3 Aquifer Transport

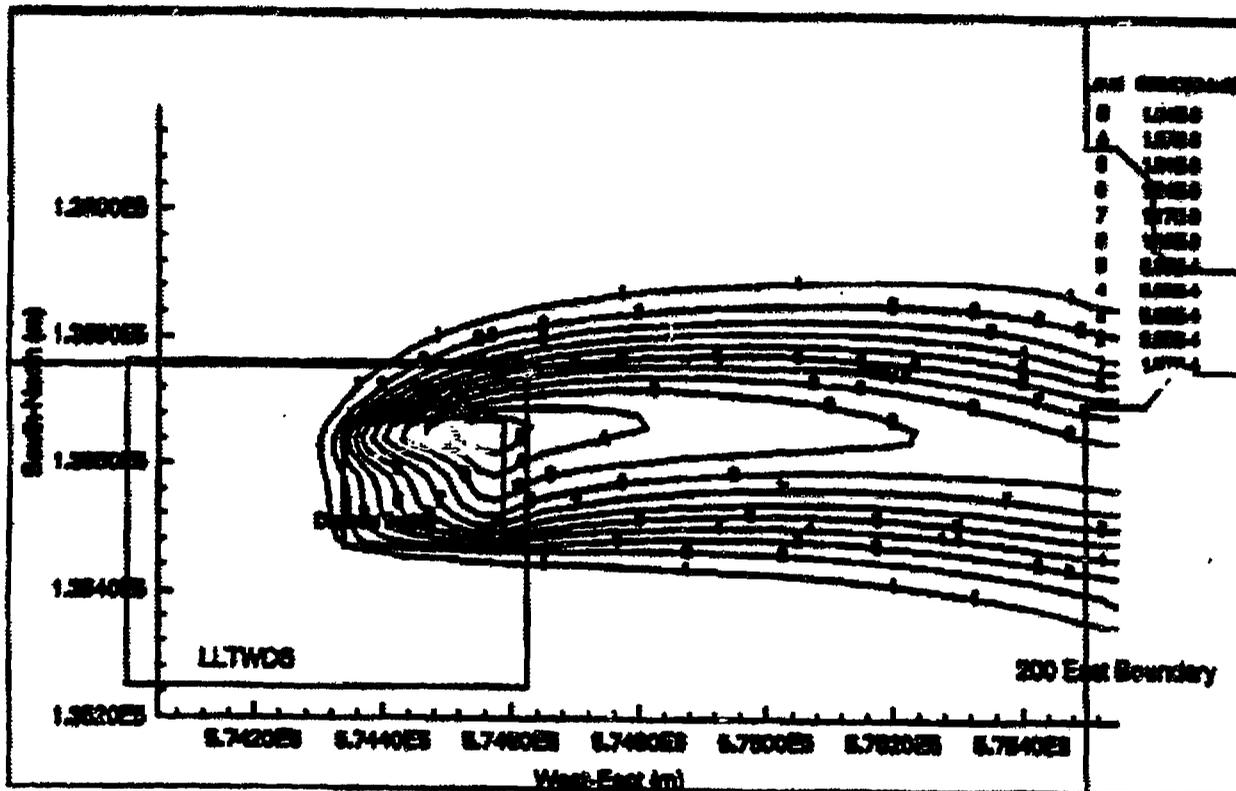
These results are based on applying the Hanford site wide groundwater model as described in Section 3.5.3.4. Two models were used, one with high spatial resolution near the disposal site and one with a lower resolution describing the flow and transport all the way down to the Columbia River. A fuller description is given in Lu 1996 which assumed a recharge rate of 1 mm/y. The results of Lu 1996 have been modified to reflect actual recharge rates (normally 3 mm/y) by multiplying the results of Lu (1996) by the recharge rate.

The results for the close-in model are shown in Figures 4-11 and 4-12. Figure 4-11 shows the concentration ratio contours (concentration at the well relative to the concentration in the vadose zone underneath the disposal facility) 120 years after the flux starts to enter the aquifer at the aquifer's surface. The plume is basically west to east with a slight northerly bias as suggested by the groundwater flows depicted in Figure 3-1. At 100 meters downgradient, the width of the plume is predicted to be about 25 meters (full width at the half maximum value), increasing only slightly (about 30 meters) 900 meters downgradient. Figure 4-12 shows the time history of the concentration ratio at the well 100 meters down gradient from the disposal facility and at the 200 Area fence (about 900 meters downgradient). At the well 100 meters downgradient, the concentration ratio reaches a steady state value (5.31×10^{-3}) after 30 years. At a well 900 meters downgradient (the 200 East Area boundary, a steady state value (4.08×10^{-3}) is reached after about 60 years. The steady state values are summarized in Table 4-5.

The flow paths for the distant well sites are displayed in Figure 4-13. The relative contamination levels for 400 years after the contaminants enter the aquifer are shown in Figure 4-14. Time histories for the eight wells shown in Figure 4-15 are displayed in Figure 4-15. Although there is some compression of the flow lines, dispersion of the contaminants is much more important. The concentration ratio for a point near the river is less than 2×10^{-4} for a unit concentration entering the aquifer beneath the disposal site and it takes about 400 years to reach the Columbia River. The steady-state concentration ratios are summarized in Table 4-5.

The consistency of the two aquifer models can be judged by comparing the results of the models at the 200 East Area Boundary

Figure 4-11. Concentration Ratios 120 Years after Contaminants Enter Aquifer. Larger square in lower left hand quarter is the disposal site. Smaller square in upper right quarter of the larger square is the location of modelled vaults. (Lu 1996). Assumes concentration of 1 Ci/m³ in the vadose zone and a recharge rate of 1 mm/y. Since the actual recharge rate is 3 mm/y, actual concentrations will be 3 times higher than shown.



(about 900 meters downgradient from the disposal facility). The near model gives 4.08×10^{-3} , while the geometric interpolation of wells W1 (-750 meters downgradient) and W2 (-1200 meters downgradient) give 4.17×10^{-3} .

Figure 4-12. Concentration Ratio as a Function of Time at Points of Maximum Concentration 100 Meters Downgradient and at the 200 East Boundary (about 900 Meters Downgradient). (Lu 1996)

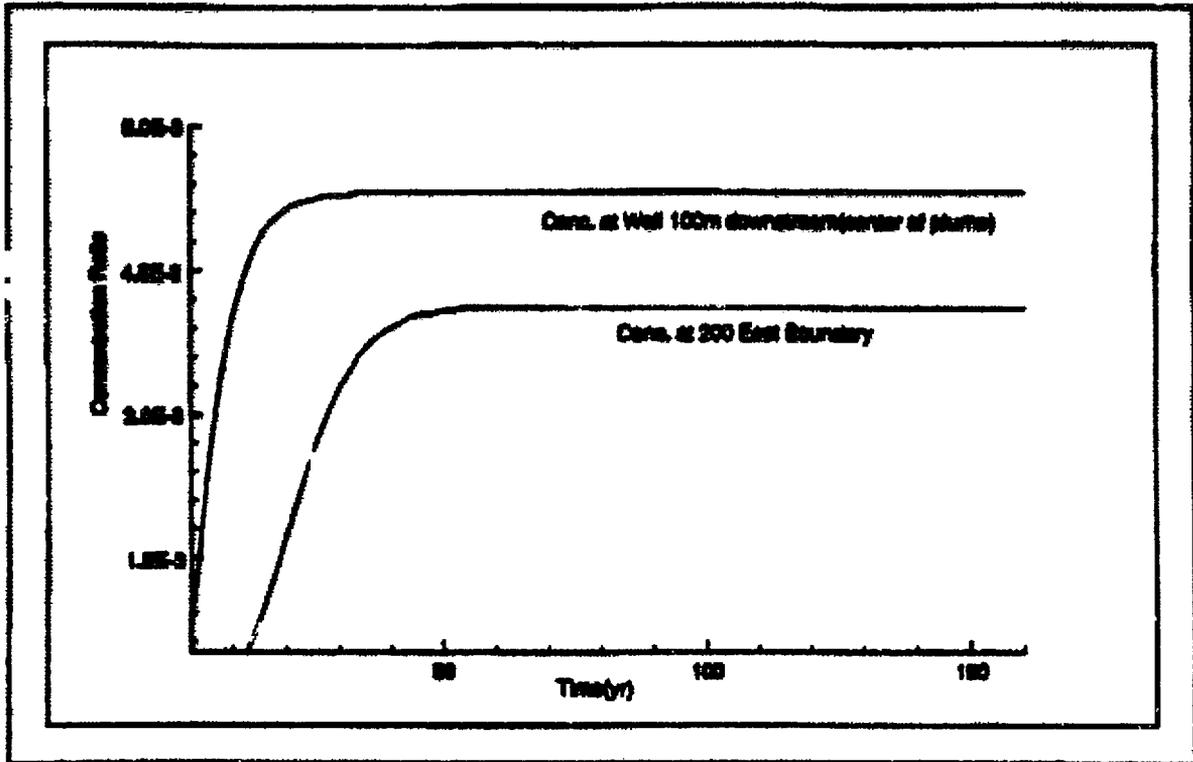
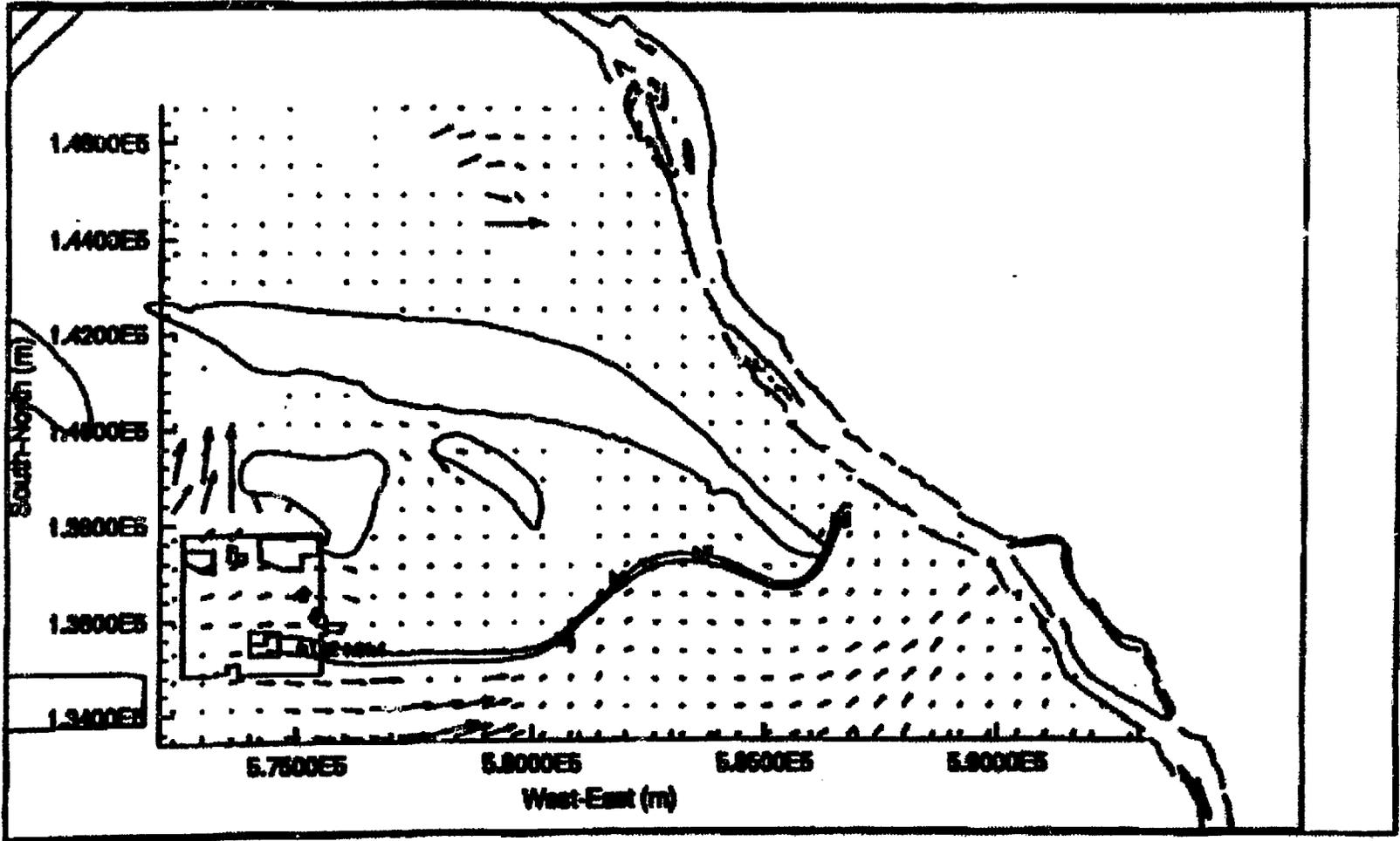


Figure 4-13. Flow Paths for Distant Well Sites. (Lu 1996)

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Figure 4-14. Concentration Ratio Contours 400 Years after the Contaminants Enter the Aquifer (Lu 1995) Assumes concentration of 1 Ci/m³ in the vadose zone and a recharge rate of 1 mm/y. Since actual recharge is 3 mm/y, actual concentrations will be 3 times higher than shown.

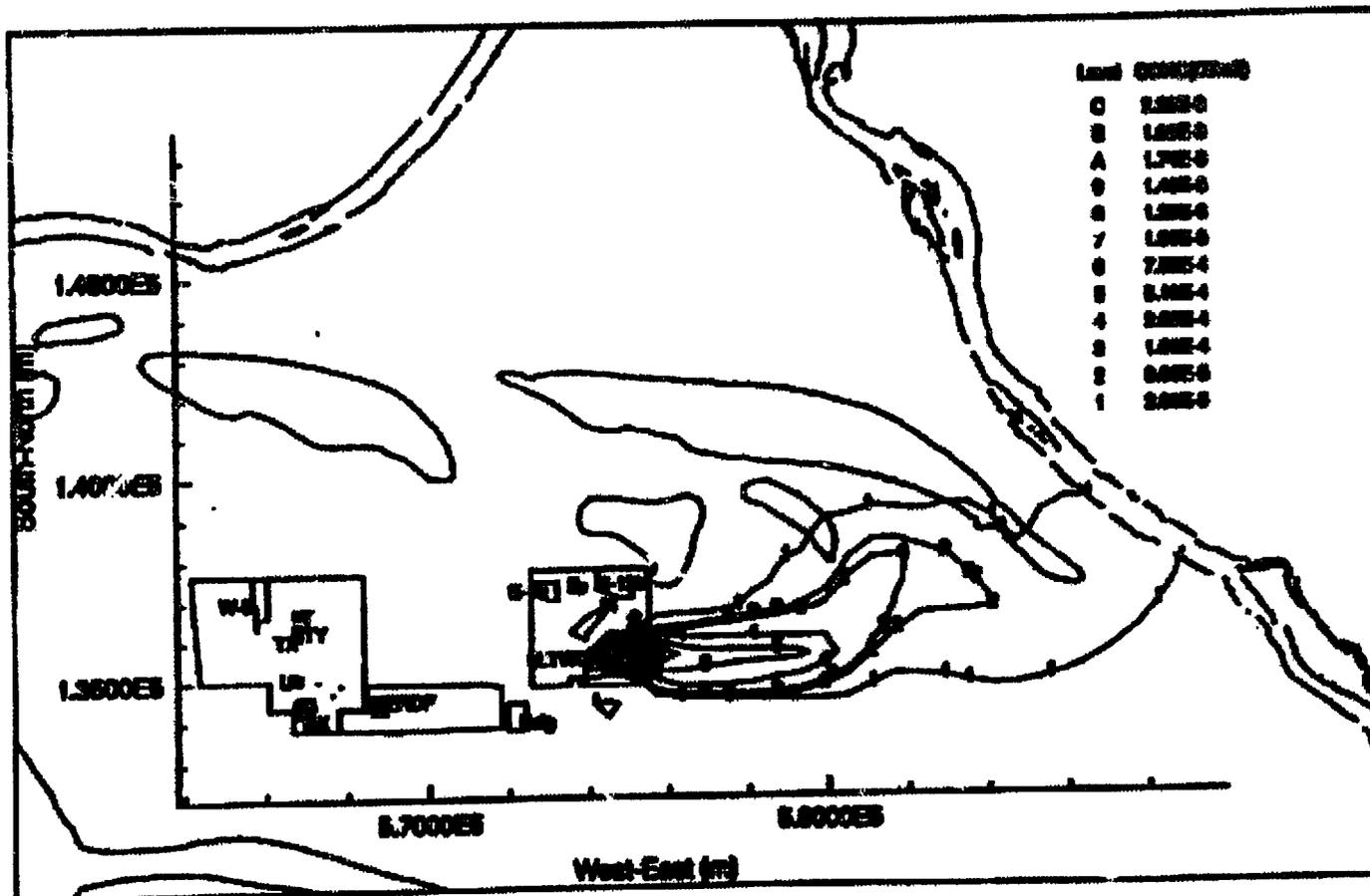


Figure 4-15. Concentration Ratio Histories at Downstream Hypothetical Wells. (In 1996) Locations h1 through h8 are shown in Figure 4-13 and defined in Table 4-3.

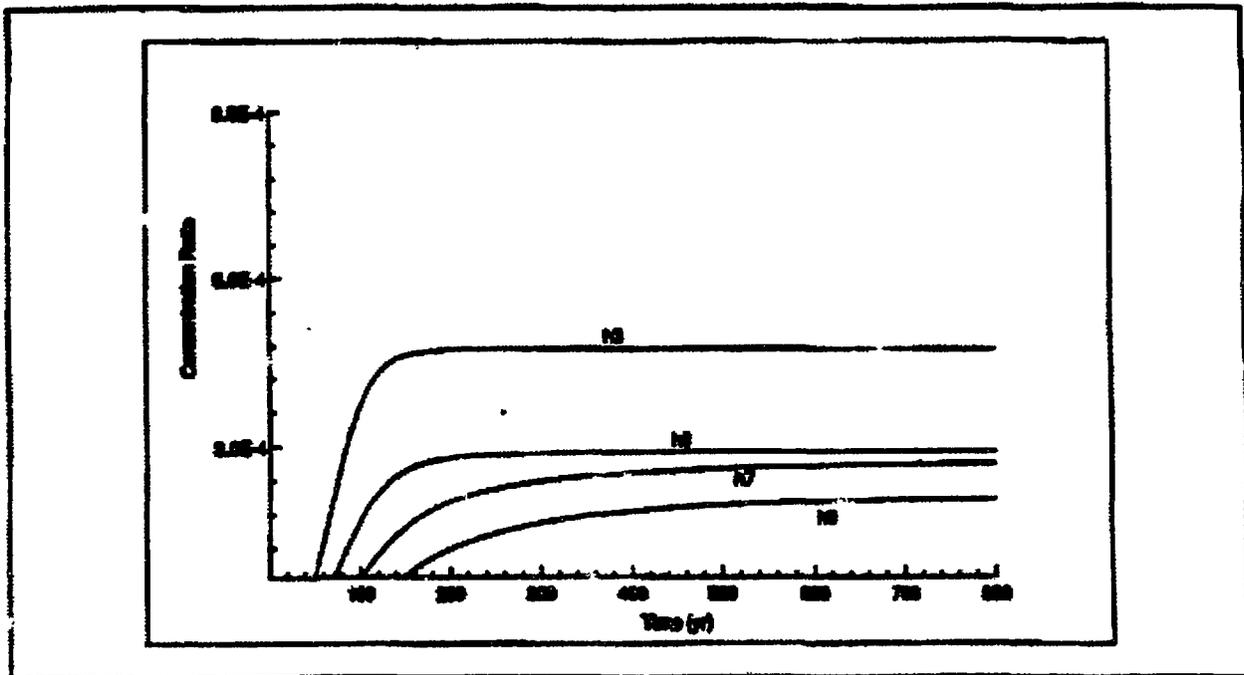
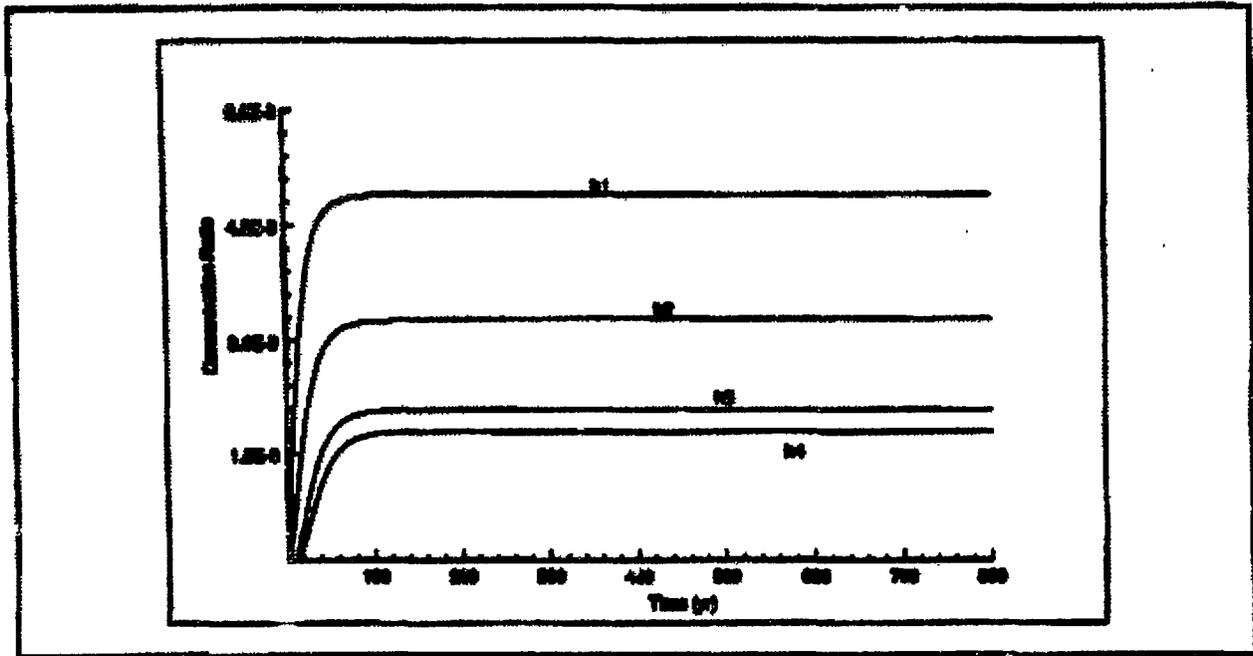


Table 4-5. Concentration Ratios at Hypothetical Wells Relative to Unit Concentration Entering Aquifer Under Disposal Facility

| Well Number | Distance downgradient (meters) | Concentration Ratio |
|-------------|--------------------------------------|-----------------------|
| -- | 100. | 5.31×10^{-3} |
| h1 | -750. | 4.89×10^{-3} |
| -- | 200 East Area Boundary (-900 meters) | 4.08×10^{-3} |
| h2 | -1,200. | 3.27×10^{-3} |
| h3 | -1,750. | 2.07×10^{-3} |
| h4 | -2,500. | 1.79×10^{-3} |
| h5 | -6,000. | 4.77×10^{-4} |
| h6 | -12,000. | 2.91×10^{-4} |
| h7 | -15,000. | 2.54×10^{-4} |
| h8 | -20,000. | 1.86×10^{-4} |

4.3.4 Integration

This section describes the result of combining the results of the vadose zone transport (Section 4.3.2), the results of the aquifer transport (Section 4.3.3), the amounts of the radionuclides (Section 3.2.2), and the exposure parameters (Section 3.4.8).

The computer program PORCON (described in Mann 1996) was used to combine the results of the PORFLOW runs. Thus one file would contain all K_d bins even though PORFLOW was limited to 4 bins per run. The program INTEG (described in Section 3.5.2.5) then combines the results of the transport simulations (vadose zone and aquifer) with inventory and exposure parameters to calculate the dose and radionuclide concentration at a well.

Concept 1 is the facility design used for the base analysis case. This section describes in detail the impacts of simulation results for this case. The impacts are estimated for water drawn from a well 100 meters downgradient of the disposal facility, from a well just before the groundwater mixes with the Columbia River, and from the Columbia River itself.

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As shown in Table 4-6, the impacts estimated at a well 100 meters downgradient from the disposal facility are less than the performance objectives set in Section 1.5. The beta/photon and total drinking water doses as a function of time are displayed in Figure 4-16. Also shown in Figure 4-16 are the doses from ⁹⁹Tc and ⁷⁵Se, the two biggest contributors to the dose. Table 4-7 shows the major contributors to the beta/photon dose at 10,000 years. Figure 4-17 shows the alpha-emitting radionuclide concentration as a function of time at the same well. Table 4-8 shows the major contributors to the alpha-emitting radionuclide concentration at 10,000 years. Figure 4-18 and Table 4-9 show the all-pathways dose and major contributors to that dose, respectively.

Table 4-6. Estimated Impact from Base Analysis Case at a Well 100 Meters Downgradient from the Disposal Facility at 10,000 years.

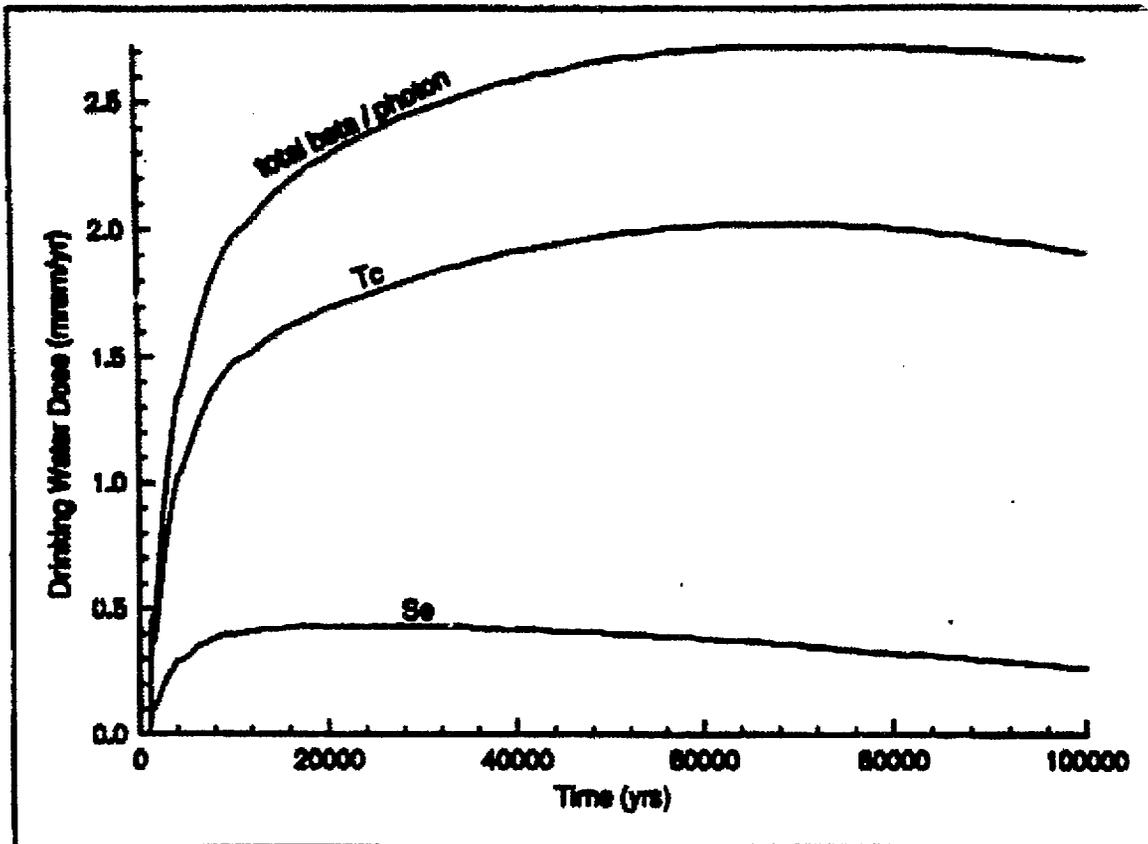
| Type of Impact | Value | Performance Objective |
|---|--------|-----------------------|
| Dose from Beta/Photon Emitting Radionuclides (mrem in a year) | 2.0 | 4.0 |
| All-Pathways Dose (mrem in a year) | 6.4 | 25. |
| Concentration of Alpha-Emitting Radionuclides (pCi/l) | 1.65 | 15. |
| Radium Concentration (pCi/l) | <0.001 | 3. |
| Uranium Concentration (pCi/l) | 1.65 | --- |

Table 4-7. Major Contributors at 10,000 Years to the Estimated Beta/Photon Drinking Water Dose at a Well 100 Meters Downgradient from the Disposal Facility for the Base Analysis Case.

| Radionuclide | Dose (mrem/year) | Concentration (pCi/l) |
|---------------------|------------------|-----------------------|
| ⁹⁹ Tc | 1.48 | 1560. |
| ⁷⁵ Se | 0.40 | 67. |
| others ^a | 0.09 | 2. |
| total | 1.97 | 1630. |

^aMainly beta-emitting daughters of uranium

Figure 4-16. Drinking Water Doses for the Base Analysis Case at a Well 100 Meters Downgradient.



Doses and radionuclide concentrations were also calculated just before the radionuclides enter the Columbia River. Because the travel time in the unconfined aquifer is so short, the main difference between the impact 100 meters downgradient and the impact at the Columbia River (~20,000 meters) is that more mixing occurs in the unconfined aquifer. Table 4-10 shows the estimated dose and radionuclide concentrations.

For all the impacts considered, the value of the impact is still rising at 10,000 years. As noted in Section 4.3.2.5, detailed computer simulations were carried out for each K_d group for 100,000 years, while approximations were used out to 100,000,000 years. Table 4-11 presents the estimated maxima.

The last calculation for the base analysis case is the calculation of the integrated dose. Two cases are presented: a public drinking water system supplying 25 people located near the disposal facility and a population of 5 million drinking water from the Columbia River after the contaminants are mixed with the river. Although not realistic, it is assumed that all the water consumed by the 5 million people comes from the well that intersects the groundwater just before the groundwater reaches

the Columbia River. Even so, the estimated integrated dose of 0.05 person-rem/y and slightly less than 5 person-rem/y, respectively are far below the performance objective of 500 person-rem/y.

Figure 4-17. Alpha-Emitting Radionuclide Concentrations for the Base Analysis Case at a Well 100 Meters Downgradient from the Disposal Facility.

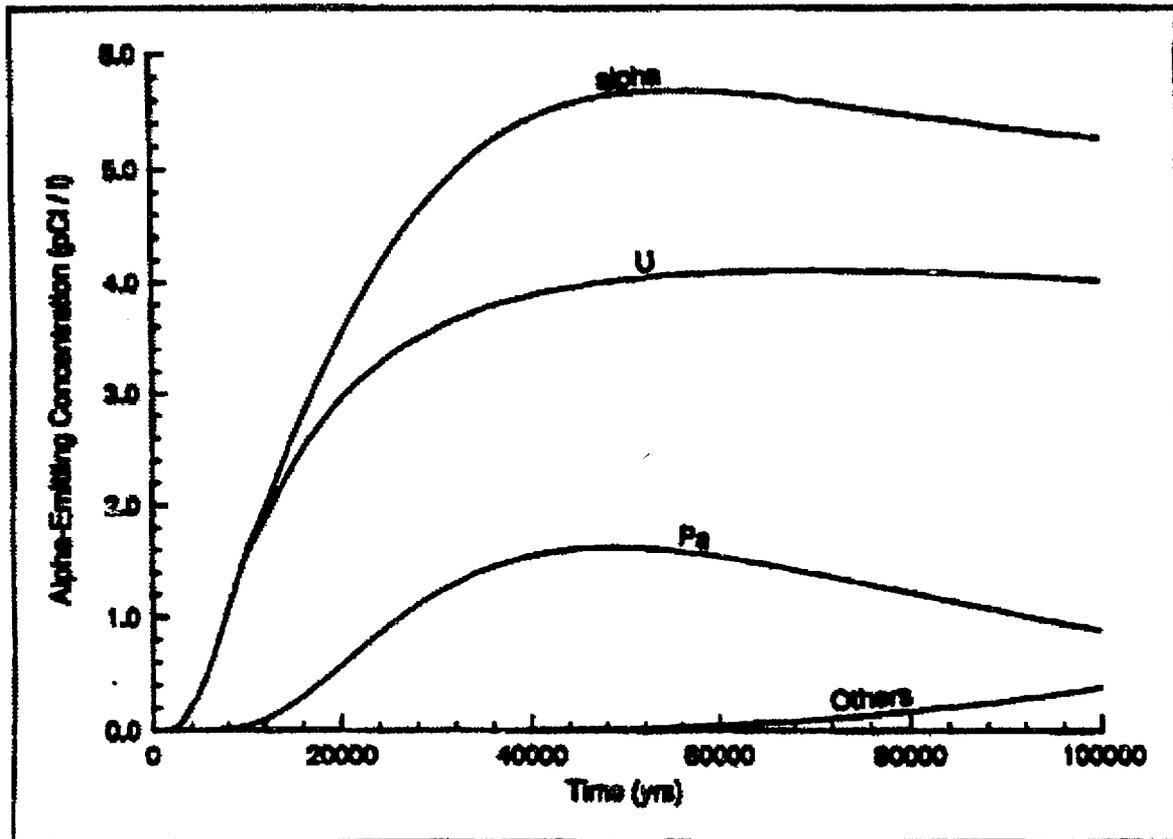


Table 4-8. Major Contributors at 10,000 Years to the Alpha-Emitting Radionuclide Concentration at a Well 100 Meters Downgradient of the Disposal Facility for the Base Analysis Case.

| Radionuclide | Dose (mrem/year) | Concentration (pCi/l) |
|-------------------|------------------|------------------------|
| ²²⁶ Ra | 0.00 | 4. x 10 ⁻¹² |
| ²²⁸ Ra | 0.00 | 9. x 10 ⁻¹² |
| ²³¹ Pa | 0.42 | 0.053 |
| ²³² U | 0.01 | 0.013 |
| ²³⁵ U | 0.12 | 0.64 |
| ²³⁴ U | 0.08 | 0.47 |
| ²³³ U | 0.00 | 0.019 |
| ²³⁶ U | 0.00 | 0.014 |
| ²³⁸ U | 0.08 | 0.46 |
| others | <0.01 | <0.01 |
| total | 0.71 | 1.65 |

Table 4-9. Major Contributors at 10,000 Years to the All-Pathways Dose at a Well 100 Meters Downgradient of the Disposal Facility for the Base Analysis Case.

| Radionuclide | Dose (mrem/year) |
|-------------------|------------------|
| ⁹⁹ Tc | 4.86 |
| ⁷⁶ Se | 0.73 |
| ²³¹ Pa | 0.46 |
| ²³³ U | 0.14 |
| ²³⁴ U | 0.10 |
| ²³⁸ U | 0.09 |
| others | <0.03 |
| total | 6.4 |

Figure 4-18. All-Pathways Doses for the Base Analysis Case at a Well 100 Meters Downgradient.

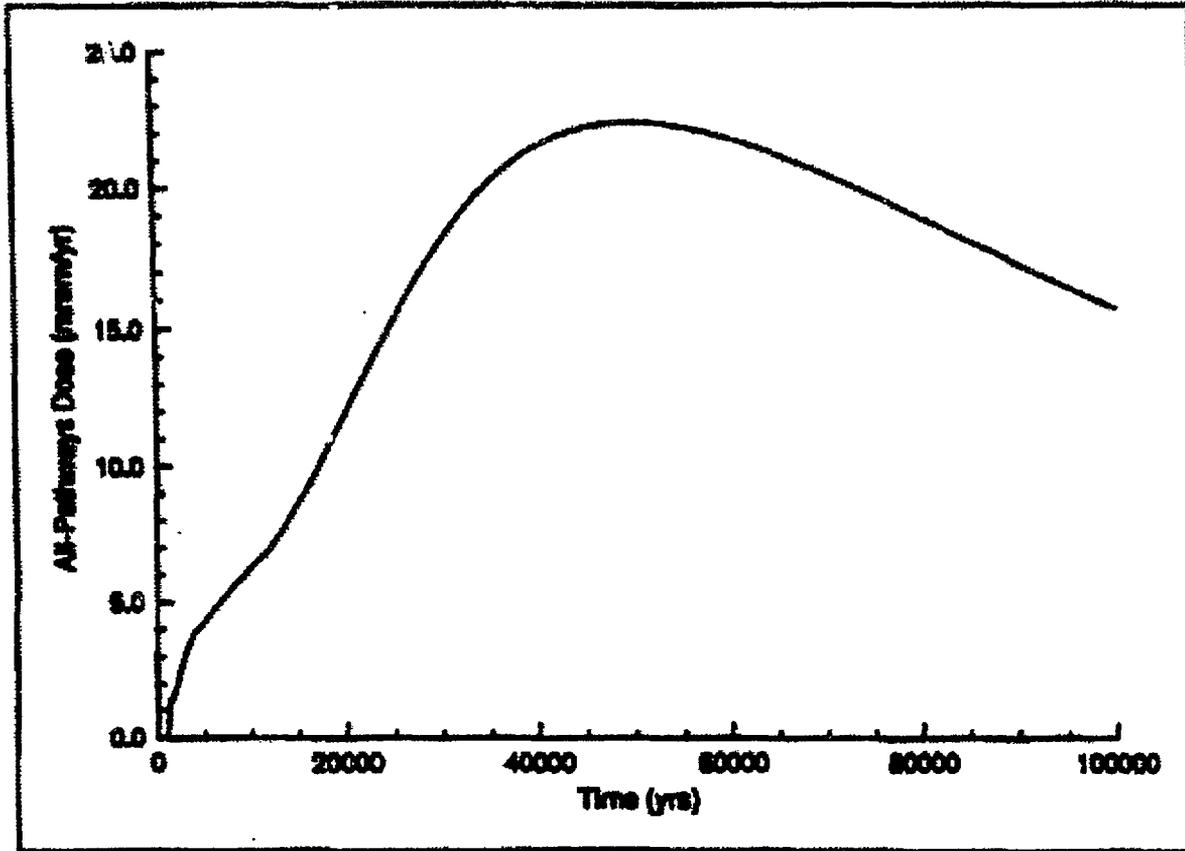


Table 4-10. Estimated Impact From Base Analysis Case from Groundwater Just Before Mixing with the Columbia River at 10,000 Years.

| Type of Impact | Value | Performance Objective |
|---|---------------------|-----------------------|
| Dose from Beta/Photon Emitting Radionuclides (mrem in a year) | 0.069 | 1.0 |
| All-Pathways Dose (mrem in a year) | 0.22 | 25. |
| Concentration of Alpha-Emitting Radionuclides (pCi/l) | 0.058 | 15. |
| Radium Concentration (pCi/l) | 2×10^{-11} | 3. |
| Uranium Concentration (pCi/l) | 0.056 | --- |

Table 4-11. Estimated Maximum Impact From Base Analysis Case Using the Groundwater Scenario.

| Impact | <10 ³ years ^(a) | | < 10 ⁶ years ^(b) | |
|--|---------------------------------------|-------------------------------|--|-----------------------------------|
| | Value | Time | Value | Time |
| Maximum Drinking Water Dose from Beta/photon Emitting Nuclides at a Nearby Well (100 meters downgradient from the disposal facility) | 2.7 mrem/y | 71 x 10 ³ years | 14. ^(c) mrem/y | 65 x 10 ⁶ years |
| Maximum All-Pathways Dose at a Nearby Well | 23. mrem/y | 50 x 10 ³ years | 23. mrem/y | 50 x 10 ³ years |
| Maximum Concentration of Alpha-Emitting Radionuclides at a Nearby Well | 5.7 pCi/l | 55 x 10 ³ years | 18. ^(d) pCi/l | 51 x 10 ⁶ years |
| Maximum Concentration of Radium Isotopes at a Nearby Well | 0.075 pCi/l | @10 ⁵ years | 2.2 pCi/l | 10 x 10 ⁶ years |
| Maximum Concentration of Uranium Isotopes at a Nearby Well | 4.1 pCi/l | 71 x10 ³ years | 5.6 pCi/l | 400 x 10 ³ years |
| Maximum Drinking Water Dose from Beta/photon Emitting Nuclides at the Columbia River | 0.10 mrem/y | 71 x 10 ³ years | 0.49 mrem/y | 65 x 10 ⁶ years |
| Maximum All-Pathways Dose at the Columbia River | 0.79 mrem/y | 50 x 10 ³ years | 0.79 mrem/y | 50 x10 ³ years |
| Maximum Concentration of Alpha-Emitting Radionuclides at the Columbia River | 0.20 pCi/l | 55 x 10 ³ years | 0.65 pCi/l | 51 x 10 ⁶ years |
| Maximum Concentration of Radium Isotopes at the Columbia River | 0.003 pCi/l | @10 ⁵ years | 0.08 pCi/l | 11 x10 ⁶ years |
| Maximum Concentration of Uranium Isotopes at the Columbia River | 0.14 pCi/l | 71 x 10 ³ years | 0.20 pCi/l | 400 x10 ³ years |

Detailed computer simulations were performed out to 100,000 years.

- * Values between 100,000 years and 100,000,000 years were inferred by using the $K_d=0$ results and adjusting the time by $(1 + 6.6 * K_d)$.

- * The drinking water dose from beta/photon emitters at a well 100 meters downgradient is estimated to exceed 4 mrem/year at about 750,000 years.
- * The alpha-emitting radionuclide concentration at a well 100 meters downgradient is estimated to exceed 15 pCi/l at 2.5 million years.

4.4 RESULTS OF GROUNDWATER SCENARIOS - BASE SENSITIVITY CASES

4.4.1 Overview.

Beside the base analysis case, sensitivity cases were built around two other cases. The first case involved using the full facility model of Concept 2. The second involved using the Unit Cell Model for vadose zone transport and the geometry of Concept 1 for aquifer transport. These additional cases were chosen to highlight the differences between Concept 1 and Concept 2 and to reduce computer resource requirements, respectively.

This section provides the results from these two base sensitivity case runs.

4.4.2 Concept 2.

4.4.2.1 Overview. Because Concept 2 forms the basis for many sensitivity runs, the estimated impacts are described here. The data and models used for this case (known as the Concept 2 base sensitivity case) are the same as for the base analysis case except that the Concept 2 design is used. The reasons for the differences between these results and those for the base analysis case (Concept 1) are explained in Section 4.6.2.4.

4.4.2.2 Vadose Zone Transport Simulation of the Concept 2 Main Analysis Case. Figure 4-19 displays the normalized flux to the aquifer for the three fastest groups ($K_d = 0, 0.1, \text{ and } 0.6 \text{ ml/g}$). Table 4-12 presents the relevant parameters for each of the K_d groups. Since the mean horizontal path from the side walls to the waste is much shorter for the Concept 2 design (about 8 meters) than for the Concept 1 design (about 70 meters), the moisture content in the disposal facility and below the disposal facility is higher for the Concept 2 design than for the base analysis case. Because of this higher moisture content, contaminants reach the aquifer more quickly using the Concept 2 facility design.

4.4.2.3 Integration of Vadose Zone and Other Data. Table 4-13 provides the estimated impacts at a well 100 meters downgradient at 10,000 years using Concept 2. Table 4-14 provides the estimated maximum impacts at the same well. The estimated impacts at the Columbia River are the same as for Concept 1 (Tables 4-10 and 4-11).

Figure 4-19. Normalized Contaminant Flux to the Unconfined Aquifer for $K_d = 0., 0.1, \text{ and } 0.6 \text{ ml/g}$ for Concept 2 (Full Facility Model).

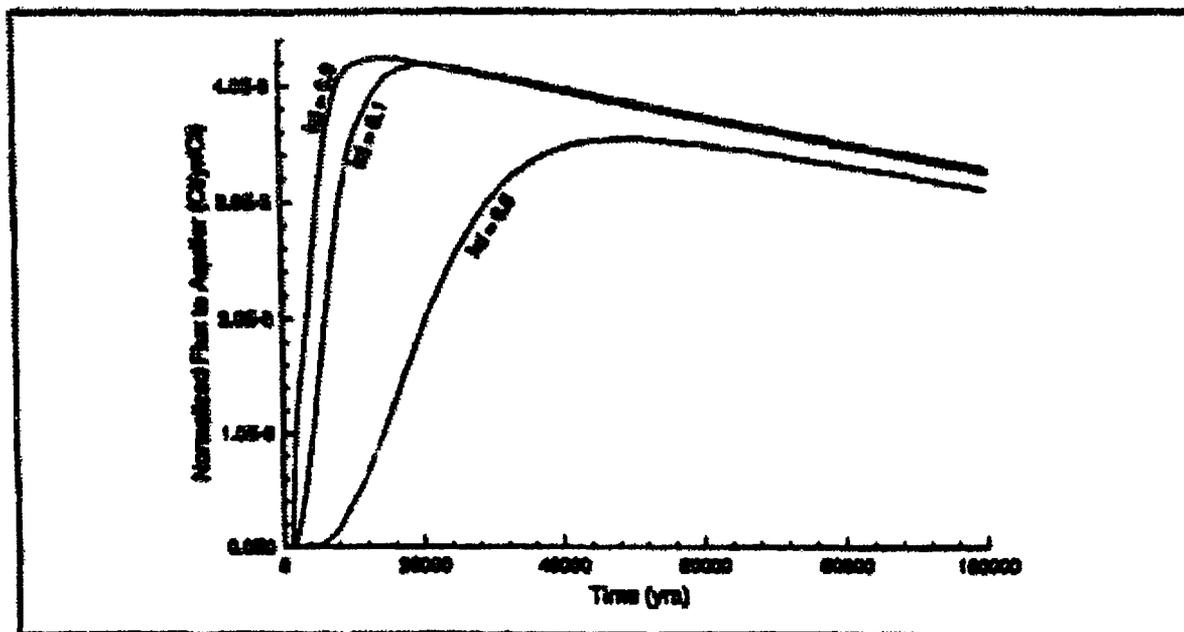


Table 4-12. Major Parameters Describing the Normalized Contaminant Flux to the Aquifer for Concept 2. (Full Facility Model).

| K_d (ml/g) | Value at 10K Years (Ci/y/Ci) | Peak Value in First 100K Years ⁽¹⁾ (Ci/y/Ci) | Time of True Peak Value (y) | Time of 0.5*True Peak Value ⁽²⁾ (y) | Time of 10^{-6} *True Peak Value ⁽²⁾ (y) |
|-----------------|------------------------------------|---|--------------------------------------|--|---|
| 0. | 4.22 e-6 | 4.25 e-6 | 13,000 | 2,600 | 500 |
| 0.1 | 3.69 e-6 | 4.19 e-6 | 21,000 | 6,600 | 900 |
| 0.6 | 0.53 e-6 | 3.10 e-6 | >100,000 | 22,000 | 2,000 |
| 3.0 | 4.6 e-11 | 2.80 e-6 | >100,000 | >100,000 | 8,000 |
| 15. | 5.6 e-22 | 2.1 e-8 | >100,000 | >100,000 | 38,000 |
| 40 | 6.9 e-23 | 3.2 e-12 | >100,000 | >100,000 | >100,000 |
| 100. | 2.6 e-24 | 9.6 e-20 | >100,000 | >100,000 | >100,000 |

¹ The value given is for the peak value in the first 100,000 years.

² Unless an actual peak was obtained in the first 100,000 years, the true peak value was taken as 4×10^{-6} Ci/y/Ci.

Table 4-13. Estimated Impact Using Concept 2 Geometry at a Well 100 Meters Downgradient from the Disposal Facility at 10,000 Years. (Full Facility Model)

| Type of Impact | Value | |
|---|-----------------------|--------|
| Dose from Beta/Photon Emitting Radionuclides | 1.11 | mrem/y |
| All-Pathways Dose | 3.3 | mrem/y |
| Concentration of Alpha-Emitting Radionuclides | 0.27 | pCi/l |
| Radium Concentration | $<1. \times 10^{-10}$ | pCi/l |
| Uranium Concentration | 0.27 | pCi/l |

Table 4-14. Estimated Maximum Impact Using Concept 2 Geometry at 100 Meters Downgradient from the Disposal Facility. (Full Facility Model)

| Impact | <10 ⁵ years ^(a) | | < 10 ⁶ years ^(b) | |
|---|---------------------------------------|----------------------------|--|----------------------------|
| | Value | Time | Value | Time |
| Maximum Drinking Water Dose from Beta/Photon Emitting Nuclides at a Nearby Well | 1.12 mrem/y | 15 x 10 ³ years | 5.0. ^(c) mrem/y | 13 x 10 ⁶ years |
| Maximum All-Pathways Dose at a Nearby Well | 7.9 mrem/y | 72 x 10 ³ years | 7.9 mrem/y | 72 x 10 ³ years |
| Maximum Concentration of Alpha-Emitting Radionuclides at a Nearby Well | 2.6 pCi/l | 62 x 10 ³ years | 6.9 pCi/l | 3 x 10 ⁶ years |
| Maximum Concentration of Radium Isotopes at a Nearby Well | 0.002 pCi/l | @10 ⁵ years | 0.78 pCi/l | 3 x 10 ⁶ years |
| Maximum Concentration of Uranium Isotopes at a Nearby Well | 2.1 pCi/l | 47 x 10 ³ years | 2.1 pCi/l | 47 x 10 ³ years |

^a Detailed computer simulations were performed out to 100,000 years.

^b Values between 100,000 years and 100,000,000 years were inferred by using the $K_d=0$ results and adjusting the time by $(1. + 6.6 \times K_d)$.

^c The drinking water dose from beta/photon emitters at a well 100 meters downgradient is estimated to exceed 4 mrem/year at about 3 million years.

4.4.3 Unit Cell Model.

4.4.3.1 Overview. Because the Unit Cell Model is used in many of the sensitivity runs, the calculated impacts are described here. The Unit Cell Model takes a canister-wide slice of the Concept 1 facility concept, but without the sand-gravel capillary barrier. The case presented here (known as the Unit Cell Model base sensitivity case) retains the values used in the base analysis case. The reasons for the differences between these results and those for the base analysis case (Concept 1) is presented in Section 4.6.3.2.

4.4.3.2 Vadose Zone Transport Simulation of the Unit Cell Model Main Analysis Case. Table 4-15 summarizes the calculated normalized fluxes to the unconfined aquifer. Figure 4-20 displays those fluxes as a function of time. Figure 4-21 presents the normalized fluxes from the disposal facility to the vadose zone. Major features include a constant flux (due to the constant release rate) and a faster rise (due to the absence of a hydraulic diverter) than for the full facility models. A more complete description is given in Kline (1996).

As mentioned in Section 4.3.2.2, the $K_0=0$ case shows a spike at early times due to changing the infiltration rate at 1,000 years. Thus in the results discussed below, the $K_0=0.1$ ml/g (which do not show the spike) are used.

Table 4-15. Major Parameters Describing the Normalized Contaminant Flux to the Aquifer Using the Unit Cell Model.

| K_0 (ml/g) | Value at 10K Years (Ci/y/Ci) | Peak Value ^(a) (Ci/y/Ci) | Time of Peak Value (y) | Time of 0.5*True Peak Value ^(b) (y) | Time of 10^{-6} *True Peak Value ^(b) (y) |
|-----------------|------------------------------------|---|---------------------------------|--|---|
| 0. | 4.37 e-6 | 6.9 e-6 ^(c) | 2,150 | 1,200 | 170 |
| 0.1 | 4.37 e-6 | 4.42 e-6 | 17,000 | 3,000 | 350 |
| 0.5 | 2.65 e-6 | 4.42 e-6 | 39,000 | 9,100 | 1,500 |
| 3. | 2.01 e-9 | 4.35 e-6 | >100,000 | 39,000 | 6,200 |
| 6. | 1.6 e-12 | 3.26 e-6 | >100,000 | 76,000 | 11,000 |
| 15. | 1.4 e-18 | 3.27 e-7 | >100,000 | >100,000 | >100,000 |
| 40. | 0. | 2.9 e-10 | >100,000 | >100,000 | >100,000 |
| 100. | 0. | 2.4 e-15 | >100,000 | >100,000 | >100,000 |

^a The value given is for the peak value in the first 100,000 years.

^b Unless a peak value was obtained in the first 100,000 years, the true peak value was taken as 4×10^{-6} Ci/y/Ci.

^c Value results from changing properties at 2,000 years.

Figure 4-20. Normalized Contaminant Flux to the Unconfined Aquifer for $K_d = 0., 0.1, 0.6,$ and $3. \text{ ml/g}$ using the Unit Cell Model.

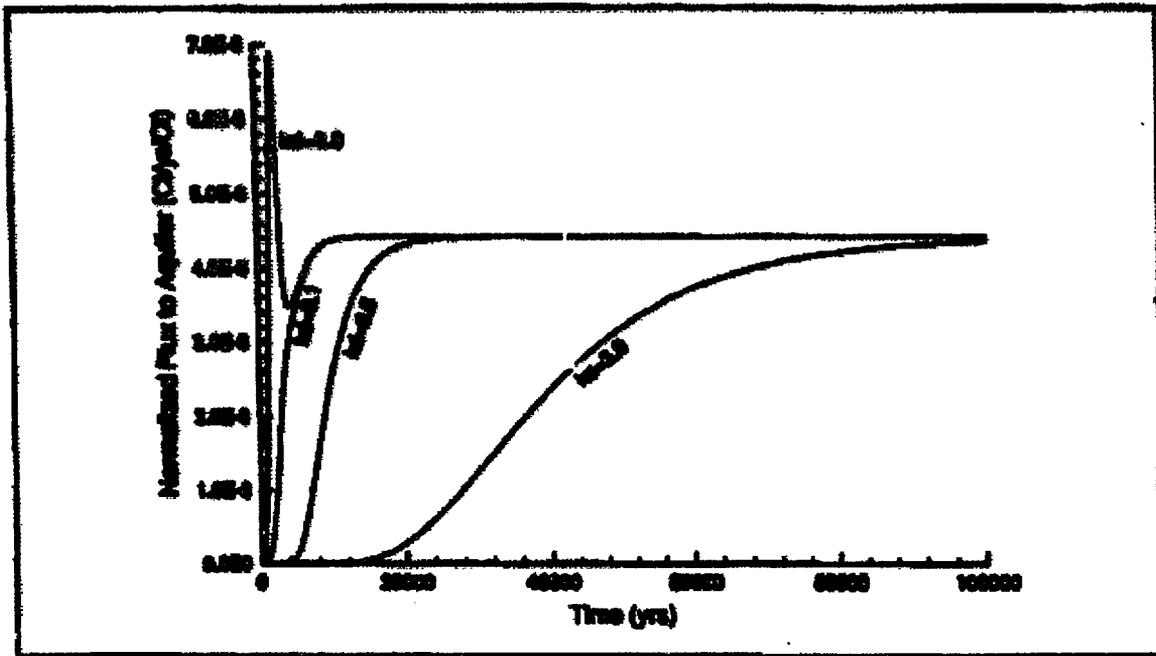
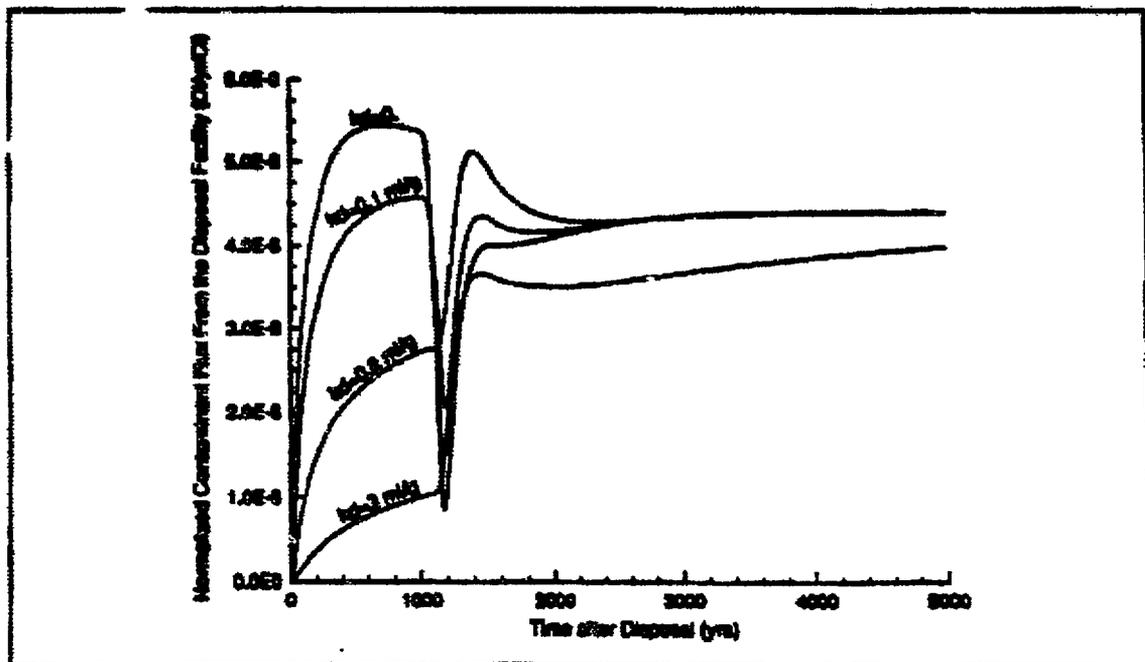


Figure 4-21. Normalized Contaminant Flux from the Disposal Facility to the Vadose Zone using the Unit Cell Model



4.4.3.3 Integration of Vadose Zone Calculations and Other Data. Table 4-16 provides the estimated impacts at a well 100 meters downgradient at 10,000 years using the Unit Cell Model for the vadose zone calculations and the Concept 1 geometry for the aquifer calculations. Table 4-17 provides the estimated maximum impacts at the same well.

Table 4-16. Estimated Impact at 10,000 Years from Groundwater at a Well 100 Meters Downgradient Using the Unit Cell Model and Concept 1 Geometry. The Unit Cell Model does not have a hydraulic diverter.

| Type of Impact | Value |
|---|-------------------------|
| Dose from Beta/Photon Emitting Radionuclides | 4.4 mrem/y |
| All-Pathways Dose | 13. mrem/y |
| Concentration of Alpha-Emitting Radionuclides | 5.9 pCi/l |
| Radium Concentration | <10 ⁻⁶ pCi/l |
| Uranium Concentration | 5.9 pCi/l |

Table 4-17. Estimated Maximum Impact from Groundwater at a Well 100 Meters Downgradient Using the Unit Cell Model for Concept 1 Design. The Unit Cell Model does not have a hydraulic diverter.

| Impact | <10 ⁵ years ^(a) | |
|---|---------------------------------------|----------------------------|
| | Value | Time |
| Maximum Drinking Water Dose from Beta/photon Emitting Nuclides at a Nearby Well | 4.5 ^(b) mrem/y | 15 x 10 ³ years |
| Maximum All-Pathways Dose at a Nearby Well | 63. ^(c) mrem/y | 50 x 10 ³ years |
| Maximum Concentration of Alpha-Emitting Radionuclides at a Nearby Well | 15.0 ^(d) pCi/l | 49 x 10 ³ years |
| Maximum Concentration of Radium Isotopes at a Nearby Well | 0.12 pCi/l | @10 ³ years |
| Maximum Concentration of Uranium Isotopes at a Nearby Well | 9.5 pCi/l | 25 x10 ³ years |

- ^a Detailed computer simulations were performed out to 100,000 years.
- ^b The beta/photon drinking water dose is estimated to exceed 4 mrem in a year at 7,200 years.
- ^c The all-pathways dose is estimated to exceed 25 mrem/year at 22,000 years.
- ^d The concentration of alpha-emitting radionuclides is estimated to exceed 15 mrem in a year at 46,000 years.

4.5 RESULTS OF GROUNDWATER SCENARIOS - WASTE FORM SENSITIVITY CASES

4.5.1 Overview

The performance of the waste form is one of the most important inputs to this performance assessment, yet it is one of the least well-known parameters. For the base analysis case, the initial release of contaminants is assumed to happen at the same rate as the dissolution of the waste form for the non-technetium inventory as specified in the RFP for low-level tank waste immobilization (DOE-RL 1996). Subsequent release rates are established by the available surface area. The RFP specified an initial rate of 4 parts per million per year. This section discusses the sensitivity of using different interpretations of the RFP as well as using more mechanistic approaches to determine glass performance.

4.5.2 Contaminant Release Rates from Waste Form

Although the contaminant release rate from the RFP forms the basis of the base analysis case, sensitivity runs were performed using a mechanistic model for glass corrosion and contaminant release. The AREST-CT computer code (Section 3.5.2.2 and Appendix C) simulated the dissolution of LD6-5412 glass, the release of contaminants from the glass, and the transport of those contaminants through the bottom of the disposal vaults.

Because of financial restraints and current limitations of the model, certain effects were not modelled in this analysis but will be modelled in the final performance. For example, water consumed during glass dissolution is not removed from the system in this analysis. The surface area of the glass is assumed to decrease as the glass dissolves. Processes which could increase the surface area (such as cracking subsequent to cooling) are not considered.

The simulations performed for this analysis show that the ion exchange of sodium for hydrogen in the glass waste form

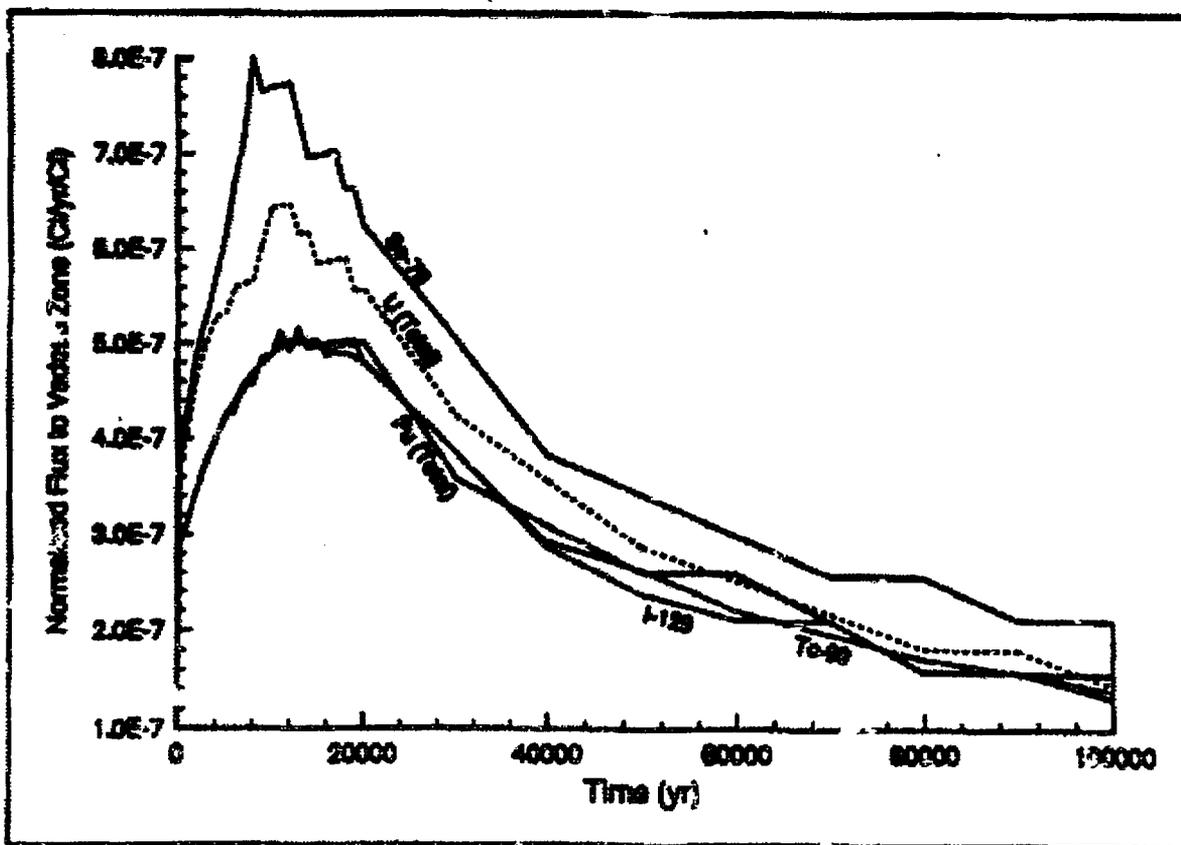


is very important at the low temperatures expected in the disposal vault. Because of this ion exchange reaction, the computed pH in the glass/water interface rises to over 12. Since the glass LD6-5412 is much less stable at these high pH levels, the dissolution rate is significant (see Figure 4-22.). Using water-saturated, low-temperature, batch tests with LD6-5412 glass, the sodium ion-exchange reaction was identified only as a minor secondary reaction that contributed to an enhanced rate of sodium release as compared with other major glass components, including boron and silicon. However, in an unsaturated environment where little water is present, the importance of this reaction mechanism was first revealed through computer

Table 4-18. Maximum Release Rate through Vault Floor as Calculated by ARREST-CG.

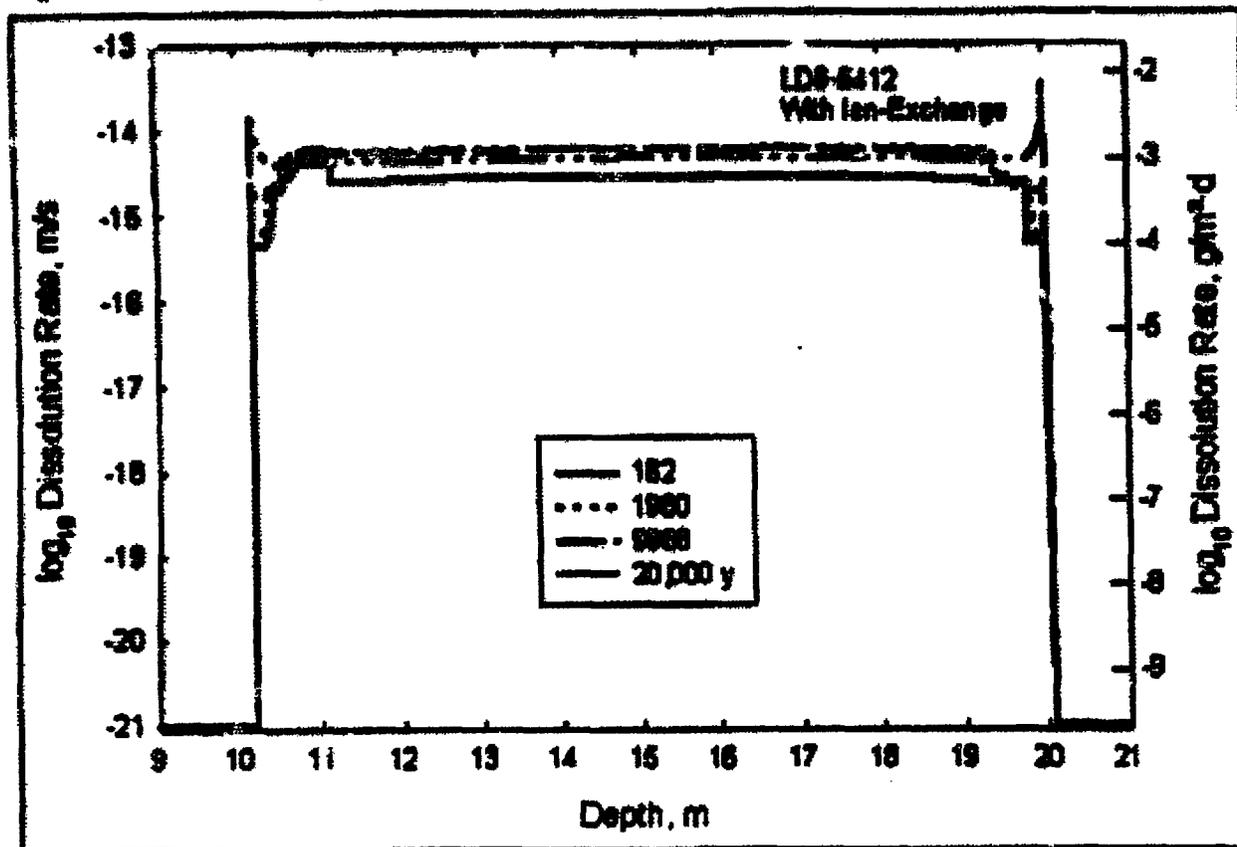
| Element | Release Rate (ppm/y) |
|--------------------------------------|----------------------|
| Request for Proposal All elements | 4.4 |
| Selenium | 0.78 |
| Technetium: full simulation | 0.50 |
| no sodium ion exchange | 0.02 |
| high pore velocity | 1.4 |
| Iodine | 0.50 |
| Uranium | 0.64 |
| Plutonium | 0.50 |

Figure 4-23. Estimated Release Rates through the Vault Floor.



simulations that properly couple chemical reactions and transport.

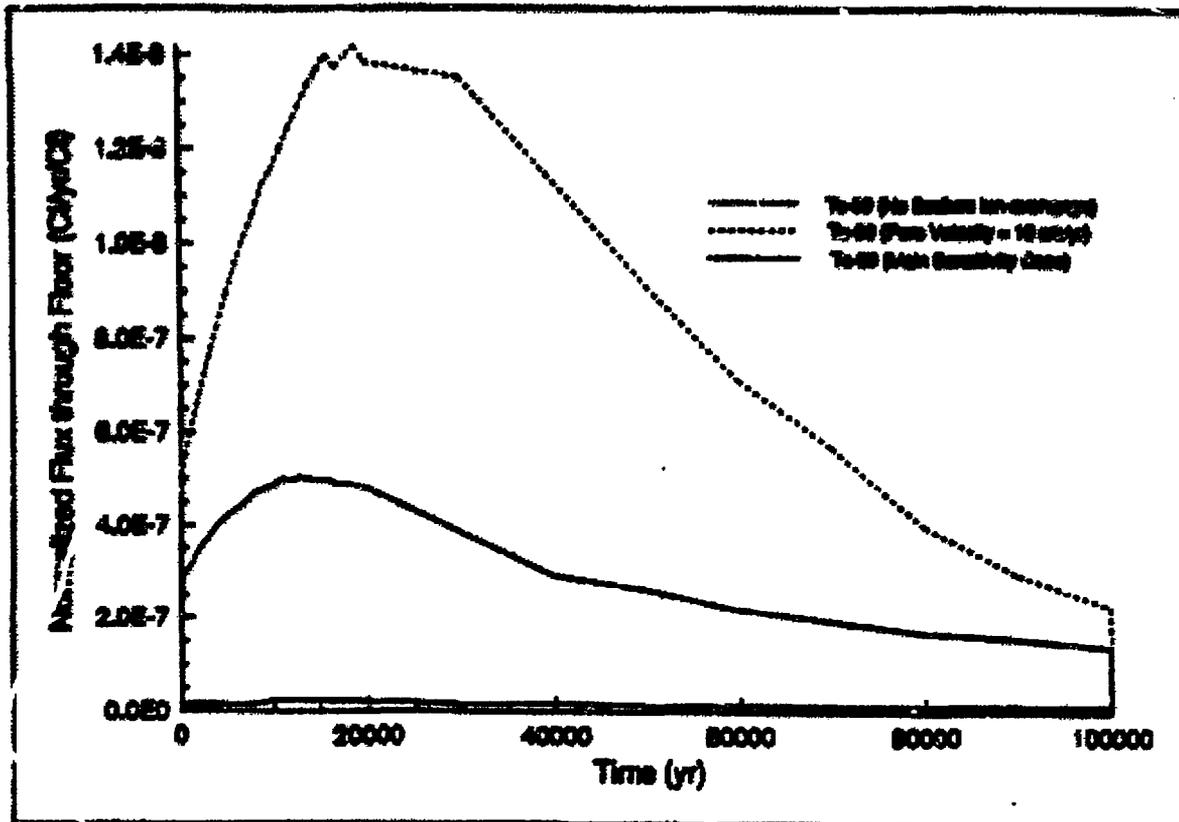
Figure 4-23. Glass Dissolution Rate as a Function of Time and Space in the Disposal Vault.



The ARIST-CT computer code was also used to transport the contaminants through the vault floor once they were released from the glass. The maximum release rate through the vault floor is shown in Table 4-18. Figure 4-23 displays the time dependence of the release rate through the floor. These calculations assume that the concrete floor has degraded and has the hydraulic parameters of gravel. Note that all of the calculated release rates are smaller than those specified in the RFP (DOE-RL 1996).

To determine the actual importance of the ion exchange reaction, the Tc release rate was recalculated with the ion exchange reaction absent from the simulation. Without the sodium ion exchange reaction, the pH peaks at only about 10.5. Such a lower pH reduces the glass corrosion rate by about a factor of 30, resulting in a glass corrosion rate that is three or four orders of magnitude lower than the forward rate of reaction for LD6-5412. The maximum release rate is shown in Table 4-18 and the time dependence of the release rate through the floor is displayed in Figure 4-24.

Figure 4-24. Normalized Tc Fluxes Through the Vault Floor for Various Assumptions. The Unit Cell Model Base Sensitivity Case Assumed the Sodium Ion-Exchange Reaction Occurred and the Pore Velocity was 1.0 cm/y.



Finally, the ARES-CT calculation simulated a case with more water available in the vault system, resulting in an pore velocity of 10.0 cm/y rather than 1.0 cm/y. The technetium release rate increased by a factor of 3 as seen in Table 4-18 and Figure 4-24.

4.5.3 Impact on Exposure Calculations

4.5.3.1 Overview. This section describes the sensitivity of the estimated impacts to various assumptions made concerning the waste form. Included in the discussion are the effects caused by the treatment of the time dependence of the release rate, to the special treatment of technetium in the RFP, and to the release rates calculated by the mechanistic model.

4.5.3.2 Constant Mass Release. The base analysis case assumes that the rate of waste form dissolution (and hence of contaminant release) is proportional to the amount of surface area of the waste form. Thus the base analysis case has a declining amount

of contaminants being released as a function of time. A sensitivity case was run to determine the effect of constant contaminant release at a rate of 4.4×10^{-4} g/m. This is equivalent to assuming that the waste form has the shape of a thin plate. Figure 4-25 displays the normalized flux to the aquifer for the $K_1=0$ group for the Concept 2 base sensitivity case and for the case of constant contaminant release using Concept 2. Table 4-19 presents the parameters for the curves of the various K_1 groups. The results for the two cases are very similar for the first 10,000 years. They diverge thereafter as the results for the constant release case go to the expected value of 4.4×10^{-4} , while the results of the case with release proportional to surface area decline. The results for the constant release case go to the expected value, thus supporting the values calculated using the time-dependent release rate.

Because the normalized fluxes are so close for the constant release and for the time-varying release, the estimated impacts differ very little except at long times (>50,000 years).

Figure 4-25. Normalized Flux to the Aquifer for $K_1 = 0$ for Concept 2 Simulations Using Constant Contaminant Release and Using Contaminant Release Proportional to Surface Area (Full Facility Model).

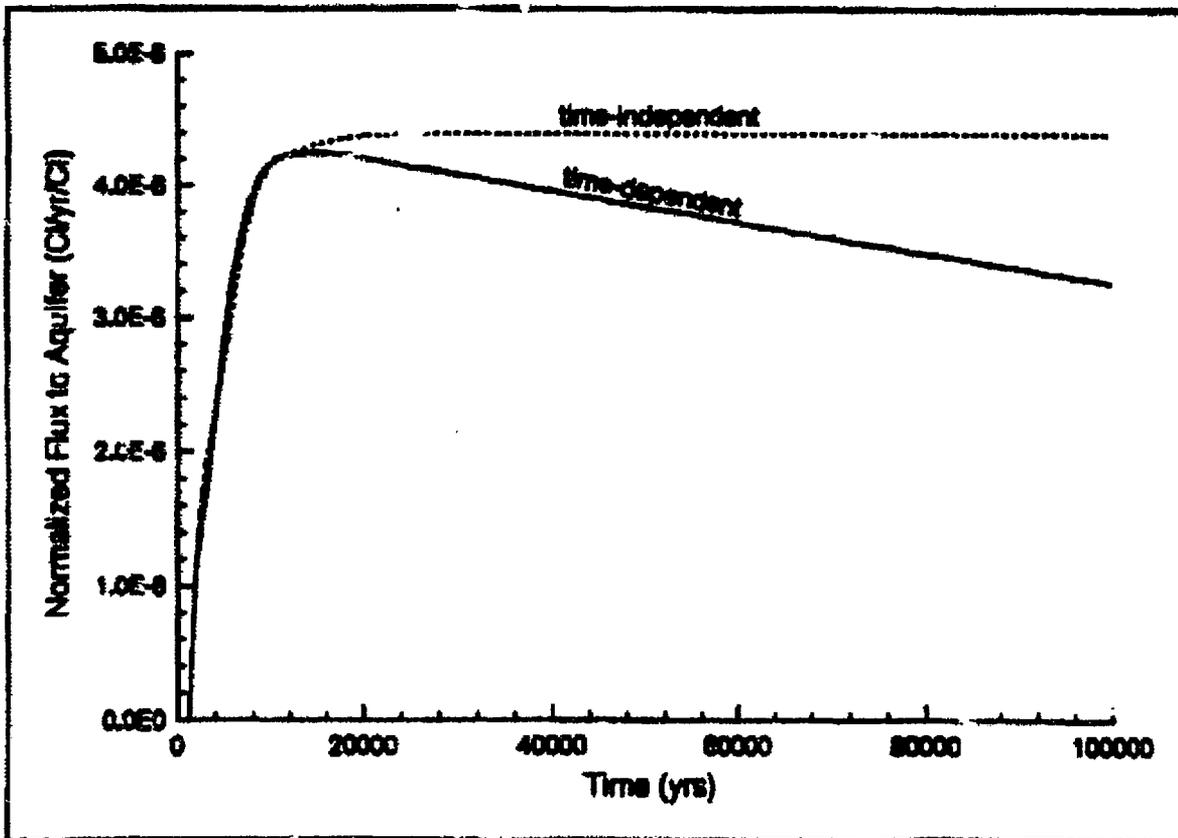


Table 4-19. Major Parameters Describing the Normalized Contaminant Flux to the Aquifer for Concept 2 Using Constant Contaminant Release (Full Facility Model).

| K_d (ml/g) | Value at 10K Years (1/Y) | Peak Value ^(a) (1/Y) | Time of Peak Value (Y) | Time of 0.5*Peak Value ^(a) (Y) | Time of 10 ⁻⁶ *Peak Value ^(a) (Y) |
|-----------------|--------------------------------|---------------------------------------|---------------------------------|--|--|
| 0. | 4.21x10 ⁻⁶ | 4.39x10 ⁻⁶ | 35,600 | 3,700 | 650 |
| 0.1 | 3.46x10 ⁻⁶ | 4.35x10 ⁻⁶ | 50,000 | 6,900 | 1,150 |
| 0.6 | 0.42x10 ⁻⁶ | 3.95x10 ⁻⁶ | >100,000 | 22,000 ^(b) | 2,100 ^(b) |

The value given is for the peak value in the first 100,000 years. It is expected that true peak value is about 4.x10⁻⁶.

^b Time of K = true peak value is about that listed.

4.5.3.3 Reduced Release Rate for Technetium. The RPP for tank waste immobilization (DOE-RL 1996) specified a lower release rate for technetium (by a factor of 5) than for the other radionuclides. This lower rate could be achieved by reducing the amount of technetium in the waste (and returning technetium to DOE) or by having a better performing waste form. For this section, it is assumed that the waste form has a release rate that is five times better than the base analysis case. The results are similar to the base analysis case and to the Concept 2 base sensitivity case for the first 100,000 years except the normalized flux to the aquifer is a factor of five lower.

Table 4-20 provides the effects of better performing waste forms, assuming that only technetium is affected and assuming that all $K_d=0$ radionuclides are affected. The doses do not decrease by a factor of five from the base analysis case because other radionuclides become important. For example, if the improved factor of five performance only affects technetium, then ⁹⁰Se is calculated to be the most important radionuclide. The beta/photon drinking water dose at 10,000 years being 50 percent from ⁹⁰Se and 47 percent from ⁹⁹Tc. Similarly when the performance is improved for all the $K_d=0$ radionuclides, then the impact of the $K_d=0.6$ ml/g radioisotopes (mainly uranium and its daughters) is enough to provide one-third of the dose.

4.5.3.4 Mechanistic Approaches to Waste Form Performance. Silicate glass is a leading candidate for the waste form. As described in Section 4.5.2, the AREST-CT code was used to estimate the release of contaminants from the waste form and the transport of those contaminants through the vault floor. This section presents the results of the Unit Cell Model following those contaminants through the vadose zone and the unconfined aquifer to the well. Table 4-21 displays the estimated impacts

Table 4-20. Sensitivity of Impacts Caused by Different Interpretations of Waste Immobilization Request for Proposal.

| Case | Time | Beta/Photon Drinking Water Dose (mrem/y) | All-Pathways Dose (mrem/y) |
|--|--------|--|----------------------------|
| Base Analysis Case | 10K y | 2.0 | 6.4 |
| | MAX | 2.7 @ 71K | 23. @ 50K |
| Tc has 5 times smaller release rate | 10K y | 0.87 | 2.8 |
| | MAX | 1.20 @ 100K | 18. @ 49K |
| All $K_d=0$ radionuclides have 5 times smaller release rates | 10K y | 0.57 | 2.3 |
| | MAX | 0.99 @ 100K | 17. @ 49K |
| All radionuclides have 5 times smaller release rates | 10K y | 0.40 | 1.3 |
| | MAX | 0.54 @ 71K | 4.6 @ 50K |
| Concept 2 base sensitivity case | 10K y | 1.11 | 3.3 |
| | MAX | 1.12 @ 15K | 7.9 @ 72K |
| Tc has 5 times smaller release rate | 10K y | 0.42 | 1.05 |
| | MAX | 1.34 @ 99K | 8.9 @ 99K |
| All $K_d = 0$ radionuclides have 5 times smaller release rates | 10K y | 0.24 | 0.72 |
| | MAX | 1.43 @ 99K | 9.0 @ 99K |
| All radionuclides have 5 times smaller release rates | 10K y | 0.22 | 0.66 |
| | MAX | 0.23 @ 15K | 1.6 @ 72K |
| Release rate constant at 4.4 ppm/y | 10 K y | 1.11 | 3.3 |
| | MAX | 1.15 @ 25K | 8.4 @ 74K |

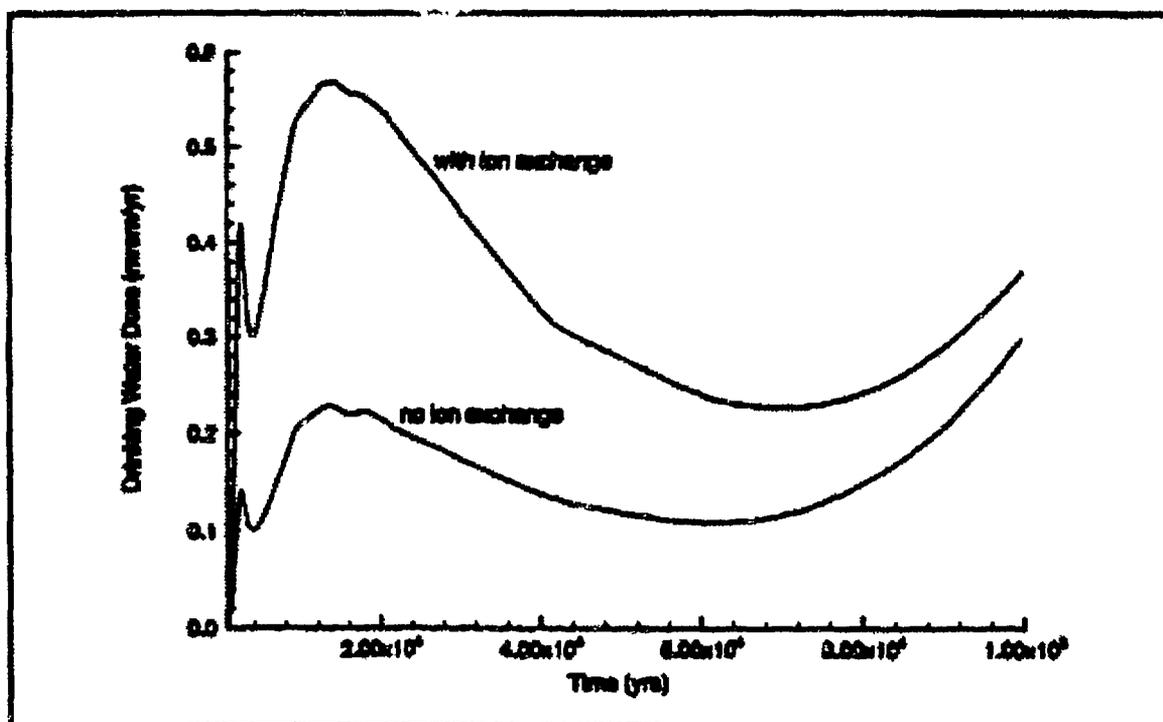
using the calculated glass release rates as a source term. Figure 4-26 shows the estimated beta/photon drinking water dose when sodium ion exchange is included and excluded.

Because the release rate for each element is reduced by about a factor of 8 (Table 4-18), the impacts are reduced by about the same factor. ^{99}Se is a bit more important (contributing -30 percent to the beta/photon drinking water dose in this case as contrasted to -20 percent for the base analysis case) when a mechanistic model is used than when all elements have the same release rate, because it has a slightly higher calculated release rate than technetium.

Table 4-21. Estimated Impacts When Using Calculated Glass Release Rates at a Well 100 Meters Downgradient from a Concept 1 Facility (Unit Cell Model).

| Case | Beta/Photon Drinking Water Dose (mrem/y) | Alpha-Emitting Radionuclide Concentration (pCi/l) | All-Pathways Dose (mrem/y) |
|---|--|---|----------------------------|
| Base Sensitivity Case | 4.4 | 5.9 | 13.4 |
| Glass Mechanistic Model (with sodium ion exchange) | 0.53 | 0.63 | 1.5 |
| Glass Mechanistic Model without sodium ion exchange - Tc only | 0.20 | 0.63 | 0.5 |
| Glass Mechanistic Model high pore velocity - Tc only | 0.97 | 0.63 | 3.0 |

Figure 4-26. Beta/Photon Drinking Water Dose When Using Glass Release as a Source Term for a Well 100 Meters Downgradient of a Concept 1 Facility (Unit Cell Model).



As noted in Section 4.5.2, sodium ion exchange has an important effect, significantly increasing the pH level and hence the glass corrosion rate. If the effect of sodium ion exchange is excluded for the technetium calculations, then the effects are even less. The pH of the system stays in the 8 and 9 region, resulting in much slower glass dissolution. However, the peak release rate is achieved sooner since without the sodium exchange reaction, less time is needed to reach the peak pH (and hence peak release rate) level.

For the calculations shown in Table 4-21 and Figure 4-26, only the release rate for technetium is reduced. Thus the estimated impacts are the result of the elements other than technetium (primarily selenium and uranium). If all elements are affected in a manner similar to technetium, then the effects would drop by a factor of about 4⁰ from the base analysis case.

These sets of calculations involve contaminant transport as well as release. However, AREST-CT was only used to model the interior of the vault, so its model is incomplete. As a sensitivity case, the pore velocity was increased to 10.0 cm/y (from 1.0 cm/y). The resulting release rate through the floor increases by only a factor of only 2.7.

4.6 RESULTS OF GROUNDWATER SCENARIOS - DISPOSAL FACILITY SENSITIVITY CASES

4.6.1 Overview

At present no designs for the disposal facility have been developed. Concepts 1 and 2 are simply preconceptual ideas that reflect possible facility components, shapes, and sizes. For this performance assessment, the effect of vault layout and degradation, as well as other effects were investigated.

4.6.2 Vault Layout

4.6.2.1 Overview. Sections 4.6.2.2 through 4.6.2.4 report the results for assuming different layouts of the vaults. Included are increasing the number of rows of Concept 1, rotating Concept 1 by 90°, and by inserting soil between the vault rows (Concept 2).

4.6.2.2 Number of Vault Rows. The number of canisters that will be produced is uncertain because the vendors have to optimize a number of factors. The number of rows is not expected to be significantly less than the base analysis case, but could be more depending on the choice of sodium loading and waste loading in the glass. Doubling the number of rows results in reducing the aquifer mixing factor (the well/vadose-zone concentration ratio)

by 30% and increasing the area by 2. Thus the estimated dose and concentrations decrease by 65 percent.

4.6.2.3 Orientation. Because the shape of Concept 1 is nearly square (208 meters by 246 meters), rotating the facility 90° has little effect. The calculations show a 2 percent increase in the well/vadose-zone concentration ratio (and impacts). This is because the initial orientation of Concept 1 had the long side nearly perpendicular to the groundwater flow path. A larger effect would be seen if Concept 2 were rotated by 90°, because Concept 2 is less square in shape (246 meters by 315 meters).

However, as will be seen in Section 4.6.3.4, irrigation in other parts of the Hanford Central Plateau could change the direction slightly of groundwater flow. Thus, although the orientation of the vaults would affect the estimated doses, the exact effect is difficult to determine. The present orientation results in among the highest estimated impacts.

4.6.2.4. Concept 2. The major difference between the Concept 1 and Concept 2 facility design concepts is that in Concept 2 the vault rows are separated from each other by soil (Figures 2-20 and 2-21), while in Concept 1 the vault rows shared walls. This difference leads to two major effects and some minor ones. The major effects are in opposite directions, an increased release rate from the facility for Concept 2 and a decrease in groundwater concentration because the site area is larger. This section discusses these major effects caused by the differences in Concepts 1 and 2, the minor effects and the effects produced by the Concept 2 vault layout.

In both Concepts 1 and 2, the hydraulic barrier above the waste is predicted to divert most of the water around the disposal facility (Figures 4-6 through 4-9). The moisture content of the filler material is predicted to be the same for either Concept 1 or 2, but the two concepts differ in the magnitude of rain shadow beneath the disposal facility. Directly beneath the center of the facility, the moisture content increases from 0.035 cm³/cm³ in Concept 1 to 0.038 cm³/cm³ in Concept 2. At the edge of the facility, the increase is from 0.036 cm³/cm³ (Concept 1) to 0.041 cm³/cm³ (Concept 2). A similar increase is seen as one progresses down the vadose zone.

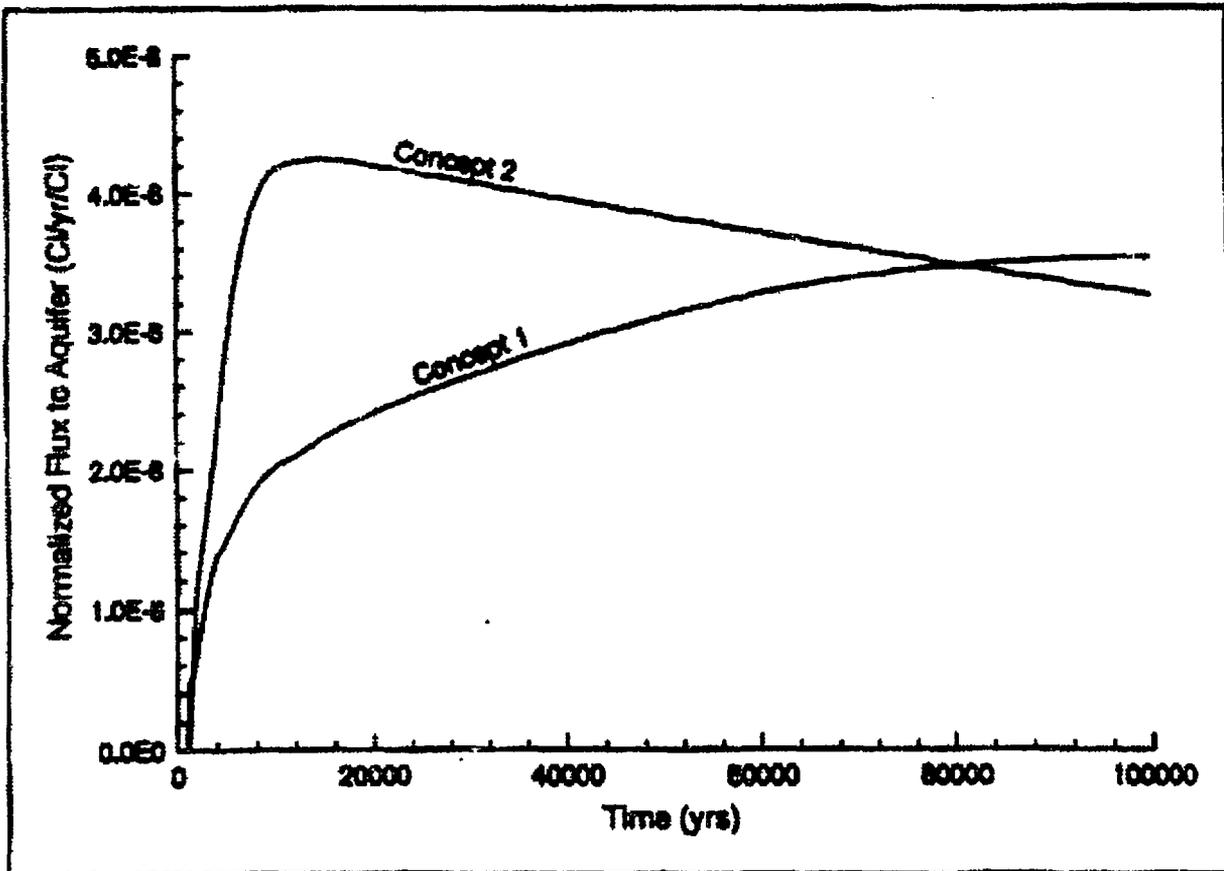
Figure 4-27 displays the normalized flux entering the aquifer for the unretarded group of chemicals ($K_d=0$) for Concepts 1 and 2. Although the normalized fluxes approach the same peak value (the rate at which contaminant is released from the waste form), the contaminants reach the aquifer much more quickly in Concept 2 (the flux reaches half its height in -3,600 years in Concept 2 versus -10,000 years in Concept 1).

However, the waste is more dispersed in Concept 2 than in Concept 1. Thus the flux entering the aquifer mixes with a larger volume of water. Modeling each row as a separate source, the aquifer mixing factor (or concentration ratio) is reduced to

0.00381 for Concept 2 (versus 0.00531 for Concept 1). This yields a higher mixing factor (0.00381 versus 0.00309) than would be indicated by just the increase in area, because the vadose zone fluxes are peaked over each row rather than uniform over the entire area of the disposal facility. Because of lateral spreading in the vadose zone, which is not taken into account using the Unit Cell Model, the actual aquifer mixing factor will be between 0.00381 and 0.00309.

Minor differences in effects caused by Concepts 1 and 2 relate to the effectiveness of the hydraulic barriers. The hydraulic barrier over Concept 1 is much longer and has a much shallower slope. The relative performance of such a shallower slope was not investigated separately in these analyses. Concept 1 also has a larger amount of water moving by the side walls. The effect of this on degradation of the barrier or side walls was also not investigated.

Figure 4-27. Normalized Flux to the Aquifer for $K_1 = 0$ Elements from Concepts 1 and Concept 2. The Effects of Increased Area and a Smaller Aquifer Mixing Factor, However, Result in a Smaller Dose at 10,000 Years from Concept 2. (Full Facility Models)



Finally, the release rate of the contaminants was assumed to be independent of the moisture, but the corrosion rate of glass (and presumably other waste forms) does depend on the amount of water present. Because the interior of the Concept 2 facility is expected to have somewhat more moisture, the contaminant release rate should change.

4.6.3 Facility Design Options

4.6.3.1 Overview. Because only a preconceptual idea exists for the facility design, relatively few sensitivity cases were run on vault components. The components examined were the sand-gravel capillary hydraulic barrier above the disposal vault, a similar barrier on the sides of the vault and the type of filler material between the canisters. The effect of other possible components is discussed in Section 4.6.4.

4.6.3.2 Hydraulic Diverter. Both the Concept 1 and 2 facilities have a sloping barrier above the disposal vaults and a barrier along the vault rows, the purpose of which is to divert moisture away from the waste form. This diverter, also known as a sand-gravel capillary barrier, works on the principle that the overlying sand is forced to become very nearly saturated before the water in the sand will drain into the gravel. Being near saturation (while not being at or above the air entry potential of the gravel), the relatively high unsaturated hydraulic conductivity of the sand layer when combined with its sloping configuration, offers the moisture an easier route downward by allowing it to move laterally until it comes to the edge of the capillary barrier and then downward through the vadose zone profile. The coarse gravel component of the barrier exhibits relatively large open pores which are not wet by the moisture until the overlying sand layer reaches the air entry potential of the gravel.

The Unit Cell Model calculations did not model this diverter, so a comparison of the base analysis case (Concept 1) and the Unit Cell Model base sensitivity case for the Unit Cell Model provides an indication of the usefulness of the barrier. The beta/photon drinking water dose for Concept 1 increases by a factor of 2.2 with the alpha-emitting radionuclide concentration increasing a factor of 3.5. See Table 4-22.

The cause for this increase is that when no diverter is present the vault area the sediments immediately below the vault area are more moist (Figure 4-28.). Hence the contaminants are more easily flushed from the vault zone and the vadose zone when there is no hydraulic diverter. This is reflected in the travel times which are much faster in the Unit Cell Model (-1,300 years for the unretarded group) than in the Concept 1 Full Facility Model (-10,000 years).

For concept 2, the effect of the hydraulic diverter is small for the beta/photon drinking dose (the effect being about 10

Table 4-22. Effect of Facility Design Options on Estimated Impacts

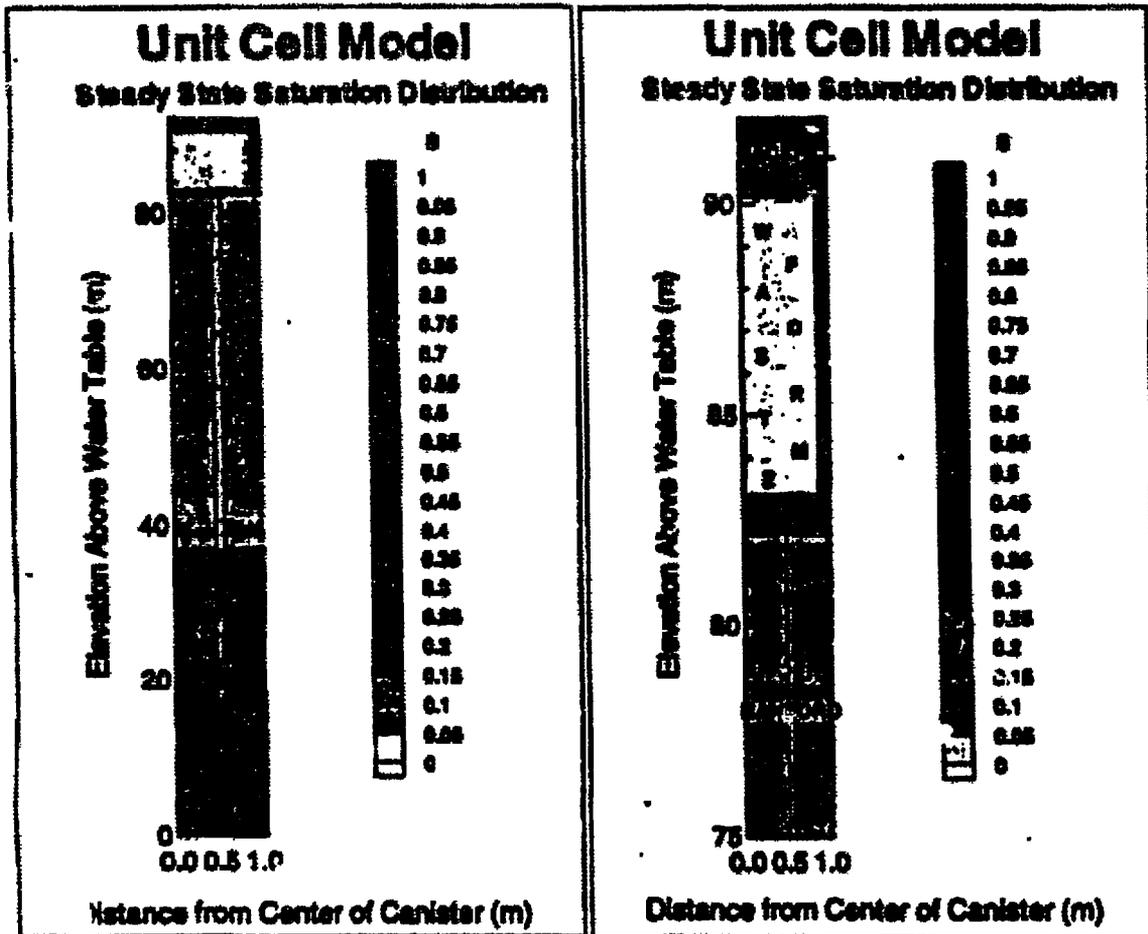
| Disposal Facility Feature | Beta/photon Drinking Water Dose (mrem/y) | Alpha-emitting Radionuclide Concentration (pCi/l) | All-Pathways Dose (mrem/y) |
|---|--|---|----------------------------|
| Concept 1 Geometry | | | |
| Full Facility Model with hydraulic barrier (Base Analysis Case) | 2.0 | 1.7 | 6.4 |
| Unit Cell Model which has no hydraulic barrier | 4.4 | 5.9 | 13.4 |
| Unit Cell Model. Material between canisters is sand | 4.4 | 5.6 | 13.3 |
| Concept 2 Geometry | | | |
| Full Facility Model with hydraulic barrier | 1.11 | 0.27 | 3.3 |
| Unit Cell Model which has no hydraulic barrier | 1.23 | 1.66 | 3.8 |
| Full Facility Model but without side gravel walls | 1.16 | 0.72 | 3.5 |

percent). However, the effect of the diverter on the concentration of alpha-emitting radionuclides becomes larger (increasing to a factor of 6.1). The beta/photon dose does not significantly increase because the unretarded group for Concept 2 is already near its maximum value, the travel time being about 3,500 years. However, the effect of speeding the uranium group is significant (travel time for Concept 2 Full Facility Model is about 20,000 years, for the Unit Cell Model about 10,000 years).

The changes in the alpha-emitting radionuclide concentration are greater than the changes in the beta/photon drinking water dose when there is no hydraulic diverter. The flux of the unretarded group (selenium and technetium) is nearly at its maximum value even with a hydraulic barrier. However, with a hydraulic diverter the $K_d=0.6$ ml/g group (uranium) the flux is far below its maximum value. Thus for a design without a

far below its maximum value. Thus for a design without a hydraulic diverter for which the flux of both groups reach their maximum value, the effect is larger for the uranium group and hence for the impact concerning alpha-emitters.

Figure 4-28. Moisture Values of Unit Cell Model for steady state. The moisture content is given as saturation which is volumetric moisture content divided by the porosity of the material.



4.6.3.3 Side Hydraulic Diverter. Calculations were performed with a hydraulic diverter on top but not on the sides. The presence of the side hydraulic diverter for Concept 2 has about a 5 percent effect on performance for the beta/photon drinking water dose and about a 50 percent effect for the alpha-emitting radionuclide concentration. The cause of the performance change is the same for the top hydraulic barrier, but the effect is less because the moisture has to move horizontally rather than downward.

The effect of a side hydraulic diverter was not calculated for Concept 1. However, because of its extended lateral dimensions, the effect of such a side hydraulic diverter should not be significant.

4.6.3.4 Filler Material. The base analysis case uses the hydraulic properties for the filler material between the canisters in the vaults. If hydraulic properties of sand are used instead, the effects do not change significantly. The travel times are 2 percent longer causing some decrease in the alpha-emitting radionuclide concentration.

4.6.4 Degradation

Relatively little analysis has been performed on degradation of the disposal facility because of the conceptual nature of the facility design and because much of the facility is presumed to be made of natural materials. However, the effect of the concrete floor remaining intact, trapping water, and then failing has been investigated. The effect of having the hydraulic barrier above the waste fail in one location was also investigated.

The effect of trapping water in concrete for 2,000 years, then having the floor fail releasing the water was investigated for both Concepts 1 and 2. There was less than a 3 percent difference in the normalized flux at the aquifer for the different K_f groups studied, with most groups having differences less than 1 percent. Hence little difference (<1 percent) showed up in the estimated impacts.

A failure in the hydraulic barrier was postulated in the Concept 2 design about two-thirds of the way down the barrier. Again there is relatively little differences in the normalized flux (<5 percent) at the aquifer and in the dose.

Some additional simulations were made as part of an earlier study (Mann 1995d) to determine the sensitivity of design choices. According to these calculations, the barrier still diverted water as long as the sand formed a continuous path and did not for some reason subside completely into the gravel.

4.7 RESULTS FOR GROUNDWATER SCENARIOS - TRANSPORT SENSITIVITY CASES

4.7.1 Overview

A number of sensitivity cases were run to determine the effect of using different values for the hydraulic parameters, the geochemical parameters, and the infiltration rate. Each of these parameters affect the rate at which the contaminants enter the unconfined aquifer.

4.7.2 Hydraulic Parameters

4.7.2.1 Overview. Hydraulic parameters are important in two distinct areas of the model: the disposal facility and the vadose zone.

4.7.2.2 Disposal Facility Hydraulic Properties. As noted, the disposal facility has not yet been designed. Sensitivity cases were run for the hydraulic and diffusion properties of the filler material between the canisters.

As noted in Section 4.6.3.4, a sensitivity run substituted the hydraulic properties of sand for back-filled soil. No significant change to the estimated impacts was noted.

The present philosophy concerning the design of the disposal facility is to keep the waste form and surrounding filler material as dry as possible to minimize waste form corrosion and transport of the released materials. In such a low-moisture facility, the transport of contaminants may be dominated more by diffusion (movement of contaminants in water) than by advection (movement of contaminations with water flow).

The simulations of Concepts 1 and 2 in the base analysis case used the Scheidegger diffusion model (see Section 3.5.3.2). As discussed in that section, the effective diffusion term could be lower. A sensitivity case with an effective value 20 times lower results in a much lower calculation of contaminant flux and, hence, dose. Figure 4-29 displays the normalized unretarded contaminant flux to the aquifer as a function of time for the two diffusion cases for Concept 1. Table 4-23 shows the estimated beta/photon drinking water dose for the two diffusion cases for both Concept 1 and 2. The relative change for other estimated impacts is similar. Concept 2 shows a much smaller effect because the path out of the facility is shorter in Concept 2 and because filler material is more moist and hence more advection occurs in Concept 2.

Figure 4-29. Estimated Unretarded Contaminant Flux to Aquifer for Concept 1 for Different Diffusion Coefficients (Full Facility Model).

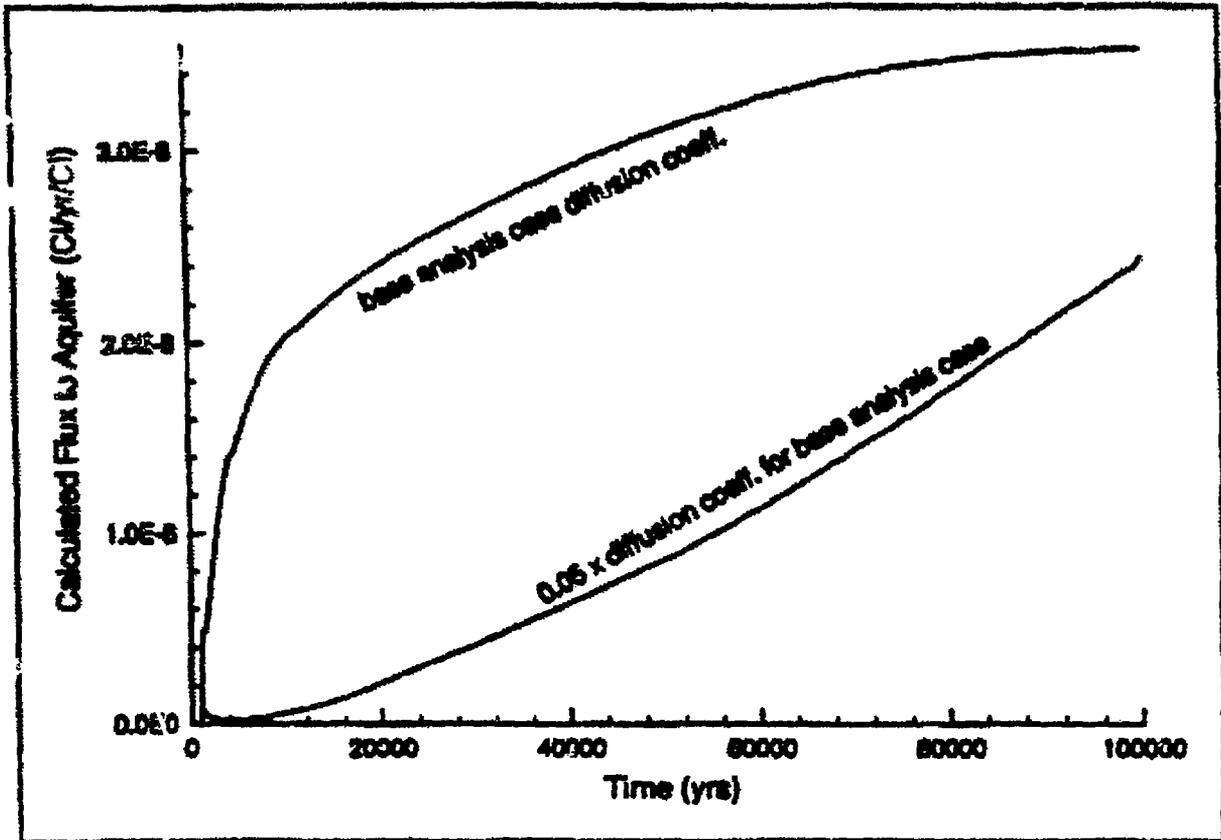


Table 4-23. Estimated Beta/Photon Drinking Water Dose at 10,000 years at a Well 100 Meters Downgradient for Different Diffusion Coefficients.

| Concept | Diffusion Coefficient | Beta/Photon Dose at 10,000 Years (mrem/y) |
|---------|---------------------------|---|
| 1 | Base Analysis Case | 1.97 |
| | 0.05 * Base Analysis Case | 0.06 |
| 2 | Base Analysis Case | 1.11 |
| | 0.05 * Base Analysis Case | 0.20 |

4.7.2.3 Vadose Zone Hydraulic Properties. The effects on dose rates of both vadose zone hydraulic properties (moisture retention and unsaturated conductivity relationships) and dispersion coefficients were investigated in the sensitivity studies.

Because the hydraulic properties are so strongly correlated with stratigraphy, changing the positions of the strata in the vadose zone model changed the hydraulic properties of the simulation. The base analysis case assumed that the first 6 meters were from the upper gravel sequence, the next 60 meters were from the sandy sequence, and the bottom 35 meters were from the lower gravel sequence. The results of using different strata (and, hence, different moisture retention and conductivity curves) are shown in Table 4-24. Figure 4-30 shows the normalized unretarded contaminant flux entering the unconfined aquifer.

Table 4-24. Estimated Impact at 10,000 Years Assuming Different Strata (and hence Hydraulic Properties).

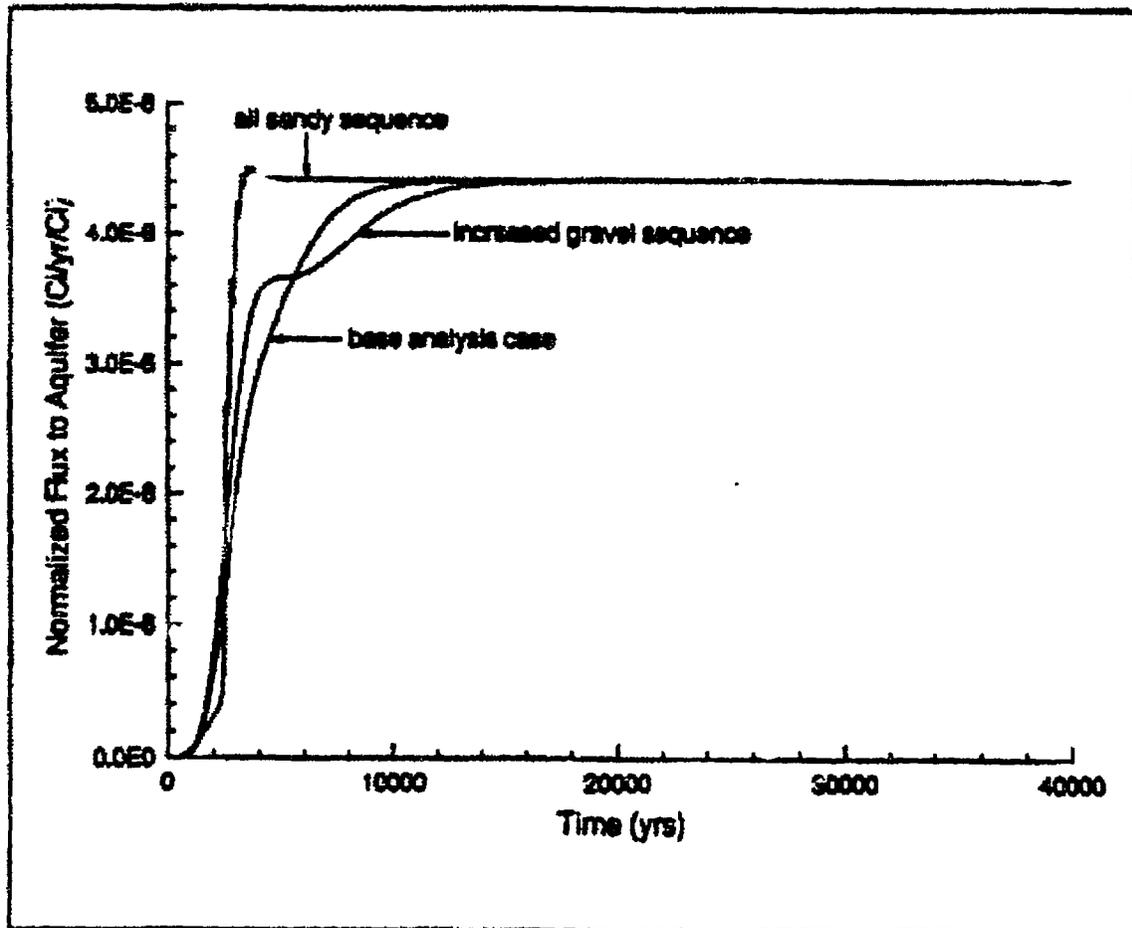
| Strata | Beta/Photon Drinking Water Dose (mrem/y) | Alpha-Emitting Radionuclide Concentration (pCi/l) | All-Pathways Dose (mrem/y) |
|--|--|---|----------------------------|
| Base Analysis Case | 2.0 | 1.7 | 6.4 |
| Unit Cell Model (no hydraulic barrier) Vadose zone - 6m gravel sequence 60m sandy sequence 35m gravel sequence | 4.4 | 5.9 | 13.4 |
| Unit Cell Model Vadose zone - 101m sandy sequence | 4.6 | 9.9 | 18.8 |
| Unit Cell Model Vadose zone - 6m gravel sequence 45m sandy sequence 50m gravel sequence | 4.1 | 4.2 | 12.5 |

If the hydraulic parameters of the sandy sequence are used throughout the vadose zone, then the bottom 35 meters are a bit less moist and the contaminants travel faster (-2,500 years versus -5,000 years for the unretarded group, and -5,400 years versus -9,100 years for the uranium group). This does not result in much of a change in the beta/photon drinking water dose since selenium and technetium are on the plateau of the flux curve. However, the changes place the uranium isotopes also on the plateau of the flux curve, resulting in a 50 percent increase in the estimated alpha-emitting radionuclide concentration. Note, however, that the travel times for the uranium group for Concept 1 (-100,000 years) and for Concept 2 (-20,000 years) are much longer than for the Unit Cell Model. A full facility model

simulation would show less of a change in alpha-emitting radionuclide concentration (or the all-pathway dose) than the unit cell model simulation. Using the full facility simulation, the steepest part of the contaminant curve would not happen beyond 10,000 years. Even with a 50 percent increase predicted by the Unit Cell Model, the results for neither Concept 1 nor 2 would exceed the performance objectives.

The second sensitivity case increased the thickness of the lower gravel sequence at the expense of the sandy sequence. The predicted impacts declined (-20 percent for alpha-emitting radionuclide concentration), but not significantly. The reason for the asymmetry is that, in the Unit Cell Model, the unretarded group still reaches the unconfined aquifer before 10,000 years for both the Unit Cell Model base sensitivity case and for the increased-gravel-layer case, and in neither case is the impact of the uranium group dominant.

Figure 4-30. Normalized Unretarded Contaminant Flux Entering the Unconfined Aquifer for Three Different Sets of Hydraulic Properties in the Vadose Zone (Unit Cell Model).



The position of the water table also affects the amount of uranium ($K_d = 0.6 \text{ ml/g}$) flux reaching the aquifer at 10,000 years as seen in Table 4-25. The flux of the unretarded group (selenium and technetium) is near its maximum and does not change. However, with the travel time estimated by the Unit Cell Model being close to 10,000 years, changes in the water table position do matter. As noted, however, if a full facility model is used, the sensitivity disappears because the travel time is significantly longer than 10,000 years.

Table 4-25. Normalized Contaminant Flux Reaching the Unconfined Aquifer at 10,000 years as a Function of Water Table Position.

| Depth to Water Table (m) | $K_d = 0$ | | $K_d = 0.6 \text{ ml/g}$ | |
|--------------------------|------------------------|-----------------|--------------------------|-----------------|
| | Flux at 10,000 Y (1/y) | Travel Time (Y) | Flux at 10,000 Y (1/y) | Travel Time (Y) |
| 96 | 4.38 e-6 | 2,600 | 3.42 e-6 | 7,500 |
| 101 | 4.37 e-6 | 3,000 | 2.65 e-6 | 9,100 |
| 110 | 4.29 e-6 | 3,300 | 1.99 e-6 | 10,600 |

The dispersion coefficient describes the spreading of the contaminants as they move with the flow. Sensitivity cases were run for the full facility model for Concept 2 with twice the value for the dispersion coefficient used in the base analysis case and with one-half of the value used in the base analysis case. The difference in the calculated unretarded ($K_d=0$) flux in both magnitude and time of arrival is only a few percent. However, for the uranium group ($K_d = 0.6 \text{ ml/g}$), the fluxes change by 25 percent at 10,000 years, reflecting the wider spreading with higher dispersion values. As expected, the calculations show that the center of the contaminant flux and the peak value are unaffected. Thus, changing the dispersion coefficient results in very little change in either the beta/photon dose or all-pathways dose at 10,000 years or for peak doses, but there is a larger percentage change (-10 percent) for the alpha-emitting radionuclide concentration at 10,000 years. A similar effect is seen for the Unit Cell Model as shown in Table 4-26. The travel time does not change much, but the slope of the curve changes significantly, becoming much more sharp as the dispersion coefficient is lowered.

Table 4-26. Effect of Dispersion on $K_d = 0.6$ ml/g Normalized Contaminant Fluxes to the Aquifer, Unit Cell Model.

| Dispersion Coefficient | Flux value at 10,000 years (γ^{-1}) | Time When 0.5*Peak Value Occurs (γ) | Time When 10^{-6} *Peak Value Occurs (γ) |
|--------------------------|--|--|---|
| 0.1 * Base Analysis Case | 2.54×10^{-6} | 9,600 | 4,000 |
| 0.5 * Base Analysis Case | 2.51×10^{-6} | 9,400 | 2,800 |
| Base Analysis Case | 2.65×10^{-6} | 9,100 | 1,500 |
| 2.0 * Base Analysis Case | 2.73×10^{-6} | 8,700 | 950 |

4.7.3 Geochemical

Retardation of contaminant transport greatly limits the number of isotopes that are important in the groundwater scenario. The cases described in this section investigate the sensitivity of the calculations to the geochemical parameters. Table 4-27 summarizes the effects on the beta/photon dose, the alpha-emitting radionuclide concentration, and the all-pathways dose at 10,000 years at a well 100 meters downgradient.

Previous Hanford Site performance assessments (Wood 1994b, Kincaid 1995, Wood 1995, and Wood 1996) have assumed a conservative value for the uranium K_d of 0. Using such a value greatly increases the movement of uranium and its daughters. Thus, the alpha-emitting radionuclide concentration at 10,000 years increases significantly (by a factor of 2 for Concept 1 and by a factor of 3 for Concept 2). The beta/photon dose increases by 10 percent because of the presence of beta emitters in the decay chain. However, the estimated results are still below the performance objectives.

Uranium is known to strongly adsorb in concrete, having a chemical distribution coefficient (K_d) value of 100 ml/g. Using this value in the floor of the Unit Cell Model increases the travel time for the uranium group by a factor of 4 (from 9,100 years to 39,000 years) and reduces the alpha-emitting radionuclide concentration at 10,000 years by a factor of 3 from the case of assuming the K_d of uranium is 0 and a factor of 2 from the case of assuming the value is 0.6 ml/g.

The base analysis case assumes that selenium and technetium move through the vadose zone without retardation. Major experiments on Hanford Site soils support this conclusion. However, to determine the sensitivity to the value of K_d chosen,

a sensitivity case with a slightly higher value (0.1 ml/g) was evaluated. Only a 15 percent decrease was noted at 10,000 years in the beta/photon drinking water and the all-pathways dose.

If a material could be found that would chemical trap technetium (and selenium), then the performance of the disposal facility would be significantly improved. Assuming that the K_d for technetium was 100 ml/g in the floor results in a 60 percent reduction in the beta/photon dose at 10,000 years. If both selenium and technetium could be trapped, then the dose falls by 75 percent. It should be emphasized that such a material has not yet been found.

Table 4-27. Effect of Geochemical Parameters on Impacts at a Well 100 Meters Downgradient at 10,000 Years.

| Geochemical Effect | Beta/Photon Dose (mrem/y) | Alpha-Emitting Radionuclide Concentration (pCi/l) | All-Pathways Dose (mrem/y) |
|--|---------------------------|---|----------------------------|
| Concept 1 - Full Facility Model | | | |
| Base Analysis Case | 1.97 | 1.65 | 6.4 |
| K_d for Uranium = 0 | 2.1 | 4.6 | 7.1 |
| K_d for Se and Tc = 0.1 ml/g | 1.66 | 1.65 | 5.5 |
| Concept 2 - Full Facility Model | | | |
| Base Sensitivity Case | 1.11 | 0.27 | 3.3 |
| K_d for uranium = 0 | 1.23 | 2.6 | 3.8 |
| K_d for Se and Tc = 0.1 ml/g | 0.94 | 0.27 | 2.8 |
| Unit Cell Model - Concept 1 Geometry | | | |
| Base Sensitivity Case | 4.4 | 5.9 | 13.4 |
| K_d for uranium = 0 | 4.6 | 9.7 | 14.3 |
| K_d for uranium concrete = 100 ml/g vadose zone = 0 | 4.2 | 1.6 | 12.6 |
| K_d for technetium concrete = 100 ml/g vadose zone = 0 | 1.72 | 6.3 | 3.4 |
| K_d for Se and Tc concrete = 100 ml/g vadose zone = 0 | 0.98 | 6.3 | 4.7 |

4.7.4 Infiltration Rate

4.7.4.1 Overview. In most performance assessments, the infiltration has a large effect in either increasing (for higher infiltration rates) or decreasing (for lower infiltration rates) the impact relative to the base analysis case. For this performance assessment where the release time is long, the sensitivity to infiltration rate is more one sided. Increasing the infiltration rate from the base analysis case does not significantly increase the impacts. However, decreasing the infiltration rate can greatly reduce the impacts, particularly at 10,000 years.

An important assumption of this analysis is that the contaminant release rate is independent of the moisture flux through the facility. As noted in Section 4.5.2, mechanistic simulations of contaminant release show an increase in release in release as the infiltration is increased. Moreover, since water is needed to corrode glass, at very low infiltration rates the glass dissolution rate may also be affected. This effects will be studied in future assessments as the waste form and facility design are determined.

4.7.4.2 Low Infiltration Rates. The base analysis case assumed that the infiltration rate would be 1 mm/y for the first 1,000 years. The surface barrier is assumed to instantaneously degrade, resulting in a natural recharge rate of 3 mm/y thereafter. A series of sensitivity cases investigated the result of other low infiltration rates. Table 4-28 presents a summary. Figure 4-31 shows the normalized contaminant flux at the unconfined aquifer as a function of time for various infiltration rates. Figure 4-32 shows the fluxes for the uranium group.

Assuming a steady state infiltration rate of 3 mm/y raised the impacts slightly. The calculated travel times for the unretarded group decreased to -2,400 years from the Unit Cell Model base sensitivity case of -3,000 years (Concept 1 being -10,000 years and Concept 2 -4,000 years). The travel time for the uranium group ($K_d = 0.6$ ml/g) also decreases to 6,600 years from 9,100 years. Thus both the unretarded contaminants and the next group of contaminants are on the plateau and not much change is seen when at 10,000 years using the Unit Cell Model for a surface barrier with a 1,000-year life.

If the surface barrier has a much longer life, then the infiltration rate does not exceed 1 mm/y. The estimated beta/photon drinking water dose using the Unit Cell Model at 10,000 years decreases by 20 percent while the alpha-emitting radionuclide concentration declines by a factor of 4. The beta/photon dose does not decline by much because the travel time for unretarded elements like selenium and technetium (-6,500 years) is still small compared to 10,000 years. However, the travel time for the uranium group increases to -24,000 years.

Table 4-28. Effect of Infiltration Rates on Estimated Impacts at 10,000 Years for a Well 100 Meters Downgradient from the Facility.

| Recharge case | Beta/Photon Drinking Water Dose (mrem/y) | Alpha-Emitting Radionuclide Concentration (pCi/l) | All-Pathways Dose (mrem/y) |
|---|--|---|----------------------------|
| Concept 1 Geometry - Unit Cell Model | | | |
| 3. mm/y for 1000 years, 1. mm/y thereafter | 4.4 | 5.9 | 13.4 |
| 100 mm/y (steady) | 5.0 | 31. | 194.0 |
| 3.0 mm/y (steady) | 4.4 | 5.9 | 13.4 |
| 1.0 mm/y (steady) | 3.5 | 0.19 | 10.3 |
| 0.1 mm/y (steady) | <0.001 | <0.001 | 0.001 |
| Concept 2 - Full Facility Model | | | |
| 3. mm/y for 1000 years, 1. mm/y thereafter | 1.11 | 0.27 | 3.3 |
| 100 mm/y | 1.37 | 2.0 | 3.2 |

yielding a significant decrease. If a hydraulic break is present (that is, using the results for Concept 1 or 2), then the unretarded groups would also show significant decreases. The travel times for unretarded elements for a constant 1-mm/year infiltration rate would increase to ~30,000 years for Concept 1 and ~11,000 years for Concept 2.

If the infiltration rate is even less (0.1 mm/y), then the travel times become so long (~25,000 years for $K_d = 0$ and over 100,000 years for $K_d = 0.6 \text{ ml/g}$) that at 10,000 years no significant impacts are seen.

4.7.4.3 High Infiltration Rates. If the infiltration rate should increase, the contaminants move much more quickly to the aquifer. Figure 4-33 shows the calculated normalized contaminant fluxes to the aquifer for the Concept 2 base sensitivity case and for the case of 100 mm/y infiltration rate. The peak value is somewhat higher ($4.8 \times 10^{-4} \text{ y}^{-1}$ for the case of 100 mm/y versus $4.2 \times 10^{-4} \text{ y}^{-1}$ for the base analysis case) because the release rate is higher at shorter times. However, because the contaminant flux is limited by the release rate from the waste form, the major effect of the high recharge rate is that the

Figure 4-31. Normalized Contaminant Fluxes at the Unconfined Aquifer for Unretarded Contaminants for Various Infiltration Rates. (Unit Cell Model)

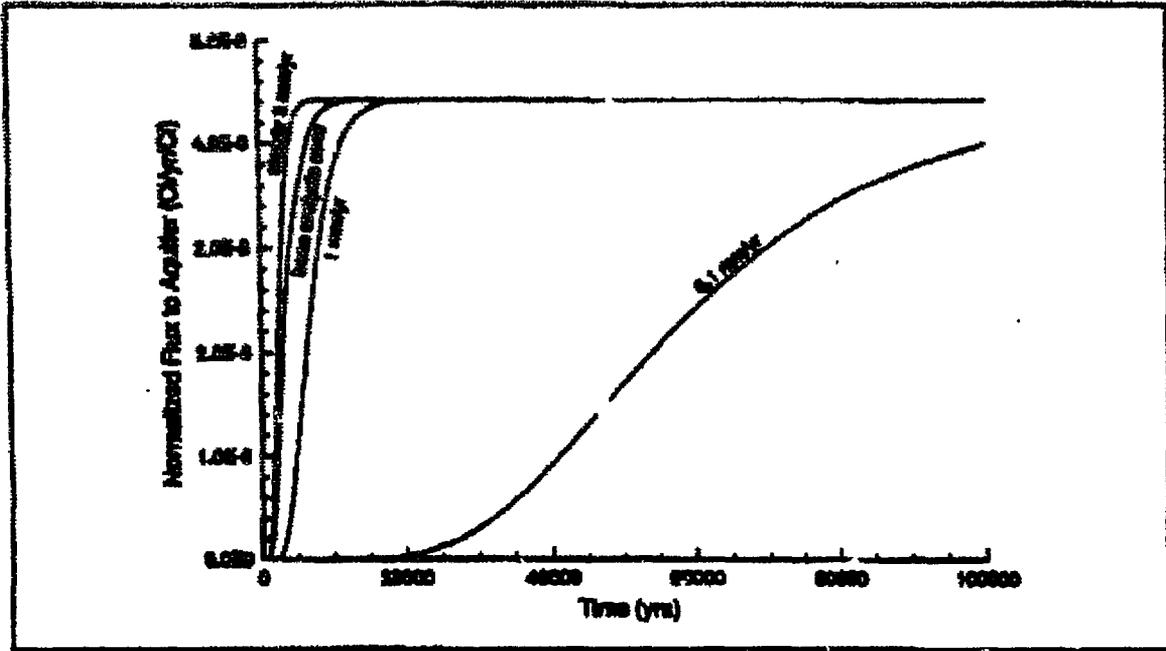


Figure 4-32. Normalized Contaminant Fluxes at the Unconfined Aquifer for $\lambda_c = 0.6$ ml/g Contaminants for Various Infiltration Rates. (Unit Cell Model)

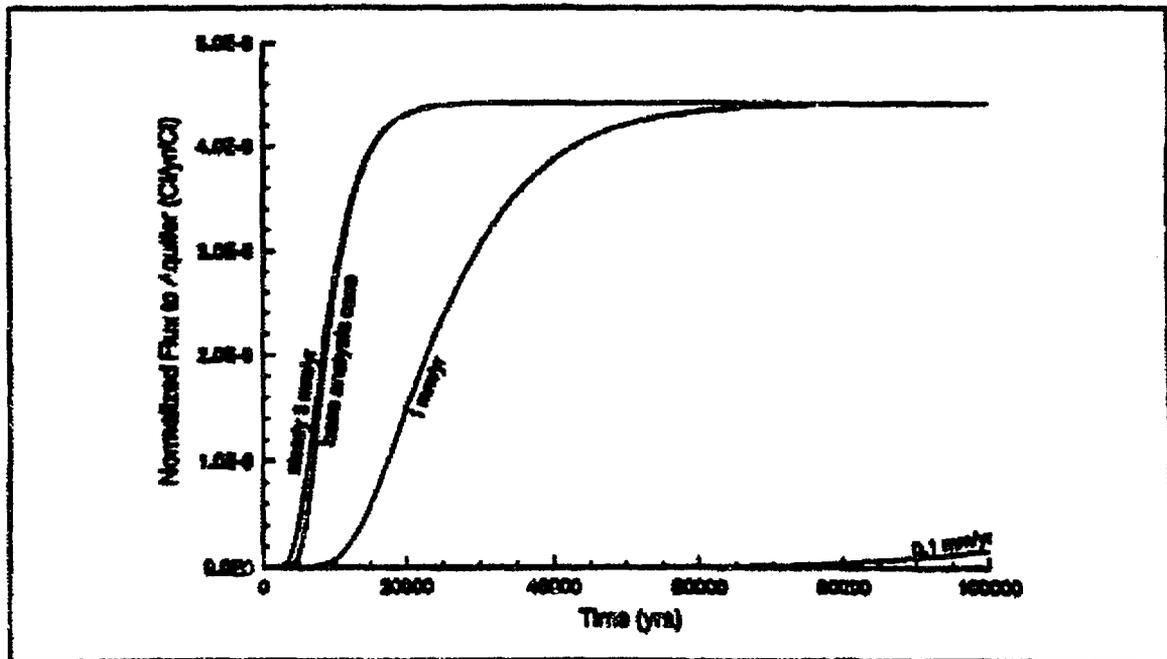
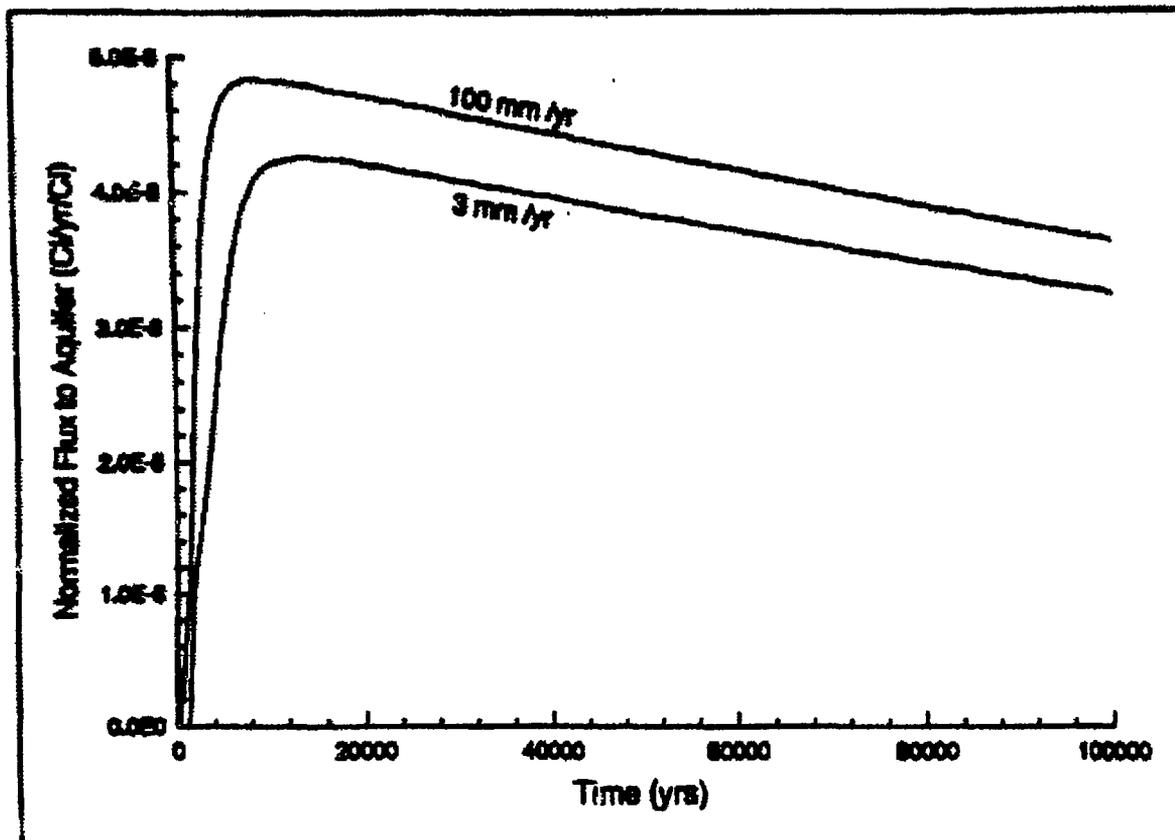


Figure 4-33. Normalized Unretarded Contaminant Fluxes at the Unconfined Aquifer Using the Concept 2 Geometry For Infiltration Rates of 3 and 100 mm/y. (Unit Cell Model)



contaminants reach the aquifer sooner. The timing of the arrival is such that it is still long compared to the half-lives of ^{137}Cs and ^{90}Sr , so these nuclides still do not contribute to the dose. However, at 10,000 years the contaminant flux for the uranium group ($K_d = 0.6 \text{ ml/g}$) is nearer its peak, so the relative contribution by uranium isotopes and their daughters to the all-pathways dose is higher than for the base analysis case.

Table 4-28 presents the impacts. The estimated beta/photon drinking water dose at 10,000 years does increase, but only by about 20 percent. More importantly, the peak moves to 9,300 years. The alpha-emitting radionuclide concentration for the high infiltration case increases significantly from 0.92 pCi/l to 2.7 pCi/l, which is still well below the performance objective of 15 pCi/l. Such a large increase is caused by the uranium isotopes arriving at the well inside of 10,000 years. The magnitude of the increase in the all-pathways peak is similar to that of the beta/photon drinking water dose.

The importance of the hydraulic diverter is seen when comparing the Unit Cell Model results (no diverter) to the

Concept 2 case). Without a diverter and with a 100-mm/y infiltration rate, the alpha-emitting radionuclide concentration and all-pathways dose increase by factors of 30 and 40 respectively. The reason is that the soil beneath the disposal facility stays relatively dry (moisture content = 0.041 cm³/cm³) even for an infiltration rate of 10 mm/y with a hydraulic diverter while it becomes almost saturated (43 percent saturation, implying a moisture content of 0.15 cm³/cm³) without a diverter.

4.8 RESULTS OF GROUNDWATER SCENARIOS - OTHER SENSITIVITY CASES

4.8.1 Overview

This section describes the sensitivity to the amount of radionuclides in the waste (inventory), to the land use assumed, to the library of dosimetry parameters chosen, to the location of the facility, and to various calculational assumptions.

4.8.2 Inventory

As noted in section 4.3.4, ⁹⁹Tc, ⁷⁵Se, and uranium isotopes with their daughters are the largest contributors by far. This section describes the effect of changing the inventories of these materials.

The RFP requires that the release rate of ⁹⁹Tc be 0.88 ppm (of the amount of ⁹⁹Tc supplied to the vendor) per year. This release rate, which is five times more restrictive than for other isotopes, can be met by separating out up to 80 percent of the ⁹⁹Tc and returning it to DOE for immobilization into high-level immobilized waste. Table 4-29 displays the results of assuming that the vendor does return 80 percent of the ⁹⁹Tc to the DOE and puts the remaining 20 percent into the low-level immobilized waste. The calculated results are very similar to those for the case (Section 4.5.3.2) where all the technetium is in the waste form, but where technetium is assumed to have a release rate five times lower than other materials. The beta/photon emitter dose at 10,000 years is nearly the same (0.82 mrem/year for reduced inventory versus 0.90 mrem/year for the reduced release rate). The all-pathways dose at 10,000 years is the same for the two cases. The doses do not decline in proportion to the ⁹⁹Tc inventory, because as the ⁹⁹Tc inventory is decreased, ⁷⁵Se becomes more important. If the ⁹⁹Tc inventory is reduced by a factor of 5, ⁹⁹Tc would be responsible for less than half of the estimated beta/photon drinking water or all-pathways dose.

Uncertainties for selenium and uranium inventories have not been established. Also the exact amount of iodine that will escape from the melter and be trapped by filters is not yet known. Impacts of increasing the inventory of these elements by

Table 4-29. Effect of Inventory Changes on Estimated Results at 10,000 Years at a Well 100 Meters Downgradient from the Facility. (Concept 1 - Full Facility Model)

| Inventory Assumption | Beta/Photon Drinking Water Dose (mrem/y) | Alpha-Emitting Radionuclide Concentration (pCi/l) | All-Pathways Dose (mrem/y) |
|--|--|---|----------------------------|
| Base Analysis Case | 1.97 | 1.65 | 6.4 |
| Technetium at 20% of original inventory | 0.79 | 1.65 | 2.5 |
| Selenium at twice original inventory | 2.4 | 1.65 | 7.1 |
| Iodine at 5 times the original inventory | 1.97 | 1.65 | 6.4 |
| Uranium at twice original inventory | 2.05 | 3.2 | 6.8 |

a factor of 2 for selenium and uranium and 5 for iodine are shown in Table 4-29.

Doubling the selenium inventory produces a 20 percent increase in the beta/photon drinking water dose and a 10 percent increase in the all-pathways dose. A five-fold increase in iodine has no calculated effect. Doubling the uranium inventory while keeping the same isotopic ratios increases the alpha-emitting radionuclide concentration by almost a factor of 2 and the all-pathways dose by 25 percent.

Short-life isotopes like ¹³⁷Cs and ⁹⁰Sr decayed away before they reach the groundwater. Thus even though the exact amount of these isotopes awaits NRC determination, these isotopes will not contribute to postulated doses for the groundwater pathway.

4.8.3 Land Use

4.8.3.1 Overview. Land use mainly affects the travel of contaminants in the unconfined aquifer. Land uses that could affect the infiltration rate are described in Section 4.7.4.3. L and uses that result in intrusion into the disposal facility itself are described in Section 4.2.2. This section describes

land uses that affect the properties of the groundwater system beneath the Hanford Site. For more details, see Lu (1996).

4.8.3.2 Irrigation at the Disposal Facility. Even though lands on the Hanford Central plateau are not expected to be irrigated, lands near the Hanford Site are presently being irrigated. As described in Section 4.7.4.3, infiltration rates of 100 mm/y were used to describe the effects of possible irrigation at the disposal site.

4.8.3.3 Irrigation on the Hanford Central Plateau. Surrounding the Hanford Site, there are large areas under irrigation. Because radioactive plumes are present in the groundwater, irrigation is not expected to occur on the present Hanford Site, even after the land is released by the federal government. However, sensitivity cases based on irrigating large plots of land were simulated nonetheless. In all cases an infiltration rate of 100 mm/y was used.

The first case assumed that all the area immediately north of the Hanford 200 Areas would be irrigated. At the disposal site, the groundwater table would rise 2 meters, the direction of water flow would change to the southeast, but the increase in water flux in this 2 meter interval would be significant because the interval is in a high permeability zone (the Hanford formation). Thus, the concentration ratio (and hence impacts) decreases by 42 percent.

The second case assumes that all the area immediately to the west of the 200 West Area would be irrigated. This would result in groundwater mounding just west of the 200 West Area (extending slightly into the 200 West Area). The result at the disposal site would be a small rise in the water table, but this higher water level would reside in the high permeability zone. For this case, the concentration ratio and hence impacts would be reduced to 80 percent of the value of the base analysis case.

The third and last irrigation case assumed that all the areas north, west, and south of the 200 Areas would be irrigated, but not the area between 200 West and 200 East Areas. Because of the large area south of the 200 Areas, the water table would rise significantly (about 8 meters at the disposal site) and the direction of flow would be northerly over almost all of the 200 Areas. The calculated concentration ratio and hence the impacts would drop by a factor of 5.

Because of the uncertainty in the recharge rate, another sensitivity case was run with the recharge rate over the 200 Areas being reduced by a factor of 2. No change was calculated for the aquifer mixing factor and hence no changes in the estimated impacts resulted. This result is to be expected because the source of water for the unconfined aquifer lies significantly west of the 200 Areas with the infiltration of water from the 200 Areas making a very small contribution to the aquifer.

In summary, irrigation increases the amount of water in the unconfined aquifer. Because the bottom of the unconfined aquifer is fixed, added water forces an increase in the thickness of the aquifer which in most cases will result in part of the unconfined aquifer being in the more conductivity Hanford formation. The end result is a decrease in the calculated well/vadose-zone concentration ratio and hence the impacts according to the portion of the aquifer residing in the high permeability zone. However, as noted, because of land use restrictions, such irrigation is not expected to occur.

4.8.3.4 Level of the Water Table. For the base analysis case, the location of the top of the unconfined aquifer (the water table) is deeper than the current location because discharges at the Hanford Site of liquid effluents to the ground will have stopped. Thus the level of the water table is expected to decline with time until it reaches a pre-Hanford operations level. However, the amount of contaminant mixing in the groundwater is very sensitive to the level of the water table because the predicted level is near the interface of two geologic formations that have very different hydraulic properties. Therefore, sensitivity cases were run using the pumping model: one raised the water table 7 meters (to its current location) and the other lowered it by 7 meters.

If the level of the water table is raised 7 meters, then the upper portions of the groundwater lie within the Hanford formation, whose hydraulic conductivity is 37 times that of the base analysis case. Two effects are observed, the aquifer mixing factor is reduced by 65 percent to 2.64×10^{-4} and the flow from the disposal site to the 200 East Area fence is east to southeast rather than almost due east, as in the base analysis case. Thus, if the level of the water table is raised 7 meters, all impacts will be about an order of magnitude lower than calculated for the base analysis case.

If the level of the water table is lowered 7 meters, then the main effect is that the thickness of the unconfined aquifer is reduced from 28 meters to 21 meters. Just as in the base analysis case, all of the unconfined aquifer is in the Ringold Formation. Lowering the water table results in a smaller amount of water with which the contaminants can mix, resulting in a well/vadose-zone concentration ratio (and estimated impacts) about 40 percent higher than the base analysis case.

4.8.3.5. Position of the Well. As discussed in Section 4.3.3, the transport within the aquifer was calculated for various well positions. The calculated dose or alpha-emitting radionuclide concentration is proportional to the relative concentrations in Table 4-7. As expected, as the distance from the disposal facility increases, the estimated impact declines. The estimated impact at a well at the 200 Area baseline is only 77 percent of the value at a well 100 meters down gradient of the disposal facility, assuming that the disposal facility is west of the PUREX facility.

4.8.3.6. Pumping at the well. The amount of pumping at the well can distort the groundwater flow field and change the predicted dose. Table 4-30 provides the effect of various pumping rates at a well 100 meters downgradient from the disposal facility normalized to a pumping rate of 0.01 m³ per day. This pumping rate corresponds to 10 liters per day. Thus the base analysis case of a well supplying drinking water to 25 people would correspond to a pumping rate of 0.25 m³ per day. Such a small pumping rate has practically no effect (< 0.1 percent) on the predicted dose rates. Much larger pumping rates would lower the predicted dose as more uncontaminated water would be used.

Table 4-30. Effect of Pumping Rates on Aquifer Mixing Ratio at a Well 100 Meters Downgradient of Facility

| | Pumping Rate (m ³ /day) | | | | |
|-----------------------------|------------------------------------|------|------|------|------|
| | 0.01 | 10. | 50. | 100. | 150. |
| 100 meter downgradient well | 1.00 | 0.95 | 0.75 | 0.57 | 0.45 |

4.8.4 Dosimetry Parameters

For the base analysis case (Section 3.4.6.2), the selection of dose factors was based on using the best data, rather than using a common source. The internal dose factors were taken from the DOE and the external dose factors from the EPA. Other choices could be made. Table 4-31 shows the estimated doses at a well 100 meters downgradient at 10,000 years. The changes are relatively small for a variety of database choices with none of the results exceeding performance objectives.

Assumptions concerning ingestion rates, inhalation rates, and times of exposure only affect the all-pathways dose. Most of the all-pathway dose comes from drinking water (53 percent) or from ingesting vegetable percent (34 percent). Therefore, the estimated all-pathway dose is relatively insensitive to inhalation rates and times of exposure. The calculation is only moderately sensitive to ingestion rates or uptake factors (with technetium uptake factors being the most important).

Table 4-31. Effect of Different Dose Factor Libraries on the Beta/Photon Drinking Water Dose and All-Pathways Dose at a Well 100 Meters Down Gradient at 10,000 Years.

| Source | Beta/Photon Dose (mrem/y) ^a | All-Pathways Dose (mrem/y) ^a |
|---|--|---|
| Base Analysis Case | 1.97 | 6.4 |
| Department of Energy | 1.97 (0%) | 6.4 (0%) |
| Environmental Protection Agency | 2.2 (10%) | 7.0 (9%) |
| GENII (Hanford Environmental Computer Code) | 3.0 (52%) | 9.9 (55%) |

Numbers in parenthesis are percentage increases from base analysis case

4.8.5 Location of the Facility

This performance assessment assumes that the location of the disposal facility is just west of the PUREX Site. However, it is possible (Burbank 1996) that some of the waste may be disposed of in the Grout Facility Area, which is just east of the PUREX site. Because the two sites are so close (about a kilometer apart) and the geology does not vary significantly, both vadose zone and aquifer transport are expected to be similar. The vadose zone transport runs discussed in Section 4.7.2 show a weak dependence on the geologic layers (less than 10 percent).

A calculation of aquifer transport at the Grout Facility showed the same well/vadose-zone concentration factor as for the base analysis case. The more important effect is that the grout facility is right next to the 200 East Area fence. Thus there is about 25 percent less mixing before the contaminants hit the fence line than in the base analysis case.

4.8.6 Computational Assumptions

A number of sensitivity runs using the Unit Cell Model were made to test calculational assumptions. These included increasing the number of nodes in the model, changing the initial amount of moisture in the construction materials, and rotating the canister so that the long side (1.8 meters) was being modeled rather than the short (1.2 meters). None of the results differed significantly from the Unit Cell Model base sensitivity analysis case (see Table 4-32).

Table 4-12. Test of Unit Cell Computational Assumptions:
 Normalized Flux Entering Unconfined Aquifer ($K_1 = 0.1 \text{ ml/g}$).

| Case | Value at 10K Y (2/y) | Peak Value (1/y) | Time of Peak Value (y) | Time of 0.5* Peak Value (y) |
|--|----------------------------|------------------------|------------------------------|-----------------------------------|
| Base Sensitivity Case | 4.37e-6 | 4.42e-6 | 17,000 | 3,140 |
| Double number of horizontal nodes | 4.37e-6 | 4.42e-6 | 17,000 | 3,150 |
| Initial moisture = 0.2 in construction materials | 4.37e-6 | 4.42e-6 | 17,000 | 3,100 |
| Initial moisture = residual level in construction materials | 4.37e-6 | 4.42e-6 | 17,000 | 3,100 |
| Rotate canister orientation by 90° | 4.37e-6 | 4.42e-6 | 17,000 | 3,150 |

4.6.7 Neglected Processes.

The major processes involved in contaminant transport have been modeled. However, the following processes also should be discussed:

- Preferential flow through the vadose zone
- Upward diffusion of contaminants
- Upward migration by capillary action
- Consumption of water in glass dissolution process.

Clastic dikes are very localized vertical geologic features of the Hanford plateau that exhibit enhanced flow under saturated conditions. Future work will characterize the hydraulic properties of these features and determine the effect (if any) of these features at the site of the disposal facility.

Upward diffusion and upward migration only become important with extremely low infiltration rates. Both processes produce a characteristic time, T , which depends on the soil diffusivity, D , and on the length to be traversed, L ,

$$T = L^2 / D.$$

For the case of upward diffusion, the equation can be derived from Fick's law (see Section 4.11). For the case of capillary

rise, the equation can be derived by neglecting the gravity term in the flow equation. Using a length of 6 meters (the total thickness of the sand-gravel capillary barrier, water-conditioning layer, and the vault roof) and a soil diffusivity of $1.25 \times 10^{-7} \text{ cm}^2/\text{s}$ (from Section 3.4.4.3), the characteristic time is almost 100,000 years.

Moreover, as noted in Section 3.4.5.4, water must be present to dissolve the glass. Because the aquifer is so far below the disposal facility, capillary action could not bring water up from the waste. Thus the only source for the quantity of water needed to dissolve a significant amount of the waste form is from infiltration. Therefore, under extremely dry conditions, there would be no mobile contaminants to move.

4.9 IMPACT OF OTHER HANFORD ACTIONS ON GROUNDWATER

The Defense Nuclear Facilities Safety Board recommended (DNFSB 1994) that, in the evaluation of the impact of the disposal of radioactive waste, DOE consider not just the impact from the disposal action under consideration but also all other government actions that might affect those impacts. The analysis presented here will be brief because the location of the disposal facility has not yet been determined. A more complete study is being conducted at Hanford and will be published separately.

The main pathway that is affected in such an integrated analysis is the groundwater pathway. Inadvertent intruder scenarios and releases to the air are controlled at the source point. As will be seen in Section 4.12, the impacts of catastrophic events on disposed of waste are not significant.

Assuming that the disposal facility is placed just southwest of the PUREX facility, the previous Hanford Site actions that would affect groundwater downgradient of the disposal facility are those activities that are upgradient of the facility. From Figure 3-1, those actions are the operations at the S, SX, SY, and U Tank Farms and the disposal of waste at the Environmental Remediation Disposal Facility and at the commercial low-level waste disposal site (operated by U.S. Ecology).

Using the aquifer model described in Section 3.5.3.4, mixing effects were calculated (appendix of Lu 1995) for the transport of contaminants from these potential sources to a well 100 meters downgradient of the disposal facility. The mixing factors are displayed in Table 4-33. Because of the distance from the sources, the mixing factors are significantly less than from the low-level tank waste disposal site.

Both the Department of Energy (DOE 1988b) and the Nuclear Regulatory Commission (10 CFR 61-4) mandate that at the edge of the disposal facility a member of the general public can receive

an exposure of no more than 25 mrem in a year. Thus assuming that the other sources have their maximum impact and ignoring any time factors which might reduce the effect of the overlap, the other sources could add no more than 10.3 mrem in a year. Adding this to the amount estimated in Section 4.3.4.2, yields a total dose of less than 19 mrem in a year for the first 10,000 years. Moving the point of compliance to the 200 East Area fence will reduce the estimated compliance dose, but by less than 25 percent.

Table 4-11. Mixing Factors from Other Sources for a Wall 100 Meters Downgradient of the Low-Level Tank Waste Disposal Site.

| | Upstream Sources | | | | |
|--------------------------------|---------------------------|-----------------------|-----------------------|-----------------------|------------------------------|
| | Low-Level Tank Waste Site | ERDF Site | S, SX, SY Tank Farm | U Tank Farm | Commercial LLW Disposal Site |
| Mixing Factor | 1.7×10^{-3} | 3.01×10^{-4} | 2.08×10^{-4} | 1.25×10^{-4} | 8.91×10^{-5} |
| Fraction of Base Analysis Case | 1.00 | 0.17 | 0.12 | 0.07 | 0.05 |

4.10 SUMMARY OF GROUNDWATER SCENARIO

4.10.1 Overview

Tables 4-8 and 4-12 show that the performance objectives for the groundwater scenario are met for the base analysis case. Table 4-14 shows using Concept 2, the performance objectives are again met. However, for both Concepts 1 and 2, the estimated doses from beta/photon emitters at a wall 100 meters downgradient from the facility (2.0 and 1.1 mrem in a year, respectively) are only a factor of 2 to 4 lower than the performance objective of 4 mrem in a year. Also the beta/photon doses are estimated to exceed 4 mrem in a year at a time far in the future (~750,000 years for Concept 1 and 3 million years for Concept 2).

This section discusses the main causes for these results and provides a feeling for the robustness of the estimates. The next section presents the most important factors for the maximum value, while Section 4.10.3 extends the discussion to the value at 10,000 years.

4.10.2 Maximum Impact of the Groundwater Scenario

4.10.2.1 Overview. Although the performance objectives are for a time period up to 10,000 years, the maximum impact is of interest for three reasons:

- The maximum value allows a determination of whether the disposal action has a significant impact at any time
- A comparison of the impact at the time of compliance to the maximum impact allows a determination of how sensitive the result is to choice of conceptual model and model parameters
- An examination of the time history of doses allows an identification of models and model parameters which have the greatest overall impact.

Therefore, this section describes the value of the maximum impact and those few parameters which determine that value.

4.10.2.2 Value of Maximum Impact. Table 4-34 shows the maximum impact at 10,000 years for Concept 1 assuming instantaneous transport through the vadose zone and a time-independent waste form release rate of 4.4 parts per million per year. The corresponding values for Concept 2 would be 40 percent lower. Using the values in Table 4-34, it can be seen that only a very few contaminants would be important even if the vadose zone did not retard their movement. For the beta/photon drinking water dose, ^{99}Tc , ^{129}I , and the daughters of the uranium isotopes are the most important contaminants. ^{99}Tc , neptunium and its daughters, and americium and its daughters are the next most important. For the alpha-emitting radionuclide concentration, the most important radiocontaminants are the uranium and plutonium isotopes (and their daughters). For the all-pathways dose, the above radiocontaminants plus the americium isotopes (and daughters) are of the greatest concern. However, americium, plutonium, and tin are expected to be very highly retarded (having K_d values ≥ 40 ml/g), resulting in travel times of millions of years, and hence, significant decay, making their impacts insignificant.

Therefore, the main radiocontaminants of interest are ^{99}Tc , the uranium isotopes (and their daughters), and other $K_d=0$ contaminants (primarily ^{99}Tc). Thus at 10,000 years, assuming Concept 1, a waste form release rate of 4.4 ppm/y, and no effect of the vadose zone, the impacts from technetium, uranium, and selenium are

| | |
|---|------------------------|
| beta/photon drinking water dose | < 12.7 mrem in a year |
| alpha-emitting radionuclide concentration | < 25. pCi/l |
| all-pathways dose | < 27.4 mrem in a year. |

Although these values are above the performance objectives, they are at most a factor of 3.5 above and are a worst case,

neglecting the important known effects of facility design and vadose zone transport. Including these effects drops the estimated doses below the performance objectives.

Table 4-34. Maximum Contribution from Contaminants at 10,000 Years at a Well 100 Meters Downgradient from the Facility, Assuming Instantaneous Vadose Zone Transport, a Core at Waste Form Release Rate of 4.4 ppm/y, and Concept 1.

| Contaminants | K_d in base case (ml/g) | Beta/Photon Drinking Water Dose (mrem/y) | Alpha-Emitting Radionuclide Concentration (pCi/l) | All-Pathways Dose (mrem/y) |
|---|---------------------------|--|---|----------------------------|
| Performance Objective | --- | 4.0 | 15. | 25. |
| ¹²⁹ I | 0.0 | 0.87 | 0. | 1.6 |
| ⁹³ Zr+ ⁹³ Nb ^a | 40. | 0.012 | 0. | 0.034 |
| ⁹⁹ Tc | 0.0 | 3.2 | 0. | 10.5 |
| ¹³⁵ Sr | 100. | 3.1 | 0. | 12.1 |
| ¹²⁹ I | 3.0 | 0.21 | 0. | 0.42 |
| Thorium and daughters | 40. | 0.008 ^(d) | 0.028 ^(e) | 0.018 ^(e) |
| Uranium and daughters | 0.6 | 8.6 | 23.2 | 11.3 |
| Neptunium and daughters | 15. | 1.67 | 0.65 | 1.83 |
| Plutonium and daughters | 40. | 0.013 | 282. ^(e) | 966. ^(e) |
| Americium and daughters | 40. | 1.03 ^(d) | 4.2 ^(e) | 15.0 ^(e) |
| Curium and daughters | 100. | 0.001 ^(d) | 0.018 ^(f) | 0.06 ^(f) |

^a ¹³⁷Cs, ⁹⁰Sr, ¹³⁷Cs, and ²³²Sm have doses less than 0.001 mrem/y.

^b ²²⁶Ra, ²²⁸Ra, and ²²⁷Ac have alpha-emitting radionuclide concentrations less than 0.001 pCi/l

^c Peak value (which is shown) is at -8,000 years

^d Peak value (which is shown) is at -7,000 years

^e Peak Value (which is shown) is at -2,000 years

^f Peak value (which is shown) is at -5,000 years

4.10.2.3 Important Parameters Determining Maximum Impact.

Because the contaminant transport rather than waste from release sets the time scale in most performance assessments, the maximum response in those analyses depends on many variables. The total

amount of contaminant reaching a point is fixed, and the peak response is inversely proportional to the width of the transport curve. In this analysis, the release rate of the waste form sets the time scale. The response mirrors the release rate and the maximum depends only on a few variables.

These few parameters can be found by using the equation described in Section 3.5.2.5

$$\text{Response} = \sum_i \frac{I_i \Gamma_i w D_i}{r A}$$

and noting that for the small amount of recharge characteristic of the Hanford Site that the aquifer mixing factor w can be written as

$$w(x) = w(x_0) \frac{x}{x_0} \frac{A}{A_0} = N_0 \frac{x}{x_0} \frac{A}{A_0} = \bar{w}_0 r A$$

and that for very-long-lived nuclides released very slowly from the waste form that

$$\Gamma_i(t) = R_i(t - t_0)$$

resulting in

$$\text{Response} = \frac{w(x_0)}{x_0 A_0} \sum_i I_i R_i D_i$$

where

- I_i - the inventory of contaminant i
- Γ_i - the flux of contaminants at the bottom of the vadose zone
- w - the ratio of contaminant concentration at the well to the concentration at the bottom of the vadose zone
- D_i - the dosimetry factor relating response to concentration of contaminant i
- r - is the recharge rate
- A_0 - reference area over which the contaminants leave the vadose zone (taken to be the area of the disposal facility)
- x_0 - reference recharge rate (taken as 1 mm/y)
- R_i - the release rate of contaminant i from the waste form at a time corrected for the vadose zone travel time t_0 .

The second equation follows that for small recharge rates the concentration of contaminants in water in the vadose zone is proportional to the recharge and area but that the concentration of contaminant in water in the well depends only on the much

larger amount of groundwater. The third equation reflects that the time dependence of the problem is driven by the slow release of the waste form rather than the travel in the vadose zone. For convenience, the effect of retardation on the aquifer mixing factor w is neglected, and one value is used for all elements.

The maximum response depends on the inventory, the waste form release rate, the dosimetry factor for each long-lived contaminant, and a quantity that reflects the mixing in the unconfined aquifer. Each of these terms has an uncertainty associated with it.

The inventory of each major radionuclide taken as an upper limit is reasonably well known. As the result of the pre-treatment and the immobilization processes, the amount of radionuclides may drop but it is not expected to be significantly above the values used in this study.

The waste form release rate used in this study comes from the RFP. This rate is defined at short times in the RFP and was extended to longer times using a simple model. As noted in Section 4.5.2 which describes a mechanistic approach to estimate release rate, the release rate could be significantly different in magnitude and shape. However, how the vendors will proceed will not be known until mid 1998.

Different sets of dosimetry factors exist and the results show some sensitivity to them. However, the sensitivity is minor.

The mixing of the contaminants in the groundwater depends on the flow rate and dispersion in the unconfined aquifer. Although some uncertainty (factor of ~ 2) exists about what the flow rate will be thousands of years in the future, the values used in this study are probably near the low end.

Uncertainty remains in the calculated maximum, but this uncertainty mainly reflects a lack of knowledge of processes that will be selected in the next few years. Better information on the inventories and the flow of the unconfined aquifer will also help to increase our confidence.

4.10.3 Impact of the Groundwater Scenario at 10,000 Years

4.10.3.1 Overview. The time of compliance is for the first 10,000 years. Therefore the values of the calculated responses during this time are the most important. Section 4.3.4 describes the analysis for the base analysis case. This section will describe the general understanding of the calculated results for the first 10,000 years.

Unlike the maximum value, the value of an impact at 10,000 years depends on most of the input variables. However, the

variables can be grouped by the manner in which they affect the results:

- The parameters affecting travel time
- The parameters affecting how quickly the estimated impact rises from small values to the maximum value
- the parameters affecting how the estimated impact decreases after the maximum value is reached.

4.10.3.2 Travel Time. Travel time is very important because it separates the contaminants into groups. For times significantly greater than the travel time, the value of the response for that group is at its maximum and depends only on a few variables. For times much less than the travel time, that group contributes very little compared to groups that have already reached the maximum value. The exception is for the unretarded group, which is the first group to reach the unconfined aquifer. For times around the travel time, the response for the group is not only significant but changes quickly. The sensitivity cases have shown that the major parameters affecting the travel time are as follows:

- The vault layout (Section 4.6.2)
- The hydraulic diverter (Section 4.6.3.2)
- The hydraulic parameters of the disposal facility and of the vadose zone (Section 4.7.2)
- The infiltration rate (Section 4.7.4)
- The transport and hydraulic diffusion parameter in the filler material between canisters (Section 4.7.2.2)
- the geochemical K_d values within the disposal system and in the natural environment (Section 4.7.3).

The first four parameters affect the moisture content in the disposal facility or in the vadose zone.

The vault layout is important because the vaults cast a moisture shadow if their design contains a hydraulic diverter. Water tends to go down rather than horizontally, so that once the water is laterally displaced, relatively dry sediments exist beneath the engineered disposal system. The larger the engineered disposal system, the larger the shadow. The unretarded travel time is calculated to be four times longer when all the vaults are a single unit than when only vault rows are used.

The hydraulic diverter or, more properly, the sand-gravel capillary barrier creates the moisture shadow. If no diverter is used, then the flow is almost totally vertical. The unretarded

travel time for the base analysis case is only 1,100 years without a barrier but about 10,000 years with one.

The hydraulic parameters establish how moisture flows and how wet (or dry) the soil is for a particular infiltration rate. Assuming various strata and hence different hydraulic properties, the travel time for the uranium isotopes can vary by about 15 percent.

The inside of the disposal facility is expected to be so dry that the movement of contaminants is likely to be by diffusion through the moisture rather than movement with the moisture. Which process is more important will be determined by the parameters describing diffusion and moisture transport inside the facility. In the base analysis case diffusion is more important than advection. If the diffusion parameter is decreased by 20, the travel time to the aquifer increases by a factor of 6.

The retardation of contaminant travel by geochemical processes allows most of the most troublesome isotopes to decay before they reach the aquifer. For example, it is calculated to take ⁹⁰Sr 5,000 half-lives to reach the aquifer, ¹³⁷Cs 150,000 half-lives, and ²³⁹Pu 75 half-lives.

4.10.3.3 Rise of the Response. Not only will the variables described in Section 4.10.3.2 affect travel time, but also the amount of contamination spreading, both laterally and temporarily. These effects combine to define the shape of the rise of the response at the water table. For the uranium group, the rise time from 10% of the peak value to half of the peak value ranges from 80 percent of the travel time for the base analysis case to 50 percent when the dispersion coefficient is decreased by an order of magnitude.

4.10.3.4 Fall of the Response After the Maximum Value is Reached. The fall of the response curve is important because doses from later retarded groups will add to the first maximum value. Without a falloff, the maximum dose would be a sum of the values shown in Table 4-34. In reality, two effects (decay of the isotopes and reduced waste form release rate) greatly reduces the total.

Although the half-lives of the radiocontaminants are very long, they are short compared to the travel times for plutonium and americium. For example, the travel time of plutonium is about 8 ⁹⁹Tc half-lives while the travel time for americium is about 20. Thus ⁹⁹Tc, the dominant isotope, at early times is not significant at the times when plutonium and americium contribute.

The waste form release rate is expected to decline significantly as time passes. Using either a release rate proportional to surface area or one resulting from the computer simulations from Section 4.5.2, shows that the release rate is approximately 25 percent lower (using surface area) or a factor

of 4 (using the simulation) lower than the peak value which is reached just after just 100,000 years.

4.11 RESULTS OF SCENARIOS WITH RELEASES TO THE AIR

In previous performance assessments, three radionuclides were considered (³H, ¹⁴C, and ²²²Rn) as candidates for atmospheric release. Gaseous release from a vitrified waste form is not a very credible scenario because the waste form is assumed to be stable over such a long time. The waste form is assumed to release less than 4.4×10^{-6} of its initial inventory per year.

As discussed in Section 3.3.5 the transport of vapors is governed by Fick's equation, the solution (Wood 1995) to which is

$$J = C \sqrt{\lambda D} \exp(-x\sqrt{\lambda D})$$

where

- J - the flux at the surface (Ci m⁻² y⁻¹),
- C - the concentration of the radionuclide in the ground (Ci/L³),
- x - the depth of the source (m),
- λ - the mean life of the radionuclide (= 6.64×10^{-3} y⁻¹ for ³H, 1.2×10^{-4} y⁻¹ for ¹⁴C and 65.9 y⁻¹ for ²²²Rn), and
- D - the diffusion coefficient ($= 10^{-7}$ cm²/s = 3.14 m²/y) [from Section 3.4.4.3].

The concentration of ¹⁴C is simply the inventory (7.73 Ci) times the fractional amount release from the waste form (taken as 4.4×10^{-6} in a year) divided by the waste volume (3.2×10^5 m³). However, the inventory of ³H and ²²²Rn changes as a function of time because of the short half-life of ³H and the decay of ²²²Rn's parents (primarily ²³⁴U and ²³⁸U). The inventory for ³H is taken at 0 years after closure and the release fraction as 4.4×10^{-6} in a year. The inventory for ²²²Rn as a function of time is shown in Table 4-35. As expected, the ²²²Rn inventory starts at the initial activity of its parent ²²⁶Ra, and builds until it reaches the activity of ²²⁶U.

Because the top of the waste form is greater than 10 meters from the surface, the depth of the source will be taken to be 10 meters for these calculations. The calculated releases to the atmosphere are

| | | |
|-------------------------------|---|---|
| ³ H (500 y): | 7.51×10^{-10} Ci m ⁻² y ⁻¹ | $= 2.4 \times 10^{-16}$ pCi m ⁻² s ⁻¹ |
| ¹⁴ C: | 1.95×10^{-12} Ci m ⁻² y ⁻¹ | $= 6.2 \times 10^{-9}$ pCi m ⁻² s ⁻¹ |
| ²²² Rn (10,000 y): | 7.31×10^{-25} Ci m ⁻² y ⁻¹ | $= 2.3 \times 10^{-26}$ pCi m ⁻² s ⁻¹ |
| (peak): | 1.02×10^{-23} Ci m ⁻² y ⁻¹ | $= 3.2 \times 10^{-19}$ pCi m ⁻² s ⁻¹ |

The very small fluxes of ²²²Rn result from the short half-life of ²²²Rn and the very deep burial of the waste. Practically all of the radon decays before it can reach the surface.

Table 4-35. Inventory of ^{222}Rn as a Function of Time.

| Time (y) | Inventory (Ci) | Time (y) | Inventory (Ci) |
|----------|----------------|----------|----------------|
| 0. | 2.35E-03 | 1000. | 3.27E-02 |
| 2000. | 1.10E-01 | 3000. | 2.19E-01 |
| 5000. | 4.99E-01 | 7500. | 8.74E-01 |
| 10000. | 1.28E+00 | 20000. | 2.64E+00 |
| 30000. | 3.96E+00 | 50000. | 6.27E+00 |
| 75000. | 8.63E+00 | 100000. | 1.05E+01 |
| 200000. | 1.49E+01 | 300000. | 1.66E+01 |
| 500000. | 1.76E+01 | 750000. | 1.78E+01 |
| 1000000. | 1.78E+01 | | |

To convert the ^3H and ^{14}C flux into a dose, the following equation is used

$$D = J A (X/Q) B F$$

where

| | | |
|---------|--------------------------------------|---|
| D = | the annual inhalation dose | (mrem/y), |
| J = | the flux at the surface | ($\mu\text{Ci}/\text{m}^2/\text{y}$ above), |
| A = | the area of the facility [Concept 1] | ($4.45 \times 10^4 \text{ m}^2$), |
| (X/Q) = | normalized integrated exposure | ($1.0 \times 10^{-6} \text{ s}/\text{m}^3$), |
| B = | inhalation rate | ($2.67 \times 10^{-6} \text{ m}^3/\text{s}$), |
| F = | dose conversion factor | ($^3\text{H}: 9.5 \times 10^4 \text{ mrem}/\text{Ci}$) ($^{14}\text{C}: 2.1 \times 10^6 \text{ mrem}/\text{Ci}$) |

The values for (X/Q), B, and F are taken from the *Performance Assessment for the Disposal of Low-Level Waste in the 200 West Area Burial Grounds* (Wood 1994b-3). The resulting annual dose is 2.7×10^{-17} mrem at 500 years for ^3H and 4.8×10^{-9} mrem (steady state) for ^{14}C .

Thus the predicted release of ^3H , ^{14}C and ^{222}Rn are far below the corresponding performance objectives (10 mrem in a year for ^3H and ^{14}C and $20 \text{ pCi m}^{-3} \text{ y}^{-1}$ for ^{222}Rn).

These calculations for ^3H are sensitive to the amount of ^3H in the waste form, taken to be 100 percent, and to the time of compliance taken as 500 years. Because of the short half-life, ^3H should decay long before the waste form releases any of the amount that will actually be in the waste form.

The calculations for ^{14}C are relatively insensitive to the various parameters. However, the amount of ^{14}C might be as high

as 100 Ci (WMC 1996), compared with 7.73 Ci of the base analysis case. Using the higher estimate of ^{14}C inventory would raise the predicted dose to 6.3×10^{-8} mrem in a year, still much less than the performance objective of 10 mrem in a year.

Because so much of the ^{222}Rn is predicted to decay by the time it reaches the surface, the ^{222}Rn calculation is extremely sensitive to the waste depth and the diffusion coefficient of Rn in the soil. If the waste is only 5 meters deep rather than the 10 meters assumed or if the diffusion coefficient is 10^{-3} cm²/s, the value used in the Hanford Burial Grounds Performance Assessment (Wood 1994b-3), then the predicted flux increases by over 10 orders of magnitude. However, the predicted dose is still orders of magnitude less than the performance objective.

4.12 RESULTS OF CATASTROPHIC EVENTS

Based on the discussion presented in Section 3.3.3, the only scenario considered is that of an ice-age flood that scrapes away all material down to 20 meters (the depth of the disposal facility) and then redeposits the material over the area of the Hanford Site. As noted in Section 2.2.4.4, the next such event might be expected in about 50,000 years. Using the farm scenario as the exposure scenario and assuming that all the waste is in a form that can be inhaled or ingested, the predicted dose is estimated to be 0.76 mrem (EDE) in a year. Practically all of the predicted dose (>98 percent) comes from the external exposure of ^{135}Sn and its daughters. If the glacier flood occurs as early as 10,000 years, the predicted dose increases to 1.01 mrem (EDE) in a year. If the flood occurs at 100,000 years, the predicted dose is 0.53 mrem (EDE) in a year. All of these values are much less than the 25 mrem (EDE) in a year maximum established for the first 10,000 years for the all-exposure pathways. If the flood only redistributes the waste over an area equivalent to the 200 Areas (78 km²), the predicted dose at 50,000 years [14 mrem (EDE) in a year] is still less than the all-pathways limit.

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5. PERFORMANCE EVALUATION

5.1 OVERVIEW

This chapter compares the estimated impacts from Chapter 4 with the performance objectives established in Chapter 1. It also discusses changes needed to meet the performance objectives and future work that is planned.

5.2 COMPARISON OF ESTIMATED IMPACTS TO PERFORMANCE OBJECTIVES

5.2.1 Overview

The comparison of estimated impacts to performance objectives is given for each area of protection cited in Section 1.5:

- Protection of the general public
- Protection of the inadvertent intruder
- Protection of groundwater resources
- Protection of surface water resources
- Protection of air resources.

5.2.2 Protection of General Public

Table 5-1 compares the performance objectives for protecting the general public with the results from the base analysis case. The estimated all-pathways doses are significantly lower than the performance objectives during the first 10,000 years (the time of compliance). The sensitivity cases show that for the all-pathways performance objective to be exceeded would require one or more of the following:

- The waste form not meeting the specifications in the RFP for TWRS Privatization (DOE-RL 1996) or not performing at long times as modelled in this analysis
- A high infiltration rate and a disposal facility design without a hydraulic diverter
- A significantly larger inventory.

None of the measures are estimated to exceed the value of the performance objectives at any time. However, the maximum value of the all-pathways dose (23 mrem in a year) is estimated to occur at about 50,000 years; is just below the value of the performance objective (25 mrem in a year). The other two measures (all-pathways including other Hanford Site sources and ALARA) are estimated to remain significantly lower than the performance objectives at all times.

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Table 5-1. Comparison of Estimated Impacts with Performance Objectives for Protecting the Public. Time of Compliance is 10,000 Years. Point of Compliance is Well 100 Meters Downgradient of the Facility.

| Performance Measure | Performance Objective | Estimated Impact |
|--|-----------------------|------------------|
| All-pathways [mrem in a year] | 25. | 6.4 |
| All-pathways, including other Hanford sources [mrem in a year] | 100. | <19. |
| ALARA (all-pathways) [persons-rem/y] | 500. | 5. |

5.2.3 Protection of Inadvertent Intruders

Table 5-2 compares the estimated impacts to the performance objectives for protecting the inadvertent intruder. The time of compliance starts at 500 years after closure. For both acute and continuous exposure, the performance objective is met by at least a factor of three. ¹²⁶Sr is the most important radionuclide. The estimated dose values for inadvertent intrusion are larger than expected because the well and garden size used in this analysis are conservative. Also, the actual inventory of ¹²⁶Sr will probably be smaller than used here because much of it will go into the high-level waste fraction. Finally, there are indications that the value for the half-life of ¹²⁶Sr used in this analysis is too small which results in an overprediction of dose.

Table 5-2. Comparison of Estimated Impacts with Performance Objectives for Protecting the Inadvertent Intruder. Time of Compliance Starts at 500 years.

| Performance Measure | Performance Objective | Estimated Impact |
|--------------------------------------|-----------------------|------------------|
| Acute exposure [mrem] | 500. | 5.5 |
| Continuous exposure [mrem in a year] | 100. | 27.5 |

5.2.4 Protection of Groundwater Resources

Table 5-3 compares the estimated impacts to the performance objectives for protecting the groundwater resources. The time of compliance is 10,000 years and the point of compliance is at a well 100 meters down gradient of the disposal facility. The estimated impact from beta/photon emitters is a factor of two less than the performance objectives and a factor of nine less

than the performance objectives for the alpha-emitting radionuclides. The concentration of radium is insignificant. The most important drivers are the inventory of technetium and uranium, the release rate from the waste form, and the amount of mixing in the aquifer. For the impact for alpha-emitting radionuclides, the amount of retardation experienced by the uranium isotopes is also important.

Table 5-3. Comparison of Estimated Impacts with Performance Objectives for Protecting Groundwater Resources. Time of Compliance is 10,000 Years. Place of Compliance is a Well 100 Meters Downgradient of the Facility.

| Performance Measure | Performance Objective | Estimated Impact |
|---------------------------------------|-----------------------|------------------|
| Beta/Photon Emitters [mrem in a year] | 4. | 2.0 |
| Alpha-emitting radionuclides [pCi/l] | 15. | 1.7 |
| Ra [pCi/l] | 3. | <0.001 |

5.2.5 Protection of Surface Water Resources

Table 5-4 compares of the estimated impacts to the performance objectives for protecting the surface water resources. The time of compliance is 10,000 years and the point of compliance is at a well intercepting the groundwater just before it mixes with the Columbia River. The estimated impacts are over an order of magnitude lower than the performance objectives. Because of the large flow of the Columbia River and the tremendous mixing that occurs in a relatively few miles of the river, the predicted impacts from the use of water from the Columbia River would be far lower.

Table 5-4. Comparison of Estimated Impacts with Performance Objectives for Protecting Surface Water Resources. Time of Compliance is 10,000 Years. Place of Compliance is a Well Intercepting the Groundwater Prior to Entering the Columbia River.

| Performance Measure | Performance Objective | Estimated Impact |
|---------------------------------------|-----------------------|------------------|
| Beta/Photon Emitters [mrem in a year] | 1. | 0.070 |
| Alpha-emitting radionuclides [pCi/l] | 15. | 0.060 |
| Ra [pCi/l] | 3. | <0.001 |

beta/photon drinking water dose, and the concentration of alpha-emitting radionuclides in groundwater are less than a factor of 10 lower than the corresponding performance objective. As new information is obtained for the project, the estimated impacts will probably decline and more easily meet the performance objectives.

5.3 CHANGES REQUIRED TO MEET PERFORMANCE OBJECTIVES

All performance objectives were met in this analysis.

However, this analysis was based on making enabling assumptions concerning disposal facility location and design as well as waste form performance. As the project matures, these enabling assumptions may become faulty. In that case, changes may need to be made in order to achieve the performance objectives.

5.4 WASTE ACCEPTANCE CRITERIA

No waste acceptance criteria are being established in this analysis. This analysis does show that the specifications for the waste form contained in the Request for Proposal for tank waste immobilization (DOE-RL 1996) when combined with an acceptable disposal facility design can meet performance objectives established in this document. A waste acceptance activity for the first phase of tank waste immobilization is just starting.

The waste form specifications for the bulk of the low-activity tank waste will be established in 2005. The results of the final performance assessment will be used in setting the specifications for that waste. Also the waste acceptance activity will use the results of those analyses.

5.5 CONTINUED WORK

5.5.1 Overview

As often noted in this report, the type of waste form, the inventory in the waste form, the location of the disposal facility, and the design of the disposal facility have not yet been decided. However, many of the decisions affecting these items will be made in 1997 and 1998. This section describes the overall schedule for the performance assessment activity as well as plans for data collection.

3.2.6 Protection of Air Resources

Table 5-5 displays a comparison of the estimated impacts to the performance objectives for protecting air resources. The time of compliance is 10,000 years and the point of compliance is just above the disposal facility. The estimated impacts are over an order of magnitude lower than the performance objectives.

Table 5-5. Comparison of Estimated Impacts with Performance Objectives for Protecting Air Resources. Time of Compliance is 10,000 Years. Place of Compliance is Just Above the Disposal Facility.

| Performance Measure | Performance Objective | Estimated Impact |
|--|-----------------------|------------------|
| Radon [$\text{pCi m}^{-3} \text{ s}^{-1}$] | 20. | <0.001 |
| Other radionuclides (^3H and ^{14}C) [mrem in a year] | 10. | < 10^{-4} |

3.2.7 Application to Existing TWRS Disposal Facility

Some 6 to 13 percent of the low-level tank waste may be disposed of in four existing vaults just east of the PUREX facility. This waste may have a slightly higher (at most a factor of 2) concentration of technetium than waste to be processed later. The present structures are similar to those in Concept 2, but their long side is shorter than Concept 2, but still long compared to the width. Therefore, the impact of using the four existing vaults would meet the performance objectives for protecting the general public, groundwater, surface water, and air resources. Because the inventory of radiocontaminants such as ^{129}Sn in the initial 6 to 13 percent of the low-level tank waste is not known, how such a disposal would affect inadvertent intruders is not yet known, but should not differ greatly from the forecast described in Section 5.2.3.

The impact from the disposal of the remainder of the waste in alternative facilities should closely follow the analysis presented. The inventory of waste not disposed of in the four existing vaults is nearly the same as the inventory assumed in this analysis.

3.2.8 Summary

Most of the estimated effects easily meet the performance objectives set out in Section 1.5. However, the estimated all-pathways dose, the continuous dose to an inadvertent homesteader,

beta/photon drinking water dose, and the concentration of alpha-emitting radionuclides in groundwater are less than a factor of 10 lower than the corresponding performance objective. As new information is obtained for the project, the estimated impacts will probably decline and more easily meet the performance objectives.

5.3 CHANGES REQUIRED TO MEET PERFORMANCE OBJECTIVES

All performance objectives were met in this analysis.

However, this analysis was based on making enabling assumptions concerning disposal facility location and design as well as waste form performance. As the project matures, these enabling assumptions may become faulty. In that case, changes may need to be made in order to achieve the performance objectives.

5.4 WASTE ACCEPTANCE CRITERIA

No waste acceptance criteria are being established in this analysis. This analysis does show that the specifications for the waste form contained in the Request for Proposal for tank waste immobilization (DOE-RL 1996) when combined with an acceptable disposal facility design can meet performance objectives established in this document. A waste acceptance activity for the first phase of tank waste immobilization is just starting.

The waste form specifications for the bulk of the low-activity tank waste will be established in 2005. The results of the final performance assessment will be used in setting the specifications for that waste. Also the waste acceptance activity will use the results of those analyses.

5.5 CONTINUED WORK

5.5.1 Overview

As often noted in this report, the type of waste form, the inventory in the waste form, the location of the disposal facility, and the design of the disposal facility have not yet been decided. However, many of the decisions affecting these items will be made in 1997 and 1998. This section describes the overall schedule for the performance assessment activity as well as plans for data collection.

3.5.2 Overall Schedule

Table 5-6 displays the schedules for the major events in the performance assessment activity. This schedule assumes that two sets of performance assessments will be written, one for waste to be disposed of at an existing TWRS disposal facility and another for an alternative location (probably consisting of new facilities). In addition, a strong research plan has been laid out to obtain the waste form, geotechnical, and other data that will be needed in the preliminary and final performance assessments.

Table 5-6. Schedule of Major Events in Performance Assessment Activity. Abbreviations are Defined at the End of the Table.

| Event | Date |
|---|------------|
| Review, Revise, and Reissue of this Document | Sept. 1997 |
| Publish Data Packages for the EDF PPA | March 1999 |
| Send EDF PPA to PRP for comment | March 2000 |
| Publish Data Packages for the AS PPA | March 2000 |
| Receive PRP comments on EDF PPA | Jan. 2001 |
| Send AS PPA to PRP for comment (Draft TPA Milestone 90-05T due 9/01) | March 2001 |
| Publish Data Packages for the EDF PPA | March 2001 |
| Receive PRP comments on AS PPA | Nov. 2001 |
| Send EDF PPA to DOE for approval | Dec. 2001 |
| Publish Data Packages for AS PPA | March 2002 |
| Send AS PPA to DOE for approval | Dec. 2002 |

AS PPA - Alternate Site Final Performance Assessment
 AS PPA - Alternate Site Preliminary Performance Assessment
 EDF PPA - Existing TWRS Disposal Facility Final Performance Assessment
 EDF PPA - Existing TWRS Disposal Facility Preliminary Performance Assessment
 PRP - Peer Review Panel

3.5.3 Data Collection Activities

3.5.3.1 Overview. An extensive data collection activity is planned for the low-level tank waste performance assessment activity. The data to be collected fall into three natural groupings: data related to waste form performance, data related to the transport of contaminants from the waste form to the point of compliance, and other data.

Much data have already been collected. The intent is to issue documents containing all the data to be used in each performance assessment. These documents would be similar to *Data Packages for the Hanford Low-Level Tank Waste Interim Performance Assessment* (Mann 1995a), which forms the basis of this performance assessment.

5.5.3.2 Waste Form Data. Because of the expected very slow release of contaminants from the waste form, most of the impacts of this disposal action are proportional to the performance of the waste form. At the time of this writing, the waste form to be used has not been decided. However, silicate glass is the most likely candidate.

The release of contaminants from a glass waste form in a dry environment over thousands of years is very complex. Many data paths are being pursued. Short-term experiments are being run to determine glass corrosion rates as a function of temperature, pH, and other environmental conditions. Other short-term experiments determine the mineral phases that form after glass corrodes. Still other experiments reveal the rate of corrosion under unsaturated conditions. Finally, long-term (over many years) experiments are being performed to integrate the information.

All this information is being used to formulate, test, and calibrate computer models. These models are being further developed to be more robust and accurate. More chemical processes are being modeled. The intent is to have a computer model that simulates the influx of water to the disposal facility, the corrosion of the glass, the release of the contaminants from the original glass waste form and its secondary mineral phases, and the transport of those contaminants out of the engineered disposal system.

5.5.3.3 Disposal Facility Data. To model the disposal facility, not only is the design needed but also are the hydraulic and transport properties of the waste form and near-field environment. Movement of moisture through cracks in glass and the determination of hydraulic and geochemical properties of the original and degraded materials will be the subject of research. Efforts to support design efforts for moisture barriers (both surface and sand-gravel capillary), getter materials, and water conditioning layers are part of the multi-year plan.

5.5.3.4 Geotechnical Data. Geotechnical data are those data that describe the vadose zone and the unconfined aquifer. The vadose zone and the unconfined aquifer play an important role in the performance assessment because the vadose zone delays the arrival of contaminants and the aquifer supplies additional water in which the contaminants can mix.

In each of the next three years a borehole will be drilled in the locations where the disposal facilities will be sited. The boreholes will not only provide samples for determining other geotechnical information, but will also allow access to the

vadose zone for in-situ moisture experiments and to the unconfined aquifer for groundwater testing.

The samples from the boreholes (as well as samples from other locations on the Hanford Central Plateau) will be used to determine the geologic strata underlying the disposal facilities and the hydraulic and geochemical properties of those strata. In addition, the samples will be used to determine chlorine content as a function of depth and infiltration rates as a function of time.

Other analyses will also use and support the determination of geotechnical data needed for the preliminary and final performance assessments. For example, the computer simulations of moisture flow in Hanford Site surface sediments will combine the long-term infiltration rates determined by chlorine measurements, with short-term (a few decades) determination of the infiltration rate and with climate, soil, and vegetation studies. Enhanced contaminant transport through colloidal movement or in clastic dikes will also be studied. Studies of the spatial variability of soil hydraulics data and alternate conceptual models will be important for the completion of the preliminary and final performance assessments.

5.5.3.5 Other Data. Large amounts of data are generated outside of the performance assessment activity. These data must be sought out and their quality determined. Examples are inventory estimation, facility design data, and dosimetry data. Inventory estimates depend on the amount of radionuclides in the Hanford Site tanks, the type of processing used to separate the low-activity fraction from the high-level waste fraction, and the techniques used to immobilize the low-activity waste fraction. For facility design data, close cooperation will be maintained with the design team to ensure that accurate facility design data are used and to ensure that current performance assessment estimates are factored into design concepts and calculations.

5.6 CONCLUSION

This analysis of the long-term effects from the proposed disposal of low-level Hanford Site tank waste used the methods and formats required by the Peer Review Panel to satisfy DOE Order 5820.2A. Many decisions (choice of location, choice of waste form, choice of facility design) remain to be made. However, the calculations presented in this analysis show that it is likely that once these decisions are made and the additional data are collected, the performance objectives will be met.

6.0 RESUMES OF PREPARES

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Prior to joining DOE, Neil was a post doctoral fellow at the Argonne National Laboratory where he studied corrosion characteristics of waste glass and soil remediation. At DOE, Neil has overseen technology development for the Low-Level Waste Program as well as the development of TWRB Privatization Specifications. Neil reviewed this document.

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From 1985 to 1989, Dr. Chen worked as a lecturer at the China University of Geosciences. While earning his Ph.D. in geochemistry at Indiana University under Professor Peter Ortoleva, he developed a reactive-transport simulator CIRF.A. Since joining PNNL in 1994, he has been the principal developer of the AREST-CT code. His expertise is in reaction-transport modeling of subsurface systems. He is the co-author of one book and has published and presented over 22 papers. Dr. Chen performed the AREST-CT calculations for this analysis.

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Cheryl was the main co-author of this document. She also produced the facility concepts used in this assessment and oversaw the material science research conducted for the overall performance assessment effort. She has more than 10 years experience in metallurgical related research and development, technical support, and project coordination for government, foreign, and private industry.

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Dr. Kincaid is the Hanford representative on the DOE Peer Review Panel. He was the technical manager and key contributor to the *Performance Assessment of Grouted Double-Shell Tank Waste Disposal at Hanford*. He has been the Technical Group Leader of the Soil Physics Group and of the Subsurface Transport Group. He was a key contributor in the development of contaminant transport codes and has contributed to various performance assessments. Charlie reviewed this document and advised on its development.

**RAZIUDDIN KHALEEL, Fellow Engineer, Environmental Modeling,
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Dr. Khaleel has over 25 years of experience in groundwater hydrology and numerical simulations of subsurface flow and transport. He was a key contributor to the Hanford solid waste performance assessments, particularly in the area of conceptual model development, direction of modeling, and in writing the document. For this document, Raz reviewed the approach, models, and results.

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Mr. Kline has been an employee of BCS Richland, Inc. at the Hanford Site since January of 1978. He has nearly 20 years of experience in mathematical modeling and numerical simulation of physical systems. For the past 15 years, Mr. Kline has concentrated on modeling and simulation of isothermal and nonisothermal flow and transport in both groundwater and the vadose zone. For this performance assessment, Miall developed and tested the unit cell model and performed the unit cell simulations of vadose zone flow and transport.

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Mr. Lamont is a Project Director in the DOE-RL Hanford Tank Waste Remediation System Office. He has more than 20 years of experience in nuclear waste management. Mr. Lamont reviewed the interim performance assessment as part of his responsibility for management of projects for storage/disposal of the immobilized waste products from the planned treatment of Hanford tank waste.

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Dr. Lu has been employed at the Hanford Site since 1979. He has worked on a variety of nuclear engineering projects. Most recently, he has been in charge of various modeling studies using the VAM3D-3D flow and transport code. In particular, he was responsible for the source term and modeling for the Hanford solid waste performance assessments. For this document, Allen performed the aquifer calculations.

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Dr. Mann is the team leader for the Tank Waste Performance Assessment Activity, which is charged with preparing this performance assessment. He has worked for over twenty years in the field of nuclear data and the collection of that data to large energy facilities. He has advised the Department of Energy and the International Atomic Energy Agency. He was the main author of this document.

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Mr. McGrail has over 14 years of experience in fundamental and applied research on immobilization and disposal of hazardous and radioactive wastes. He is a principal investigator on performance assessment projects for high-level waste disposal in Japan and the U.S., and for the Hanford low-level waste disposal project. He is a co-developer of the AREST-CT code, which is used to simulate the release and transport of contaminants modified by both kinetic- and equilibrium-controlled chemical reactions. He is the principal developer of the Tank Waste Simulator code, which is used to model coupled fluid, heat, and chemical mass transport processes in underground storage tanks. In addition to his modeling research, Mr. McGrail has also invented several novel experimental techniques to evaluate the kinetics and thermodynamics of waste form-water reactions including a two-phase single-pass flow-through method and the pressurized unsaturated flow (PUF) method. Mr. McGrail has published and presented over 100 papers on all aspects of his waste management research. Mr. McGrail supervised the AREST-CT calculations for this analysis.

MEL G. PIEPHO, Senior Specialist, Hydrological/Numerical Modeling Section, Daniel B. Stephens and Associates, Inc.

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| Ph.D. | Physics, Indiana University | 1974 |

Dr. Piepho has over twenty years of mathematical modeling, numerical analysis, and computer science experience. For the last ten years, he has concentrated in studies of vadose zone flow and contaminant transport. He supplied the flow and transport calculations for the Hanford Grout performance assessment. For this performance assessment, Mel performed the vadose zone calculations for the facility model.

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Dr. Reidel has been studying the geology and geohydrology of the Columbia Basin for over 25 years, with nearly 20 years spent at the Hanford Site. At Hanford he has worked in the fields of commercial nuclear waste disposal, groundwater management and protection, waste management, site characterization, and natural phenomena hazards. He is a recognized expert on the geology of the Hanford Site. He is currently an Associate Adjunct Professor at Washington State University and a part time faculty member at Yakima Valley Community College. Steve provided much of the geology for this assessment and reviewed the document.

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Dr. Rittmann has employed at the Hanford Site since 1980 and has been using environmental transport and dose models since 1983. He is a member of the Hanford Environmental Dose Overview Panel. He was responsible for the dosimetry analyses for the Hanford solid waste performance assessments. For this document, Paul performed supplied the dosimetry data and equations.

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Dr. Schmittroth has worked for Westinghouse Hanford Company since 1970. Primary activities have supported nuclear data analysis; specifically in the areas of nuclear cross sections, decay heat, and calculations of radionuclide inventories from both fast and thermal reactors. Recent activities have included groundwater modeling (vadose zone and unconfined aquifers), statistical analyses, and Monte Carlo transport calculations of molecular flow. Frank reviewed this document.

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| Ph.D. | Geology, Michigan State University | 1975 |

Dr. Tallman has nineteen years of experience in geology and geotechnical studies and applications at the Hanford Site. Her work has been applied to site characterization and selection studies and to the design and construction of new facilities. She is the point of contact for the Hanford Site in matters relating to natural phenomena hazards (NPH) and NPH design criteria. Prior to coming to Hanford, she was an assistant professor of geology at Smith College. Ann provided the section on seismic analysis and reviewed the entire document.

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| B.S. | Metallurgical Engineering, Purdue University | 1962 |
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Mr. Williamson is the project Manager for this activity. George has 30 years of technical and project management experience in the nuclear field associated with the fabrication of nuclear fuels for commercial power reactors and mixed waste treatment and disposal projects for defense wastes. He participated in the early development of the performance assessment for the grouting of Hanford tank wastes. George was the project manager for this activity and reviewed this performance assessment.

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 - [2. Section 61.55 describes waste classification. (May 1989)]
 - [3. Subpart C, sections 61.40 through 61.44 stated the performance objectives.]
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- [2. Section 4.7 contains the discussion on socioeconomics]
- [3. Section 4.3.1.5 describes flooding on the Hanford Site]
- [4. Section 4.5 contains ecological data]

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- [2. Sections 3.4.12 on page 3.69 and 3.4.13 starting on page 3.70 describe the vadose zone hydrologic parameters.]
- [3. Section 3.3.6.6 on page 3.62 describes the effective diffusion constant for the vadose zone.]
- [4. Section 2.6 describes the Grout Disposal Facility.]
- [5. The population along the Columbia River is found as footnote f to Table 4.2 on page 4.12.]
- [6. Appendix G.1 describes code selection.]
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- [2. Section D.2 discusses the role and timing assumptions for engineered systems.]

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- [1. Section 3.1.9 describes plans for recharge rate determination.]
- [2. Section 3.1 D describes the integrated borehole activity. Other activities described in the SOW will obtain samples from these boreholes.]

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- [1. Section 1.6, page 1-8 discusses the time of compliance.]
- [2. P. 3-31 provides the discussion of the radon diffusivity coefficient.]
- [3. Section 4.3.1 provides the calculation of the release of contaminants to air]

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**APPENDIX A
SPECIFICATIONS FOR IMMOBILIZATION
(USDOE/RL 1996)**

[References are given in Section 2.2.1
and not necessarily in Chapter 7.]

Specification 2: Immobilized Low-Activity Waste

- 2.1 Scope:** This Specification defines the requirements for the *Immobilized Low-Activity Waste (ILAW)* product, one of the final waste products identified in Section C.4 of this *Statement of Work*.
- 2.2 Requirements:**
- 2.2.1 References:**
- 2.2.1.1 10 CFR 61. *Licensing Requirements for Land Disposal of Radioactive Waste*, Code of Federal Regulations. U.S. Nuclear Regulatory Commission, Washington, D.C.
 - 2.2.1.2 40 CFR 268. *Land Disposal Restrictions*. Code of Federal Regulations. U.S. Environmental Protection Agency, Washington, D.C.
 - 2.2.1.3 49 CFR 172.101. *Table 2 - Radionuclides*. Code of Federal Regulations. U.S. Department of Transportation, Washington, D.C.
 - 2.2.1.4 49 CFR 173. *Shippers-General Requirements for Shipments and Packaging. Subpart I - Radioactive Materials*, Code of Federal Regulations. U.S. Department of Transportation, Washington, D.C.
 - 2.2.1.5 ANSI Standard N14.5. January 16, 1987. *American National Standard for Radioactive Materials - Leakage Tests on Packages for Shipments*. American National Standards Institute, New York, New York.
 - 2.2.1.6 ANS/ANS-16.1. April 14, 1986. *Measurement of the Leachability of Solidified Low-Level Radioactive Wastes by a Short Term Test Procedure*. American National Standards Institute/American Nuclear Society, La Grange Park, Illinois.
 - 2.2.1.7 ANS/ANS-55.1. July 28, 1992. *American National Standard for Solid Radioactive Waste Processing System for Light-Water-Cooled Reactor Plants; Appendix B - Testing for Free Liquids in Solidified Matrices*. American National Standards Institute/American Nuclear Society, La Grange Park, Illinois.
 - 2.2.1.8 ASTM B553-79. May 25, 1979. *Standard Test Methods of Electroplated Plastics*. American Society for Testing and Materials. Easton, Maryland.

- 2.2.1.9 **ASTM C39-94. November 15, 1994. *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.* American Society for Testing and Materials, Easton, Maryland.**
- 2.2.1.10 **ASTM C1285-94. October 15, 1994. *Standard Test Methods for Determining Chemical Durability of Nuclear Waste Glasses: Product Consistency Test (PCT).* American Society for Testing and Materials, Easton, Maryland.**
- 2.2.1.11 **ASTM G21-90. October 26, 1990. *Standard Practice for Determining Resistance of Synthetic Polymeric Materials to Fungi.* American Society for Testing and Materials, Easton, Maryland.**
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- 2.2.1.13 **DOE Order 5820.2A. September 26, 1988. *Radioactive Waste Management.* U.S. Department of Energy, Washington, D.C.**
- 2.2.1.14 **NRC. January 1995. *Branch Technical Position on Concentration Averaging and Encapsulation.* Division of Waste Management, Office of Nuclear Material Safety and Safeguards, U.S. Nuclear Regulatory Commission, Washington, D.C.**
- 2.2.1.15 **NRC. January 1991. *Technical Position on Waste Form, Rev. 1, Low-Level Waste.* Division Management Branch, Office of Nuclear Material Safety and Safeguards, U. S. Nuclear Regulatory Commission, Washington, D.C.**
- 2.2.1.16 **NUREG/BR-0204. April 1995. *Instructions for Completing NRC's Uniform Low-Level Radioactive Waste Manifest.* U.S. Nuclear Regulatory Commission, Washington, D.C.**
- 2.2.1.17 **NUREG-1293. Rev. 1. April 1991. Pittiglio, C. L., Jr., and D. Hedges. *Quality Assurance Guidance for a Low-Level Radioactive Waste Disposal Facility.* Division of Low-Level Waste Management and Decommissioning, Office of Nuclear Material Safety and Safeguards, U.S. Nuclear Regulatory Commission, Washington, D.C.**
- 2.2.1.18 **SW-846, Method 9095. Rev. 0. September 1986. *Paint Filter Liquids Test.* In *Test Methods for Evaluating Solid Waste, Volume 1C: Laboratory Manual Physical/Chemical Methods,* U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Washington, D.C.**
- 2.2.1.19 **WA 7890008967. Rev. 2. August 1995 (as modified). *Dangerous Waste Portion of the Resource Conservation and Recovery Act Permit for the Treatment, Storage and Disposal of Dangerous Waste.* Hanford Facility, Washington State Department of Ecology, Olympia, Washington.**
- 2.2.1.20 **WAC 173-303. 1995. *Dangerous Waste Regulations.* Washington Administrative Code, as amended.**

2.2.2 Product Requirements:

- 2.2.2.1 Package Description:** The ILAW products shall be in the form of a package. The constituent parts of each package are: a sealed metal container enclosing a waste form, in which the ILAW product is emplaced; an optional matrix material, which may be used to encapsulate the waste form; and an optional filler material, which may be used to fill void spaces in the container before it is closed.
- 2.2.2.2 Waste Loading:** For every gram-mole of sodium provided to the Contractor in Waste Envelopes A and C, the Contractor may produce up to 100 cm³ of ILAW product (based on the external dimensions of the package). For every gram-mole of sodium in Waste Envelope B, the Contractor may produce up to 250 cm³ of ILAW product (based on the external dimensions of the package).
- 2.2.2.3 Size and Configuration:** The package shall be a rectangular metal container and shall have an external dimension, including all appurtenances, of 1.8m (length) x 1.2m (width) x 1.2m (height), ± 0.2m. Once a package size is selected, the dimension of all packages shall be constant and have a dimensional tolerance of ± 0.01m.
- 2.2.2.4 Mass:** The mass of each package shall not exceed 10,000 kg.
- 2.2.2.5 Void Space:** The head space in the fully loaded package shall not exceed 1 percent of the total internal volume of the container. A non-compactable filler material (screened to 4 mesh size or smaller) may be used to meet this requirement. If the waste form and matrix materials are loaded into the container in a manner that results in void spaces between the emplaced pieces, the filler material shall be used to fill the void spaces. If a filler material is used, it shall be compatible with the other materials in the package.
- 2.2.2.6 Chemical Composition Documentation:** The Contractor shall identify in the *Products and Secondary Wastes Plan* the chemical composition of the waste form, matrix material, and filler material for each package. The reported composition shall include elements (excluding oxygen) present in concentrations greater than 0.5 percent by weight. Crystalline and noncrystalline phases expected to be present shall be identified and the amount of each phase shall be estimated for the waste form, matrix material, and filler material.
- 2.2.2.7 Radiological Composition Documentation:** The Contractor shall identify the individual package inventory of radionuclides that are significant as defined in NUREG/BR-0204 and 49 CFR 172.101 (Table 2), in the *Products and Secondary Wastes Plan*. ⁹⁹Techetium (⁹⁹Tc) shall be considered to be significant at concentrations greater than 0.003 Ci/m³ in the ILAW form. The inventories shall be indexed to the year 2000. The documentation shall be consistent with the Radiological Description format described in NUREG/BR-0204.

- 2.2.2.8 Radionuclide Concentration Limitations:** The radionuclide concentration of the ILAW form shall be less than Class C limits as defined in 10 CFR 61.55 and as described in *Branch Technical Position on Concentration Averaging and Encapsulation*. In addition, the average concentrations of ^{137}Cs (Cesium (^{137}Cs), ^{90}Sr (Strontium (^{90}Sr), and ^{99}Tc shall be limited as follows: $^{137}\text{Cs} < 3 \text{ Ci/m}^3$, $^{90}\text{Sr} < 20 \text{ Ci/m}^3$ and $^{99}\text{Tc} < 0.3 \text{ Ci/m}^3$. The average concentrations shall be calculated by adding the inventories of each of the above radionuclides in the packages that have been presented to date for acceptance and dividing by the total volume of waste in these packages.
- 2.2.2.9 Surface Dose Rate Limitations:** The dose rate at any point on the external surface of the package shall not exceed 1,000 mR/m/hr.
- 2.2.2.10 Surface Contamination Limitations:** Removable contamination on the external surfaces of the package shall not exceed 367 Bq/m² for alpha and 3670 Bq/m² for beta-gamma contamination when measured using the method described in 49 CFR 173.443(a).
- 2.2.2.11 Labeling and Manifesting:** Each package shall have a label attached or stamped on the outer surfaces of at least two sides of the container in a readily accessible location. The label shall contain a unique identification (e.g., serial number) which shall be assigned to each package and the corresponding documentation. Labels and markings shall have a predicted service life of 50 years assuming that the packages are stored in a ventilated enclosure at ambient temperatures.
- The Contractor shall prepare a shipping manifest for delivery with each shipment of ILAW product. Information on the manifest shall satisfy the requirements in DOE Order 5820.2A, Chapter III, Section 3.4, and NUREG/BR-0204. Any package containing dangerous waste must be labeled and manifested in accordance with WAC 173-303-370 and the *Dangerous Waste Portion of the Resource Conservation and Recovery Act Permit for the Treatment, Storage, and Disposal of Dangerous Wastes* (Permit No. WA 7890008967).
- 2.2.2.12 Closure and Sealing:** The fully loaded package shall be closed, sealed, and a Tamper Indicating Device applied. The closure system shall be leak tight as defined by *ANSI Standard N14.5*. The closure system shall be designed to ensure that the seal remains intact for a storage period of 50 years in an ambient-temperature, ventilated enclosure.
- 2.2.2.13 External Temperature:** The temperature of the accessible external surfaces of the package shall not exceed 50°C when returned to DOE. This temperature constraint shall assume a shaded, still air environment at an ambient temperature of 38°C.
- 2.2.2.14 Free Liquids:** The package shall contain no detectable free liquids as prescribed in ANSI/ANS-55.1 or SW-846 Method 9095.

- 2.2.2.15 Pyrophoricity or Explosivity:** The package contents shall not be pyrophoric, readily capable of detonation, or readily capable of explosive decomposition or reaction (including reaction with water) at normal pressure and temperature. The waste form and any optional matrix and filler materials shall not be ignitable or reactive as defined in WAC 173-303-090(5) and WAC 173-303-090(7).
- 2.2.2.16 Explosive or Toxic Gases:** The package shall not contain or be capable of generating quantities of explosive (e.g., hydrogen) or toxic gases, vapors, or fumes harmful to persons handling the waste.
- 2.2.2.17 Radionuclide Release Rate:** The average fractional release rates for the waste form or waste form/matrix combination shall be the following: For ⁹⁹Tc, the average fractional release rate (R_{Tc}) shall be less than $2.8E-14$ (s^{-1}); and for, ⁷⁶Selenium (⁷⁶Se), ¹²⁹Iodine (¹²⁹I), ²³⁷Nepotium (²³⁷Np), and uranium isotopes, the average fractional release rate (R) shall be less than $1.4E-13$ (s^{-1}) (see Sections 2.2.2.17.1 and 2.2.2.17.2). The basis for fractional release rate determination shall be the radionuclide inventory remaining in the liquid fraction of waste processed following solid separation.

- 2.2.2.17.1 Silicate Glass Waste Forms:** For silicate glass waste forms, compliance with the fractional release rate requirements shall be established by showing that the average value of the product of the glass corrosion rate, the glass surface area to volume ratio, and the fraction of the processed inventory of technetium that is solidified in the glass satisfies the following constraints:

$$\text{Equation TS 2.1} \quad R_{Tc} = \left(\frac{C_g}{\rho} \right) \times \left(\frac{S_g}{V_g} \right) \times F < 2.8E-14 \text{ (s}^{-1}\text{)}$$

$$\text{Equation TS 2.2} \quad R = \left(\frac{C_g}{\rho} \right) \times \left(\frac{S_g}{V_g} \right) < 1.4E-13 \text{ (s}^{-1}\text{)}$$

where:

C_g is the corrosion rate of the glass ($kg/(m^2 \cdot s)$)

ρ is the glass density (kg/m^3)

S_g is the surface area of the glass in the package that is available for corrosion (m^2)

V_g is the glass volume in the package (m^3)

F is the fraction of the soluble inventory (residual inventory in the solution after solid/liquid separation) of technetium that is solidified in the glass. F is calculated by dividing the technetium inventory solidified in each package by the average inventory to date of technetium processed per package. F shall be estimated by either sampling and analyzing the feed and glass products or from process knowledge.

The average values for R and R_{TC} shall be calculated by maintaining a running summation of the R and R_{TC} values of the packages presented to date for acceptance (excluding any that have not been accepted) and dividing by the number of packages accepted to date.

The corrosion rate (C_c) shall be the average rate determined to occur at 20°C over a period of 7 days when statistical product inventory information of the waste form is tested using the Product Consistency Test (PCT) (ASTM C1285-94). The 20°C rates shall be determined as follows:

- The normalized release of sodium, silicon, and boron (if present as a constituent in the glass) shall be measured using a 7-day PCT run at 20°C (ASTM C1285-94). Alternatively, the normalized releases may be measured at any temperature in the range of 20°C to 90°C provided the Contractor develops and applies an empirical correlation to relate the elevated temperature results to those at 20°C.
- The normalized release of Si shall be used to calculate the average corrosion rate of the glass ($\text{kg}/(\text{m}^2\text{-s})$) over the 7-day test period. Secondary mineral formation and phase separation shall not affect the PCT.

The surface area to volume ratio (S_s/V_p) of the glass product shall be the average surface area to volume ratio of the products expected based on information obtained from destructive examination of prototypical non-radioactive products produced during product qualification.

2.2.2.17.2

Waste Forms Other Than Silicate Glass: The Contractor shall identify how the fractional release rates, R_{TC} and R , are to be determined for waste forms and waste form/matrix combinations other than silicate glass if applicable. The Contractor shall be responsible for identifying an appropriate approach and testing method to show that the waste form products proposed will meet or exceed the specified radionuclide release requirements when immersed in deionized water at 20°C. The approach and testing methods do not necessarily require direct measurement of the radionuclides identified in this specification; measurement of a waste form characteristic (e.g., the corrosion rate for silicate glass waste forms) to which the radionuclide release rate can be related may be more appropriate.

2.2.2.18

Compressive Strength: The Contractor shall determine the mean compressive strength of the waste form (and any optional matrix and filler materials) by testing representative non-radioactive samples. The compressive strength shall be at least 3.45E6 Pa when tested in accordance with ASTM C39-94 or an equivalent testing method.

- 2.2.2.19 Thermal, Radiation, Biodegradation and Immersion Stability:** The ILAW product shall be resistant to thermal, radiation, biodegradation and immersion degradation, as described in *NRC Technical Position on Waste Form*. Resistance to each of these types of degradation shall be established by showing that the mean compressive strength of representative samples shall be equal to or greater than 3.45E06 Pa and not less than 75 percent of the initial compressive strength after subjecting the samples to the following:
- 2.2.2.19.1 Thermal degradation:** 30 thermal cycles between a high of 60°C and a low of -40°C in accordance with the ASTM B553-79 or an equivalent testing method.
 - 2.2.2.19.2 Radiation degradation:** Exposure to a minimum radiation dose of 1.0E06 rad or to a dose equivalent to the maximum level of exposure expected from self-irradiation during storage, transportation and disposal if this is greater than 1.0E06 rad.
 - 2.2.2.19.3 Biodegradation:** No evidence of culture growth when representative samples are tested in accordance with ASTM G21-90, ASTM G22-76, or equivalent methods.
 - 2.2.2.19.4 Immersion degradation:** Immersion for 90 days under the ANSVANS-16.1 testing conditions.
- 2.2.2.20 Waste Form Leach Testing:** The waste form shall have a sodium leachability index greater than 6.0 when tested for 90 days in deionized water using the ANSVANS-16.1 procedure.
- 2.2.2.21 Dangerous Waste Limitations:** The ILAW product shall be acceptable for land disposal under the State of Washington *Dangerous Waste Regulations*, WAC 173-303 and 40 CFR 268. The Contractor shall perform sampling and testing necessary to support designation of the ILAW product for dangerous waste characteristics, dangerous waste criteria and dangerous waste sources as specified in WAC 173-303-070. Information needed to show that the treated waste in the ILAW product is not prohibited from land disposal pursuant to WAC 173-303-140 and 40 CFR 268 shall be provided by the Contractor. Also, information specified in WAC 173-303-072 to pursue an exemption or categorical exclusion from the dangerous waste requirements shall be provided by the Contractor in the *Products and Secondary Wastes Plan*. The sampling, preparation and testing methods shall conform to the requirements in WAC 173-303-110.
- 2.2.2.22 Compression Testing:** Each fully loaded package shall be able to withstand a compression load of 50,000 kg force. Compliance with this specification shall be established by using the compression test described in 49 CFR 173.465(d). The Contractor shall demonstrate the integrity of the package by showing that the dimensions of the tested packages are within the tolerance range and by showing that the seal remains intact in accordance with Section 2.2.2.12.

2.2.2.23 Container Material Degradation: The container shall be resistant to degradation by microbial action, moisture, radiation effects, or chemical reactions with the container contents under the expected storage conditions that may reasonably occur during storage (in an ambient-temperature, ventilated enclosure) and handling and disposal operations. The container and handling appurtenances shall be designed to allow safe lifting and movement (in accordance with Section 2.2.3.1) after a storage period of 50 years. The integrity of the container shall not be jeopardized by wind, blowing sand, precipitation, sunlight, or extreme temperatures (+60°C, -40°C).

2.2.3 Handling Requirements:

2.2.3.1 Package Handling: The package shall be compatible with forklift and crane lifting and movement. The package shall be equipped with lifting and other handling appurtenances designed to allow safe lifting, movement, and stacking of the packages when fully loaded. The package shall maintain its integrity during handling, transportation, and stacking. The package shall allow for vertical stacking of six packages.

2.3 Inspection and Acceptance: The *Products and Secondary Wastes Plan* provided as a Part A deliverable in Standard 3, *Waste Products and Secondary Wastes*, shall define the content and delivery of Contractor documentation required to demonstrate compliance with the requirements of this specification. Product inspection and acceptance requirements will be performed in accordance with Section E, *Inspection and Acceptance* and NUREG-1293. In addition to Section E requirements for ILAW, the Contractor shall conform to the Contractor Certification Program as described in DOE Order 5620.2A, Chapter ~ Section 3.E.(4).

APPENDIX B DOSIMETRY DOSE FACTORS

This appendix provides tables of factors to convert radionuclide concentrations to dose rates. The scenarios are described in Section 3.3.6 and the underlying parameters in Section 3.4.8. Five tables are given:

- B-1 Drinking Water Scenario Dose Factors
- B-2 All-Pathways Dose Factors
- B-3 Drilling Scenario Dose Factors
- B-4 Intruder Scenario Dose Factors
- B-5 Ratio of Intruder Dose Factors for 2500 m² garden relative to 500 m² garden.

Table B-1. Drinking Water Scenario Dose Factors^a

| Nuclide | Drinking Water Dose Factor (mrem/y per pCi/l) | Nuclide | Drinking Water Dose Factor (mrem/y per pCi/l) |
|----------|---|----------|---|
| H-3 | 4.60E-05 | Eu-155 | 9.49E-04 |
| Be-10 | 3.07E-03 | Gd-152 | 1.10E-01 |
| C-14 | 1.53E-03 | Ho-166m | 5.69E-03 |
| Na-22 | 8.76E-03 | Re-187 | 6.06E-06 |
| Cl-36 | 2.19E-03 | Tl-204 | 2.34E-03 |
| K-40 | 1.39E-02 | Pb-210+D | 4.92E+00 |
| Mn-54 | 1.97E-03 | Bi-207 | 3.58E-03 |
| Fe-55 | 4.23E-04 | Po-209 | 1.46E+00 |
| Co-60 | 1.90E-02 | Ra-226+D | 8.04E-01 |
| Ni-59 | 2.16E-04 | Ra-228+D | 8.77E-01 |
| Ni-63 | 3.94E-04 | Ac-227+D | 1.07E+01 |
| Se-79 | 6.06E-03 | Ta-228+D | 5.50E-01 |
| Rb-87 | 3.50E-03 | Th-229+D | 2.85E+00 |
| Sr-90+D | 1.02E-01 | Th-230 | 3.87E-01 |
| Zr-93 | 1.17E-03 | Th-232 | 2.04E+00 |
| Nb-93m | 3.87E-04 | Pa-231 | 8.03E+00 |
| Nb-94 | 3.72E-03 | U-232 | 9.49E-01 |
| Mo-93 | 9.49E-04 | U-233 | 1.97E-01 |
| Tc-99 | 9.49E-04 | U-234 | 1.90E-01 |
| Ru-106+D | 1.53E-02 | U-235+D | 1.83E-01 |

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| Nuclide | Drinking Water Dose Factor (mrem/y per pCi/l) | Nuclide | Drinking Water Dose Factor (mrem/y per pCi/l) |
|-----------|---|-----------|---|
| Pd-107 | 1.02E-04 | U-236 | 1.83E-01 |
| Ag-108m+D | 5.48E-03 | U-238+D | 1.77E-01 |
| Cd-109 | 8.76E-03 | Np-237+D | 2.85E+00 |
| Cd-113m | 1.10E-01 | Pu-236 | 9.49E-01 |
| In-115 | 1.02E-01 | Pu-238 | 2.77E+00 |
| Sn-121m+D | 1.45E-03 | Pu-239 | 3.14E+00 |
| Sn-126+D | 1.34E-02 | Pu-240 | 3.14E+00 |
| Sb-125+D | 2.51E-03 | Pu-241+D | 6.28E-02 |
| I-129 | 2.04E-01 | Pu-242 | 2.99E+00 |
| Cs-134 | 5.40E-02 | Pu-244+D | 2.92E+00 |
| Cs-135 | 5.18E-03 | Am-241 | 3.29E+00 |
| Cs-137+D | 3.65E-02 | Am-242m+D | 3.13E+00 |
| Ba-133 | 2.34E-03 | Am-243+D | 3.29E+00 |
| Pm-147 | 6.94E-04 | Cm-243 | 2.12E+00 |
| Sm-147 | 1.31E-01 | Cm-244 | 1.68E+00 |
| Sm-151 | 2.48E-04 | Cm-245 | 3.29E+00 |
| Eu-150 | 4.53E-03 | Cm-246 | 3.29E+00 |
| Eu-152 | 4.38E-03 | Cm-247+D | 2.99E+00 |
| Eu-154 | 6.64E-03 | Cm-248 | 1.17E+01 |

Nuclides with "+D" added to the name include the contributions from short-lived progeny, which are assumed to be in equilibrium at all times.

Table B-2. All-Pathways Dose Factors* (Well Water)

| Nuclide | All-Pathways Dose Factor (mrem/y per pCi/l) | Ratio to Drinking Water Dose Factor | Nuclide | All-Pathways Dose Factor (mrem/y per pCi/l) | Ratio to Drinking Water Dose Factor |
|-----------|---|-------------------------------------|----------|---|-------------------------------------|
| H-3 | 5.30E-05 | 1.15 | Eu-155 | 1.36E-03 | 1.43 |
| He-10 | 3.41E-03 | 1.11 | Gd-152 | 1.28E-01 | 1.17 |
| C-14 | 1.79E-03 | 1.17 | Ho-166m | 1.85E-02 | 3.25 |
| Na-22 | 5.71E-02 | 6.52 | Ra-187 | 8.56E-06 | 1.41 |
| Cl-36 | 3.40E-02 | 15.5 | Tl-204 | 4.95E-03 | 2.12 |
| K-40 | 3.06E-02 | 2.21 | Pb-210+D | 5.50E+00 | 1.12 |
| Mn-54 | 6.48E-03 | 3.29 | Bi-207 | 1.44E-02 | 4.02 |
| Fe-55 | 6.57E-04 | 1.55 | Po-209 | 1.69E+00 | 1.15 |
| Co-60 | 4.84E-02 | 2.55 | Ra-226+D | 9.20E-01 | 1.14 |
| Ni-59 | 1.90E-04 | 1.30 | Ra-228+D | 9.98E-01 | 1.14 |
| Ni-63 | 5.13E-04 | 1.30 | Ac-227+D | 1.16E+01 | 1.09 |
| Se-79 | 1.09E-02 | 1.80 | Th-228+D | 6.08E-01 | 1.11 |
| Rb-87 | 7.75E-03 | 2.21 | Th-229+D | 3.11E+00 | 1.09 |
| Sr-90+D | 1.26E-01 | 1.24 | Th-230 | 4.22E-01 | 1.09 |
| Zr-93 | 1.42E-03 | 1.21 | Th-232 | 2.23E+00 | 1.09 |
| Nb-93m | 3.15E-03 | 8.14 | Pa-231 | 8.75E+00 | 1.09 |
| Nb-94 | 4.12E-02 | 11.1 | U-232 | 1.09E+00 | 1.15 |
| Mo-93 | 1.28E-03 | 1.35 | U-233 | 2.26E-01 | 1.15 |
| Tc-99 | 3.12E-03 | 3.29 | U-234 | 2.18E-01 | 1.15 |
| Ru-106+D | 1.85E-02 | 1.20 | U-235+D | 2.12E-01 | 1.15 |
| Pd-107 | 1.99E-04 | 1.95 | U-236 | 2.10E-01 | 1.15 |
| Ag-108m+D | 2.57E-02 | 4.70 | U-238+D | 2.04E-01 | 1.15 |
| Cd-109 | 1.04E-02 | 1.19 | Np-237+D | 3.11E+00 | 1.09 |
| Cd-113m | 1.30E-01 | 1.19 | Pu-236 | 1.03E+00 | 1.09 |
| In-115 | 1.31E-01 | 1.28 | Pu-238 | 3.02E+00 | 1.09 |
| Sn-121m+D | 4.28E-03 | 2.94 | Pu-239 | 3.42E+00 | 1.09 |
| Sn-126+D | 5.29E-02 | 3.96 | Pu-240 | 3.42E+00 | 1.09 |
| Sb-125+D | 5.52E-03 | 2.20 | Pu-241+D | 6.84E-02 | 1.09 |

| Nuclide | All-Pathways Dose Factor (mrem/y per pCi/l) | Ratio to Drinking Water Dose Factor | Nuclide | All-Pathways Dose Factor (mrem/y per pCi/l) | Ratio to Drinking Water Dose Factor |
|----------|---|-------------------------------------|-----------|---|-------------------------------------|
| I-129 | 4.13E-01 | 2.02 | Pu-242 | 3.26E+00 | 1.09 |
| Cs-134 | 1.22E-01 | 2.25 | Pu-244+D | 3.18E+00 | 1.09 |
| Cs-135 | 1.09E-02 | 2.09 | Am-241 | 3.58E+00 | 1.09 |
| Cs-137+D | 8.02E-02 | 2.20 | Am-242m+D | 3.41E+00 | 1.09 |
| Ba-133 | 4.93E-03 | 2.11 | Am-243+D | 3.58E+00 | 1.09 |
| Pm-147 | 8.31E-04 | 1.20 | Cm-243 | 2.31E+00 | 1.09 |
| Sm-147 | 1.58E-01 | 1.20 | Cm-244 | 1.83E+00 | 1.09 |
| Sm-151 | 2.98E-04 | 1.20 | Cm-245 | 3.58E+00 | 1.09 |
| Eu-150 | 1.54E-02 | 3.39 | Cm-246 | 3.58E+00 | 1.09 |
| Eu-152 | 1.28E-02 | 2.93 | Cm-247+D | 3.27E+00 | 1.09 |
| Eu-154 | 1.61E-02 | 2.43 | Cm-248 | 1.27E+01 | 1.09 |

Nuclides with "+D" added to the name include the contributions from short-lived progeny, which are assumed to be in equilibrium at all times.

Table B-3. Drilling Scenario Dose Factors* (Soil) (Assumes that waste height is 8 m, actual height is 7.2 m)

| Nuclide | Drilling Dose Factor (mrem/y per Ci/m ³) | Nuclide | Drilling Dose Factor (mrem/y per Ci/m ³) |
|-----------|---|----------|---|
| H-3 | 3.63E-03 | Eu-155 | 2.08E+01 |
| Be-10 | 2.16E-01 | Gd-152 | 3.08E+01 |
| C-14 | 2.82E-02 | Ho-166m | 1.04E+03 |
| Na-22 | 1.34E+03 | Re-187 | 1.10E-04 |
| Cl-36 | 3.00E-01 | Tl-204 | 4.98E-01 |
| K-40 | 9.75E+01 | Pb-210+D | 8.79E+01 |
| Mn-54 | 5.11E+02 | Bi-207 | 9.24E+02 |
| Fe-55 | 7.60E-03 | Po-209 | 2.84E+01 |
| Co-60 | 1.54E+03 | Ra-226+D | 1.09E+03 |
| Ni-59 | 2.67E-03 | Ra-228+D | 5.84E+02 |
| Ni-63 | 7.15E-03 | Ac-227+D | 1.21E+03 |
| Se-79 | 1.07E-01 | Th-228+D | 9.90E+02 |
| Rb-87 | 7.67E-02 | Th-229+D | 4.61E+02 |
| Sr-90+D | 4.42E+00 | Th-230 | 4.54E+01 |
| Zr-93 | 5.87E-02 | Th-232 | 2.28E+02 |
| Nb-93m | 2.19E-02 | Pa-231 | 3.16E+02 |
| Nb-94 | 9.65E+02 | U-232 | 9.73E+01 |
| Mo-93 | 8.70E-02 | U-233 | 1.92E+01 |
| Tc-99 | 3.15E-02 | U-234 | 1.90E+01 |
| Ru-106+D | 1.31E+02 | U-235+D | 1.02E+02 |
| Pd-107 | 3.3 E-03 | U-236 | 1.76E+01 |
| Ag-108m+D | 9.8 E+02 | U-238+D | 3.11E+01 |
| Cd-109 | 1.84E+00 | Np-237+D | 2.27E+02 |
| Cd-113m | 2.13E+00 | Pu-236 | 3.57E+01 |
| In-113 | 2.21E+00 | Pu-238 | 1.03E+02 |
| Sn-121m+D | 2.67E-01 | Pu-239 | 1.16E+02 |
| Sn-126+D | 1.20E+03 | Pu-240 | 1.16E+02 |
| Sb-125+D | 2.52E+02 | Pu-241+D | 2.29E+00 |
| I-129 | 5.02E+00 | Pu-242 | 1.09E+02 |

| Nuclide | Drilling Dose Factor (mrem/y per Ci/m ³) | Nuclide | Drilling Dose Factor (mrem/y per Ci/m ³) |
|----------|---|-----------|---|
| Cs-134 | 9.53E+02 | Pu-244+D | 3.12E+02 |
| Cs-135 | 9.41E-02 | Am-241 | 1.24E+02 |
| Cs-137+D | 3.45E+02 | Am-242m+D | 1.23E+02 |
| Ba-133 | 2.10E+02 | Am-243+D | 2.19E+02 |
| Pm-147 | 2.17E-02 | Cm-243 | 1.43E+02 |
| Sm-147 | 1.08E+01 | Cm-244 | 6.15E+01 |
| Sm-151 | 7.88E-03 | Cm-245 | 1.60E+02 |
| Eu-150 | 8.90E+02 | Cm-246 | 1.22E+02 |
| Eu-152 | 6.86E+02 | Cm-247+D | 3.07E+02 |
| Eu-154 | 7.56E+02 | Cm-248 | 4.30E+02 |

Nuclides with "+D" added to the name include the contributions from short-lived progeny, which are assumed to be in equilibrium at all times.

Table B-4. Intruder Scenario Dose Factors^a (Soil) (Assumes waste height is 8 m, actual height is 7.2 m)

| Nuclide | External (mrem/y per Ci/m ³) | Internal (mrem/y per Ci/m ³) | | | | Total (mrem/y per Ci/m ³) |
|---------|--|--|-------------------|------------|----------|---|
| | | Inhalation | Soil Ingestion | Vegetables | Subtotal | |
| H-3 | 0.0 | 4.05E-04 | 5.93E-04 | 2.85E-01 | 3.26E-01 | 3.26E-01 |
| Be-10 | 5.43E-01 | 1.02E+00 | 7.71E-01 | 1.67E+00 | 3.46E+00 | 4.00E+00 |
| C-14 | 6.73E-03 | 5.95E-03 | 3.76E-01 | 1.63E+02 | 1.64E+02 | 1.64E+02 |
| Na-22 | 5.30E+03 | 2.04E-02 | 1.93E+00 | 7.15E+01 | 7.34E+01 | 5.37E+03 |
| Cl-36 | 1.07E+00 | 5.32E-02 | 5.05E-01 | 2.23E+04 | 2.23E+04 | 2.23E+04 |
| K-40 | 4.34E+02 | 3.45E-02 | 3.46E+00 | 1.19E+03 | 1.19E+03 | 1.63E+03 |
| Mn-54 | 1.57E+03 | 1.27E-02 | 3.39E-01 | 6.14E+01 | 6.18E+01 | 1.63E+03 |
| Fe-55 | 0.0 | 6.65E-03 | 9.38E-02 | 1.79E-01 | 2.79E-01 | 2.79E-01 |
| Co-60 | 6.49E+03 | 4.07E-01 | 4.46E+00 | 3.59E+01 | 4.08E+01 | 6.53E+03 |
| Ni-59 | 0.0 | 3.77E-03 | 3.67E-02 | 9.68E-01 | 1.01E+00 | 1.01E+00 |
| Ni-63 | 0.0 | 8.68E-03 | 9.88E-02 | 2.61E+00 | 2.72E+00 | 2.72E+00 |
| Se-79 | 9.53E-03 | 2.58E-02 | 1.52E+00 | 2.51E+01 | 2.67E+01 | 2.67E+01 |
| Rb-87 | 7.18E-02 | 9.55E-03 | 8.78E-01 | 3.95E+01 | 4.04E+01 | 4.05E+01 |
| Sr-90 | 1.16E+01 | 6.74E-01 | 2.51E+01 | 4.11E+03 | 4.14E+03 | 4.15E+03 |
| Zr-93 | 1.25E-03 | 9.31E-01 | 2.96E-01 | 4.42E-01 | 1.67E+00 | 1.67E+00 |

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| Nuclide | External (mrem/y per Ci/m ³) | Internal (mrem/y per Ci/m ³) | | | | Total (mrem/y per Ci/m ³) |
|---------|--|--|-------------------|------------|----------|---|
| | | Inhalation | Soil Ingestion | Vegetables | SubTotal | |
| Nb-93m | 5.21E-02 | 7.93E-02 | 9.49E-02 | 4.20E-01 | 5.95E-01 | 6.47E-01 |
| Nb-94 | 4.34E+03 | 9.57E-01 | 9.35E-01 | 4.10E+00 | 5.99E+00 | 4.34E+03 |
| Mo-93 | 2.99E-01 | 8.19E-02 | 2.37E-01 | 9.43E+00 | 9.75E+00 | 1.00E+01 |
| Tc-99 | 3.80E-02 | 1.29E-02 | 1.41E-01 | 1.58E+02 | 1.58E+02 | 1.58E+02 |
| Ru-106 | 4.25E+02 | 9.22E-01 | 2.78E+00 | 3.65E+01 | 4.02E+01 | 4.65E+02 |
| Pd-107 | 0.0 | 3.76E-02 | 2.56E-02 | 6.88E-01 | 7.51E-01 | 7.51E-01 |
| Ag-106m | 4.40E+03 | 5.78E-01 | 1.37E+00 | 6.51E+01 | 6.71E+01 | 4.47E+03 |
| Cd-109 | 5.80E+00 | 2.23E-01 | 1.69E+00 | 1.82E+02 | 1.84E+02 | 1.90E+02 |
| Cd-113m | 3.18E-01 | 3.95E+00 | 2.67E+01 | 2.63E+03 | 2.66E+03 | 2.66E+03 |
| In-115 | 2.03E-01 | 9.87E+00 | 2.57E+01 | 3.72E+01 | 7.27E+01 | 7.29E+01 |
| Sn-121m | 1.07E+00 | 2.67E-02 | 3.63E-01 | 1.85E+00 | 2.24E+00 | 3.32E+00 |
| Sn-126 | 5.41E+03 | 2.19E-01 | 3.36E+00 | 1.71E+01 | 2.07E+01 | 5.43E+03 |
| Sb-125 | 9.98E+02 | 2.93E-02 | 5.56E-01 | 7.45E+00 | 8.03E+00 | 1.01E+03 |
| I-129 | 5.79E+00 | 4.56E-01 | 4.48E+01 | 1.49E+03 | 1.54E+03 | 1.54E+03 |
| Cs-134 | 3.64E+03 | 1.16E-01 | 1.15E+01 | 3.64E+02 | 3.75E+02 | 4.01E+03 |
| Cs-135 | 1.96E-02 | 1.31E-02 | 1.30E+00 | 3.85E+01 | 3.98E+01 | 3.98E+01 |
| Cs-137 | 1.53E+03 | 9.18E-02 | 9.07E+00 | 2.69E+02 | 2.78E+02 | 1.81E+03 |

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| Nuclide | External (mrem/y per Ci/m ³) | Internal (mrem/y per Ci/m ³) | | | | Total (mrem/y per Ci/m ³) |
|---------|--|--|-------------------|------------|----------|---|
| | | Inhalation | Soil Ingestion | Vegetables | Subtotal | |
| Ba-133 | 9.13E+02 | 1.93E-02 | 5.67E-01 | 6.75E+00 | 7.33E+00 | 9.20E+02 |
| Pm-147 | 2.25E-02 | 8.67E-02 | 1.53E-01 | 5.94E-01 | 8.34E-01 | 8.56E-01 |
| Sr-147 | 0.0 | 2.06E+02 | 3.30E+01 | 1.22E+02 | 3.61E+02 | 3.61E+02 |
| Sr-151 | 5.03E-04 | 8.38E-02 | 6.21E-02 | 2.29E-01 | 3.75E-01 | 3.76E-01 |
| Cs-150 | 3.96E+03 | 7.76E-01 | 1.13E+00 | 4.16E+00 | 6.06E+00 | 3.97E+03 |
| Cs-152 | 3.01E+03 | 6.23E-01 | 1.07E+00 | 3.99E+00 | 5.69E+00 | 3.01E+03 |
| Cs-154 | 3.24E+03 | 7.26E-01 | 1.61E+00 | 6.00E+00 | 8.34E+00 | 3.25E+03 |
| Cs-155 | 8.71E+01 | 1.06E-01 | 2.23E-01 | 8.43E-01 | 1.17E+00 | 8.83E+01 |
| Cd-152 | 0.0 | 6.97E+02 | 2.75E+01 | 1.01E+02 | 8.25E+02 | 8.25E+02 |
| Nb-166m | 4.69E+03 | 2.09E+00 | 1.43E+00 | 5.26E+00 | 8.78E+00 | 4.70E+03 |
| Re-187 | 0.0 | 1.41E-04 | 1.51E-03 | 3.44E-01 | 3.46E-01 | 3.46E-01 |
| Tl-204 | 1.88E+00 | 6.10E-03 | 5.37E-01 | 8.05E-01 | 1.35E+00 | 3.23E+00 |
| Pb-210 | 3.01E+00 | 6.13E+01 | 1.22E+03 | 5.05E+03 | 6.32E+03 | 6.33E+03 |
| Bi-207 | 4.11E+03 | 4.02E-02 | 8.89E-01 | 4.05E+00 | 4.98E+00 | 4.11E+03 |
| Po-209 | 8.86E+00 | 2.90E+01 | 3.66E+02 | 8.25E+02 | 1.22E+03 | 1.23E+03 |
| Ra-226 | 4.83E+03 | 2.39E+01 | 2.21E+02 | 6.64E+02 | 9.09E+02 | 5.74E+03 |
| Ra-228 | 3.07E+03 | 1.53E+02 | 2.29E+02 | 6.74E+02 | 1.06E+03 | 4.12E+03 |

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| Nuclide | External (mrem/y per Ci/m ³) | Internal (mrem/y per Ci/m ³) | | | | Total (mrem/y per Ci/m ³) |
|---------|--|--|-------------------|------------|----------|---|
| | | Inhalation | Soil Ingestion | Vegetables | SubTotal | |
| Ac-227 | 9.56E+02 | 1.92E+04 | 2.64E+03 | 3.74E+03 | 2.56E+04 | 2.65E+04 |
| Th-228 | 3.56E+03 | 7.63E+02 | 1.16E+02 | 1.57E+02 | 1.04E+03 | 4.60E+03 |
| Th-229 | 7.57E+02 | 5.86E+03 | 7.17E+02 | 9.05E+02 | 7.48E+03 | 8.24E+03 |
| Th-230 | 1.66E+00 | 9.29E+02 | 9.73E+01 | 1.23E+02 | 1.15E+03 | 1.15E+03 |
| Th-232 | 1.76E+02 | 4.65E+03 | 5.28E+02 | 6.71E+02 | 5.85E+03 | 6.03E+03 |
| Pa-231 | 1.07E+02 | 4.08E+03 | 2.06E+03 | 2.74E+03 | 8.88E+03 | 8.99E+03 |
| U-232 | 6.76E+02 | 2.06E+03 | 2.57E+02 | 8.38E+02 | 3.16E+03 | 3.83E+03 |
| U-233 | 7.22E-01 | 3.74E+02 | 4.91E+01 | 1.70E+02 | 5.93E+02 | 5.94E+02 |
| U-234 | 2.03E-01 | 3.73E+02 | 4.72E+01 | 1.64E+02 | 5.84E+02 | 5.85E+02 |
| U-235 | 3.74E+02 | 3.45E+02 | 4.57E+01 | 1.58E+02 | 5.49E+02 | 9.22E+02 |
| U-236 | 1.08E-01 | 3.45E+02 | 4.54E+01 | 1.57E+02 | 5.48E+02 | 5.48E+02 |
| U-238 | 6.02E+01 | 3.45E+02 | 4.41E+01 | 1.53E+02 | 5.42E+02 | 6.02E+02 |
| Np-237 | 5.17E+02 | 1.38E+03 | 6.94E+02 | 2.74E+03 | 4.81E+03 | 5.33E+03 |
| Pu-236 | 2.21E+00 | 4.21E+02 | 2.13E+02 | 2.69E+02 | 9.04E+02 | 9.06E+02 |
| Pu-238 | 7.70E-02 | 1.33E+03 | 6.95E+02 | 8.36E+02 | 2.86E+03 | 2.86E+03 |
| Pu-239 | 1.46E-01 | 1.48E+03 | 7.89E+02 | 9.48E+02 | 3.22E+03 | 3.22E+03 |
| Pu-240 | 7.51E-02 | 1.48E+03 | 7.89E+02 | 9.48E+02 | 3.22E+03 | 3.22E+03 |

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| Nuclide | External (mrem/y per Ci/m ³) | Internal (mrem/y per Ci/m ³) | | | | Total (mrem/y per Ci/m ³) |
|---------|--|--|-------------------|------------|----------|---|
| | | Inhalation | Soil Ingestion | Vegetables | SubTotal | |
| Pu-241 | 2.70E-02 | 2.95E+01 | 1.61E+01 | 1.92E+01 | 6.48E+01 | 6.48E+01 |
| Pu-242 | 6.56E-02 | 1.39E+03 | 7.53E+02 | 9.04E+02 | 3.05E+03 | 3.05E+03 |
| Pu-244 | 9.15E+02 | 1.37E+03 | 7.35E+02 | 8.83E+02 | 3.01E+03 | 3.93E+03 |
| Am-241 | 2.24E+01 | 1.51E+03 | 8.25E+02 | 1.03E+03 | 3.37E+03 | 3.39E+03 |
| Am-242m | 3.35E+01 | 1.48E+03 | 7.88E+02 | 9.84E+02 | 3.25E+03 | 3.29E+03 |
| Am-243 | 4.46E+02 | 1.51E+03 | 8.27E+02 | 1.03E+03 | 3.37E+03 | 3.81E+03 |
| Cm-243 | 2.86E+02 | 1.00E+03 | 5.26E+02 | 6.35E+02 | 2.16E+03 | 2.45E+03 |
| Cm-244 | 6.34E-02 | 7.69E+02 | 4.14E+02 | 5.01E+02 | 1.69E+03 | 1.69E+03 |
| Cm-245 | 1.72E+02 | 1.57E+03 | 8.26E+02 | 9.92E+02 | 3.39E+03 | 3.56E+03 |
| Cm-246 | 5.96E-02 | 1.57E+03 | 8.26E+02 | 9.92E+02 | 3.39E+03 | 3.39E+03 |
| Cm-247 | 8.83E+02 | 1.42E+03 | 7.53E+02 | 9.04E+02 | 3.08E+03 | 3.96E+03 |
| Cm-248 | 4.50E-02 | 5.52E+03 | 2.94E+03 | 3.53E+03 | 1.20E+04 | 1.20E+04 |

Nuclides with "m" added to the name include the contributions from short-lived progeny, which are assumed to be in equilibrium at all times.

Table B-5. Ratio of Intruder Dose Factors for 2500 m² garden relative to 500 m² garden.^a

| Nuclide | Ratio | Nuclide | Ratio | Nuclide | Ratio |
|---------|-------|----------|-------|----------|-------|
| H-3 | 4.88 | Sn-126+D | 1.10 | Th-230 | 4.97 |
| Be-10 | 3.37 | Sb-125+D | 1.10 | Th-232 | 4.53 |
| C-14 | 5.00 | I-129 | 4.93 | Pa-231 | 4.80 |
| Na-22 | 1.10 | Ce-134 | 1.10 | U-232 | 3.07 |
| Cl-36 | 5.00 | Ce-135 | 4.99 | U-233 | 4.98 |
| K-40 | 2.56 | Ce-137+D | 1.24 | U-234 | 4.99 |
| Mn-54 | 1.13 | Ba-133 | 1.10 | U-235+D | 2.04 |
| Fe-55 | 5.00 | Pm-147 | 4.57 | U-236 | 5.00 |
| Co-60 | 1.10 | Sm-147 | 5.00 | U-238+D | 3.68 |
| Ni-59 | 5.00 | Sm-151 | 4.98 | Np-237+D | 3.71 |
| Ni-63 | 5.00 | Eu-150 | 1.09 | Pu-236 | 4.96 |
| Se-79 | 4.99 | Eu-152 | 1.09 | Pu-238 | 5.00 |
| Rb-87 | 4.97 | Eu-154 | 1.09 | Pu-239 | 5.00 |
| Sr-90+D | 4.95 | Eu-155 | 1.10 | Pu-240 | 5.00 |
| Zr-93 | 4.99 | Gd-152 | 5.00 | Pu-241+D | 4.99 |
| Nb-93m | 3.88 | Ho-166m | 1.09 | Pu-242 | 5.00 |
| Nb-94 | 1.09 | Re-187 | 5.00 | Pu-244+D | 2.73 |
| Mo-93 | 4.52 | Tl-204 | 1.62 | Am-241 | 4.88 |

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| | | | | | |
|-----------|------|----------|------|-----------|------|
| Tc-99 | 5.00 | Pb-210+D | 4.99 | Am-242m+D | 4.82 |
| Ru-106+D | 1.17 | Bi-207 | 1.09 | Am-243+D | 3.52 |
| Pd-107 | 5.00 | Po-209 | 4.87 | Cm-243 | 3.53 |
| Ag-108m+D | 1.11 | Ra-226+D | 1.25 | Cm-244 | 5.00 |
| Cd-109 | 4.51 | Ra-228+D | 1.37 | Cm-245 | 4.26 |
| Cd-113m | 5.00 | Ac-227+D | 4.43 | Cm-246 | 5.00 |
| In-115 | 4.95 | Th-228+D | 1.33 | Cm-247+D | 2.78 |
| Sn-121m+D | 2.31 | Th-229+D | 3.76 | Cm-248 | 5.00 |

Nuclides with "+D" added to the name include the contributions from short-lived progeny, which are assumed to be in equilibrium.

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APPENDIX C WASTE FORM RELEASE COMPUTER CODES

C.1 Overview

This section provides a brief summary on the waste form release modeling for those sensitivity cases involving computer simulation of the release. More information is given than is justified by the importance of the three sensitivity cases, as later performance assessments will probably be heavily based on this type of simulation.

C.2 Governing Equations

C.2.1 Mass Conservation of Aqueous Solutes

Based on the continuum theory, the model can be represented by a set of partial differential equations (PDEs) that describe the mass conservation of solutes in pore fluids. Under the assumption that the rock matrix does not deform, the mass conservation law of solutes can be written as

$$\frac{\partial(\phi S_w \rho_w C_i)}{\partial t} = -\nabla \cdot \vec{J}_i + \sum_{j=1}^{N_r} \nu_{ij} W_j, \quad i=1,2,\dots \quad (1)$$

where

- ϕ denotes the porosity,
- S_w denotes the water saturation,
- ρ_w the density of the aqueous solution,
- C_i is the molal concentration of solute i ,
- \vec{J}_i is the flux of species i ,
- ν_{ij} is the stoichiometric coefficient of species i in reaction j ,
- N_r is the number of total reactions, and
- W_j is the rate of reaction j .

In general, the reaction rate is a non-linear function of the concentrations. Through the term W_j , one solute species is non-linearly coupled with other species. The non-linear partial differential equation (1) simply states that the time rate of change of aqueous species concentrations consists of two parts; one is the contribution of transport and the other is the contribution of all reactions. Assuming the phenomenon of hydrodynamic dispersion can be represented by a Fickian type law, the first term on the right-hand side can be expanded into

$$-\nabla \cdot \vec{J}_i = -\nabla \cdot (-\phi S_w \rho_w D_i \nabla C_i + \vec{u} \phi S_w \rho_w C_i) \quad (2)$$

where

- D_i is the dispersion coefficient of i and
- \vec{u} is the velocity of pore fluid.

The second term at the right-hand side of equation (1) represents all types of reactions, including aqueous speciation, redox reactions, solid precipitation and dissolution, adsorption,

etc. In general, chemical reactions can be treated as either equilibrium-controlled or kinetic-controlled. Several of the available reaction-transport models can only treat equilibrium reactions (Mangold 1991). In this case, the non-linear equation (1) can be transformed into a linear equation and thus is numerically easier to solve. However, many reactions are kinetically controlled, especially solid dissolution and precipitation reactions. Consequently, both equilibrium and kinetic reactions are included in the model used here. To emphasize this, the reaction term in Equation (1) is split into two parts: one represents the contributions from equilibrium reactions, the other from kinetic reactions

$$\sum_{j=1}^{N_e} v_{ij}^e W_j^e + \sum_{j=1}^{N_k} v_{ij}^k W_j^k, \quad (3)$$

where v_{ij}^e and v_{ij}^k are the stoichiometric coefficients in equilibrium reactions and kinetic reactions, respectively, while W_j^e and W_j^k are the rates of equilibrium and kinetic reactions, respectively.

To define the mathematical form of the W 's, note that for any kinetic reaction j involving aqueous and solid species m with the form

$$\sum v_{mj} B_m = 0, \quad (4)$$

using the law of mass-action, with activity corrections, the rate can be expressed as

$$W_j^k = A_j k_j \left[\prod_{i,j^<0} (\gamma_i C_i)^{\nu_{ij}^k} - \prod_{i,j^>0} (\gamma_i C_i)^{\nu_{ij}^k} / K_j^{eq} \right] \quad (5)$$

where A_j is a factor. For aqueous reactions, $A_j = 1$. For solid dissolution and precipitation reactions, A_j is the effective reaction surface in unit volume of the porous medium. If we further assume that all solids are spherical grains or can be represented as equivalent spherical grains with radii of R_1 , and that the effective reaction surface is proportional to water saturation then,

$$W_j^k = 4\pi R_1^2 n_1 S_w k_j \left[\prod_{i,j^<0} (\gamma_i C_i)^{\nu_{ij}^k} - \prod_{i,j^>0} (\gamma_i C_i)^{\nu_{ij}^k} / K_j^{eq} \right] \quad (6)$$

where n_1 denotes the number of grains in unit volume of porous medium,
 k_j is the rate constant, and
 γ_i is the activity coefficient which is a function of the concentrations of all species.

There are several formulas, such as Davies equation; B-dot equation, Pitzer's model etc., that can be used to calculate γ_i . The B-dot equation with modifications for neutral species adopted by Wolery (1992) is computationally economic and stable, and can

handle moderate salinity; thus it is the most suitable for reaction-transport problems. Although Pitzer's model can handle high ionic strength, computationally it is not feasible for reaction-transport simulations because of its complicated structure and the lack of Pitzer constants for all but a few aqueous species.

C.2.2 Texture Dynamics

Dissolution and precipitation reactions can change the volume fractions of solids as a function of time. For spherical grains, the change rate is

$$\frac{\partial V_l}{\partial t} = 4\pi R_l^2 n_l \frac{\partial R_l}{\partial t} \quad (7)$$

while

$$\frac{\partial R_l}{\partial t} = \sum_j k_j \left[\prod_{i \in U^+} (\gamma_i C_i)^{\nu_i} - \prod_{i \in U^0} (\gamma_i C_i)^{\nu_i} / K_j^{\text{eq}} \right] / \rho_l \quad (8)$$

where V_l is the volume fraction of solid l ,
 R_l is the change rate in radius of solid l , and
 ρ_l is the molar density of l .

Equation (8) serves as the bridge between aqueous phase and solid phases so that the whole system is mass-conserved.

C.2.3 Contaminant Release Rate From Glass

The equation for the contaminant release rate from glass is taken as

$$J_i = \nu_i a_H^{\eta} k_0 e^{-\frac{E_a}{RT}} \left[1 - \left(\frac{Q}{K} \right)^{\sigma} \right]$$

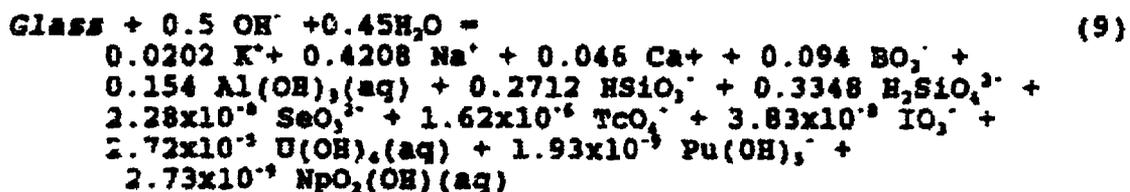
where J_i is the flux of element i ,
 ν_i is the stoichiometric coefficient of element i ,
 a_H is the activity of H^+ ,
 η is the pH power law coefficient,
 T is the temperature,
 k_0 is the intrinsic rate constant,
 E_a is the activation energy,
 R is the gas constant,
 Q is the ion activity product,
 K is the pseudoequilibrium constant, and
 σ is the average stoichiometric parameter for the overall reaction.

C.2.4 Reactions Considered

Three types of reactions are considered:

- The dissolution of the glass
- Equilibrium reactions
- Other kinetic reactions.

The glass considered in our simulations is LD6-5412, with a formula of the major glass components of $Al_{0.1533}B_{0.099}Ca_{0.046}K_{0.0202}Na_{0.4208}Si_{0.694}O_{1.9314}$. Flow-through experiments show that two reaction mechanisms are involved in the glass dissolution (McGrail 1995). One is the network dissolution reaction



the other is an ion-exchange reaction



The measured rate constant for reaction (9) at 14°C is $3.03 \times 10^{-14} \text{ mol} \cdot \text{m}^{-3} \cdot \text{s}^{-1} = 1.68 \times 10^{-7} \text{ g} \cdot \text{m}^{-3} \cdot \text{d}^{-1}$, and for Reaction (10) it is $1.74 \times 10^{-11} \text{ mol} \cdot \text{m}^{-3} \cdot \text{s}^{-1} = 9.6 \times 10^{-5} \text{ g} \cdot \text{m}^{-3} \cdot \text{d}^{-1}$. Radionuclide release is assumed to only occur via Reaction (9); the release of all radionuclides is assumed to be congruent.

Thirty-eight aqueous species, 14 solid species plus glass were considered in the simulations. The selection of species is based on speciation calculations and observations from glass testing experiments. Table C-1 lists all reactions considered in the simulations, including 21 equilibrium reactions and 16 kinetic reactions.

C.3 Code Selection

The selection of AREST-CT for modeling the release rate of contaminants from the glass waste form was based on meeting the criteria and requirements for the disposal system release model (McGrail 1994). The ten codes considered were

- AREST-CT (Engel 1995)
- BLT-EC (MacKinnion 1994)
- CAT (Kervevan 1994)
- CHEQMATE (Haworth 1988)
- CRMTRNS (Ncorishad 1987)
- CIRP-A (Chen 1994)
- HYDROGEOCHEM (Yeh 1990)
- TRCC (Carnahan 1986)
- UNSATCHEM-2D (Simunek 1993)
- UT-CHEM (Bhuyan 1989).

Table C-1. List Of Reactions Considered in Glass Performance

Equilibrium Reactions

1. $H_2O = H^+ + OH^-$
2. $CO_2(aq) + H_2O = H^+ + HCO_3^-$
3. $HCO_3^- = H^+ + CO_3^{2-}$
4. $Al(OH)_3 + H^+ = Al(OH)_2^+ + H_2O$
5. $H_2SiO_4^{2-} + 2H^+ = SiO_2(aq) + H_2O$
6. $HSiO_3^- + H^+ = SiO_2(aq) + H_2O$
7. $BO_2^- + H^+ = B(OH)_2(aq)$
8. $CaCO_3(aq) + H^+ = Ca^{2+} + HCO_3^-$
9. $CaHCO_3^+ = Ca^{2+} + HCO_3^-$
10. $CaOH^+ + H^+ = Ca^{2+} + H_2O$
11. $UO_2CO_3(OH)_2 + 4H^+ = 2UO_2^{2+} + HCO_3^- + 3H_2O$
12. $UO_2CO_3(aq) + H^+ = HCO_3^- + UO_2^{2+}$
13. $UO_2(CO_3)_2^{2-} + 2H^+ = UO_2^{2+} + 2HCO_3^-$
14. $UO_2(CO_3)_3^{4-} + 3H^+ = UO_2^{2+} + 3HCO_3^-$
15. $UO_2OH^+ + H^+ = UO_2^{2+} + H_2O$
16. $UO_2(OH)_2(aq) + 2H^+ = UO_2^{2+} + 2H_2O$
17. $UO_2(OH)_3^- + 3H^+ = UO_2^{2+} + 3H_2O$
18. $U(OH)_4(aq) + 0.5 O_2(aq) + 2H^+ = UO_2^{2+} + 3H_2O$
19. $NpO_2OH(aq) = OH^- + NpO_2^+$
20. $NpO_2(CO_3)^- = NpO_2^+ + CO_3^{2-}$
21. $HSeO_4^- = H^+ + SeO_4^{2-}$

Kinetic Reactions

1. $Glass + 0.5 OH^- + 0.45H_2O =$
 $0.0202 K^+ + 0.4208 Na^+ + 0.046 Ca^{2+} + 0.094 BO_2^- +$
 $0.154 Al(OH)_2^+(aq) + 0.2712 HSiO_3^- + 0.3348 H_2SiO_4^{2-}$
 $+ 2.28 \times 10^{-8} SeO_4^{2-} + 1.62 \times 10^{-6} TeO_4^{2-} + 3.83 \times 10^{-8} IO_3^-$
 $+ 2.72 \times 10^{-5} U(OH)_4(aq) + 1.93 \times 10^{-3} Pu(OH)_3^+$
 $+ 2.73 \times 10^{-9} NpO_2(OH)(aq)$
2. $Glass - 0.4208 Na + 0.4208 H^+ = 0.4208 Na^+ + Glass - 0.4208$
3. $Quartz + OH^- = HSiO_3^-$
4. $Calcite = Ca^{2+} + CO_3^{2-}$
5. $Albite(high) + 2OH^- = Na^+ + Al(OH)_2^+(aq) + 3HSiO_3^-$
6. $K-feldspar + 2OH^- = K^+ + Al(OH)_2^+(aq) + 3HSiO_3^-$
7. $Illite + 2.4 OH^- = 0.6 K^+ + 0.25 Mg^{2+} + 2.3 Al(OH)_3(aq)$
 $+ 3.5 HSiO_3^-$
8. $Analcline + 0.96 H^+ = 0.96 Na^+ + 0.96 Al(OH)_2^+(aq) +$
 $2.04 SiO_2(aq) + 5.04 H_2O$
9. $Chalcedony = SiO_2(aq)$
10. $NaAlSi_3O_8 \cdot 6H_2O + OH^- = Na^+ + Al(OH)_2^+(aq) + 2HSiO_3^- + 4H_2O$
11. $Phillipsite + 3H^+ = K^+ + Ca^{2+} + 3Al(OH)_2^+(aq) + 5SiO_2(aq) +$
 $3H_2O$
12. $Tobermorite + 10H^+ = 5Ca^{2+} + 6SiO_2(aq) + 10.5 H_2O$
13. $Gobbsinite + 6H^+ = 4Na^+ + Ca^{2+} + 6Al(OH)_2^+(aq) +$
 $10SiO_2(aq) + 8H_2O$
14. $Haiweeite + 6H^+ = Ca^{2+} + 6SiO_2(aq) + 2UO_2^{2+} + 8H_2O$
15. $Schoepite + 2H^+ = UO_2^{2+} + 3H_2O$
16. $PuO_2(s) + 3H_2O = H^+ + Pu(OH)_3^+$

To be considered, a code must have met the criteria and requirements given in Mann 1995c and at least 50% of all requirements given in McGrail 1994. Briefly, the criteria were that the codes would be:

- Based on scientific principles
- Documented
- Maintained under a software quality management program
- Allow the use of site and facility specific data
- Capable of monitoring long simulations.

The requirements given in Mann 1995c were based on capabilities of the code. The source term codes needed to be capable of:

- Simulating radionuclide release from unstable and stable vitrified waste
- Modelling various chemical processes
- Simulating radionuclide releases controlled by solubility limits or adsorption
- Accepting specific release rates then simulating the disposal facility release until the inventory was depleted.

The additional requirements listed in McGrail (1994) fit into one of four groups -- physical processes, chemical processes, numerical methods, and functionality. The first two groups contained a list of related principal processes. These processes were expected to affect LLW glass corrosion and the mobility of radionuclides. The numerical method group contained a list of related numerical methods needed to solve the related equations in the first two groups. Functionality covered a variety of program options such as graphical users interface and a software quality management program.

AREST-CT was chosen over the nine other codes because the program out scored the others. All the requirements in McGrail (1994) were given a merit score. This score was based on the importance of the process to modeling the performance of the disposal facility and on the degree of difficulty in adding the capability to an existing code. Codes having a specific capability were assigned the merit score for that capability. All the merit scores for each code were tabulated for a total merit score for the code. Based on the totals, AREST-CT had the largest merit score of 361. The next code had a total score of 264. For the scores of other codes, see McGrail 1994.

C.4 Verification and Benchmarking

Because AREST-CT is still being developed, its verification, benchmarking, and validation history are short. However, the comparisons between experimental results produced for this

interim performance assessment and the AREST-CT calculations for this document give confidence to the validity of the AREST-CT code.

The verification of AREST-CT, Version 1, was done to assure that modules of the program were correctly implemented and worked together (Chen 1995). The verification had two parts. First, specific portions or modules of AREST-CT were unit tested to verify that the modules were performing correctly. Unit testing consists of evaluating individual code modules against hand calculations, analytical solutions, or other existing numerical codes. Each module was unit tested before being implemented into AREST-CT. All modules were considered acceptable for current usage.

The second part of the verification of AREST-CT consisted of testing the computer code as a whole object. At the time of verification, no analytical solutions existed for solving the reaction-transport problems designed for AREST-CT. The code was benchmarked against simulation results from a similar reaction-transport code.

The benchmark test case that was a 1-D idealization of a low-level waste engineered system. The system consisted of 7 solids and 12 aqueous species. Two types of reactions were considered -- equilibrium aqueous reactions and solid dissolution/precipitation reactions. More details on the testing are given in Chen (1995). The results of the test showed that AREST-CT simulations quantitatively compared very well with the analytical solutions and other reactive-transport codes.

Further testing and verification tests will be conducted as the AREST-CT code develops. Future testing will include integration testing for mechanisms of radioactive decay and decay chain in growth, and for 2-D simulation. Plans for code development include increasing the number of grid nodes and decreasing the size of time steps for the one-dimensional transport case in order to improve convergence. Also the program will be coupled with an unsaturated flow solver. Currently, the program uses the water velocity data from PORFLOW. With the flow solver, AREST-CT will model infiltration velocity changes with porosity as a result of solid dissolution/precipitation reactions.

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APPENDIX D
MOISTURE FLOW AND CONTAMINANT TRANSPORT COMPUTER CODES

D.1 Overview

This appendix provides detailed information about the moisture flow and transport codes [PORFLOW (ACRi 1994a) and VAM3D-CG (Huyakorn 1994)] used in this performance assessment. The following sections cover the governing equations, the detailed reasons for code selection, verification / benchmarking / validation efforts, and the input decks for the base analysis case.

D.2 Governing Equations**D.2.1 Overview**

This section discusses the equations important in the calculation of moisture flow and contaminant transport. The first section presents the equations on which the water flow calculations are based. The next section discusses contaminant transport associated with moisture flow. The final section describes moisture movement under diffusive conditions.

D.2.2 Moisture Flow

Two distinct moisture content regimes are present during contaminant transport: the unconfined aquifer and the vadose zone. In the unconfined aquifer, all the pore spaces are filled with water; that is, the medium is saturated with water. In the vadose zone, by contrast, the pore spaces between the soil particles are only partially filled with water. The vadose zone is unsaturated.

Water flow through a saturated porous medium, such as the unconfined aquifer, is governed by the empirical relationship known as Darcy's Law (Freeze 1979) and by the conservation of mass. Darcy's law can be expressed as

$$\vec{v} = -K \nabla h$$

where \vec{v} is the velocity vector (L/T),
 K is the hydraulic conductivity tensor (L/T), and
 h is the hydraulic head vector (L).

By using the conservation of water entering and leaving a volume and by using Darcy's law to relate the hydraulic gradient to the rate at which water enters and leaves the same volume, transient water flow in a saturated porous media can be expressed as

$$\nabla \cdot [K \nabla h] = S \frac{\partial h}{\partial t} + Q$$

where S is the specific storage (L^{-1}) and
 Q is the source or sink of moisture (T^{-1}).

Darcy's law defines the discharge of water through a cross section of porous media. However, in contamination transport, the average velocity of water flowing through the media is important. This is because contaminants which are not geochemically retarded move with the water. The average velocity of the pore water is determined by dividing the velocity of the water by the porosity of the media. Porosity is defined as the ratio of void space to total volume.

In an unsaturated media, the pores are not completely filled with water. Additional effects (capillary forces, the dependence of hydraulic conductivity on moisture content) must be considered. Richards equation (Richards 1931) becomes the governing equation:

$$\nabla \cdot [K(\psi) \nabla \psi] + \partial K_{zz}(\psi) / \partial z = (d\theta/d\psi) (\partial \psi / \partial t) + Q$$

where K is again the hydraulic conductivity tensor (L/T), but now depends on the pressure head,
 ψ is the pressure head (L) which is dependent on the moisture content θ , and
 θ is the moisture content (dimensionless).
 z is the vertical column of moisture (L).

The relationship between the pressure head and the hydraulic head is simply

$$h = \psi + z.$$

For the performance assessment calculations, the hydraulic conductivity tensor is reduced to a single function, with

$$K_{ij} = K, \text{ for } i = j \text{ and} \\ K_{ij} = 0, \text{ for } i \neq j.$$

The functional dependence of the pressure head on moisture content and of the hydraulic conductivity on pressure head and ultimately on moisture content is discussed in Section 3.4.4.3 (Vadose Zone Hydraulic Parameters).

For extremely dry conditions, vapor diffusion may be important. In such conditions, water does not move as a collective body but rather as single molecules. Such diffusion can be described by Fick's equation,

$$dm/dt = -D_e A dc/dx$$

where dm/dt is the mass rate of water vapor diffusion (M/T),
 D_e is the effective vapor diffusion coefficient (L^2/T),

- A is the cross section area (L^2),
 C is the water vapor mass concentration in the gas phase (M/L^3), and
 dC/dx is the water vapor mass concentration gradient (M/L^4).

D.2.3 Advective and Diffusive Transport

The equation for the advective and diffusive transport of contaminants can be viewed as a mass balance on a differential volume. The advective-dispersive equation for solute movement through a porous medium with a constant, steady state flow velocity was developed (Codell 1982) for the limiting case of unidirectional advective transport with three-dimensional dispersion in a homogeneous, saturated aquifer,

$$n_e \frac{\partial C}{\partial t} + (n - n_e) \frac{\partial G}{\partial t} + (1 - n) \frac{\partial P}{\partial t} + n_e u \frac{\partial C}{\partial x} =$$

$$n_e \left[E_x \frac{\partial^2 C}{\partial x^2} + E_y \frac{\partial^2 C}{\partial y^2} + E_z \frac{\partial^2 C}{\partial z^2} \right] +$$

$$(n - n_e) \left[E_x^1 \frac{\partial^2 G}{\partial x^2} + E_y^1 \frac{\partial^2 G}{\partial y^2} + E_z^1 \frac{\partial^2 G}{\partial z^2} \right] -$$

$$n_e \lambda C - (1 - n) \lambda P - (n - n_e) \lambda G$$

where

- C = dissolved concentration in the liquid phase in voids which are interconnected and allow flow [flowing voids] (M/L^3 or C_i/L^3),
 C_i = dissolved concentration in the liquid phase in voids which are not interconnected and do not allow flow [non-flowing voids] (M/L^3 or C_i/L^3),
 P = particulate concentrations on the solid phase (Mass/Mass or C_i/Mass),
 n = total porosity (dimensionless),
 n_e = effective porosity (dimensionless),
 t = time (T),
 u = the x-component of groundwater or pore water velocity (L/T)
 E_i = dispersion coefficient in the flowing voids in the i-th (where i = x, y, or z) direction (L^2/T),
 E_i^1 = diffusion coefficient in the non-flowing voids in the i-th direction (L^2/T), and
 λ = decay constant [= (ln 2)/half life] (T^{-1}).

Each term in the equation represents some aspect of the solute movement through the porous medium. The first term on the

left of the equal sign is the accumulation (storage) of the solute in the liquid phase in the flowing void. The next term is the accumulation in the liquid phase in the non-flowing void. The following term is the accumulation in the solid phase; and the term to the left of the equal sign is x-direction advective transport in the flowing voids in the liquid phase. The first term to the right of the equal sign represents the dispersive transport in the flowing voids in the liquid phase in each direction. The next term represents the diffusive transport in the non-flowing voids in the liquid phase in each direction. The last terms are the chemical degradation or radioactive decay in the liquid phase in the flowing void, in the solid phase, and in the liquid phase in the nonflowing void respectively.

Using the following assumptions:

- The dissolved concentration in the non-flowing flows (G) equals the dissolved concentration in the flowing voids (C) for each time and for each position
- The contaminant absorption process can be described by a constant ($K = \rho * K_d / (1 - n)$) representing the ratio between the contaminant absorbed to the soil matrix (P) and the contaminant dissolved in solution (C)
- The diffusion in the nonflowing void (E'_1) is comparable with the dispersion in the flowing void (E_1),

the above equation can be simplified to

$$\frac{\partial C}{\partial t} + \frac{u}{R_f} \frac{\partial C}{\partial x} = \frac{D_x}{R_f} \frac{\partial^2 C}{\partial x^2} + \frac{D_y}{R_f} \frac{\partial^2 C}{\partial y^2} + \frac{D_z}{R_f} \frac{\partial^2 C}{\partial z^2} - \lambda C$$

in which

$$D_1 = n E_1 / n_0$$

and

$$R_f = n / n_0 + (\rho * K_d) / n_0$$

and where

- D_1 = pseudodispersion coefficient (L^2/T)
- R_f = retardation factor (dimensionless)
- ρ = bulk density (M/L^3)
- K_d = equilibrium (partition or distribution) coefficient (L^3/M).

The retardation factor (R_f) is used as a measure of the mobility of constituents in a porous medium.

By making the following substitutions,

$$u' = u / R_f$$

and

$$D_1' = D_1 / R_f$$

the contaminant transport equation can be written as

$$\frac{\partial C}{\partial t} + u \frac{\partial C}{\partial x} = D_x \frac{\partial^2 C}{\partial x^2} + D_y \frac{\partial^2 C}{\partial y^2} + D_z \frac{\partial^2 C}{\partial z^2} - \lambda C$$

The first equation of this section specifically address the general conditions for saturated flow and solute movement. However, it can also be applied to the unsaturated zone if minor modifications are made:

- The porosities (n and n_s) are assumed to be equal to the soil matrix moisture content
- The one-dimensional flow is in the vertical direction.

For this case, the retardation factor is defined by

$$R_f = 1 + (\rho \cdot K_d) / \theta$$

where θ is the moisture content of the partially saturated zone and dispersion is only considered in the flow direction.

D.2.4 Vapor Transport

Some contaminants may move upward from the disposal facility to the surface because they are in the vapor phase. Such movement is governed by Fick's second law,

$$D \frac{\partial^2 C}{\partial z^2} = \frac{\partial C}{\partial t}$$

where C is the concentration, z is the distance, t is time, and D is the diffusion coefficient. The solution for concentration C in the z direction over time t is given by:

$$\frac{C}{C_0} = \text{erfc}\left(\frac{z}{2\sqrt{Dt}}\right)$$

where erfc is the complimentary error function and C/C_0 is the relative concentration. The mass transport across the surface becomes

$$\frac{\partial C}{\partial t} = \frac{C_0}{\sqrt{4\pi Dt}} \frac{z}{t} \exp[-z^2/(4Dt)]$$

D.3 Code History

D.3.1 PORFLOW

Many versions of PORFLOW codes have been adapted for a variety of problems over the past fifteen years. The bibliography of reports describing the code developments and problems to which they have been applied has grown to include about 100 documents. A partial listing of some of these reports is contained in the user documentation for the newest releases (ACRI 1994a; ACRI, 1994b). Many of the available references give detailed technical descriptions of the mathematical modeling, numerical methods and computational algorithms embodied in the various computer code versions along with pointed discussions of complex engineering problems to which they are applied. This section will provide a brief and accessible description of what the PORFLOW computer code is, what it does, and how it is used for the interim performance assessment of low-level tank waste disposal.

The PORFLOW code allows simulation of flow of two fluids and a passive air phase, conductive and convective heat transfer, and transport of up to four dissolved contaminant species in a variably saturated, heterogeneous, anisotropic, fractured porous continuum. The remaining paragraphs in this section chronicle a few major steps in the development of the PORFLOW codes series and exemplify typical past and present usage.

About 30 years ago, Gosman et al. (1969) developed the Nodal Point Integration technique for use in simulating heat transfer and mass transport in a circulating fluid. Nodal Point Integration is used to render a discrete system of simultaneous linear equations from a continuous mathematical model involving coupled partial differential equations. The advantage of Nodal Point Integration over classical finite difference schemes is assurance that the discrete model is conservative at every point of interest (i.e., errors in the amounts of fluid volume, heat, and mass of transported species are sufficiently small at every point in space as well as in the global totals). Use of Nodal Point Integration is one of the defining characteristics of the PORFLOW series of codes.

In the 1970's the Nodal Point Integration technique was used in development of a model for simulating thermally disturbed groundwater movement in the vicinity of a high level radioactive waste repository (Runchal 1979). The computer code was called GWTHERM and was a forerunner to the PORFLOW codes. In the 1980's during the Basalt Waste Isolation Project (BWIP), the two-dimensional PORFLO code (Kline 1983; Eyler 1984; Runchal 1985) was developed out of the GWTHERM prototype for use in assessing performance of a deep geologic repository for high level nuclear waste. The PORFLO code was used principally to calculate near-field estimates of water flow (seepage) rates in the vicinity of the proposed repository, temperature distribution around the repository, and contaminant mass release rates to the far-field

and/or accessible environment (e.g. in DOE-RL 1982 and Baca 1984). The PORFLO code was limited to saturated media (e.g. a repository at depth, below the water table) and transport of a single dissolved contaminant species.

The PORFLO-3 computer code (Sagar 1990; Runchal 1992) is a three-dimensional generalization of the PORFLO code. In addition to being fully three-dimensional, the PORFLO-3 code is tailored for simulation of flow and transport in saturated and unsaturated media. The PORFLO-3 code also has the conduction and convection heat transfer capabilities, but thermal disturbance is typically not a condition in many of the unsaturated flow modeling applications where the code has been used. For instance, PORFLO-3 has been used in three-dimensional predictive modeling of saturated flow and transport of tracers and residual contaminants in support of the remedial investigation process for the 300-FF-5 groundwater operable unit (DOE-RL 1994a). Estimation of travel times through the vadose (unsaturated) zone from various surface facilities (cribs, trenches) to groundwater for discharged water and various contaminants along with estimation of relative arrival concentrations have been performed with PORFLO-3 models in support of the Liquid Effluent program (WMC 1990; Reidel 1993; Singleton 1994). Analysis of single shell tank (SST) leaks during waste retrieval operations has been conducted with PORFLO-3 models to provide approximate impact on groundwater (Lowe 1993) and later to quantify the umbrella effect of SST's on infiltrating precipitation (Kline 1995a) and further refine estimates of vertical penetration and lateral spreading of leaked contaminants in the vadose zone. The PORFLO-3 code has also been used in analysis of the effectiveness of capillary barriers (Kline 1995b), particularly to assess diversion capacity of a capillary barrier used to limit infiltration of precipitation into a near-surface disposal facility for low-level waste.

The most recent PORFLOW codes (Versions 2.0 and higher) comprise extension of PORFLO-3 to allow two fluids (such as water and CCl_4) or two phases (such as liquid water and water vapor), in addition to a passive air phase in variably saturated media. These code versions also allow simulation of multiple contaminant species transport, including chain decay. While the capability of simulating simultaneous seepage of two distinct fluids has undergone preliminary testing by Piepho and Runchal (Piepho 1991), some of the newer features (e.g. phase changes, decay chains) implemented in the PORFLOW codes have not been used extensively at Hanford. Most notably PORFLOW has been used to simulate seepage of infiltrating precipitation and simultaneous transport (advection and diffusion) of several dissolved contaminant species through a near-surface disposal facility and underlying vadose zone to groundwater. Contaminant fluxes to groundwater are subsequently postprocessed by an auxiliary computer code to provide dose estimates through various pathways (e.g. intrusion, drinking water) as was done in performance assessment by Kincaid et al. (Kincaid 1995) for Hanford grouted tank waste. The same simulation capabilities have also been used to calculate dose estimates as a means of evaluating impacts of

disposal system design options on low-level glass waste disposal system performance (Rawlins 1994; Mann 1995d; Kline 1995a). The PORFLOW code used in those grout and glass waste disposal analyses is designated Version 2.394gr and has been tested extensively by Piepho et al (Piepho 1994). Version 2.394gr of PORFLOW is also the code version used for the present interim performance assessment of low-level tank waste disposal.

D.3.2 VAM3D-CG

Earlier versions of VAM3D-CG (VAM2D and VAM3D) have been used for Hanford risk assessments. Version 2.4b of VAM3D-CG was used in the Hanford 200 West Area Burial Grounds Performance Assessment (Wood 1994b). Version 3.1 of VAM3D-CG was obtained because of the greater model complexity required for the model for the Environmental Restoration Disposal Facility Performance Assessment (Wood 1995) and for the Hanford sitewide groundwater model (Law 1996). Version 3.1 was used in this interim performance assessment and was also used in the Hanford East Area Burial Ground Performance Assessment (Wood 1996).

D.4 Verification and Benchmarking

D.4.1 PORFLOW- Verification and Benchmarking

The version of PORFLOW being used in this analysis, Version 2.394gr, has been extensively verified and benchmarked (Piepho 1994). Verification and benchmarking efforts were based on

- Comparing the results of the Version 2.394gr of PORFLOW with earlier versions of PORFLOW
- Reproducing the results of analytical solutions from other verification problems
- Comparing the results with other codes for complex problems.

PORFLOW Version 2.394gr was used to run five cases that were used in an extensive verification effort of PORFLOW at the Idaho National Engineering Laboratory (Magnuson 1990). The five cases were

- Transient unsaturated flow in a one-dimensional vertical column (denoted as problem vt1 by Magnuson)
- Transient drawdown of pressure head due to pumping a confined aquifer of constant thickness that is fully penetrated by a well (denoted as vt2)

- Steady state two dimensional saturated-unsaturated flow (denoted as bt1),
- Transient two-dimensional unsaturated flow simulating the infiltration of water into relatively dry, heterogeneous soils (bt2)
- Steady-state saturated flow in a porous media with two distinct fractures (bt3).

In each case, there is excellent agreement between the results of Magnuson et al. and those using PORFLOW 2.394gr.

There were four cases against which PORFLOW 2.394gr could be compared against analytical solutions:

- Case vt1 of Magnuson (1990)
- Case vt2 of Magnuson (1990)
- Two-dimensional nonuniform infiltration into dry homogenous soil (Warrick 1976)
- Mass transport in a two-dimensional groundwater model with a strip source (Cleary 1978).

Again very good agreement was obtained.

Finally as part of the Hanford Grout Performance Assessment (Kincaid 1995-7), the results of PORFLOW 2.394gr and another code, TRACR3D (Travis 1991), were compared for models of the Hanford grouted waste. Again the results show good agreement. Piepho (1994) provides the details.

D.4.2 VAM3D-CG - Verification and Benchmarking

Version 2.4b of VAM3D-CG (Lu 1994) and Version 3.1 (Lu 1995) were tested by

- Comparing the results of the installed version against those published by the vendor (Huyakorn 1993)
- Benchmarking these versions against results of PORFLO-3 Version 1.0 (Sagar 1990) for Hanford relevant problems.

The tests against the vendor-supplied results included:

- Transient one-dimensional horizontal flow in a soil slab
- Transient vertical infiltration in a soil column
- Transient two-dimensional flow in a rectangular soil slab

- Transient two-dimensional transport in a rectangular soil slab
- Three-dimensional transport in uniform groundwater flow.

The benchmarking tests consisted of

- Modeling the 217-U-17 Crib in the 200 West Area
- Modeling a clay cap.

In all cases, good agreement was found.

D.5 Field Testing

D.5.1 PORFLOW- Field Testing

Testing of PORFLOW against Hanford field experiments (Hanford Injection Test) and accidents (T106 Tank Leak) is now being performed.

D.5.2 VAM3D-CG - Field Testing

Field testing efforts were performed for both Versions 2.4b and 3.1. The calibration/validation effort for Version 2.4b (Lu 1993) used data from the Hanford Injection Test experiment (Sisson 1984). The calibration/validation effort for Version 3.1 used data from the reevaluation of the Hanford Injection Test Experiment and from new experiments (Fayer 1995b).

D.6 Input for Base Analysis Case

D.6.1 Disposal Facility Model (Concept 1) - PORFLOW

TITLE base1-ld - base case w .2Dw diffusion(20x base1-ln) for concept 1 LLW disposal facility with 50 canisters (45 canisters)
 USER PIKEPO - Mel Piepho of Daniel B. Stephens & Assoc., Richland, WA 99352;
 509-946-6627

GRID 166 by 133 \$ including PORFLOW boundary cells

/2345678911234567892123456789312345678941234567895123456789612345678971234567899/

COORD X user specified

The following numbers represent the actual PORFLOW grid lines in the X direction. It includes 45 canisters, each with a 1.8 m width

| | | | | | | | |
|--------|-------|--------|--------|--------|--------|--------|--------|
| -0.25 | 0.25 | 0.75 | 1.15 | 2.6 | 2.9 | 3.2 | 4.7 |
| 5 | 5.3 | 6.8 | 7.1 | 7.4 | 8.9 | 9.2 | 9.5 |
| 11 | 11.3 | 11.6 | 13.1 | 13.4 | 13.7 | 15.2 | 15.5 |
| 15.8 | 17.3 | 17.6 | 17.9 | 19.35 | 19.75 | | |
| 20.25 | 20.75 | 21.25 | 21.65 | 23.1 | 23.4 | 23.7 | 25.2 |
| 25.3 | 25.8 | 27.3 | 27.6 | 27.9 | 29.4 | 29.7 | 30 |
| 31.5 | 31.8 | 32.1 | 33.6 | 33.9 | 34.2 | 35.7 | 36 |
| 36.3 | 37.8 | 38.1 | 38.4 | 39.85 | 40.25 | | |
| 40.75 | 41.25 | 41.75 | 42.15 | 43.6 | 43.9 | 44.2 | 45.7 |
| 46 | 46.3 | 47.8 | 48.1 | 48.4 | 49.9 | 50.2 | 50.5 |
| 52 | 52.3 | 52.6 | 54.1 | 54.4 | 54.7 | 56.2 | 56.5 |
| 56.8 | 58.3 | 58.6 | 58.9 | 60.35 | 60.75 | | |
| 61.25 | 61.75 | 62.25 | 62.65 | 64.1 | 64.4 | 64.7 | 66.2 |
| 66.5 | 66.8 | 68.3 | 68.6 | 68.9 | 70.4 | 70.7 | 71 |
| 72.5 | 72.8 | 73.1 | 74.6 | 74.9 | 75.2 | 76.7 | 77 |
| 77.3 | 78.8 | 79.1 | 79.4 | 80.85 | 81.25 | | |
| 81.75 | 82.25 | 82.75 | 83.15 | 84.6 | 84.9 | 85.2 | 86.7 |
| 87 | 87.3 | 88.8 | 89.1 | 89.4 | 90.9 | 91.2 | 91.5 |
| 93 | 93.3 | 93.6 | 95.1 | 95.4 | 95.7 | 97.2 | 97.5 |
| 97.8 | 99.3 | 99.6 | 99.9 | 101.35 | 101.75 | | |
| 102.25 | 103. | 103.75 | 104.25 | 104.75 | 105.25 | 105.75 | 106.25 |
| 107.25 | 108 | 110 | 112 | 115 | 118 | 122 | 126 |

SCALE by 0.01

COORD Y user specified

| | | | | | | | | |
|-------|-------|-------|-------|-------|-------|-------|-------|-----|
| -25. | 25. | 75. | 165. | 235. | 305. | 385. | | 1 1 |
| 485. | 585. | 685. | 785. | 885. | 985. | 1085. | 1185. | 1 2 |
| 1285. | 1385. | 1485. | 1585. | 1685. | 1785. | 1885. | 1985. | 1 3 |
| 2085. | 2185. | 2285. | 2385. | 2485. | 2585. | 2685. | 2785. | 1 4 |
| 2885. | 2985. | 3085. | 3185. | 3285. | 3385. | 3485. | | 1 5 |
| 3585. | 3685. | 3735. | 3805. | 3905. | 4005. | 4105. | 4205. | 1 6 |
| 4305. | 4405. | 4505. | 4605. | 4705. | 4805. | 4905. | 5005. | 1 7 |
| 5105. | 5205. | 5305. | 5405. | 5505. | 5605. | 5705. | 5805. | 1 8 |
| 5905. | 6005. | 6105. | 6205. | 6305. | 6405. | 6505. | | 1 9 |
| 6605. | 6705. | 6805. | 6905. | 7005. | 7105. | 7205. | | 110 |
| 7305. | 7405. | 7505. | 7605. | 7705. | 7805. | 7905. | 8005. | 111 |
| 8105. | 8205. | 8245. | 8285. | 8315. | 8355. | 8455. | 8555. | 112 |
| 8655. | 8755. | 8855. | 8955. | 9000. | 9040. | 9100. | 9180. | 113 |
| 9220. | 9255. | 9295. | 9325. | 9355. | 9395. | 9410. | 9425. | 114 |
| 9440. | 9455. | 9470. | 9485. | 9500. | 9515. | 9530. | 9545. | 115 |
| 9560. | 9575. | 9590. | 9605. | 9620. | 9635. | 9650. | 9665. | 116 |
| 9680. | 9695. | 9710. | 9725. | 9740. | 9755. | 9795. | 9850. | 117 |
| 9900. | | | | | | | | |

DATA 0., 0.

GRAVITY vector: 0, -1

READ 'base0-0.arc' START is UNFormatted mode

TIME = 0.

Zone definitions from TRACER-3D material type map.

MEC-KP-0584

| | | | |
|---------|---------------|--------------|---|
| ZONE 1 | from (1.87) | to (166.133) | \$ Backfill Soil |
| ZONE 2 | from (1.41) | to (166.86) | \$ Mansford-Sandy Seq. |
| ZONE 3 | from (1.5) | to (166.40) | \$ Mansford-Gravel Seq. |
| ZONE 4 | from (1.1) | to (166.4) | \$ Ringold |
| ZONE 5 | from (1.130) | to (7.130) | \$ GRAVEL |
| ZONE 5 | from (1.129) | to (13.129) | \$ GRAVEL |
| ZONE 5 | from (1.128) | to (19.128) | \$ GRAVEL |
| ZONE 5 | from (1.127) | to (25.127) | \$ GRAVEL |
| ZONE 5 | from (1.126) | to (31.126) | \$ GRAVEL |
| ZONE 5 | from (1.125) | to (37.125) | \$ GRAVEL |
| ZONE 5 | from (1.124) | to (43.124) | \$ GRAVEL |
| ZONE 5 | from (1.123) | to (49.123) | \$ GRAVEL |
| ZONE 5 | from (1.122) | to (55.122) | \$ GRAVEL |
| ZONE 5 | from (1.121) | to (61.121) | \$ GRAVEL |
| ZONE 5 | from (1.120) | to (67.120) | \$ GRAVEL |
| ZONE 5 | from (1.119) | to (73.119) | \$ GRAVEL |
| ZONE 5 | from (1.118) | to (79.118) | \$ GRAVEL |
| ZONE 5 | from (1.117) | to (85.117) | \$ GRAVEL |
| ZONE 5 | from (1.116) | to (91.116) | \$ GRAVEL |
| ZONE 5 | from (1.115) | to (97.115) | \$ GRAVEL |
| ZONE 5 | from (1.114) | to (103.114) | \$ GRAVEL |
| ZONE 5 | from (1.113) | to (109.113) | \$ GRAVEL |
| ZONE 5 | from (1.112) | to (115.112) | \$ GRAVEL |
| ZONE 5 | from (1.111) | to (121.111) | \$ GRAVEL |
| ZONE 5 | from (1.110) | to (127.110) | \$ GRAVEL |
| ZONE 5 | from (1.109) | to (133.109) | \$ GRAVEL |
| ZONE 5 | from (1.108) | to (140.108) | \$ GRAVEL |
| ZONE 5 | from (1.107) | to (147.107) | \$ GRAVEL |
| ZONE 5 | from (1.106) | to (154.106) | \$ GRAVEL |
| ZONE 5 | from (154.87) | to (155.105) | \$ GRAVEL |
| ZONE 6 | from (1.103) | to (153.105) | \$ Crushed Glass between gravel and cement top of vault |
| ZONE 7 | from (2.101) | to (150.102) | \$ Top CONCRETE |
| ZONE 9 | from (1.98) | to (150.100) | \$ BF Soil (matrix) above canisters |
| / | | | |
| ZONE 10 | from (4.89) | to (5.97) | \$ glass canisters |
| ZONE 10 | from (7.89) | to (8.97) | \$ glass canisters |
| ZONE 10 | from (10.89) | to (11.97) | \$ glass canisters |
| ZONE 10 | from (13.89) | to (14.97) | \$ glass canisters |
| ZONE 10 | from (16.89) | to (17.97) | \$ glass canisters |
| ZONE 10 | from (19.89) | to (20.97) | \$ glass canisters |
| ZONE 10 | from (22.89) | to (23.97) | \$ glass canisters |
| ZONE 10 | from (25.89) | to (26.97) | \$ glass canisters |
| ZONE 10 | from (28.89) | to (29.97) | \$ glass canisters |
| / | | | |
| ZONE 10 | from (34.89) | to (35.97) | \$ glass canisters |
| ZONE 10 | from (37.89) | to (38.97) | \$ glass canisters |
| ZONE 10 | from (40.89) | to (41.97) | \$ glass canisters |
| ZONE 10 | from (43.89) | to (44.97) | \$ glass canisters |
| ZONE 10 | from (46.89) | to (47.97) | \$ glass canisters |
| ZONE 10 | from (49.89) | to (50.97) | \$ glass canisters |
| ZONE 10 | from (52.89) | to (53.97) | \$ glass canisters |
| ZONE 10 | from (55.89) | to (56.97) | \$ glass canisters |
| ZONE 10 | from (58.89) | to (59.97) | \$ glass canisters |
| / | | | |
| ZONE 10 | from (64.89) | to (65.97) | \$ glass canisters |
| ZONE 10 | from (67.89) | to (68.97) | \$ glass canisters |
| ZONE 10 | from (70.89) | to (71.97) | \$ glass canisters |
| ZONE 10 | from (73.89) | to (74.97) | \$ glass canisters |
| ZONE 10 | from (76.89) | to (77.97) | \$ glass canisters |
| ZONE 10 | from (79.89) | to (80.97) | \$ glass canisters |
| ZONE 10 | from (82.89) | to (83.97) | \$ glass canisters |
| ZONE 10 | from (85.89) | to (86.97) | \$ glass canisters |
| ZONE 10 | from (88.89) | to (89.97) | \$ glass canisters |
| / | | | |
| ZONE 10 | from (94.89) | to (95.97) | \$ glass canisters |
| ZONE 10 | from (97.89) | to (98.97) | \$ glass canisters |

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ZONE 10 from (100.89) to (101.97) \$ glass canisters
 ZONE 10 from (103.89) to (104.97) \$ glass canisters
 ZONE 10 from (106.89) to (107.97) \$ glass canisters
 ZONE 10 from (109.89) to (110.97) \$ glass canisters
 ZONE 10 from (112.89) to (113.97) \$ glass canisters
 ZONE 10 from (115.89) to (116.97) \$ glass canisters
 ZONE 10 from (118.89) to (119.97) \$ glass canisters
 /
 ZONE 10 from (124.89) to (125.97) \$ glass canisters
 ZONE 10 from (127.89) to (128.97) \$ glass canisters
 ZONE 10 from (130.89) to (131.97) \$ glass canisters
 ZONE 10 from (133.89) to (134.97) \$ glass canisters
 ZONE 10 from (136.89) to (137.97) \$ glass canisters
 ZONE 10 from (139.89) to (140.97) \$ glass canisters
 ZONE 10 from (142.89) to (143.97) \$ glass canisters
 ZONE 10 from (145.89) to (146.97) \$ glass canisters
 ZONE 10 from (148.89) to (149.97) \$ glass canisters
 /
 ZONE 12 from (1.87) to (153.88) \$ Bottom CONCRETE
 /
 ZONE 13 from (1.89) to (2.102) \$ Vertical CONCRETE
 ZONE 13 from (31.89) to (32.102) \$ Vertical CONCRETE
 ZONE 13 from (61.89) to (62.102) \$ Vertical CONCRETE
 ZONE 13 from (91.89) to (92.102) \$ Vertical CONCRETE
 ZONE 13 from (121.89) to (122.102) \$ Vertical CONCRETE
 ZONE 13 from (151.89) to (153.102) \$ Vertical CONCRETE
 /
 ZONE 14 from (3.89) to (3.97) \$ BF soil matrix
 ZONE 14 from (6.89) to (6.97) \$ BF soil matrix
 ZONE 14 from (9.89) to (9.97) \$ BF soil matrix
 ZONE 14 from (12.89) to (12.97) \$ BF soil matrix
 ZONE 14 from (15.89) to (15.97) \$ BF soil matrix
 ZONE 14 from (18.89) to (18.97) \$ BF soil matrix
 ZONE 14 from (21.89) to (21.97) \$ BF soil matrix
 ZONE 14 from (24.89) to (24.97) \$ BF soil matrix
 ZONE 14 from (27.89) to (27.97) \$ BF soil matrix
 ZONE 14 from (30.89) to (30.97) \$ BF soil matrix
 /
 ZONE 14 from (33.89) to (33.97) \$ BF soil matrix
 ZONE 14 from (36.89) to (36.97) \$ BF soil matrix
 ZONE 14 from (39.89) to (39.97) \$ BF soil matrix
 ZONE 14 from (42.89) to (42.97) \$ BF soil matrix
 ZONE 14 from (45.89) to (45.97) \$ BF soil matrix
 ZONE 14 from (48.89) to (48.97) \$ BF soil matrix
 ZONE 14 from (51.89) to (51.97) \$ BF soil matrix
 ZONE 14 from (54.89) to (54.97) \$ BF soil matrix
 ZONE 14 from (57.89) to (57.97) \$ BF soil matrix
 ZONE 14 from (60.89) to (60.97) \$ BF soil matrix
 /
 ZONE 14 from (63.89) to (63.97) \$ BF soil matrix
 ZONE 14 from (66.89) to (66.97) \$ BF soil matrix
 ZONE 14 from (69.89) to (69.97) \$ BF soil matrix
 ZONE 14 from (72.89) to (72.97) \$ BF soil matrix
 ZONE 14 from (75.89) to (75.97) \$ P⁺ soil matrix
 ZONE 14 from (78.89) to (78.97) \$ soil matrix
 ZONE 14 from (81.89) to (81.97) \$ nr soil matrix
 ZONE 14 from (84.89) to (84.97) \$ BF soil matrix
 ZONE 14 from (87.89) to (87.97) \$ BF soil matrix
 ZONE 14 from (90.89) to (90.97) \$ BF soil matrix
 /
 ZONE 14 from (93.89) to (93.97) \$ BF soil matrix
 ZONE 14 from (96.89) to (96.97) \$ BF soil matrix
 ZONE 14 from (99.89) to (99.97) \$ BF soil matrix
 ZONE 14 from (102.89) to (102.97) \$ BF soil matrix
 ZONE 14 from (105.89) to (105.97) \$ BF soil matrix
 ZONE 14 from (108.89) to (108.97) \$ BF soil matrix
 ZONE 14 from (111.89) to (111.97) \$ BF soil matrix
 ZONE 14 from (114.89) to (114.97) \$ BF soil matrix

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ZONE 14 from (117.89) to (117.97) \$ BF soil matrix
 ZONE 14 from (120.89) to (120.97) \$ BF soil matrix
 /
 ZONE 14 from (123.89) to (123.97) \$ BF soil matrix
 ZONE 14 from (126.89) to (126.97) \$ BF soil matrix
 ZONE 14 from (129.89) to (129.97) \$ BF soil matrix
 ZONE 14 from (132.89) to (132.97) \$ BF soil matrix
 ZONE 14 from (135.89) to (135.97) \$ BF soil matrix
 ZONE 14 from (138.89) to (138.97) \$ BF soil matrix
 ZONE 14 from (141.89) to (141.97) \$ BF soil matrix
 ZONE 14 from (144.89) to (144.97) \$ BF soil matrix
 ZONE 14 from (147.89) to (147.97) \$ BF soil matrix
 ZONE 14 from (150.89) to (150.97) \$ BF soil matrix

/
 / ZONE 1 - SOIL G-1
 / ZONE 2 - SOIL G-2. Hanford-Sandy Seq.
 / ZONE 3 - SOIL G-3. Hanford-Gravel Seq.
 / ZONE 4 - SOIL G-4. Ringold-Upper

 /
 ROCK rho=2.720 tot=3*0.371 : ZONE 1
 ROCK rho=2.720 tot=3*0.3578 : ZONE 2
 ROCK rho=2.720 --3*0.1312 : ZONE 3
 ROCK rho=2.720 tot=3*0.1342 : ZONE 4
 ROCK rho=2.720 tot=3*0.518 ZONE 5
 ROCK rho=2.720 tot=3*0.518 : ZONE 6
 ROCK rho=2.720 tot=3*0.2258 ZONE 7
 ROCK rho=2.720 tot=3*0.371 : ZONE 9
 ROCK rho=2.720 tot=3*0.0001 ZONE 10
 ROCK rho=2.720 tot=3*0.2258 ZONE 12
 ROCK rho=2.720 tot=3*0.2258 ZONE 13
 ROCK rho=2.720 tot=3*0.371 : ZONE 14

 /
 HYDRAULIC properties: SS=1.e-5 (Kx,Ky,Kz)=3*9467.28 (m/yr) : ZONE 1
 HYDRAULIC properties: SS=1.e-5 (Kx,Ky,Kz)=3*3690.0 (m/yr) : ZONE 2
 HYDRAULIC properties: SS=1.e-5 (Kx,Ky,Kz)=3*417.0 (m/yr) : ZONE 3
 HYDRAULIC properties: SS=1.e-5 (Kx,Ky,Kz)=3*27.6 (m/yr) : ZONE 4
 HYDRAULIC properties: SS=1.e-5 (Kx,Ky,Kz)=3*583816.0 (m/yr) : ZONE 5
 HYDRAULIC properties: SS=1.e-5 (Kx,Ky,Kz)=3*583816.0 (m/yr) : ZONE 6
 HYDRAULIC properties: SS=1.e-5 (Kx,Ky,Kz)=3*1.1834e-4 (m/yr) : ZONE 7
 /HYDRAULIC properties: SS=1.e-5 (Kx,Ky,Kz)=3*9467.28 (m/yr) : ZONE 7
 HYDRAULIC properties: SS=1.e-5 (Kx,Ky,Kz)=3*9467.28 (m/yr) : ZONE 9
 HYDRAULIC properties: SS=1.e-5 (Kx,Ky,Kz)=3*1.2-30 (m/yr) : ZONE 10
 HYDRAULIC properties: SS=1.e-5 (Kx,Ky,Kz)=3*1.1834e-4 (m/yr) : ZONE 12
 HYDRAULIC properties: SS=1.e-5 (Kx,Ky,Kz)=3*1.1834e-4 (m/yr) : ZONE 13
 /HYDRAULIC properties: SS=1.e-5 (Kx,Ky,Kz)=3*9467.28 (m/yr) : ZONE 12
 /HYDRAULIC properties: SS=1.e-5 (Kx,Ky,Kz)=3*9467.28 (m/yr) : ZONE 13
 HYDRAULIC properties: SS=1.e-5 (Kx,Ky,Kz)=3*9467.28 (m/yr) : ZONE 14

 /
 MULTiphase: MINIMUM relative CONDUCTIVITY is 1.E-20 for ZONES 1 to 14 step 1
 MULTiphase: VAN MUAL n=2.00 alpha=6.83 sr=.1213 0. : ZONE 1
 MULTiphase: VAN MUAL n=1.868 alpha=15.66 sr=.06875 0. : ZONE 2
 MULTiphase: VAN MUAL n=1.613 alpha= 1.25 sr=.09604 0. : ZONE 3
 MULTiphase: VAN MUAL n=1.338 alpha= 1.22 sr=.1639 0. : ZONE 4
 MULTiphase: VAN MUAL n=2.661 alpha=353.66 sr=2.703e-2 0. : ZONE 5
 MULTiphase: VAN MUAL n=2.661 alpha=353.66 sr=2.703e-2 0. : ZONE 6
 /MULTiphase: VAN MUAL n=2.00 alpha=6.83 sr=.1213 0. : ZONE 6
 MULTiphase: VAN MUAL n=1.393 alpha=7.61e-4 sr=0.0 0. : ZONE 7
 /MULTiphase: VAN MUAL n=2.00 alpha=6.83 sr=.1213 0. : ZONE 7
 MULTiphase: VAN MUAL n=2.00 alpha=6.83 sr=.1213 0. : ZONE 9
 MULTiphase: VAN MUAL n=1.393 alpha=7.61e-4 sr=0.0 0. : ZONE 10
 MULTiphase: VAN MUAL n=1.393 alpha=7.61e-4 sr=0.0 0. : ZONE 12
 MULTiphase: VAN MUAL n=1.393 alpha=7.61e-4 sr=0.0 0. : ZONE 13
 /MULTiphase: VAN MUAL n=2.00 alpha=6.83 sr=.1213 0. : ZONE 12
 /MULTiphase: VAN MUAL n=2.00 alpha=6.83 sr=.1213 0. : ZONE 13

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MULTIphase: VAN NUAL n=2.08 alpha=6.81 sr=.1213 0. : ZONE 14

```

/-----
TRANsport C Kd=0. Dab=1.5779e-2 a= 0.00 b=0.0 : ZONE 1
TRANsport C Kd=0. Dab=1.5779e-2 a=8.500 b=.85 : ZONE 2
TRANsport C Kd=0. Dab=1.5779e-2 a=8.500 b=.85 : ZONE 3
TRANsport C Kd=0. Dab=1.5779e-2 a=8.500 b=.85 : ZONE 4
TRANsport C Kd=0. Dab=1.5779e-2 a=0.000 b= 0. : ZONE 5
TRANsport C Kd=0. Dab=1.5779e-2 a=0.000 b= 0. : ZONE 6
TRANsport C Kd=0. Dab=1.57788e-2 a=0.000 b= 0. : ZONE 7
TRANsport C Kd=0. Dab=1.5779e-2 a=0.000 b= 0. : ZONE 9
TRANsport C Kd=0. Dab=7.88940e-30 a=0.000 b= 0. : ZONE 10
TRANsport C Kd=0. Dab=1.57788e-2 a=0.000 b= 0. : ZONE 12
TRANsport C Kd=0. Dab=1.57788e-2 a=0.000 b= 0. : ZONE 13
TRANsport C Kd=0. Dab=1.5779e-2 a=0.000 b= 0. : ZONE 14
/

```

```

/-----
TRANsport C2 Kd=0.0 Dab=1.5779e-2 a= 0.00 b=0.0 : ZONE 1
TRANsport C2 Kd=0.0 Dab=1.5779e-2 a=8.500 b=.85 : ZONE 2
TRANsport C2 Kd=0.0 Dab=1.5779e-2 a=8.500 b=.85 : ZONE 3
TRANsport C2 Kd=0.0 Dab=1.5779e-2 a=8.500 b=.85 : ZONE 4
TRANsport C2 Kd=0.0 Dab=1.5779e-2 a=0.000 b= 0. : ZONE 5
TRANsport C2 Kd=0.0 Dab=1.5779e-2 a=0.000 b= 0. : ZONE 6
TRANsport C2 Kd=0.0 Dab=1.57788e-2 a=0.000 b= 0. : ZONE 7
TRANsport C2 Kd=0.0 Dab=1.5779e-2 a=0.000 b= 0. : ZONE 9
TRANsport C2 Kd=0.0 Dab=7.88940e-30 a=0.000 b= 0. : ZONE 10
TRANsport C2 Kd=0.0 Dab=1.57788e-2 a=0.000 b= 0. : ZONE 12
TRANsport C2 Kd=0.0 Dab=1.57788e-2 a=0.000 b= 0. : ZONE 13
TRANsport C2 Kd=0.0 Dab=1.5779e-2 a=0.000 b= 0. : ZONE 14
/

```

```

/-----
TRANsport C3 Kd=0.1 Dab=1.5779e-2 a= 0.00 b=0.0 : ZONE 1
TRANsport C3 Kd=0.1 Dab=1.5779e-2 a=8.500 b=.85 : ZONE 2
TRANsport C3 Kd=0.1 Dab=1.5779e-2 a=8.500 b=.85 : ZONE 3
TRANsport C3 Kd=0.1 Dab=1.5779e-2 a=8.500 b=.85 : ZONE 4
TRANsport C3 Kd=0.1 Dab=1.5779e-2 a=0.000 b= 0. : ZONE 5
TRANsport C3 Kd=0.1 Dab=1.5779e-2 a=0.000 b= 0. : ZONE 6
TRANsport C3 Kd=0.1 Dab=1.57788e-2 a=0.000 b= 0. : ZONE 7
TRANsport C3 Kd=0.1 Dab=1.5779e-2 a=0.000 b= 0. : ZONE 9
TRANsport C3 Kd=0.1 Dab=7.88940e-30 a=0.000 b= 0. : ZONE 10
TRANsport C3 Kd=0.1 Dab=1.57788e-2 a=0.000 b= 0. : ZONE 12
TRANsport C3 Kd=0.1 Dab=1.57788e-2 a=0.000 b= 0. : ZONE 13
TRANsport C3 Kd=0.1 Dab=1.5779e-2 a=0.000 b= 0. : ZONE 14
/

```

```

/-----
TRANsport C4 Kd=0.6 Dab=1.5779e-2 a= 0.00 b=0.0 : ZONE 1
TRANsport C4 Kd=0.6 Dab=1.5779e-2 a=8.5 7 b=.85 : ZONE 2
TRANsport C4 Kd=0.6 Dab=1.5779e-2 a=8.500 b=.85 : ZONE 3
TRANsport C4 Kd=0.6 Dab=1.5779e-2 a=8.500 b=.85 : ZONE 4
TRANsport C4 Kd=0.6 Dab=1.5779e-2 a=0.000 b= 0. : ZONE 5
TRANsport C4 Kd=0.6 Dab=1.5779e-2 a=0.000 b= 0. : ZONE 6
TRANsport C4 Kd=0.6 Dab=1.5779e-2 a=0.000 b= 0. : ZONE 7
TRANsport C4 Kd=0.6 Dab=1.5779e-2 a=0.000 b= 0. : ZONE 9
TRANsport C4 Kd=0.6 Dab=7.88940e-30 a=0.000 b= 0. : ZONE 10
TRANsport C4 Kd=0.6 Dab=1.57788e-2 a=0.000 b= 0. : ZONE 12
TRANsport C4 Kd=0.6 Dab=1.57788e-2 a=0.000 b= 0. : ZONE 13
TRANsport C4 Kd=0.6 Dab=1.5779e-2 a=0.000 b= 0. : ZONE 14
/

```

```

/
INITIAL H=-.7487 IN ZONE 1 ||| Soil G-1
/INITIAL H=-.8227 IN ZONE 2 ||| Soil G-2
/INITIAL H=-3.9454 IN ZONE 3 ||| Soil G-3
/INITIAL H=-2.05473 IN ZONE 4 ||| Soil G-4
INITIAL H=-.7487 IN ZONE 5 ||| Gravel above engineered vault system
INITIAL H=-.7487 IN ZONE 6 ||| Crushed Glass on top of concrete vault roof
INITIAL H=-.7487 IN ZONE 7 ||| Top concrete
INITIAL H=-.7487 IN ZONE 9 ||| BF Soil on top of canisters
INITIAL H=-.7487 IN ZONE 10 ||| Canisters

```

INITIAL H--.7487 IN ZONE 12 !!! Bottom concrete
 INITIAL H--.7487 IN ZONE 13 !!! Vertical concrete
 INITIAL H--.7487 IN ZONE 14 !!! BF Soil in vertical spacing
 INITIAL H=0.0 from (1,1) to (166,1) ! bottom

/
 INITIAL C is 0 everywhere
 INITIAL C2 is 0 everywhere
 INITIAL C3 is 0 everywhere
 INITIAL C4 is 0 everywhere
 /

BOUND P west index = -1 GRAD = 0
 BOUND P east index = 1 GRAD = 0.0
 BOUND P bottom index = -2 VALUE = -0.25 water table
 BOUND P top index = 2 FLUX = -5.0E-4 m/year
 /

BOUND C west index = -1 GRAD = 0.0
 BOUND C east index = 1 GRAD = 0.0
 BOUND C bottom index = -2 GRAD = 0.0
 BOUND C top index = 2 VALUE = 0.0
 /

BOUND C2 west index = -1 GRAD = 0.0
 BOUND C2 east index = 1 GRAD = 0.0
 BOUND C2 bottom index = -2 GRAD = 0.0
 BOUND C2 top index = 2 VALUE = 0.0
 /

BOUND C3 west index = -1 GRAD = 0.0
 BOUND C3 east index = 1 GRAD = 0.0
 BOUND C3 bottom index = -2 GRAD = 0.0
 BOUND C3 top index = 2 VALUE = 0.0
 /

BOUND C4 west index = -1 GRAD = 0.0
 BOUND C4 east index = 1 GRAD = 0.0
 BOUND C4 bottom index = -2 GRAD = 0.0
 BOUND C4 top index = 2 VALUE = 0.0
 /

PROPERTIES FOR P BY GEOMETRIC MEAN
 PROPERTIES FOR C BY HARMONIC MEAN
 PROPERTIES FOR C2 BY HARMONIC MEAN
 PROPERTIES FOR C3 BY HARMONIC MEAN
 PROPERTIES FOR C4 BY HARMONIC MEAN
 /

LOCATE SOURCE 1 from (1,89) to (3,97) \$ BF soil matrix
 LOCATE SOURCE 2 from (4,89) to (6,97) \$ BF soil matrix
 LOCATE SOURCE 3 from (7,89) to (9,97) \$ BF soil matrix
 LOCATE SOURCE 4 from (12,89) to (12,97) \$ BF soil matrix
 LOCATE SOURCE 5 from (15,89) to (15,97) \$ BF soil matrix
 LOCATE SOURCE 6 from (18,89) to (18,97) \$ BF soil matrix
 LOCATE SOURCE 7 from (21,89) to (21,97) \$ BF soil matrix
 LOCATE SOURCE 8 from (24,89) to (24,97) \$ BF soil matrix
 LOCATE SOURCE 9 from (27,89) to (27,97) \$ BF soil matrix
 LOCATE SOURCE 10 from (30,89) to (30,97) \$ BF soil matrix
 /

LOCATE SOURCE 11 from (33,89) to (33,97) \$ BF soil matrix
 LOCATE SOURCE 12 from (36,89) to (36,97) \$ BF soil matrix
 LOCATE SOURCE 13 from (39,89) to (39,97) \$ BF soil matrix
 LOCATE SOURCE 14 from (42,89) to (42,97) \$ BF soil matrix
 LOCATE SOURCE 15 from (45,89) to (45,97) \$ BF soil matrix
 LOCATE SOURCE 16 from (48,89) to (48,97) \$ BF soil matrix
 LOCATE SOURCE 17 from (51,89) to (51,97) \$ BF soil matrix
 LOCATE SOURCE 18 from (54,89) to (54,97) \$ BF soil matrix
 LOCATE SOURCE 19 from (57,89) to (57,97) \$ BF soil matrix
 LOCATE SOURCE 20 from (60,89) to (60,97) \$ BF soil matrix
 /

LOCATE SOURCE 21 from (63,89) to (63,97) \$ BF soil matrix
 LOCATE SOURCE 22 from (66,89) to (66,97) \$ BF soil matrix
 LOCATE SOURCE 23 from (69,89) to (69,97) \$ BF soil matrix
 LOCATE SOURCE 24 from (72,89) to (72,97) \$ BF soil matrix

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LOCATE SOURCE 25 from (75.89) to (75.97) \$ BF soil matrix
 LOCATE SOURCE 26 from (78.89) to (78.97) \$ BF soil matrix
 LOCATE SOURCE 27 from (81.89) to (81.97) \$ BF soil matrix
 LOCATE SOURCE 28 from (84.89) to (84.97) \$ BF soil matrix
 LOCATE SOURCE 29 from (87.89) to (87.97) \$ BF soil matrix
 LOCATE SOURCE 30 from (90.89) to (90.97) \$ BF soil matrix
 /
 LOCATE SOURCE 31 from (93.89) to (93.97) \$ BF soil matrix
 LOCATE SOURCE 32 from (96.89) to (96.97) \$ BF soil matrix
 LOCATE SOURCE 33 from (99.89) to (99.97) \$ BF soil matrix
 LOCATE SOURCE 34 from (102.89) to (102.97) \$ BF soil matrix
 LOCATE SOURCE 35 from (105.89) to (105.97) \$ BF soil matrix
 LOCATE SOURCE 36 from (108.89) to (108.97) \$ BF soil matrix
 LOCATE SOURCE 37 from (111.89) to (111.97) \$ BF soil matrix
 LOCATE SOURCE 38 from (114.89) to (114.97) \$ BF soil matrix
 LOCATE SOURCE 39 from (117.89) to (117.97) \$ BF soil matrix
 LOCATE SOURCE 40 from (120.89) to (120.97) \$ BF soil matrix
 /
 LOCATE SOURCE 41 from (123.89) to (123.97) \$ BF soil matrix
 LOCATE SOURCE 42 from (126.89) to (126.97) \$ BF soil matrix
 LOCATE SOURCE 43 from (129.89) to (129.97) \$ BF soil matrix
 LOCATE SOURCE 44 from (132.89) to (132.97) \$ BF soil matrix
 LOCATE SOURCE 45 from (135.89) to (135.97) \$ BF soil matrix
 LOCATE SOURCE 46 from (138.89) to (138.97) \$ BF soil matrix
 LOCATE SOURCE 47 from (141.89) to (141.97) \$ BF soil matrix
 LOCATE SOURCE 48 from (144.89) to (144.97) \$ BF soil matrix
 LOCATE SOURCE 49 from (147.89) to (147.97) \$ BF soil matrix
 LOCATE SOURCE 50 from (150.89) to (150.97) \$ BF soil matrix

//
 TIME STRENGTH (m**3/m**3-yr)
 /SOURCE 1 FLOW , 4 sat: (0.,0., 121.,7.29e-5, 27000.,2.92e-4, 40000.,2.92e-3)
 / C=0.0, C2=0.0, C3=0.0, C4=0.0
 SCALE .0012346
 SOURCE 1 for C 39 pairs on file 'rfprate.dat'
 /C2 is for Tc-99 which has a release rate that is 5 times smaller than
 C's,C3's,C4's,
 / hence the scale factor is reduced by a factor of 5 if same release file is
 used.
 SCALE .00024691
 SOURCE 1 for C2 5 pairs on file 'rfptcx5.dat'
 SCALE .0012346
 SOURCE 1 for C3 39 pairs on file 'rfprate.dat'
 SCALE .0012346
 SOURCE 1 for C4 39 pairs on file 'rfprate.dat'
 SCALE .0024691
 SOURCE 2 for C 39 pairs on file 'rfprate.dat'
 SCALE .00049384
 SOURCE 2 for C2 5 pairs on file 'rfptcx5.dat'
 SCALE .0024691
 SOURCE 2 for C3 39 pairs on file 'rfprate.dat'
 SCALE .0024691
 SOURCE 2 for C4 39 pairs on file 'rfprate.dat'
 SCALE .0024691
 SOURCE 3 for C 39 pairs on file 'rfprate.dat'
 SCALE .00049384
 SOURCE 3 for C2 5 pairs on file 'rfptcx5.dat'
 SCALE .0024691
 SOURCE 3 for C3 39 pairs on file 'rfprate.dat'
 SCALE .0024691
 SOURCE 3 for C4 39 pairs on file 'rfprate.dat'
 SCALE .0024691
 SOURCE 4 for C 39 pairs on file 'rfprate.dat'
 SCALE .00049384
 SOURCE 4 for C2 5 pairs on file 'rfptcx5.dat'
 SCALE .0024691
 SOURCE 4 for C3 39 pairs on file 'rfprate.dat'
 SCALE .0024691

SOUR# 4 for C4 39 pairs on file 'rfprate.dat'
 SCALE .0024691
 SOUR# 5 for C 39 pairs on file 'rfprate.dat'
 SCALE .00049384
 SOUR# 5 for C2 5 pairs on file 'rfptcx5.dat'
 SCALE .0024691
 SOUR# 5 for C3 39 pairs on file 'rfprate.dat'
 SCALE .0024691
 SOUR# 5 for C4 39 pairs on file 'rfprate.dat'
 SCALE .0024691
 SOUR# 6 for C 39 pairs on file 'rfprate.dat'
 SCALE .00049384
 SOUR# 6 for C2 5 pairs on file 'rfptcx5.dat'
 SCALE .0024691
 SOUR# 6 for C3 39 pairs on file 'rfprate.dat'
 SCALE .0024691
 SOUR# 6 for C4 39 pairs on file 'rfprate.dat'
 SCALE .0024691
 SOUR# 7 for C 39 pairs on file 'rfprate.dat'
 SCALE .00049384
 SOUR# 7 for C2 5 pairs on file 'rfptcx5.dat'
 SCALE .0024691
 SOUR# 7 for C3 39 pairs on file 'rfprate.dat'
 SCALE .0024691
 SOUR# 7 for C4 39 pairs on file 'rfprate.dat'
 SCALE .0024691
 SOUR# 8 for C 39 pairs on file 'rfprate.dat'
 SCALE .00049384
 SOUR# 8 for C2 5 pairs on file 'rfptcx5.dat'
 SCALE .0024691
 SOUR# 8 for C3 39 pairs on file 'rfprate.dat'
 SCALE .0024691
 SOUR# 8 for C4 39 pairs on file 'rfprate.dat'
 SCALE .0024691
 SOUR# 9 for C 39 pairs on file 'rfprate.dat'
 SCALE .00049384
 SOUR# 9 for C2 5 pairs on file 'rfptcx5.dat'
 SCALE .0024691
 SOUR# 9 for C3 39 pairs on file 'rfprate.dat'
 SCALE .0024691
 SOUR# 9 for C4 39 pairs on file 'rfprate.dat'
 SCALE .0012346
 SOUR# 10 for C 39 pairs on file 'rfprate.dat'
 SCALE .00024691
 SOUR# 10 for C2 5 pairs on file 'rfptcx5.dat'
 SCALE .0012346
 SOUR# 10 for C3 39 pairs on file 'rfprate.dat'
 SCALE .0012346
 SOUR# 10 for C4 39 pairs on file 'rfprate.dat'
 SCALE .0012346
 /
 SOUR# 11 for C 39 pairs on file 'rfprate.dat'
 SCALE .00024691
 SOUR# 11 for C2 5 pairs on file 'rfptcx5.dat'
 SCALE .0012346
 SOUR# 11 for C3 39 pairs on file 'rfprate.dat'
 SCALE .0012346
 SOUR# 11 for C4 39 pairs on file 'rfprate.dat'
 SCALE .0024691
 SOUR# 12 for C 39 pairs on file 'rfprate.dat'
 SCALE .00049384
 SOUR# 12 for C2 5 pairs on file 'rfptcx5.dat'
 SCALE .0024691
 SOUR# 12 for C3 39 pairs on file 'rfprate.dat'
 SCALE .0024691
 SOUR# 12 for C4 39 pairs on file 'rfprate.dat'
 SCALE .0024691
 SOUR# 13 for C 39 pairs on file 'rfprate.dat'

SCALE .00049384
SOURCE 13 for C3 5 pairs on file 'rfptcx5.dat'
SCALE .0024691
SOURCE 13 for C3 39 pairs on file 'rfprate.dat'
SCALE .0024691
SOURCE 13 for C4 39 pairs on file 'rfprate.dat'
SCALE .0024691
/
SOURCE 14 for C 39 pairs on file 'rfprate.dat'
SCALE .00049384
SOURCE 14 for C2 5 pairs on file 'rfptcx5.dat'
SCALE .0024691
SOURCE 14 for C3 39 pairs on file 'rfprate.dat'
SCALE .0024691
SOURCE 14 for C4 39 pairs on file 'rfprate.dat'
SCALE .0024691
SOURCE 15 for C 39 pairs on file 'rfprate.dat'
SCALE .00049384
SOURCE 15 for C2 5 pairs on file 'rfptcx5.dat'
SCALE .0024691
SOURCE 15 for C3 39 pairs on file 'rfprate.dat'
SCALE .0024691
SOURCE 15 for C4 39 pairs on file 'rfprate.dat'
SCALE .0024691
SOURCE 16 for C 39 pairs on file 'rfprate.dat'
SCALE .00049384
SOURCE 16 for C2 5 pairs on file 'rfptcx5.dat'
SCALE .0024691
SOURCE 16 for C3 39 pairs on file 'rfprate.dat'
SCALE .0024691
SOURCE 16 for C4 39 pairs on file 'rfprate.dat'
SCALE .0024691
SOURCE 17 for C 39 pairs on file 'rfprate.dat'
SCALE .00049384
SOURCE 17 for C2 5 pairs on file 'rfptcx5.dat'
SCALE .0024691
SOURCE 17 for C3 39 pairs on file 'rfprate.dat'
SCALE .0024691
SOURCE 17 for C4 39 pairs on file 'rfprate.dat'
SCALE .0024691
SOURCE 18 for C 39 pairs on file 'rfprate.dat'
SCALE .00049384
SOURCE 18 for C2 5 pairs on file 'rfptcx5.dat'
SCALE .0024691
SOURCE 18 for C3 39 pairs on file 'rfprate.dat'
SCALE .0024691
SOURCE 18 for C4 39 pairs on file 'rfprate.dat'
SCALE .0024691
SOURCE 19 for C 39 pairs on file 'rfprate.dat'
SCALE .00049384
SOURCE 19 for C2 5 pairs on file 'rfptcx5.dat'
SCALE .0024691
SOURCE 19 for C3 39 pairs on file 'rfprate.dat'
SCALE .0024691
SOURCE 19 for C4 39 pairs on file 'rfprate.dat'
SCALE .0012346
SOURCE 20 for C 39 pairs on file 'rfprate.dat'
SCALE .00024691
SOURCE 20 for C2 5 pairs on file 'rfptcx5.dat'
SCALE .0012346
SOURCE 20 for C3 39 pairs on file 'rfprate.dat'
SCALE .0012346
SOURCE 20 for C4 39 pairs on file 'rfprate.dat'
SCALE .0012346
/
SOURCE 21 for C 39 pairs on file 'rfprate.dat'
SCALE .00024691
SOURCE 21 for C2 5 pairs on file 'rfptcx5.dat'

SCALE .0012346
SCORE 21 for C3 39 pairs on file 'rfprate.dat'
SCALE .0012346
SCORE 21 for C4 39 pairs on file 'rfprate.dat'
SCALE .0024691
SCORE 22 for C 39 pairs on file 'rfprate.dat'
SCALE .00049384
SCORE 22 for C2 5 pairs on file 'rfptcx3.dat'
SCALE .0024691
SCORE 22 for C3 39 pairs on file 'rfprate.dat'
SCALE .0024691
SCORE 22 for C4 39 pairs on file 'rfprate.dat'
SCALE .0024691
SCORE 23 for C 39 pairs on file 'rfprate.dat'
SCALE .00049384
SCORE 23 for C2 5 pairs on file 'rfptcx3.dat'
SCALE .0024691
SCORE 23 for C3 39 pairs on file 'rfprate.dat'
SCALE .0024691
SCORE 23 for C4 39 pairs on file 'rfprate.dat'
SCALE .0024691
SCORE 24 for C 39 pairs on file 'rfprate.dat'
SCALE .00049384
SCORE 24 for C2 5 pairs on file 'rfptcx3.dat'
SCALE .0024691
SCORE 24 for C3 39 pairs on file 'rfprate.dat'
SCALE .0024691
SCORE 24 for C4 39 pairs on file 'rfprate.dat'
SCALE .0024691
SCORE 25 for C 39 pairs on file 'rfprate.dat'
SCALE .00049384
SCORE 25 for C2 5 pairs on file 'rfptcx3.dat'
SCALE .0024691
SCORE 25 for C3 39 pairs on file 'rfprate.dat'
SCALE .0024691
SCORE 25 for C4 39 pairs on file 'rfprate.dat'
SCALE .0024691
SCORE 26 for C 39 pairs on file 'rfprate.dat'
SCALE .00049384
SCORE 26 for C2 5 pairs on file 'rfptcx3.dat'
SCALE .0024691
SCORE 26 for C3 39 pairs on file 'rfprate.dat'
SCALE .0024691
SCORE 26 for C4 39 pairs on file 'rfprate.dat'
SCALE .0024691
SCORE 27 for C 39 pairs on file 'rfprate.dat'
SCALE .00049384
SCORE 27 for C2 5 pairs on file 'rfptcx3.dat'
SCALE .0024691
SCORE 27 for C3 39 pairs on file 'rfprate.dat'
SCALE .0024691
SCORE 27 for C4 39 pairs on file 'rfprate.dat'
SCALE .0024691
SCORE 28 for C 39 pairs on file 'rfprate.dat'
SCALE .00049384
SCORE 28 for C2 5 pairs on file 'rfptcx3.dat'
SCALE .0024691
SCORE 28 for C3 39 pairs on file 'rfprate.dat'
SCALE .0024691
SCORE 28 for C4 39 pairs on file 'rfprate.dat'
SCALE .0024691
SCORE 29 for C 39 pairs on file 'rfprate.dat'
SCALE .00049384
SCORE 29 for C2 5 pairs on file 'rfptcx3.dat'
SCALE .0024691
SCORE 29 for C3 39 pairs on file 'rfprate.dat'
SCALE .0024691
SCORE 29 for C4 39 pairs on file 'rfprate.dat'

SCALE .0012346
SCORE 30 for C 39 pairs on file 'rfprate.dat'
SCALE .00024691
SCORE 30 for C2 5 pairs on file 'rfptcx5.dat'
SCALE .0012346
SCORE 30 for C3 39 pairs on file 'rfprate.dat'
SCALE .0012346
SCORE 30 for C4 39 pairs on file 'rfprate.dat'
SCALE .0012346
/
SCORE 31 for C 39 pairs on file 'rfprate.dat'
SCALE .00024691
SCORE 31 for C2 5 pairs on file 'rfptcx5.dat'
SCALE .0012346
SCORE 31 for C3 39 pairs on file 'rfprate.dat'
SCALE .0012346
SCORE 31 for C4 39 pairs on file 'rfprate.dat'
SCALE .0024691
SCORE 32 for C 39 pairs on file 'rfprate.dat'
SCALE .00049384
SCORE 32 for C2 5 pairs on file 'rfptcx5.dat'
SCALE .0024691
SCORE 32 for C3 39 pairs on file 'rfprate.dat'
SCALE .0024691
SCORE 32 for C4 39 pairs on file 'rfprate.dat'
SCALE .0024691
SCORE 33 for C 39 pairs on file 'rfprate.dat'
SCALE .00049384
SCORE 33 for C2 5 pairs on file 'rfptcx5.dat'
SCALE .0024691
SCORE 33 for C3 39 pairs on file 'rfprate.dat'
SCALE .0024691
SCORE 33 for C4 39 pairs on file 'rfprate.dat'
SCALE .0024691
SCORE 34 for C 39 pairs on file 'rfprate.dat'
SCALE .00049384
SCORE 34 for C2 5 pairs on file 'rfptcx5.dat'
SCALE .0024691
SCORE 34 for C3 39 pairs on file 'rfprate.dat'
SCALE .0024691
SCORE 34 for C4 39 pairs on file 'rfprate.dat'
SCALE .0024691
SCORE 35 for C 39 pairs on file 'rfprate.dat'
SCALE .00049384
SCORE 35 for C2 5 pairs on file 'rfptcx5.dat'
SCALE .0024691
SCORE 35 for C3 39 pairs on file 'rfprate.dat'
SCALE .0024691
SCORE 35 for C4 39 pairs on file 'rfprate.dat'
SCALE .0024691
SCORE 36 for C 39 pairs on file 'rfprate.dat'
SCALE .00049384
SCORE 36 for C2 5 pairs on file 'rfptcx5.dat'
SCALE .0024691
SCORE 36 for C3 39 pairs on file 'rfprate.dat'
SCALE .0024691
SCORE 36 for C4 39 pairs on file 'rfprate.dat'
SCALE .0024691
SCORE 37 for C 39 pairs on file 'rfprate.dat'
SCALE .0024691
SCORE 37 for C2 5 pairs on file 'rfptcx5.dat'
SCALE .0024691
SCORE 37 for C3 39 pairs on file 'rfprate.dat'
SCALE .0024691
SCORE 37 for C4 39 pairs on file 'rfprate.dat'
SCALE .0024691
SCORE 38 for C 39 pairs on file 'rfprate.dat'
SCALE .00049384

```

SOURCE 38 for C2 5 pairs on file 'rfptcx5.dat'
SCALE .0024691
SOURCE 38 for C3 39 pairs on file 'rfprate.dat'
SCALE .0024691
SOURCE 38 for C4 39 pairs on file 'rfprate.dat'
SCALE .0024691
SOURCE 39 for C 39 pairs on file 'rfprate.dat'
SCALE .00049384
SOURCE 39 for C2 5 pairs on file 'rfptcx5.dat'
SCALE .0024691
SOURCE 39 for C3 39 pairs on file 'rfprate.dat'
SCALE .0024691
SOURCE 39 for C4 39 pairs on file 'rfprate.dat'
SCALE .0012346
SOURCE 40 for C 39 pairs on file 'rfprate.dat'
SCALE .00024691
SOURCE 40 for C2 5 pairs on file 'rfptcx5.dat'
SCALE .0012346
SOURCE 40 for C3 39 pairs on file 'rfprate.dat'
SCALE .0012346
SOURCE 40 for C4 39 pairs on file 'rfprate.dat'
SCALE .0012346
/
SOURCE 41 for C 39 pairs on file 'rfprate.dat'
SCALE .00024691
SOURCE 41 for C2 5 pairs on file 'rfptcx5.dat'
SCALE .0012346
SOURCE 41 for C3 39 pairs on file 'rfprate.dat'
SCALE .0012346
SOURCE 41 for C4 39 pairs on file 'rfprate.dat'
SCALE .0024691
/
SOURCE 42 for C 39 pairs on file 'rfprate.dat'
SCALE .00049384
SOURCE 42 for C2 5 pairs on file 'rfptcx5.dat'
SCALE .0024691
SOURCE 42 for C3 39 pairs on file 'rfprate.dat'
SCALE .0024691
SOURCE 42 for C4 39 pairs on file 'rfprate.dat'
SCALE .0024691
SOURCE 43 for C 39 pairs on file 'rfprate.dat'
SCALE .00049384
SOURCE 43 for C2 5 pairs on file 'rfptcx5.dat'
SCALE .0024691
SOURCE 43 for C3 39 pairs on file 'rfprate.dat'
SCALE .0024691
SOURCE 43 for C4 39 pairs on file 'rfprate.dat'
SCALE .0024691
SOURCE 44 for C 39 pairs on file 'rfprate.dat'
SCALE .00049384
SOURCE 44 for C2 5 pairs on file 'rfptcx5.dat'
SCALE .0024691
SOURCE 44 for C3 39 pairs on file 'rfprate.dat'
SCALE .0024691
SOURCE 44 for C4 39 pairs on file 'rfprate.dat'
SCALE .0024691
SOURCE 45 for C 39 pairs on file 'rfprate.dat'
SCALE .00049384
SOURCE 45 for C2 5 pairs on file 'rfptcx5.dat'
SCALE .0024691
SOURCE 45 for C3 39 pairs on file 'rfprate.dat'
SCALE .0024691
SOURCE 45 for C4 39 pairs on file 'rfprate.dat'
SCALE .0024691
SOURCE 46 for C 39 pairs on file 'rfprate.dat'
SCALE .00049384
SOURCE 46 for C2 5 pairs on file 'rfptcx5.dat'
SCALE .0024691

```

SCORE 46 for C3 39 pairs on file 'rfprate.dat'
 SCALE .0024691
 SCORE 46 for C4 39 pairs on file 'rfprate.dat'
 SCALE .0024691
 SCORE 47 for C 39 pairs on file 'rfprate.dat'
 SCALE .00049384
 SCORE 47 for C2 5 pairs on file 'rfptcx5.dat'
 SCALE .0024691
 SCORE 47 for C3 39 pairs on file 'rfprate.dat'
 SCALE .0024691
 SCORE 47 for C4 39 pairs on file 'rfprate.dat'
 SCALE .0024691
 SCORE 48 for C 39 pairs on file 'rfprate.dat'
 SCALE .00049384
 SCORE 48 for C2 5 pairs on file 'rfptcx5.dat'
 SCALE .0024691
 SCORE 48 for C3 39 pairs on file 'rfprate.dat'
 SCALE .0024691
 SCORE 48 for C4 39 pairs on file 'rfprate.dat'
 SCALE .0024691
 SCORE 49 for C 39 pairs on file 'rfprate.dat'
 SCALE .00049384
 SCORE 49 for C2 5 pairs on file 'rfptcx5.dat'
 SCALE .0024691
 SCORE 49 for C3 39 pairs on file 'rfprate.dat'
 SCALE .0024691
 SCORE 49 for C4 39 pairs on file 'rfprate.dat'
 SCALE .0012346
 SCORE 50 for C 39 pairs on file 'rfprate.dat'
 SCALE .00024691
 SCORE 50 for C2 5 pairs on file 'rfptcx5.dat'
 SCALE .0012346
 SCORE 50 for C3 39 pairs on file 'rfprate.dat'
 SCALE .0012346
 SCORE 50 for C4 39 pairs on file 'rfprate.dat'

/
 FIXED P from (6.89) to (5.97) \$ glass canisters
 FIXED P from (7.89) to (8.97) \$ glass canisters
 FIXED P from (10.89) to (11.97) \$ glass canisters
 FIXED P from (13.89) to (14.97) \$ glass canisters
 FIXED P from (16.89) to (17.97) \$ glass canisters
 FIXED P from (19.89) to (20.97) \$ glass canisters
 FIXED P from (22.89) to (23.97) \$ glass canisters
 FIXED P from (25.89) to (26.97) \$ glass canisters
 FIXED P from (28.89) to (29.97) \$ glass canisters
 /
 FIXED P from (34.89) to (35.97) \$ glass canisters
 FIXED P from (37.89) to (38.97) \$ glass canisters
 FIXED P from (40.89) to (41.97) \$ glass canisters
 FIXED P from (43.89) to (44.97) \$ glass canisters
 FIXED P from (46.89) to (47.97) \$ glass canisters
 FIXED P from (49.89) to (50.97) \$ glass canisters
 FIXED P from (52.89) to (53.97) \$ glass canisters
 FIXED P from (55.89) to (56.97) \$ glass canisters
 FIXED P from (58.89) to (59.97) \$ glass canisters
 /
 FIXED P from (64.89) to (65.97) \$ glass canisters
 FIXED P from (67.89) to (68.97) \$ glass canisters
 FIXED P from (70.89) to (71.97) \$ glass canisters
 FIXED P from (73.89) to (74.97) \$ glass canisters
 FIXED P from (76.89) to (77.97) \$ glass canisters
 FIXED P from (79.89) to (80.97) \$ glass canisters
 FIXED P from (82.89) to (83.97) \$ glass canisters
 FIXED P from (85.89) to (86.97) \$ glass canisters
 FIXED P from (88.89) to (89.97) \$ glass canisters
 /
 FIXED P from (94.89) to (95.97) \$ glass canisters

```

FIXED P from (97,89) to (98,97) $ glass canisters
FIXED P from (100,89) to (101,97) $ glass canisters
FIXED P from (103,89) to (104,97) $ glass canisters
FIXED P from (106,89) to (107,97) $ glass canisters
FIXED P from (109,89) to (110,97) $ glass canisters
FIXED P from (112,89) to (113,97) $ glass canisters
FIXED P from (115,89) to (116,97) $ glass canisters
FIXED P from (118,89) to (119,97) $ glass canisters
/
FIXED P from (124,89) to (125,97) $ glass canisters
FIXED P from (127,89) to (128,97) $ glass canisters
FIXED P from (130,89) to (131,97) $ glass canisters
FIXED P from (133,89) to (134,97) $ glass canisters
FIXED P from (136,89) to (137,97) $ glass canisters
FIXED P from (139,89) to (140,97) $ glass canisters
FIXED P from (142,89) to (143,97) $ glass canisters
FIXED P from (145,89) to (146,97) $ glass canisters
FIXED P from (148,89) to (149,97) $ glass canisters
/

```

CONvergence for P LOCAL eps=5.0e-6 ITERations=12
METHOD is PICARD

MATRIX for P=2 using AD2
MATRIX for C=2 using AD1
MATRIX for C2=2 using AD1
MATRIX for C3=2 using AD1
MATRIX for C4=1 using AD1

//RELAX P = 0.32 !!!!! S = 0.5, KR = 0.5, SE = 0.5

FLUX BALANCE FOR C ON 'basel-ld.flx' FROM (1,1) TO (166,133) EVERY 2000 STEPS
FLUX BALANCE for C from (1,87) to (153,101) every 2000 steps
FLUX BALANCE for C from (1,87) to (166,133) every 2000 steps
FLUX BALANCE for C from (1,5) to (166,86) every 2000 steps
FLUX BALANCE for C from (3,89) to (3,97) every 2000 steps
FLUX BALANCE for C from (148,89) to (149,97) every 2000 steps
FLUX BALANCE for C from (150,89) to (150,97) every 2000 steps
/HISTORY (2,2), (30,2), (40,2), (60,2), (78,2) on 'basel-ld.his' eve 200

FLUX BALANCE for P from (1,1) to (166,133) every 1000 steps
FLUX BALANCE for P from (1,87) to (153,101) every 1000 steps
FLUX BALANCE for P from (1,87) to (166,133) every 1000 steps
FLUX BALANCE for P from (1,1) to (166,86) every 1000 steps
FLUX for C from (1,87) to (166,87) every 200 steps
FLUX for C from (1,2) to (166,2) every 200 steps
FLUX for C2 from (1,2) to (166,2) every 200 steps
FLUX for C3 from (1,2) to (166,2) every 200 steps
FLUX for C4 from (1,2) to (166,2) every 200 steps
DIAGNOSTIC node at (46,2) every 20 steps
DEBUG lave 1 at step :0000

WINDOW from (1,1) to (165,133)
SOLVE AUTO 200 YEARS, STEPS=1.e-1 FAC=1.1 MAX 20.0 1.e-15 3.0 @5000
CONvergence for P LOCAL eps=1.0e-5 ITERations=12
SOLVE AUTO 300 YEARS, STEPS=1.e-1 FAC=1.1 MAX 20.0 1.e-15 3.0 @5000
SAVE U, V, C, C2, C3, C4, H, S, MOIS on 'basel-ld.arc' NOW
OUTPUT U, V, C, H, S, MOIS NOW

/Degrade the concrete here after 500 years

CONvergence for P LOCAL eps=5.0e-5 ITERations=12

HYDRAULIC properties: SS=1.e-5 (Kx,Ky,Kz)=3*417.0 (m/yr) : ZONE 7
HYDRAULIC properties: SS=1.e-5 (Kx,Ky,Kz)=3*417.0 (m/yr) : ZONE 12
HYDRAULIC properties: SS=1.e-5 (Kx,Ky,Kz)=3*417.0 (m/yr) : ZONE 13
MULTIphase: VAN MUAL n=1.613 alpha= 1.25 sr= .09604 0. : ZONE 7
MULTIphase: VAN MUAL n=1.613 alpha= 1.25 sr= .09604 0. : ZONE 12
MULTIphase: VAN MUAL n=1.613 alpha= 1.25 sr= .09604 0. : ZONE 13
/MULTIphase: VAN MUAL n=1.613 alpha= 1.25 sr= .09604 0. : ZONE 7
/MULTIphase: VAN MUAL n=1.613 alpha= 1.25 sr= .09604 0. : ZONE 12
/MULTIphase: VAN MUAL n=1.613 alpha= 1.25 sr= .09604 0. : ZONE 13
INITIAL H=-.061 IN ZONE 7 !!! Top horizontal concrete

```

INITIAL H--.001 IN ZONE 13      !!! Bottom horizontal concrete
INITIAL H--.001 IN ZONE 13      !!! Vertical concrete
SOLVE AUTO      500.0 YEARS,STEPS-1.e-1 FAC-1.1 MAX 20.0 1.e-15 3.0 85000
SAVE U, V, C, C2, C3, C4, H, S, MOIS NOW
OUTPUT U, V, C, H, S, MOIS NOW
/ Increase the recharge rate from 0.05 cm/yr to .3 cm/yr at 1000 yrs
CONvergence for P LOCAL spr-5.0e-5 ITERations-12
BOUN P west     index = -1 GRAD = 0
BOUN P east     index = 1 GRAD = 0.0
BOUN P bottom   index = -2 VALUE = -0.25 water table
BOUN P top      index = 2 FLUX = -3.0E-3 m/year
/
SOLVE AUTO 3000 YEARS,STEPS-1.e-8 FAC-1.1 MAX 10.0 1.e-15 3.0 85000
SAVE U, V, C, C2, C3, C4, H, S, MOIS NOW
OUTPUT U, V, C, H, S, MOIS NOW
/
DISABLE FLOW
/
SOLVE AUTO 6000 YEARS,STEPS-3.e-1 FAC-1.1 MAX 4.0 1.e-15 3.0 85000
OUTPUT U, V, C, H, S, MOIS NOW
SAVE U, V, C, C2, C3, C4, H, S, MOIS NOW
SOLVE AUTO 90000 YEARS,STEPS-4.e-0 FAC-1.1 MAX 8.0 1.e-14 3.0 85000
END
QUIT

```

D.6.2 Unit Cell Model - PORFLOW

TITLE Performance Based on a Single Canister: Concept 1 Base Case

```

/
/   Units:  length in meters   (m)
/           mass  in kilograms (kg)
/           time  in years     (yr)
/
GRID  10 x 44
/
COORDINATES in X direction: -0.05 0.05 0.15 0.3 0.5 0.7 0.85 0.95 1.025 1.075
/
COORDINATES in Y direction: -1.0  1.0  3.0  6.0 10.0 15.0 21.0 26.0
10.0 33.0 35.0 36.5 37.5 39.0 41.0 44.0 48.0 53.0 60.0 68.0
73.0 76.0 76.0 79.5 80.5 81.2 81.7 82.1 82.4 82.75 83.25 84.0
85.0 84.0 87.0 88.0 88.75 89.5 90.0 90.4 90.9 91.4 91.85 92.15
/

```

```

/
ZONE 1 from (1,1) to (10,2) $ Ringold E
ZONE 2 from (1,3) to (10,12) $ Lower Manford Gravels (Sandy gravel)
ZONE 3 from (1,13) to (10,28) $ Upper Manford Sands
ZONE 4 from (1,29) to (10,30) $ Concrete Vault Floor (Degraded at t=0)
ZONE 5 from (1,31) to (10,44) $ Vault Interior (Backfill)
ZONE 6 from (1,31) to (7,39) $ Canister Stack (Waste Form)
ZONE 7 from (2,43) to (9,43) $ Artificial diffusion barrier
/

```

```

MULTIphase: VAN NUAL n=1.5865, a=1.22 /m, Sr=0.164, 0 Zone 1
MULTIphase: VAN NUAL n=1.530, a=1.25 /m, Sr=0.096, 0 Zone 2 4 2
MULTIphase: VAN NUAL n=2.1768, a=15.66 /m, Sr=0.069, 0 Zone 3
MULTIphase: VAN NUAL n=2.080, a=6.83 /m, Sr=0.121, 0 Zone 5 7 2
MULTIphase: VAN NUAL n=2.661, a=353.66 /m, Sr=0.027, 0 Zone 6
/

```

MULTIphase: MINIMUM kr = 1e-20

```

/
HYDRAULIC Ss 0.1 K 3*27.58 m/yr for Zone 1
HYDRAULIC Ss 0.1 K 3*416.56 for Zone 2 4 2
HYDRAULIC Ss 0.1 K 3*3592.24 for Zone 3
HYDRAULIC Ss 0.1 K 3*9467.28 for Zone 5 7 2
HYDRAULIC Ss 0.1 K 3*583815.6 for Zone 6
/

```

```

/
SOIL Rho 2720 Por 0.112 2*0.1342 for Zone 1
SOIL Rho 2720 Por 0.119 2*0.1312 for Zone 2 4 2
SOIL Rho 2720 Por 0.333 2*0.3578 for Zone 3
SOIL Rho 2720 Por 0.326 2*0.371 for Zone 5 7 2
SOIL Rho 2620 Por 0.504 2*0.518 for Zone 6
/

```

DATUM 0 0
GRAVITY 0 -1

READ 22
TIME = 0

```

/
BOUND P -1 GRAD = 0 $ Symmetry: center of canister
BOUND P +1 GRAD = 0 $ Symmetry: center of intercanister filler
BOUND P -2 VALUE = -1.0 m $ Water Table
BOUND P +2 FLUX = -0.0005 m/yr $ Assumed recharge of 0.5 mm/yr
/

```

Properties for P: GEOMETRIC mean at cell interfaces
MATRIX sweeps in X and Y directions: P=2 iterations of ADI
METHOD for nonlinearity of P is PICARD
CONVERGENCE of P: LOCAL mode with epsilon=0.0005 and maxiter=30

```

/
Transport Properties: C = Kd = 0
/
/                   C2 = Kd = 0.1 ml/gr
/                   C3 = Kd = 0.6 ml/gr
/                   C4 = Kd = 3 ml/gr
/

```

```

TRAN C Kd=0 Dm=7.889e-4 aL=8.225 aT=0.8225 for Zone 1 5 1
TRAN C Kd=0 Dm=7.889e-4 aL=8.225 aT=0.8225 for Zone 6
/

```

TRAN C2 Kd=0.0001 Dm=7.889e-4 al=8.225 at=0.8225 for Zone 1 5 1
 TRAN C2 Kd=0 Dm=7.889e-4 al=8.225 at=0.8225 for Zone 6
 TRAN C3 Kd=0.0006 Dm=7.889e-4 al=8.225 at=0.8225 for Zone 1 5 1
 TRAN C3 Kd=0 Dm=7.889e-4 al=8.225 at=0.8225 for Zone 6
 TRAN C4 Kd=0.003 Dm=7.889e-4 al=8.225 at=0.8225 for Zone 1 5 1
 TRAN C4 Kd=0 Dm=7.889e-4 al=8.225 at=0.8225 for Zone 6

/ Artificial diffusion barrier - next to top row of nodes

TRAN C 4=0 7
 TRAN C2 4=0 7
 TRAN C3 4=0 7
 TRAN C4 4=0 7

INITIAL C = 0 everywhere
 INITIAL C2 = 0 everywhere
 INITIAL C3 = 0 everywhere
 INITIAL C4 = 0 everywhere

BOUND C west index = -1 GRAD = 0.0
 BOUND C east index = 1 GRAD = 0.0
 BOUND C bottom index = -2 GRAD = 0.0
 BOUND C top index = 2 VALUE = 0.0

BOUND C2 west index = -1 GRAD = 0.0
 BOUND C2 east index = 1 GRAD = 0.0
 BOUND C2 bottom index = -2 GRAD = 0.0
 BOUND C2 top index = 2 VALUE = 0.0

BOUND C3 west index = -1 GRAD = 0.0
 BOUND C3 east index = 1 GRAD = 0.0
 BOUND C3 bottom index = -2 GRAD = 0.0
 BOUND C3 top index = 2 VALUE = 0.0

BOUND C4 west index = -1 GRAD = 0.0
 BOUND C4 east index = 1 GRAD = 0.0
 BOUND C4 bottom index = -2 GRAD = 0.0
 BOUND C4 top index = 2 VALUE = 0.0

PROPERTIES FOR C BY HARMONIC MEAN
 PROPERTIES FOR C2 BY HARMONIC MEAN
 PROPERTIES FOR C3 BY HARMONIC MEAN
 PROPERTIES FOR C4 BY HARMONIC MEAN

LOCATE SOURCE 1 at (2,31) to (7,39)
 LOCATE SOURCE 2 at (2,31) to (7,39)
 LOCATE SOURCE 3 at (2,31) to (7,39)
 LOCATE SOURCE 4 at (2,31) to (7,39)

/ Constant initial maximum volumetric fractional release rate:

SOURCE number 1 for C is VOLUMetric with 2 pairs of the form (t,f):
 (0.0,6.82e-7), (226343.5,6.82e-7)

SOUR 2 C2 VOLU 2 (0.0,6.82e-7) (226343.5,6.82e-7)
 SOUR 3 C3 VOLU 2 (0.0,6.82e-7) (226343.5,6.82e-7)
 SOUR 4 C4 VOLU 2 (0.0,6.82e-7) (226343.5,6.82e-7)

MATRIX for C-2 using ADI
 MATRIX for C2-2 using ADI
 MATRIX for C3-1 using ADI
 MATRIX for C4-1 using ADI

FLUX of P from (2,43) to (9,43) every 200 steps
 FLUX of P from (2,28) to (9,28) every 200 steps
 FLUX of P from (2,2) to (9,2) every 200 steps
 FLUX of C from (2,28) to (9,28) every 100 steps

```

FLUX of C2 from (2,28) to (9,28) every 100 steps
FLUX of C3 from (2,28) to (9,28) every 100 steps
FLUX of C4 from (2,28) to (9,28) every 100 steps
/
FLUX OF C FROM (2,2) TO (9,2) EVERY 100 STEPS
FLUX OF C2 FROM (2,2) TO (9,2) EVERY 100 STEPS
FLUX OF C3 FROM (2,2) TO (9,2) EVERY 100 STEPS
FLUX OF C4 FROM (2,2) TO (9,2) EVERY 100 STEPS
/
Diagnostic node at (5,33) every 50 steps $ History node in the waste form
WINDOW from (1,1) to (18,44)
SAVE U,V,W,P,S,MOIS, C,C2,C3,C4 NOW $ I.C.
/
SOLVE AUTO 100 YEARS, STEPS-1.e-5 FAC-1.02 MAX 0.01 1.e-9 3.0 5000000
SAVE U,V,W,P,S,MOIS, C,C2,C3,C4,NOW
/
SOLVE AUTO 100 YEARS IN STEPS OF 1.e-4 FAC 1.02 MAX 0.05 1.e-8 3.0
SAVE U,V,W,P,S,MOIS, C,C2,C3,C4 NOW
/
SOLVE AUTO 100 YEARS IN STEPS OF 1.e-3 FAC 1.02 MAX 0.1 1.e-7 3.0
SAVE NOW $ At 500 years
/
SOLVE AUTO 500 YEARS IN STEPS OF 1.e-6 FAC 1.02 MAX 0.1 1.e-12 3.0
SAVE NOW $ At 1000 years
/
Step Change in Recharge Rate from 0.5 mm/yr to 3 mm/yr
/
ROOM 9 +2 FLUX = -0.003 m/yr
/
SOLVE AUTO 500 YEARS IN STEPS OF 1.e-6 FAC 1.01 MAX 0.1 1.e-15 3.0
SAVE NOW
SOLVE AUTO 500 YEARS IN STEPS OF 1.e-4 FAC 1.02 MAX 0.2 1.e-15 3.0
SAVE NOW
/
SOLVE AUTO 500 YEARS IN STEPS OF 1.e-3 FAC 1.02 MAX 0.4 1.e-15 3.0
SAVE NOW
SOLVE AUTO 500 YEARS IN STEPS OF 0.002 FAC 1.02 MAX 0.5 1.e-15 3.0
SAVE NOW
SOLVE AUTO 1000 YEARS IN STEPS OF 0.005 FAC 1.02 MAX 0.8 1.e-15 3.0
SAVE NOW
SOLVE AUTO 1000 YEARS IN STEPS OF 0.01 FAC 1.02 MAX 1.0 1.e-15 3.0
SAVE NOW
/
SOLVE AUTO 2000 YEARS IN STEPS OF 0.02 FAC 1.02 MAX 1.0
SAVE NOW
SOLVE AUTO 3000 YEARS IN STEPS OF 0.03 1.02 1.0
SAVE NOW
/
SOLVE AUTO 5000 YEARS IN STEPS OF 0.1 FAC 1.02 MAX 2.0
SAVE NOW
SOLVE AUTO 5000 YEARS IN STEPS OF 0.2 1.02 3.0
SAVE NOW
SOLVE AUTO 5000 YEARS IN STEPS OF 0.4 fac 1.02 max 2.
SAVE NOW
SOLVE AUTO 5000 YEARS IN STEPS OF 0.5 1.02 4.
SAVE NOW
SOLVE AUTO 70000 YEARS IN STEPS OF 0.5 fac 1.01 max 5.
/
END
QUIT

```

D.6.3 Pump Model - VAM3D-C6

Because of the size of the input file, the file is not listed.

D.6.4 Site Groundwater Model

Because of the size of the input file, the file is not listed.

D.6.5 INTEC

```

#
# script to run dose calculations
#
integ.x << eof > dose.1-1d
Concept 1 base case
wif          0.00177
recharge     1.0      mm/y
area         50000.   m2
dwi          4.0      mm/yr
dwal         4.0      mm/yr
dwbl         4.0      mm/yr
conral       3.0      pCi/l
conal        15.0     pCi/l
invfile      inv.bac
t12f         t12.bac
dwfile       dw.bac
allfile      all.bac
nlbf         kd.bac
vadfile      piepho.1-1d
end
eof
mv fort.7 fort7.1-1d
    
```

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APPENDIX E DETAILED RESULTS

E.1 OVERVIEW

This appendix presents more information concerning the results of the simulations. There are four sections covering a) vadose zone simulations, b) unconfined aquifer simulations, c) the calculation of dose, and d) simulations of glass dissolution.

Because of the long-time of release from the waste form, the time-dependence of the vadose zone transport and hence of the impacts of the disposal action looks more like a step function than a peak function. The following section provides a mathematical justification for this shape.

For a point source in an infinite one-dimensional homogeneous media, the concentration of contaminants (C) can be expressed as

$$C(z, t) = \int_0^t f(T) G(z, t-T) dT$$

where

t is the time (s) since release,
z is the distance (cm) from release,
f (T) is the source term of contaminants, and
G (z, t-T) is the Green's function for transport,

$$G(z, t) = \left(\frac{1}{4n D_r t} \right)^{\frac{1}{2}} \exp(-\lambda t) \exp\left[-\frac{(z-ut)^2}{4D_r t}\right]$$

where

D_r is the retardation-corrected pseudodispersion coefficient (cm^2/s),
 λ is the decay constant (s^{-1}) of the contaminant, and
u is the retardation-corrected pore velocity (cm/s).

Both D_r and u depend upon the moisture content.

For the unretarded contaminants (in our case, technetium, selenium, and iodine), the release rate for the base analysis case is almost constant, changing less than 1 percent in 20,000 years. Thus the slowly varying release function f(t) can be removed from the integrand, leaving just the integral over the Green's function. This integral results in a step function with the first wave of contaminants followed by hundred of thousands of years of succeeding contaminants.

For the more typical case where the release from the waste form is quick relative to the travel through the vadose zone, then it is the Green's function which can be removed from the integrand, resulting in a integral that is just the inventory. The time dependence is a skewed bell-shaped curve.

E.2 VADOSE ZONE SIMULATIONS

E.2.1 Overview

This appendix provides more details concerning the computer simulations that were run to determine the contaminant flux to the underground aquifer. The next section contains a brief discussion of the calculation for very long times. The last section summarizes the fluxes for all the computer simulations (Table E-1) as well as figures displaying the contaminant fluxes.

E.2.2 Extension of Calculation to Long Times

In order to determine the peak impact, calculations of the vadose zone flux must be made for millions of years. However, computer simulations for such long times would not justify their cost. Therefore a simpler approach was used.

As has been shown in previous Hanford calculations, the normalized flux to the aquifer can be approximately calculated based on the $K_d = 0$ group. By assuming that the release rate continues indefinitely and that the waste form release controls the temporal shape, the normalized flux to the aquifer can be approximately by

$$\Gamma(K_d, t \cdot [1 + \alpha K_d]) = \Gamma(K_d=0, t).$$

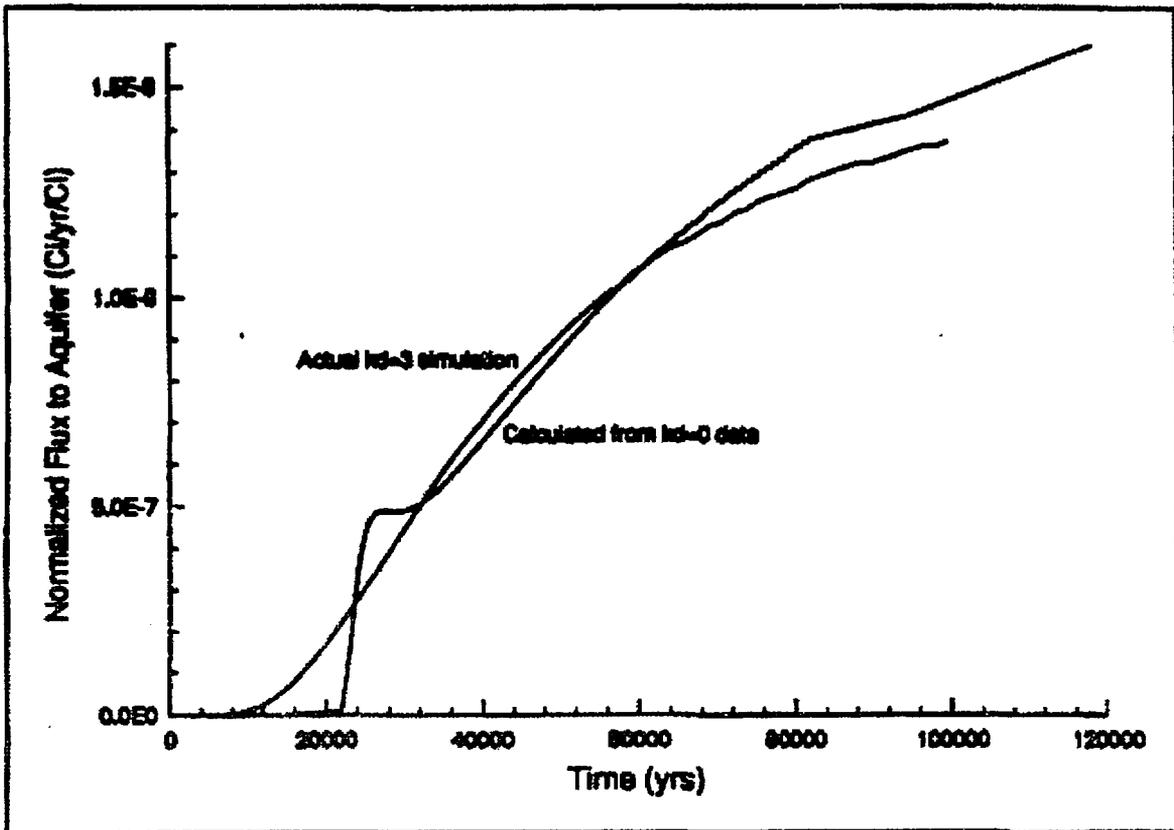
By comparing the time of occurrence for $\Gamma = 10^{-4}$ per year for $K_d=0$ and $K_d = 3$ ml/g, α is found to be 6.6 l/mg. Figure E-1 compares the $K_d = 3$ mg/l group as found by computer simulations and as predicted using the above simple formula.

E.2.3 Values

The results of all the vadose zone simulations are displayed in Table E-1 (where cases beginning with 1 were performed with the Concept 1 Full Facility Model, beginning with 2 were performed with the Concept 2 Full Facility Model, and beginning with 3 were performed with the Unit Cell Model). The results for each simulation are ordered by the value of the K_d parameter. Because for most of the simulations, the peak value occurs after the simulations end at 100,000 years, values in the table for half height and for 1 ppm height are given both for the actual peak value and for the peak value in the first 100,000 years.

No figures are given in this section, since the curve shapes are so similar. Please see the figures in Sections 4.3 through Section 4.6. More explanation of the results is given in Kline 1996 and Piepho 1996.

Figure E-1. Comparison of $K_d = 3$ mg/l Using Computer Simulations and An Approximation



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Table E-1. Summary of Vadose Zone Simulations for the Normalized Contaminant Flux Reaching the Unconfined Aquifer. Case numbers reflect archival filenames.

(Values with * Assume Peak Value is $4 \times 10^{-6} \text{ y}^{-1}$)

(Values with ‡, Calculated only to 40,000 Years)

(Values in Parentheses Reflect Peak Values in First 100k Years)

| Case | Subcase | Value at 10K Years | Peak Value in 100K Years | Time of Peak Value | Time of 0.5*Peak | Time of 10 ⁻⁶ *Peak |
|--------------------------|--|--------------------|--------------------------|--------------------|----------------------|--------------------------------|
| 1-1d, Base Analysis Case | kd=0 | 2.04 e-6 | 3.53 e-6 | 100,000* | 12,000* (6,900) | 450* (400) |
| | kd=0.1 | 1.71 e-6 | 2.84 e-6 | 100,000* | 12,000* (7,000) | 650* (620) |
| | kd=0.6 | 0.724 e-6 | 2.02 e-6 | 100,000* | >100,000 (15,000) | 1,300* (1,250) |
| | kd=3.0 | 0.0013e-6 | 1.37 e-6 | 100,000* | >100,000 (23,000) | 3,400* (3,100) |
| | kd=15. | 9.3 e-15 | 0.202 e-6 | 100,000* | >100,000 (79,000) | 17,000* (13,500) |
| | kd=40. | 2.4 e-23 | 0.004 e-6 | 100,000* | >100,000 (91,000) | 44,000* (25,000) |
| | kd=100. | 0.0 | 2.1 e-12 | 100,000* | >100,000 (94,000) | >100,000 (25,000) |
| | kd=0, factor of 5 reduced release rate | 0.526 e-6 | 0.802 e-6 | 40,000‡ | 8,500* (5,500) | 450* (400) |

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| Case | Subcase | Value at 10K Years | Peak Value in 100K Years | Time of Peak Value | Time of 0.5*Peak | Time of 10-6*Peak |
|--------------------|----------------------------|--------------------|--------------------------|--------------------|----------------------|----------------------|
| 2-1d, Concept 2 | kd=0 | 4.22 e-6 | 4.25 e-6 | 13,000 | 3,600 | 500 |
| | kd=0.1 | 3.69 e-6 | 4.19 e-6 | 21,000 | 6,600 | 900 |
| | kd=0.6 | 0.534 e-6 | 3.10 e-6 | 100,000* | 22,000 (17,000) | 2,000* (1,900) |
| | kd=3.0 | 4.6 e-11 | 2.80 e-6 | 100,000* | >100,000 (86,000) | 8,000 (8,000) |
| | kd=15. | 5.6 e-22 | 2.1 e-8 | 100,000* | >100,000 (89,000) | 38,000 (27,000) |
| | kd=40. | 6.9 e-23 | 3.2 e-12 | 100,000* | >100,000 (95,000) | >100,000 (46,000) |
| | kd=100. | 2.6 e-24 | 9.6 e-20 | 100,000* | >100,000 (97,000) | >100,000 (17,000) |
| | kd=0, reduced release rate | 0.855 e-6 | 0.671 e-6 | 17,000 | 3,600 | 500 |

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| Case | Subcase | Value at 10K Years | Peak Value in 100K Years | Time of Peak Value | Time of 0.5*Peak | Time of 10-6*Peak |
|---|--------------------------------|--------------------|--------------------------|--------------------|-----------------------|-------------------|
| i-1de, kd=0 extend to other kd's | kd=0. | 2.02 e-6 | 3.52 e-6 | 100,000 | 6,900 | 450 |
| | kd=0.1 | 1.65 e-6 | 2.52 e-6 | 166,000 | 11,400 | 700 |
| | kd=0.6 | 0.693 e-6 | 3.52 e-6 | 496,000 | 34,000 | 2,080 |
| | kd=3. | 1.4 e-11 | 3.52 e-6 | 2,080,000 | 113,000 | 8,700 |
| | kd=6. | 1.6 e-14 | 3.52 e-6 | 4,060,000 | 279,000 | 17,000 |
| | kd=15. | 1.7 e-16 | 3.52 e-6 | 10,000,000 | 688,000 | 42,000 |
| | kd=40. | 0.0 | 3.52 e-6 | 26,500,000 | 1,820,000 | 110,000 |
| | kd=100. | 0.0 | 3.52 e-6 | 66,000,000 | 4,550,000 | 275,000 |
| i-1n, smaller diff. coef. | kd=0 | 0.200 e-6 | 2.44 e-6 | 100,000* | 93,000* (63,000) | 560* (550) |
| | kd=0.1 | 0.025 e-6 | 1.01 e-6 | 100,000* | >100,000* (55,000) | 940* (900) |
| | kd=0.6 | 0.0015e-6 | 0.281 e-6 | 100,000* | >100,000* (65,000) | 1350* (1250) |
| | kd=0., reduced release rate | 0.018 e-6 | 0.177 e-6 | 40,000† | >40,000* (>40,000) | 560* (500) |

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| Case | Subcase | Value at 10K Years | Peak Value in 100K Years | Time of Peak Value | Time of 0.5*Peak | Time of 10 ⁻⁶ *Peak |
|--|----------------------------|--------------------|--------------------------|--------------------|-----------------------|--------------------------------|
| 1-3d, Concept 1, concrete floor degraded at 2000 years | kd=0. | 2.06 e-6 | 3.60 e-6 | 100,000* | 14,700* (7,400) | 420* (420) |
| | kd=0.1 | 1.70 e-6 | 2.88 e-6 | 100,000* | 25,000* (7,500) | 475* (470) |
| | kd=0.6 | 0.715 e-6 | 2.03 e-6 | 100,000* | >100,000* (15,000) | 1,280* (1,250) |
| | kd=0, reduced release rate | 0.532 e-6 | 0.802 e-6 | 40,000# | 7,800* (5,500) | 420* (420) |
| 2-1n, concept 2, reduced diffusion coef. | kd=0, | 0.852 e-6 | 3.31 e-6 | 81,000 | 17,500 | 650 |
| | kd=0.1 | 0.310 e-6 | 3.04 e-6 | 100,000* | 39,000* (25,000) | 1,150* (1,150) |
| | kd=0.6 | 0.0074e-6 | 1.74 e-6 | 100,000* | >100,000 (55,000) | 2,600* (2,600) |
| | kd=0, reduced release rate | 0.171 e-6 | 0.609 e-6 | 40,000# | 25,000* (17,000) | 650* (650) |

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| Case | Subcase | Value at 10K Years | Peak Value in 100K Years | Time of Peak Value | Time of 0.5*Peak | Time of 10-6*Peak |
|--|-------------------------------|--------------------|--------------------------|--------------------|----------------------|-------------------|
| 1-2d, Concept 2, constant waste form release rate | kd=0. | 4.21 e-6 | 4.39 e-6 | 35,000 | 3,700 | 650 |
| | kd=0.1 | 3.46 e-6 | 4.39 e-6 | 50,000 | 6,900 | 1,150 |
| | kd=0.6 | 0.415 e-6 | 3.95 e-6 | 100,000* | 23,000* (22,000) | 2,100 |
| | kd=0, reduced release rate | 0.841 e-6 | 0.878 e-6 | 35,000 | 3,700 | 650 |
| 2-2m, 2-2d with reduced diffusion coef | kd=0 | 0.846 e-6 | 4.08 e-6 | 100,000* | 25,000* (24,000) | 650* (650) |
| | kd=0.1 | 0.315 e-6 | 3.67 e-6 | 100,000* | 40,000* (32,000) | 1,150* (1,150) |
| | kd=0.6 | 0.0082e-6 | 1.96 e-6 | 100,000* | 100,000* (58,000) | 2,200* (2,200) |
| | kd=0, reduced release rate | 0.170 e-6 | 0.816 e-6 | 100,000* | 25,000* (24,000) | 650* (650) |
| 2-2dc, Concept 2 concrete degrades at 2000 years | kd=0 | 4.27 e-6 | 4.30 e-6 | 15,600 | 2,100 | 660 |
| | kd=0.1 | 3.76 e-6 | 4.24 e-6 | 21,600 | 5,300 | 1,150 |
| | kd=0.6 | 0.606 e-6 | 3.59 e-6 | 50,000 | 19,600 | 2,000 |
| | kd=0, reduced release rate | 0.866 e-6 | 0.882 e-6 | 17,600 | 2,100 | 660 |

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| Case | Subcase | Value at 10K Years | Peak Value in 100K Years | Time of Peak Value | Time of 0.5*Peak | Time of 10 ⁻⁶ *Peak |
|---|-------------------------------|--------------------|--------------------------|--------------------|------------------|--------------------------------|
| 2-3d, Concept 2, failed hydraulic barrier | kd=0 | 4.14 e-6 | 4.19 e-6 | 14,000 | 4,000 | 640 |
| | kd=0.1 | 3.54 e-6 | 4.14 e-6 | 20,000 | 6,100 | 1,140 |
| | kd=0.6 | 0.433 e-7 | 3.50 e-6 | 48,000 | 18,000 | 2,140 |
| | kd=0, reduced release rate | 0.839 e-6 | 0.859 e-6 | 18,000 | 4,000 | 640 |
| 2-4d, Concept 2 no side barrier | kd=0 | 4.31 e-6 | 4.31 e-6 | 10,000 | 1,900 | 640 |
| | kd=0.1 | 4.21 e-6 | 4.26 e-6 | 15,000 | 4,000 | 1,180 |
| | kd=0.6 | 3. e-6 | 3.67 e-6 | 35,000 | 13,000 | 2,600 |
| | kd=0, reduced release rate | 0.876 e-6 | 0.877 e-6 | 13,000 | 1,900 | 640 |
| 2-5d, Concept 2, 10 cm/y recharge rate | kd=0 | 4.83 e-6 | 4.84 e-6 | 9,300 | 2,000 | 15 |
| | kd=0.1 | 4.76 e-6 | 4.79 e-6 | 13,000 | 2,800 | 28 |
| | kd=0.6 | 3.19 e-6 | 4.12 e-6 | 29,000 | 6,000 | 135 |
| | kd=0, reduced release rate | 0.985 e-6 | 0.985 e-6 | 12,000 | 2,000 | 15 |

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| Case | Subcase | Value at 10K Years | Peak Value in 100K Years | Time of Peak Value | Time of 0.5*Peak | Time of 10-6*Peak |
|---|-------------------------------|-----------------------|--------------------------------|-----------------------|---------------------|----------------------|
| 2-6d, Concept 2, 0.5 * dispersion coef. | kd=0 | 4.17 e-6 | 4.24 e-6 | 15,000 | 4,000 | 750 |
| | kd=0.1 | 3.52 e-6 | 4.17 e-6 | 21,000 | 6,700 | 2,300 |
| | kd=0.6 | 0.418 e-6 | 3.52 e-6 | 51,000 | 19,000 | 3,000 |
| | kd=0, reduced release rate | 0.846 e-6 | 0.870 e-6 | 19,000 | 4,000 | 750 |
| 2-7d, concept 3 2 * dispersion coef. | kd=0 | 4.24 e-6 | 4.26 e-6 | 13,000 | 3,600 | 600 |
| | kd=0.1 | 3.79 e-6 | 4.20 e-6 | 21,000 | 6,000 | 700 |
| | kd=0.6 | 0.676 e-6 | 3.55 e-6 | 50,000 | 19,000 | 1,600 |
| | kd=0, reduced release rate | 0.860 e-6 | 0.872 e-6 | 17,000 | 3,600 | 600 |

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| Case | Subcase | Value at 10K Years | Peak Value in 100K Years | Time of Peak Value | Time of 0.5*Peak | Time of 10-6*Peak |
|---|---------|-----------------------|--------------------------------|-----------------------|----------------------|----------------------|
| 3, Unit Cell Model Main Analysis Case | kd=0 | 4.37 e-6 | 6.90 e-6 (4.42 e-6) | 2,150 (17,000) | 1,350 (1,100) | 175 (167) |
| | kd=0.1 | 4.37 e-6 | 4.42 e-6 | 17,000 | 3,000 | 350 |
| | kd=0.6 | 2.65 e-6 | 4.42 e-6 | 39,000 | 9,100 | 1,550 |
| | kd=3. | 2.01 e-9 | 4.35 e-6 | 100,000* | 39,000 (39,000) | 6,200 (6,200) |
| | kd=6. | 1.60 e-12 | 3.26 e-6 | 100,000* | 76,000 (65,000) | 11,000 (11,000) |
| | kd=15. | 1.44 e-18 | 0.327 e-6 | 100,000* | >100,000 (87,000) | >100,000 (21,000) |
| | kd=40. | 0 | 2.9 e-10 | 100,000* | >100,000 (94,000) | >100,000 (30,000) |
| | kd=100. | 0 | 2.4 e-15 | 100,000* | >100,000 (96,000) | >100,000 (45,000) |

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| Case | Subcase | Value at 10K Years | Peak Value in 100K Years | Time of Peak Value | Time of 0.5*Peak | Time of 10-6*Peak |
|---|---------|--------------------|--------------------------|--------------------|----------------------|--------------------|
| 3a, Unit Cell Model, 3mm/y recharge rate | kd=0 | 4.42 e-6 | 4.42 e-6 | 4,400 | 1,100 | 170 |
| | kd=0.1 | 4.42 e-6 | 4.42 e-6 | 10,000 | 2,400 | 355 |
| | kd=0.6 | 2.81 e-6 | 4.42 e-6 | 40,000 | 8,600 | 1,200 |
| | kd=3. | 3.0 e-9 | 4.36 e-6 | 100,000* | 38,000 (38,000) | 5,400 (5,400) |
| 3b, Unit Cell Model, 1 mm/y recharge rate | kd=0 | 4.41 e-6 | 4.42 e-6 | 12,000 | 3,000 | 460 |
| | kd=0.1 | 3.75 e-6 | 4.42 e-6 | 25,000 | 6,500 | 980 |
| | kd=0.6 | 8.40 e-8 | 4.42 e-6 | 100,000 | 24,000 | 3,400 |
| | kd=3. | 2.0 e-14 | 1.90 e-6 | 100,000* | >100,000 (77,000) | 15,000 (13,000) |
| 3d, Unit Cell Model, 0.1 mm/y recharge rate | Kd=0 | 5.9 e-08 | 4.48 e-6 | 68,000 | 24,500 | 3,600 |
| | Kd=0.1 | 7.5 e-11 | 4.00 e-6 | 100,000* | 54,000 (54,000) | 7,800 (7,800) |
| | Kd=0.6 | 8.8 e-19 | 0.166 e-6 | 100,000* | >100,000 (88,000) | 28,000 (18,500) |
| | Kd=3. | 0. | 1.4 e-13 | 100,000* | >100,000 (95,000) | >100,000 |

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| Case | Subcase | Value at 10K Years | Peak Value in 100K Years | Time of Peak Value | Time of 0.5*Peak | Time of 10-6*Peak |
|--|---------|-----------------------|--------------------------------|-----------------------|---------------------|----------------------|
| 3e, Unit Cell Model, 100 mm/y recharge rate | Kd=0 | 4.44 e-6 | 4.73 e-6 | 600 | 66 | 8 |
| | Kd=0.1 | 4.44 e-6 | 4.45 e-6 | 670 | 127 | 17 |
| | Kd=0.6 | 4.44 e-6 | 4.44 e-6 | 2,500 | 384 | 57 |
| | Kd=3.0 | 4.44 e-6 | 4.44 e-6 | 4,900 | 1,600 | 240 |
| 3f, Unit Cell Model, Sandy sequence only | Kd=0 | 4.42 e-6 | 6.25 e-6 | 2,500 | 2,250 | 170 |
| | Kd=0.1 | 4.42 e-6 | 4.49 e-6 | 3,900 | 2,500 | 275 |
| | Kd=0.6 | 4.23 e-6 | 4.42 e-6 | 21,000 | 5,400 | 1,100 |
| | Kd=3 | 4.26 e-6 | 4.42 e-6 | 84,000 | 21,000 | 3,900 |
| 3g, Unit Cell Model, filler is Hanford sand | Kd=0 | 4.37 e-6 | 7.38 e-6 | 2,150 | 1,320 (1,075) | 182 |
| | Kd=0.1 | 4.37 e-6 | 4.42 e-6 | 17,000 | 3,200 | 375 |
| | Kd=0.6 | 2.51 e-6 | 4.42 e-6 | 40,000 | 9,400 | 1,600 |
| | Kd=3. | 1.36 e-9 | 4.35 e-6 | 100,000* | 40,000 (40,000) | 6,500 (6,500) |

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| Case | Subcase | Value at 10K Years | Peak Value in 100K Years | Time of Peak Value | Time of 0.5*Peak | Time of 10 ⁻⁶ *Peak |
|---|---------|-----------------------|--------------------------------|-----------------------|---------------------|-----------------------------------|
| 3h, Unit Cell Model, Thicker Banford gravel layer | Kd=0 | 4.20 e-6 | 8.53 e-6 | 2,000 | 1,300 (1,000) | 200 |
| | Kd=0.1 | 4.20 e-6 | 4.42 e-6 | 22,000 | 2,750 | 396 |
| | Kd=0.6 | 1.88 e-6 | 4.42 e-6 | 44,000 | 10,800 | 1,700 |
| | Kd=3. | 2.71 e-10 | 4.29 e-6 | 100,000* | 45,000 (45,000) | 7,500 |
| 3i, Unit Cell Model, lower water table | Kd=0 | 4.29 e-6 | 7.08 e-6 | 2,200 | 1,400 (1,200) | 200 |
| | Kd=0.1 | 4.29 e-6 | 4.42 e-6 | 20,000 | 3,300 | 435 |
| | Kd=0.6 | 1.99 e-6 | 4.42 e-6 | 43,000 | 10,600 | 1,900 |
| | Kd=3. | 2.31 e-10 | 4.29 e-6 | 100,000* | 45,000 | 7,700 |
| 3j Unit Cell Model, higher water table | Kd=0 | 4.38 e-6 | 7.29 e-6 | 2,000 | 1,200 1,000 | 142 |
| | Kd=0.1 | 4.38 e-6 | 4.42 e-6 | 17,000 | 2,600 | 295 |
| | Kd=0.6 | 3.42 e-6 | 4.42 e-6 | 33,000 | 7,500 | 1,200 |
| | Kd=3 | 1.56 e-8 | 4.40 e-6 | 100,000* | 31,000 | 5,200 |

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| Case | Subcase | Value at 10K Years | Peak Value in 100K Years | Time of Peak Value | Time of 0.5*Peak | Time of 10-6*Peak |
|--|---------|-----------------------|--------------------------------|-----------------------|---------------------|----------------------|
| 3k Unit Cell Model, moisture - 0.2 in construct. materials | Kd=0. | 4.38 e-6 | 6.90 e-6 | 2,150 | 1,350 1,120 | 172 |
| | Kd=0.1 | 4.37 e-6 | 4.42 e-6 | 17,000 | 3,100 | 305 |
| | Kd=0.6 | 2.65 e-6 | 4.42 e-6 | 41,000 | 9,100 | 1,500 |
| | Kd=3 | 2.01 e-9 | 4.35 e-6 | 100,000* | 39,000 | 6,300 |
| 3l Unit Cell Model, moisture - residual in construct. materials | Kd=0 | 4.37 e-6 | 6.90 e-6 | 2,150 | 1,350 1,120 | 172 |
| | Kd=0.1 | 4.37 e-6 | 4.42 e-6 | 17,000 | 3,100 | 364 |
| | Kd=0.6 | 2.65 e-6 | 4.42 e-6 | 40,000 | 9,100 | 1,550 |
| | Kd=3. | 2.01 e-9 | 4.36 e-6 | 100,000* | 39,000 | 6,300 |
| 3m Unit Cell Model, canister rotated 90 degrees | Kd=0 | 4.37 e-6 | 7.29 e-6 | 2,200 | 1,330 1,080 | 175 |
| | Kd=0.1 | 4.37 e-6 | 4.42 e-6 | 17,000 | 3,150 | 365 |
| | Kd=0.6 | 2.59 e-6 | 4.42 e-6 | 40,000 | 9,200 | 1,500 |
| | Kd=3. | 1.63 e-9 | 4.35 e-6 | 100,000* | 39,000* | 6,400 |

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| Case | Subcase | Value at 10K Years | Peak Value in 100K Years | Time of Peak Value | Time of 0.5*Peak | Time of 10-6*Peak |
|--|---------|-----------------------|--------------------------------|-----------------------|---------------------|----------------------|
| 3n Unit Cell Model, increased number of nodes | Kd=0 | 4.37 e-6 | 6.84 e-6 | 2,150 | 1,350 1,140 | 173 |
| | Kd=0.1 | 4.37 e-6 | 4.42 e-6 | 17,000 | 3,150 | 305 |
| | Kd=0.6 | 2.65 e-6 | 4.42 e-6 | 40,000 | 9,100 | 1,560 |
| | Kd=3. | 2.00 e-9 | 4.35 e-6 | 100,000* | 39,000 | 6,300 |
| 3o Unit Cell Model, waste form is sand | Kd=0 | 4.37 e-6 | 5.72 e-6 | 2,200 | 1,380 1,240 | 172 |
| | Kd=0.1 | 4.37 e-6 | 4.42 e-6 | 17,000 | 3,300 | 305 |
| | Kd=0.6 | 2.65 e-6 | 4.42 e-6 | 40,000 | 9,100 | 1,590 |
| | Kd=3. | 2.00 e-6 | 4.36 e-6 | 100,000* | 39,000 | 6,300 |
| 3p Unit Cell Model, reduced diffusion coef. | Kd=0 | 4.37 e-6 | 6.91 e-6 | 2,150 | 1,350 1,120 | 210 |
| | Kd=0.1 | 4.37 e-6 | 4.42 e-6 | 17,000 | 3,150 | 365 |
| | Kd=0.6 | 2.65 e-7 | 4.42 e-6 | 40,000 | 9,100 | 1,560 |
| | Kd=3. | 2.00 e-9 | 4.36 e-6 | 100,000* | 39,000 | 6,300 |

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| Case | Subcase | Value at 10K Years | Peak Value in 100K Years | Time of Peak Value | Time of 0.5*Peak | Time of 10-6*Peak |
|---|---------|-----------------------|--------------------------------|-----------------------|---------------------|----------------------|
| Jq Unit Cell Model, twice dispersion coef. | Kd=0 | 4.37 e-6 | 5.89 e-6 | 1,990 | 1,125 980 | 107 |
| | Kd=0.1 | 4.37 e-6 | 4.42 e-6 | 17,000 | 2,750 | 355 |
| | Kd=0.6 | 2.73 e-6 | 4.42 e-6 | 54,600 | 8,700 | 642 |
| | Kd=3. | 2.90 e-8 | 4.27 e-6 | 100,000* | 37,000* | 6,300 |
| Jr Unit Cell Model, half dispersion coef. | Kd=0 | 4.37 e-6 | 8.01 e-6 | 2,270 | 1,546 1,256 | 250 |
| | Kd=0.1 | 4.37 e-6 | 4.42 e-6 | 17,000 | 3,400 | 540 |
| | Kd=0.6 | 2.51 e-6 | 4.42 e-6 | 29,000 | 9,400 | 2,800 |
| | Kd=3. | 5.4 e-11 | 4.41 e-6 | 100,000* | 40,000* | 9,900 |
| Js Unit Cell Model, 0.1 * dispersion coef. | Kd=0 | 4.37 e-6 | 10.2 e-6 | 2,350 | 1,725 1,380 | 375 |
| | Kd=0.1 | 4.37 e-6 | 4.42 e-6 | 17,000 | 3,600 | 830 |
| | Kd=0.6 | 2.54 e-6 | 4.42 e-6 | 22,000 | 9,600 | 4,000 |
| | Kd=3.0 | 3.5 e-13 | 4.42 e-6 | 94,000 | 41,000 | 11,600 |

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| Case | Subcase | Value at 10K Years | Peak Value in 100K Years | Time of Peak Value | Time of 0.5*Peak | Time of 10-6*Peak |
|---|---------|-----------------------|--------------------------------|-----------------------|---------------------|----------------------|
| 3t Unit Cell Model, Kd=100 in floor | Kd=0 | 0.805 e-7 | 3.99 e-6 | 100,000* | 31,000 (27,000) | 385 |
| | Kd=0.1 | 0.691 e-7 | 3.98 e-6 | 100,000* | 32,000 (28,000) | 782 |
| | Kd=0.6 | 0.198 e-7 | 3.89 e-6 | 100,000* | 39,000 (34,000) | 3,000 |
| | Kd=3. | 1.13 e-10 | 3.19 e-6 | 100,000* | 72,000 (59,000) | 7,700 |
| 3u, Unit Cell, Model, time dependent waste form release rate | Kd=0 | 4.26 e-6 | 6.87 e-6 4.26 e-6 | 2,150 11,400 | 1,350 1,110 | 175 |
| | Kd=0.1 | 4.27 e-6 | 4.28 e-6 | 11,200 | 3,100 | 360 |
| | Kd=0.6 | 2.62 e-6 | 4.19 e-6 | 23,500 | 9,000 | 1,540 |
| | Kd=3.0 | 2.00 e-9 | 3.73 e-6 | 82,000 | 37,000 | 6,300 |

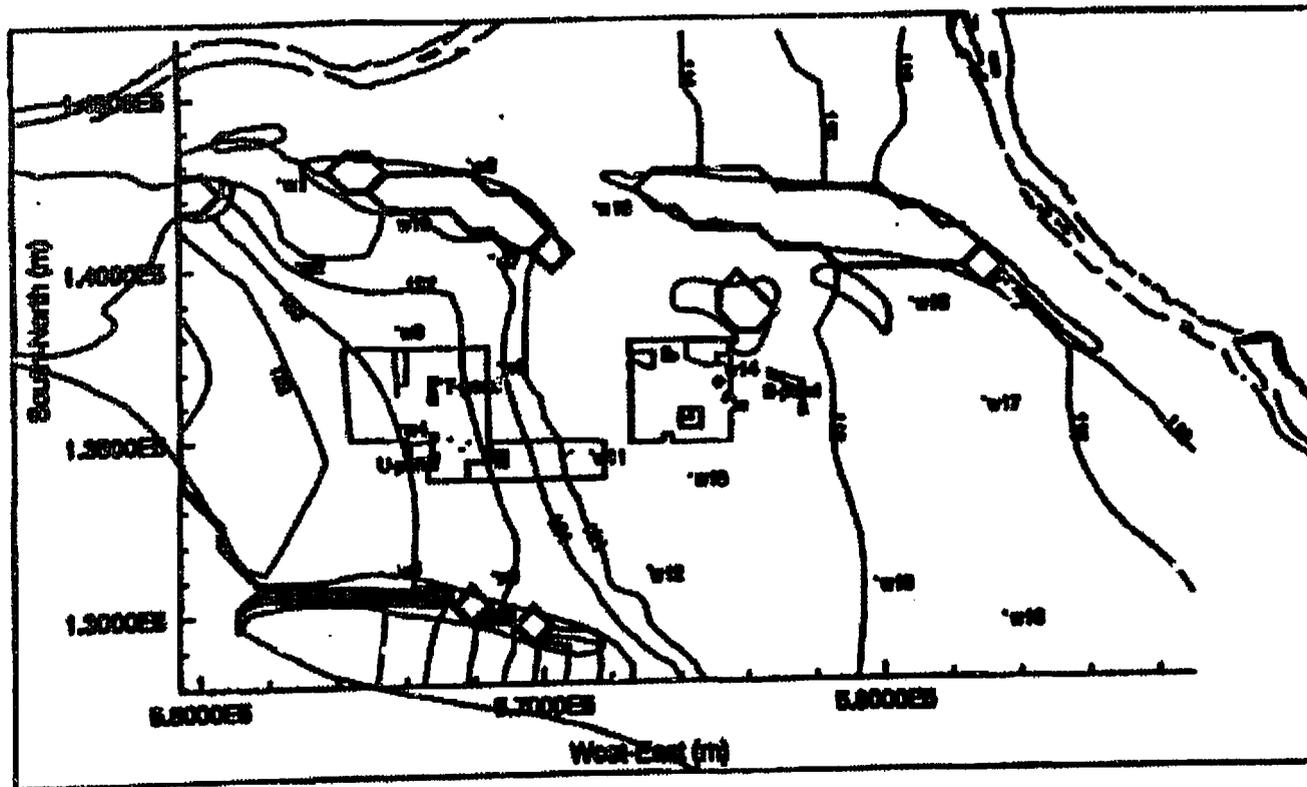
NHC-EF-0884

| Case | Subcase | Value at 10K Years | Peak Value in 100K Years | Time of Peak Value | Time of 0.5*Peak | Time of 10 ⁻⁶ *Peak |
|--|--------------------------------|-----------------------|--------------------------------|-----------------------|----------------------|-----------------------------------|
| 3v Unit Cell Model waste form release rates calculated by AREST-CT | Tc, main | 0.470 e-6 | 0.502 e-6 | 14,600 | 1,630 | 240 |
| | Tc, no Na ion exchange | 0.019 e-6 | 0.028 e-6 | 18,200 | 1,600 | 215 |
| | Tc, increased pore velocity | 1.08 e-6 | 1.38 e-6 | 18,000 | 2,000 | 225 |
| | Se | 0.767 e-6 | 0.767 e-7 | 9,700 | 1,730 | 210 |
| | U | 0.286 e-6 | 0.591 e-6 | 22,000 | 10,400 | 1,900 |
| | I | 1.37 e-10 | 0.344 e-6 | 60,000 | 34,000 | 7,400 |
| | Np | 9.3 e-17 | 2.32 e-5 | 100,000* | >100,000 (85,000) | (21,000) |
| | Pu | 0.0 | 2.72 e-11 | 100,000* | >100,000 (94,000) | |

E.3 UNCONFINED AQUIFER SIMULATIONS

Because only a few numbers are used from these simulations, only figures (Figures E-2 through E-7) will be given to give an indication of the breath of the results. For more detailed explanation see Lu 1996.

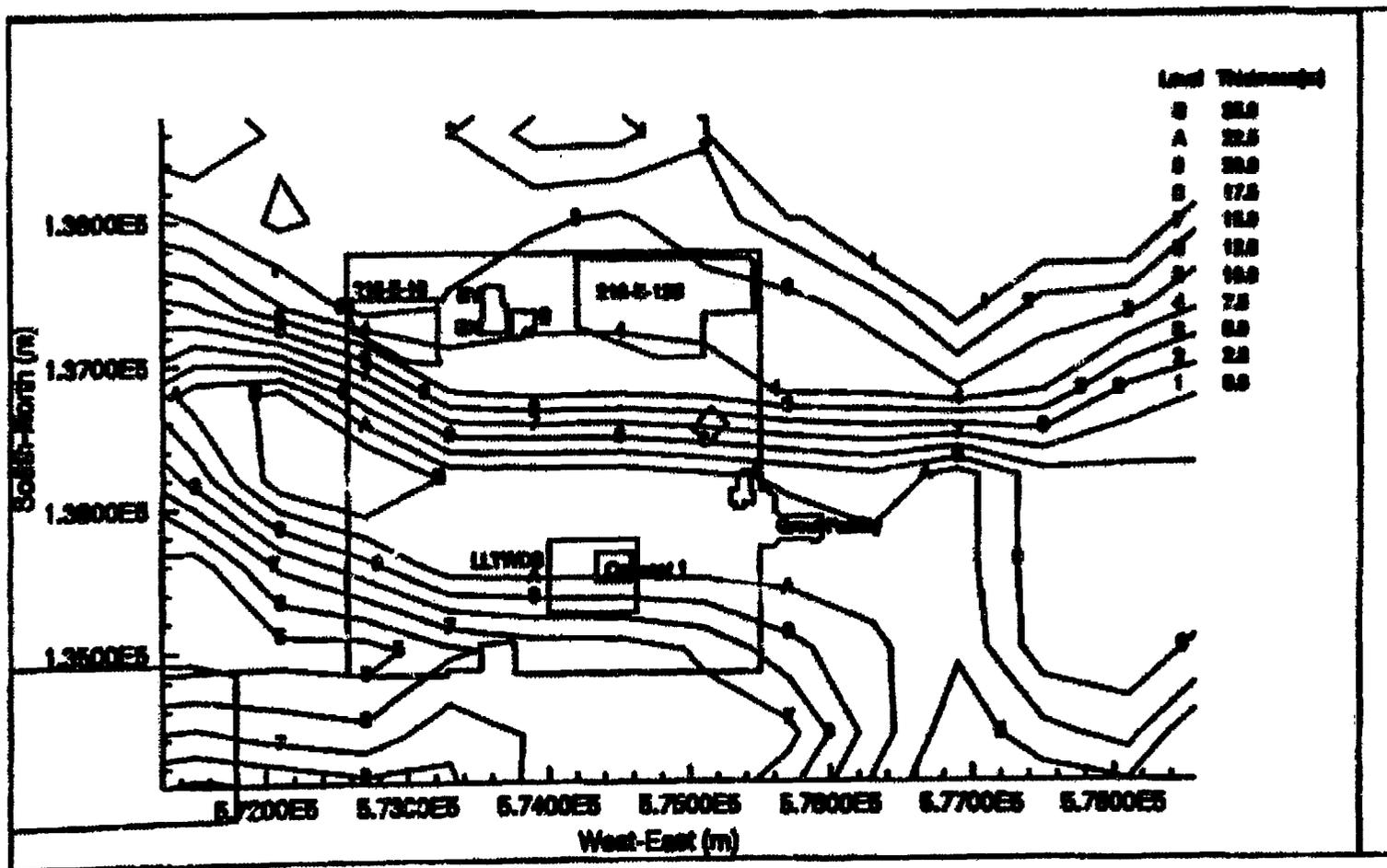
Figure E-2. Simulated Post-Hanford Operations Water Table and Well Location



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Figure E-1. Simulated Aquifer Thickness - Post Hanford Operations



E-21

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Figure E-4. Simulated Streamlines for Various Pumping Rates (10 m³/day, 50 m³/day, 100 m³/day, and 150 m³/day).

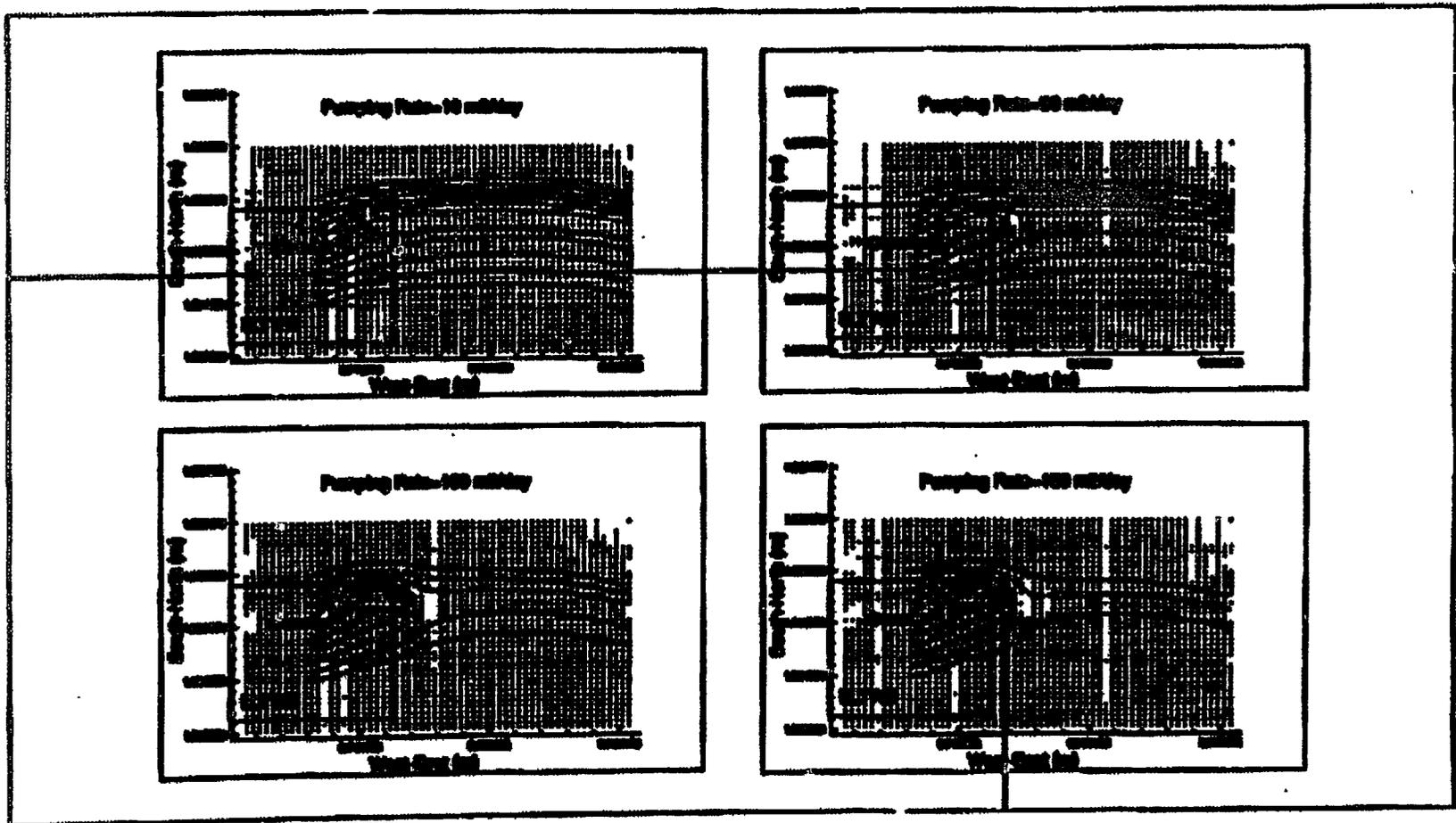
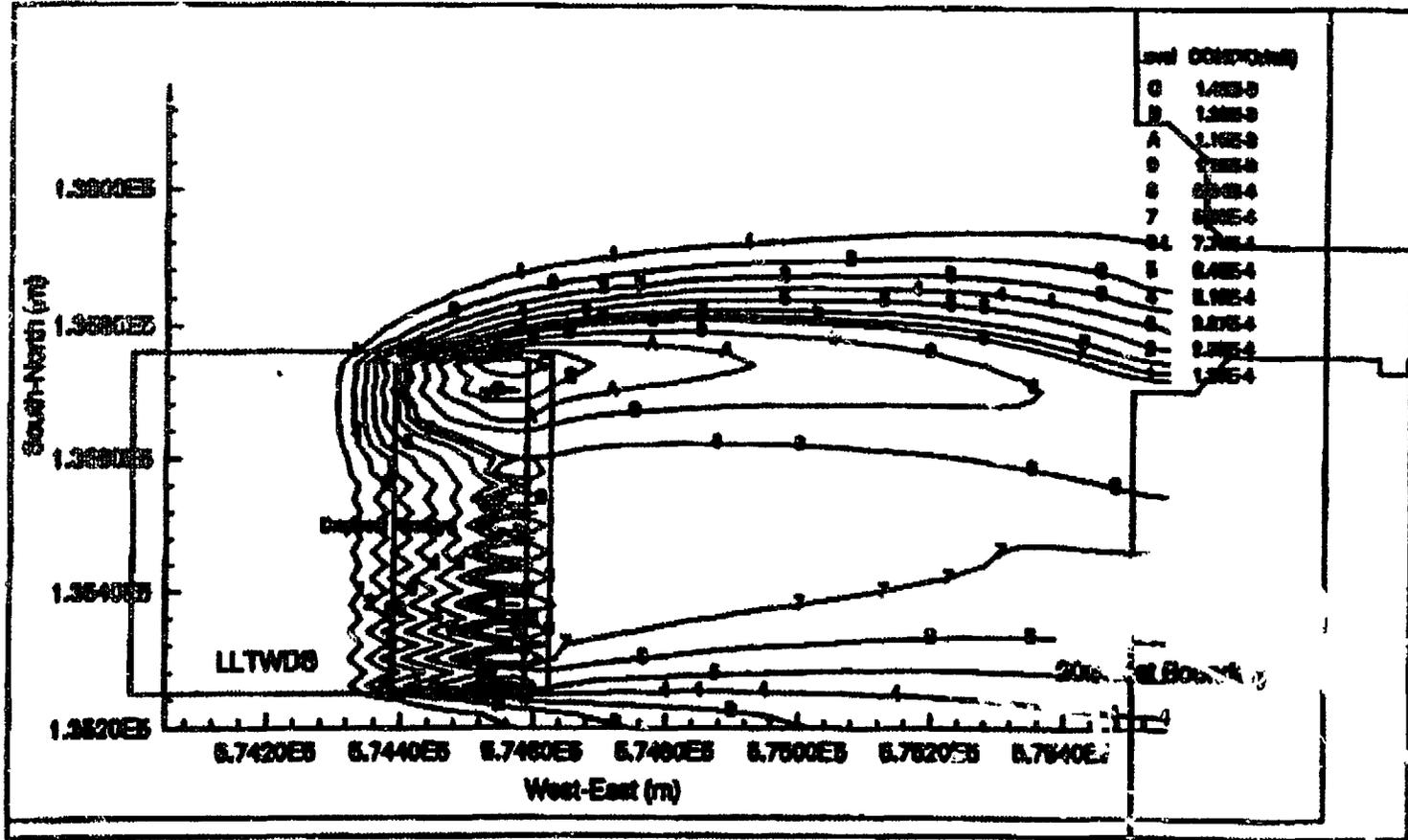


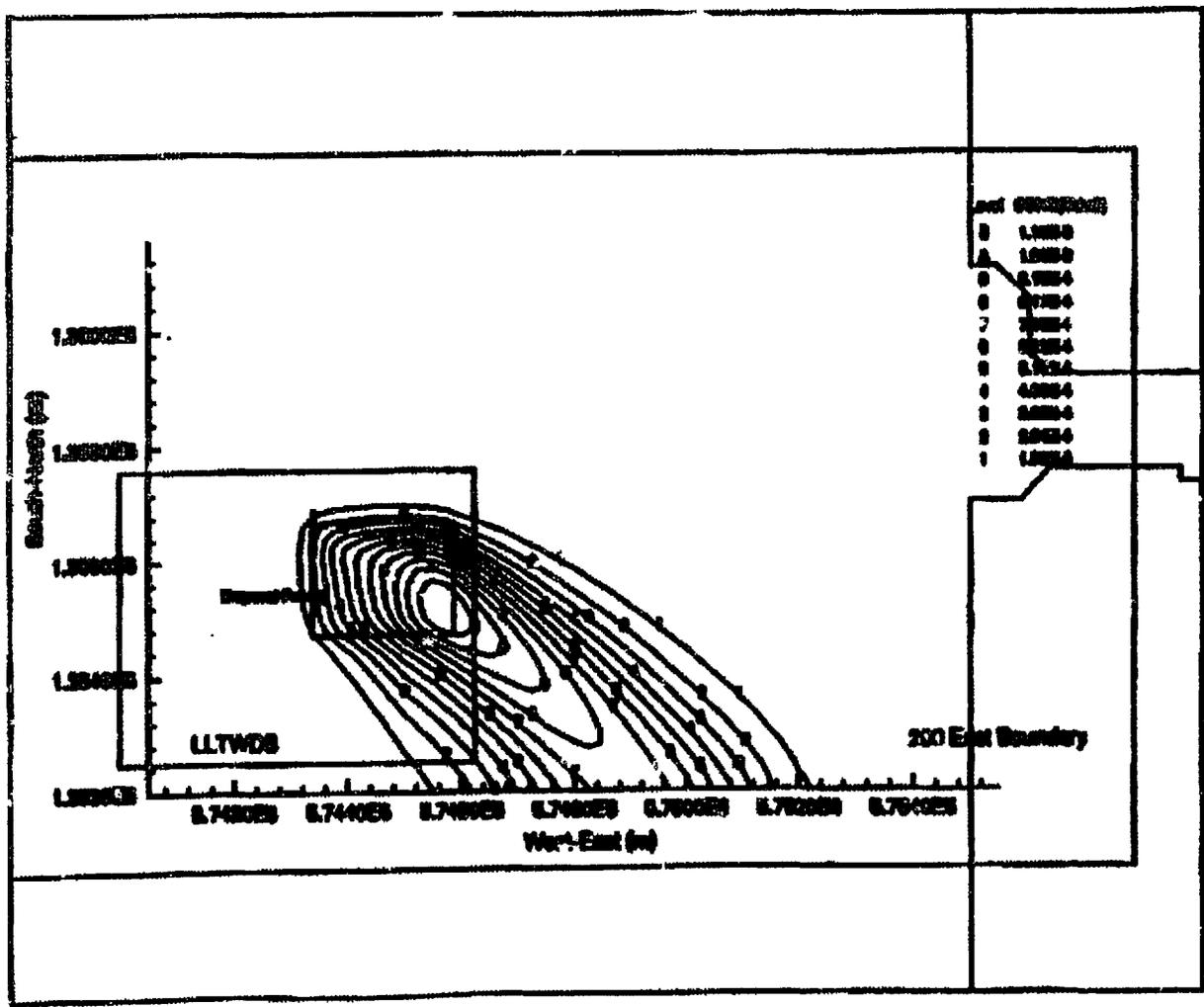
Figure E-5. Simulated Concentration Contour for Concept 2. Assumes concentration of 1 Ci/m³ in the vadose zone and a recharge rate of 1 mm/y. Since actual recharge is 3 mm/y, actual concentrations will be 3 times higher



62
63

than shown.

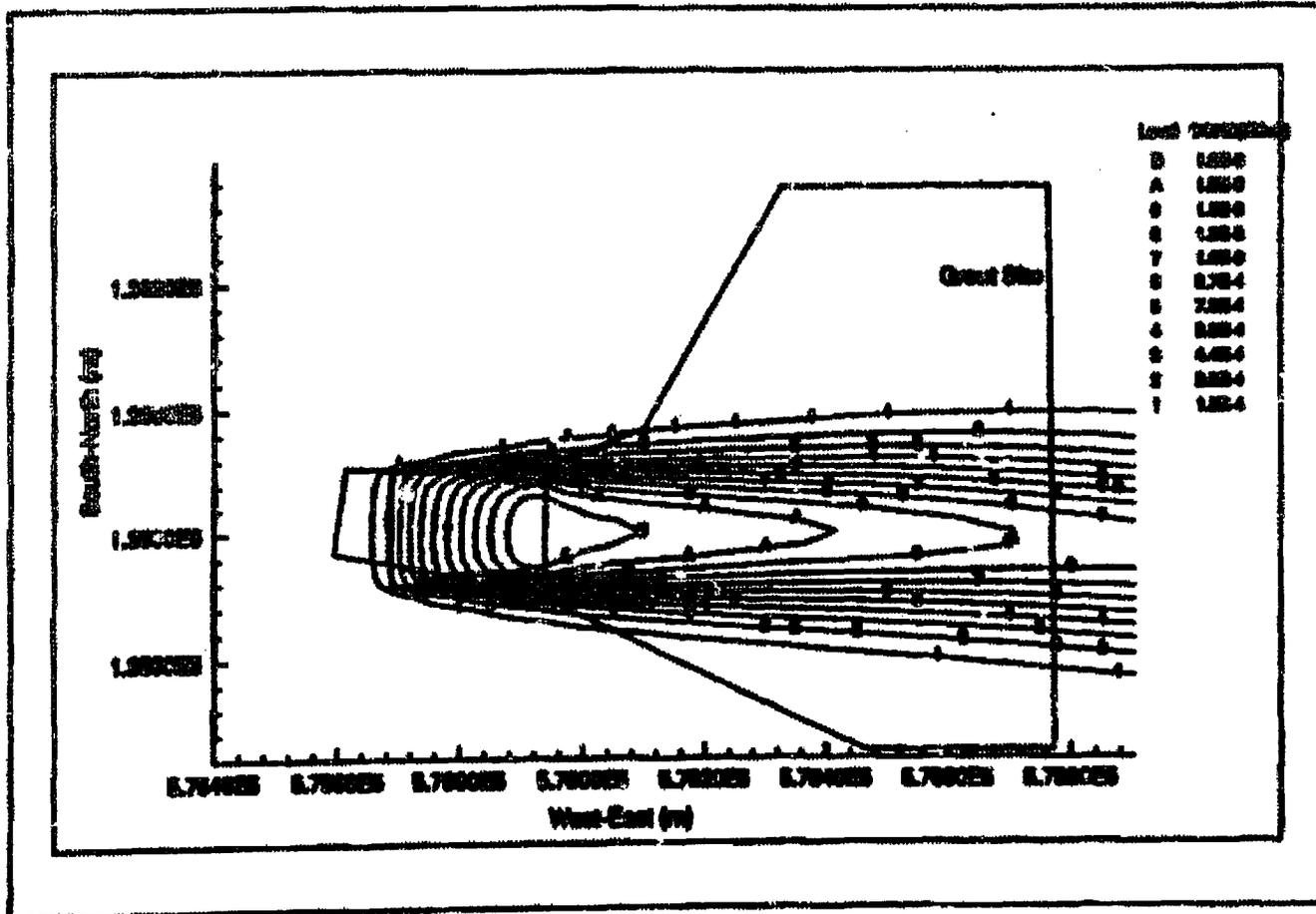
Figure E-6. Simulated Concentration Contour for Irrigation North of the 200 Area. Assumes concentration of 1 Cl/m³ in the vadose zone and a recharge rate of 1 mm/y. Since actual recharge is 3 mm/y, actual concentrations will be 3 times higher than shown.



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Figure E-7. Simulated Concentration Contour for Existing TWS Disposal Facilities. Assumes concentration of 1 Ci/m³ in the vadose zone and a recharge rate of 1 mm/y. Since actual recharge is 3 mm/y, actual concentrations will be 3 times higher than shown.



E.4 CALCULATION OF DOSE

Table E-2 summarizes the calculation of the beta/photon drinking water dose, the alpha concentration in well water, and the all-pathway dose. Since the time dependence of these impacts follows the time dependence of the vadose simulations, please refer to those figures in Sections 4.2 through 4.7.

Table E-2. Summary of Dose Calculations. Case numbers reflect archival filenames.

| Case | Time | Beta Dose (mrem/y) | Alpha Conc. (pCi/l) | All-Pathways Dose (mrem/y) |
|---|-------|--------------------|---------------------|----------------------------|
| Limit | 10K y | 4.0 | 15. | 25. |
| 1-1d Base Analysis Case | 10K y | 1.97 | 1.65 | 6.4 |
| | limit | >100K | >100K | >100K |
| | max | 2.7 @ 71K | 5.7 @ 55K | 23. @ 50K |
| 1-1ds Base Analysis Case, vadose zone flux extended to 66 million years | 10K y | 1.96 | 1.53 | 5.9 |
| | limit | @ 750K | @ 2.2M | >66M |
| | max | 14. @ 65M | 18. @ 51M | 22. @ 55K |
| 1-1dz Concept 1, flux = 0 for ka > 0.7 | 10K y | 1.97 | 1.60 | 5.9 |
| | limit | >100K | >100K | >100K |
| | max | 2.6 @ 60K | 4.1 @ 71K | 8.3 @ 63K |
| 1-1di Concept 1, Tc inv = 0.2 of base analysis case | 10K y | 1.97 | 1.65 | 2.5 |
| | limit | >100K | >100K | >100K |
| | max | 1.14 @100K | 5.7 @ 55K | 17.2 @ 49K |
| 1-1dis, Concept 1 double Se inventory from base analysis case | 10K y | 2.4 | 1.65 | 7.1 |
| | limit | >100K | >100K | >100K |
| | max | 3.1 @62K | 5.7 @55K | 23. @50 K |

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| Case | Time | Beta Dose (mrem/y) | Alpha Conc. (pCi/l) | All-Pathways Dose (mrem/y) |
|--|-------|--------------------|---------------------|----------------------------|
| Limit | 10K y | 4.0 | 15. | 25. |
| 1-ldiu, Concept 1 double U inventory from base analysis case | 10K y | 2.05 | 3.2 | 6.8 |
| | limit | >100K | >100K | >100K |
| | max | 3.0 @ 82K | 9.7 @ 62K | 23. @ 50K |
| 1-ldii, Concept 1 5 * I inventory from base analysis case | 10K y | 1.97 | 1.65 | 6.4 |
| | limit | >100K | >100K | >100K |
| | max | 3.0 @ 81K | 5.7 @ 55K | 23.0 @ 50K |
| 1-ldr, Concept 1, Tc release rate reduced by factor of 5 from base analysis case | 10K y | 0.87 | 1.65 | 2.8 |
| | limit | >100K | >100K | >100K |
| | max | 1.20 @ 41K | 5.7 @ 55K | 17.6 @ 49K |
| 1-ldra Concept 1, release rate reduced by factor of 5 from base analysis case for all Kd=0 contaminants | 10K y | 0.57 | 1.65 | 2.3 |
| | limit | >100K | >100K | >100K |
| | max | 0.99 @ 100K | 5.7 @ 55K | 17.1 @ 49K |
| 1-ldku Concept 1, Kd=0 for uranium | 10K y | 2.1 | 4.6 | 7.1 |
| | limit | >100K | >100K | >100K |
| | max | 2.9 @ 76K | 8.4 @ 71K | 23. @ 50K |
| 1-ldk0, Concept 1, Kd=0.1 mg/l for Se and Tc | 10K y | 1.66 | 1.65 | 5.5 |
| | limit | >100K | >100K | >100K |
| | max | 2.2 @100K | 5.7 @ 55K | 21. @ 49K |

| Case | Time | Beta Dose (mrem/y) | Alpha Conc. (pCi/l) | All-Pathways Dose (mrem/y) |
|---|-------|--------------------|---------------------|----------------------------|
| Limit | 10K y | 4.0 | 15. | 25. |
| 1-1d0e Concept 1, DOE dose factors | 10K y | 1.97 | 1.65 | 6.4 |
| | limit | >100K | >100K | >100K |
| | max | 2.7 @ 71K | 5.7 @ 55K | 23. @ 50K |
| 1-1d0a Concept 1, EPA dose factors | 10K y | 2.2 | 1.65 | 7.0 |
| | limit | >100K | >100K | >100K |
| | max | 3.0 @ 71K | 5.7 @ 55K | 23. @52K |
| 1-1d0n, Concept 1 GENII dose factors | 10K y | 3.0 | 1.65 | 9.9 |
| | limit | @ 41K | >100K | @ 38K |
| | max | 4.2 @70K | 5.7 @ 55K | 27. @ 50K |
| 1-1n. Concept 1 Diffusion constant reduced by factor of 20. | 10K y | 0.060 | 0.056 | 0.64 |
| | limit | >100K | >100K | >100K |
| | max | 1.80 @ 100K | 1.85 @ 58K | 16.4 @54K |
| 1-2d, Concept 1, concrete degrades at 2000 years | 10K y | 1.96 | 1.56 | 6.4 |
| | limit | >100K | >100K | >100k |
| | max | 2.8 @ 73K | 5.7 @57K | 23. @50K |
| 1-1d0d, Concept 1 U daughters have Kd of uranium | 10K y | 35. | 22. | 68. |
| | limit | @ 3.4K | @ 8.2K | @ 5.6K |
| | max | 57. @ 26K | 39. @ 30K | 107. @ 26K |

| Case | Time | Beta Dose (mrem/y) | Alpha Conc. (pCi/l) | All-Pathways Dose (mrem/y) |
|---|-------|--------------------|---------------------|----------------------------|
| Limit | 10K y | 4.0 | 15. | 25. |
| 1-dCR, Concept 1, impacts at Columbia River | 10K y | 0.069 | 0.058 | 0.22 |
| | limit | >100K* | >100K | >100K |
| | max | 0.095 @ 71K | 0.20 @ 55K | 0.79 @ 50K |
| 1-1deCR, Concept 1 impacts at Columbia River, vadose zone flux extended to 66 million years | 10K y | 0.068 | 0.054 | 0.21 |
| | limit | >100K* | >100K | >100K |
| | max | 0.49 @ 56 M | 0.65 @ 51M | 0.56 @66 K |

| Case | Time | Beta Dose (mrem/y) | Alpha Conc. (pCi/l) | All-Pathways Dose (mrem/y) |
|---|-------|--------------------|---------------------|----------------------------|
| Limit | 10K y | 4.0 | 15. | 25. |
| 2-1d, Concept 2 Main Analysis Case | 10K y | 1.11 | 0.27 | 3.3 |
| | limit | >100K | >100K | >100K |
| | max | 1.12 @ 15K | 2.6 @ 62K | 7.9 @ 72K |
| 2-1de, Concept 2 Main Analysis Case, vadose zone flux extended to 66M years | 10K y | 1.14 | 0.78 | 3.4 |
| | limit | @ 3.3M | >66M | >66M |
| | max | 5.0 @ 13M | 6.9 @ 2.7M | 10.3 @ 51K |
| 2-1di, Concept 2, Inventory of Tc = 0.2 *base case | 10K y | 0.42 | 0.27 | 1.04 |
| | limit | >100K | >100K | >100K |
| | max | 0.45 @ 25K | 2.6 @ 62K | 6.3 @ 74K |
| 2-1dr, Concept 2, Tc release rate reduced by factor of 5 from base analysis case | 10K y | 0.42 | 0.27 | 1.05 |
| | limit | >100K | >100K | >100K |
| | max | 1.34 @ 99K | 2.6 @ 62K | 8.9 @ 99K |
| 2-1dra, Concept 2, release rate for Kd=0 reduced by factor of 5 from base analysis case | 10K y | 0.24 | 0.27 | 0.72 |
| | limit | >100K | >100K | >100K |
| | max | 1.43 @ 99K | 2.6 @ 62K | 9.0 @ 99K |
| 2-1dku, Concept 2, uranium has Kd = 0 | 10K y | 1.23 | 2.6 | 3.8 |
| | limit | >100K | >100K | >100K |
| | max | 1.24 @ 11K | 2.7 @ 58K | 7.9 @ 72K |

| Case | Time | Beta Dose (mrem/y) | Alpha Conc. (pCi/l) | All-Pathways Dose (mrem/y) |
|--|-------|--------------------|---------------------|----------------------------|
| Limit | 10K y | 4.0 | 15. | 25. |
| 2-1dx0, Concept 2 Tc and Se have Kd =0.1 ml/g | 10K y | 0.94 | 0.27 | 2.8 |
| | limit | >100K | >100K | >100K |
| | max | 1.11 @ 21K | 2.6 @ 62K | 7.9 @ 72K |
| 2-1n, Concept 2 Diffusion coefficient reduced by factor of 20 | 10K y | 0.20 | 0.004 | 0.59 |
| | limit | >100K | >100K | >100K |
| | max | 0.72 @ 65K | 1.5 @ 99K | 7.4 @ 75K |
| 2-2d, Concept 2 Release rate independent of time | 10K y | 1.11 | 0.24 | 3.3 |
| | limit | >100K | >100K | >100K |
| | max | 1.15 @ 25K | 2.9 @ 72K | 8.4 @ 74K |
| 2-2dc, Concept 2 Concrete degrades at 2000 years | 10K y | 1.12 | 0.29 | 3.3 |
| | limit | >100K | >100K | >100K |
| | max | 1.14 @ 16K | 2.6 @ 62K | 7.9 @ 72K |
| 2-3d, Concept 2 Failed hydraulic barrier | 10K y | 1.10 | 0.27 | 3.3 |
| | limit | >100K | >100K | >100K |
| | max | 1.11 @ 14K | 2.6 @ 62K | 7.8 @ 72K |
| 2-4d, Concept 2 No side barrier | 10K y | 1.16 | 0.72 | 3.5 |
| | limit | >100K | >100K | >100K |
| | max | 1.17 @ 13K | 2.6 @ 59K | 7.8 @ 72K |

| Case | T _{1/2} | Beta Dose (mrem/y) | Alpha Conc. (pCi/l) | All-Pathways Dose (mrem/y) |
|---|------------------|--------------------|---------------------|----------------------------|
| Limit | 10K y | 4.0 | 15. | 25. |
| 2-5d, Concept 2 100 mm/y recharge rate | 10K y | 1.37 | 2.0 | 4.2 |
| | limit | >100K | >100K | >100K |
| | max | 1.37 @ 9.3K | 2.8 @ 58K | 8.1 @ 71K |
| 2-6d, Concept 2, 0.5 * dispersion coeff. | 10K y | 1.09 | 0.20 | 3.2 |
| | limit | >100K | >100K | >100K |
| | max | 1.12 @ 15K | 2.6 @ 63K | 7.9 @ 72K |
| 2-7d, Concept 2, 2 * dispersion coeff. | 10K y | 1.12 | 0.35 | 3.3 |
| | limit | >100K | >100K | >100K |
| | max | 1.13 @ 15K | 2.6 @ 61K | 7.9 @ 72K |
| 2-1dCR, Concept 2 impacts at Columbia River | 10K y | 0.054 | 0.013 | 0.161 |
| | limit | >100K* | >100K | >100K |
| | max | 0.055 @ 15K | 0.126 @ 62K | 0.38 @ 74K |
| 2-1dsCR, Concept 2 impacts at Columbia River, vadose zone flux extended to long times | 10K y | 0.056 | 0.011 | 0.167 |
| | limit | >100K* | >100K | >100K |
| | max | 0.25 @ 13M | 0.34 @ 2.7M | 0.50 @ 51K |

| Case | Time | Beta Dose (mrem/y) | Alpha Conc. (pCi/l) | All-Pathways Dose (mrem/y) |
|---|-------|--------------------|---------------------|----------------------------|
| Limit | 10K y | 4.0 | 15. | 25. |
| 3, Unit Cell Model, Main analysis case | 10k y | 4.4 | 5.9 | 13.4 |
| | limit | @ 7.2K | @ 46K | @ 22K |
| | max | 4.5 @ 15K | 15.0 @ 49K | 63. @ 50K |
| 32, Unit Cell Model, Concept 2 | 10K y | 1.23 | 1.66 | 3.8 |
| | limit | >100K | >100K | >100K |
| | max | 1.26 @ 15k | 4.3 @ 49K | 17.8 @ 50K |
| 3a, Unit Cell Model, 3.0 mm/y recharge rate | 10k y | 4.4 | 8.6 | 6.2 |
| | limit | @ 4.6K | @ 46K | @ 22K |
| | max | 4.5 @ 14K | 15.0 @ 49K | 63. @ 50K |
| 3b, Unit Cell Model, 3.0 mm/y recharge rate with initial drainage | 10K y | 4.4 | 5.9 | 13.4 |
| | limit | @ 7.2K | @ 49K | @ 22K |
| | max | 4.5 @ 15K | 15.0 @ 49K | 63. @ 50K |
| 3c, Unit Cell Model, 1.0 mm/y recharge rate | 10K y | 3.5 | 0.19 | 10.3 |
| | limit | @ 16K | >100K | >100K |
| | max | 4.1 @ 25K | 10.0 @ 98K | 21. @ 96K |
| 3d, Unit Cell Model, 0.1 mm/y recharge rate | 10K y | <0.001 | <0.001 | 0.001 |
| | limit | >100K | >100K | >100K |
| | max | 2.5 @ 100K | 0.33 @ 100K | 7.7 @ 100K |

| Case | Time | Beta Dose (mrem/y) | Alpha Conc. (pCi/l) | All-Pathways Dose (mrem/y) |
|---|-------|--------------------|---------------------|----------------------------|
| Limit | 10K y | 4.0 | 15. | 25. |
| 3e. Unit Cell Model, 10. cm/y recharge rate | 10K y | 4.8 | 28. | 176. |
| | limit | @ 192 | @ 1.1K | @ 800 |
| | max | 5.0 @ 5.2K | 30 @ 4.2K | 194 @ 4.2K |
| 3f. Unit Cell Model, Entire vadose zone has properties of sandy sequence | 10K y | 4.6 | 9.9 | 18.8. |
| | limit | @ 3K | @ 18K | @ 11.8K |
| | max | 4.6 @ 9.5K | 19.3 @ 32K | 99. @ 33K |
| 3g. Unit Cell Model, Filler material between canisters is Hanford sand | 10K y | 4.4 | 5.6 | 13.3 |
| | limit | @ 7.4K | >100K | @ 23K |
| | max | 4.5 @ 15K | 14.9 @ 50K | 61. @ 51K |
| 3h. Unit Cell Model, Lower Hanford gravel is 50 meters thick | 10K y | 4.1 | 4.2 | 12.5 |
| | limit | @ 9.2K | >100K | @ 26K |
| | max | 4.4 @ 17K | 14.2 @ 54K | 55. @ 55K |
| 3i. Unit Cell Model, Water table at 110 meters | 10K y | 4.2 | 4.4 | 12.7 |
| | limit | @ 8.6K | >100K | @ 26K |
| | max | 4.4 @ 16K | 14.2 @ 54K | 56. @ 55K |

| Case | Time | Beta Dose (mrem/y) | Alpha Conc. (pCi/l) | All-Pathways Dose (mrem/y) |
|--|-------|--------------------|---------------------|----------------------------|
| Limit | 10K y | 4.0 | 15. | 25. |
| 3j, Unit Cell Model, Water table at 96 meters | 10K y | 4.5 | 7.7 | 14.2 |
| | limit | @ 6.7K | @ 29K | @ 17K |
| | max | 4.5 @ 13K | 16.5 @ 42K | 75. @ 42K |
| 3k, Unit Cell Model, Initial moisture at 0.2 in for construction materials | 10K y | 4.4 | 5.9 | 13.4 |
| | limit | @ 7.2 | @ 46K | @ 22K |
| | max | 4.5 @ 15K | 15.0 @ 49K | 63. @ 50K |
| 3l, Unit Cell Model Initial moisture is residual in construction materials | 10K y | 4.4 | 5.9 | 13.4 |
| | limit | @ 7.2K | @ 46K | @ 22K |
| | max | 4.5 @ 15K | 15.0 @ 49K | 63. @ 50K |
| 3m, Unit Cell Model canisters rotated by 90 degrees | 10K y | 4.4 | 5.7 | 13.4 |
| | limit | @ 5.2K | >100K | @ 22K |
| | max | 4.5 @ 15K | 15.0 @ 50K | 62. @ 50K |
| 3n, Unit Cell Model doubled number of lateral nodes | 10K y | 4.4 | 5.9 | 13.4 |
| | limit | @ 7.2K | @ 46K | @ 22K |
| | max | 4.5 @ 15K | 15.0 @ 49K | 63. @ 50K |

| Case | Time | Beta Dose (arem/y) | Alpha Conc. (pCi/l) | All-Pathways Dose (arem/y) |
|--|-------|--------------------|---------------------|----------------------------|
| Limit | 10K y | 4.0 | 15. | 25. |
| 3o, Unit Cell Model, waste form has hydraulic properties of sand | 10K y | 4.4 | 5.8 | 13.4 |
| | limit | @ 7.2K | @ 46K | @ 22K |
| | max | 4.5 @ 15K | 15.0 @ 49K | 63. @ 50K |
| 3p, Unit Cell Model, diffusion coefficient reduced to 10^{-8} cm ² /a | 10K y | 4.4 | 5.9 | 13.4 |
| | limit | @ 7.2K | @ 46K | @ 22K |
| | max | 4.5 @ 15K | 15.0 @ 49K | 63. @ 50K |
| 3q, Unit Cell Model, doubled dispersion coefficient | 10K y | 4.4 | 6.2 | 14.4 |
| | limit | @ 7.1K | @ 44K | @ 17K |
| | max | 4.5 @ 15K | 15.0 @ 45K | 62. @ 46K |
| 3r, Unit Cell Model, halved dispersion coefficient | 10K y | 4.3 | 5.7 | 13.3 |
| | limit | @ 7.4K | @ 45K | @ 26K |
| | max | 4.5 @ 14K | 15.2 @ 52K | 65. @ 52K |
| 3s, Unit Cell Model, One-tenth dispersion coefficient | 10K y | 4.3 | 5.6 | 13.3 |
| | limit | @ 7.7K | @ 45K | @ 30K |
| | max | 4.5 @ 14K | 15.6 @ 53K | 69. @ 53K |
| 3tu0, Unit Cell Model, U has Kd = 0 everywhere | 10K y | 4.6 | 9.7 | 14.2 |
| | limit | @ 5.8 | @ 22K | @ 46K |
| | max | 4.6 @ 10.8K | 15.0 @ 48K | 63. @ 50K |

| Case | Time | Beta Dose (mrem/y) | Alpha Conc. (pCi/l) | All-Pathways Dose (mrem/y) |
|---|-------|--------------------|---------------------|----------------------------|
| Limit | 10K y | 4.0 | 15. | 25. |
| 3c. Unit Cell Model, D has $K_d = 0$ everywhere but in floor where $K_d = 100$ ml/g | 10K y | 4.2 | 1.6 | 12.6 |
| | limit | @ 4.6K | >100K | @ 22K |
| | max | 4.2 @ 7.7K | 12.3 @ 59K | 62. @ 50K |
| 3tc. Unit Cell Model, Tc has $K_d = 100$ ml/g in floor | 10K y | 1.72 | 6.3 | 4.7 |
| | limit | >100K | @ 46K | @ 24K |
| | max | 3.5 @ 100K | 15.0 @ 49K | 60. @ 51K |
| 3td. Unit Cell Model, Se and Tc have $K_d =$ 100 ml/g in floor | 10K y | 0.98 | 6.3 | 3.4 |
| | limit | >100K | @ 46K | @ 25K |
| | max | 3.4 @ 100K | 15.0 @ 49K | 60. @ 51K |
| 3u. Unit Cell Model, Release rates proportional to surface area | 10K y | 4.3 | 5.8 | 13.1 |
| | limit | @ 7.5K | >100K | @ 22K |
| | max | 4.3 @ 13K | 13.8 @ 45K | 59. @ 48K |
| 3v. Unit Cell Model Release Rates as calculated by AREST-CT | 10K y | 0.53 | 0.63 | 1.54 |
| | limit | >100K | >100K | >100K |
| | max | 0.56 @ 14K | 1.49 @ 32K | 6.0 @ 47K |

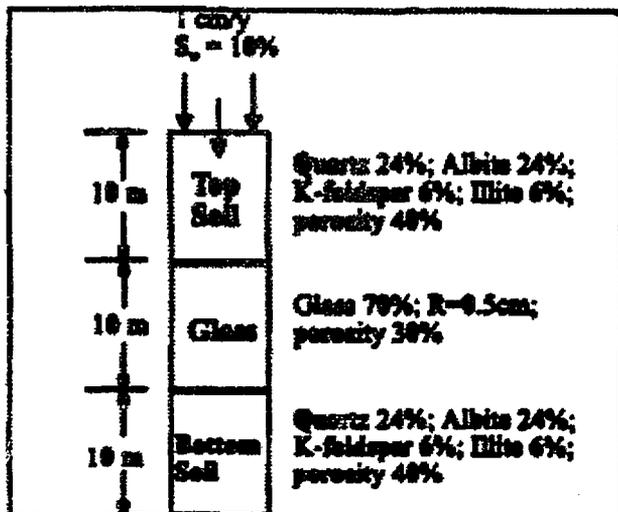
| Case | Time | Beta Dose (mrem/y) | Alpha Conc. (pCi/l) | All-Pathways Dose (mrem/y) |
|---|-------|--------------------|---------------------|----------------------------|
| Limit | 10K y | 4.0 | 15. | 25. |
| 3vxi, Unit Cell Model Release Rates as calculated by AREST-CT, but no ion exchange for Tc | 10K y | 0.20 | 0.63 | 0.47 |
| | limit | >100K | >100K | >100K |
| | max | 0.30 @ 100K | 1.49 @ 32K | 5.4 @ 48K |
| 3vpor, Unit Cell Model, Release Rates as calculated by AREST-CT, but increased pore velocity | 10K y | 0.97 | 0.63 | 3.0 |
| | limit | >100K | >100K | >100K |
| | max | 1.18 @ 20K | 1.49 @ 32K | 7.7 @ 44K |

* Limit for beta/photon drinking water dose at Columbia River is 1 mrem/y.

E.5 WASTE FORM RELEASE CALCULATIONS

E.5.1 Simulation Domain and Physical Conditions

Figure E-8. Glass Simulation Domain



The proposed disposal facility will be located in the vadose zone, about 10 meters beneath the ground surface with a height of 10 meters. Average pore-water velocity in the vadose zone is 1 cm/year, with a water saturation of 10% (Kline 1995b). The average temperature is about 14°C. The surrounding soil contains 24% quartz, 24% high albite, 6% K-feldspar, and 6% illite, with a porosity of 40% (Serne 1993). The glass is assumed to be spherical in shape with a radius of 0.5 cm, and it occupies 70% of the volume of the waste vault. The facility is modeled as a 1-D column as shown in Figure E-8.

E.5.2 Glass Composition and Dissolution Kinetics

The stoichiometric coefficients for the radioactive elements given in Reaction (9) of Appendix C.2.4 were calculated from the total waste inventory, assuming a uniform glass composition is produced totaling 210,000 m³ (Schmittroth 1995b). For historical reasons, the glass waste shapes were taken as marbles with a radius of 0.5 cm.

E.5.3 Key Results

Figure E-9 shows the calculated pH in the vault as a function of time and space where the ion-exchange Reaction (10) of Appendix C.2.4 was not considered. Peak pH values occur at the edges of the vault because this is where the glass reaction rate is largest, as is shown in Figure E-10. Glass reaction rates are largest at the interface between the vault and the surrounding soil because diffusive and advective mass transfer lowers the concentration of Si and other glass components in the aqueous phase. Consequently, the chemical affinity for the network dissolution Reaction (9) is larger, resulting in a faster dissolution kinetics. Figure E-10 shows the complex time and spatial dependence of the glass reaction rate that results from the complex interaction between mass transport and chemical reactions. In general, however, the calculations indicate an overall low rate of glass corrosion, as much as three or four

Figure E-9. Computed pH when Ion Exchange Reaction is NOT Considered.

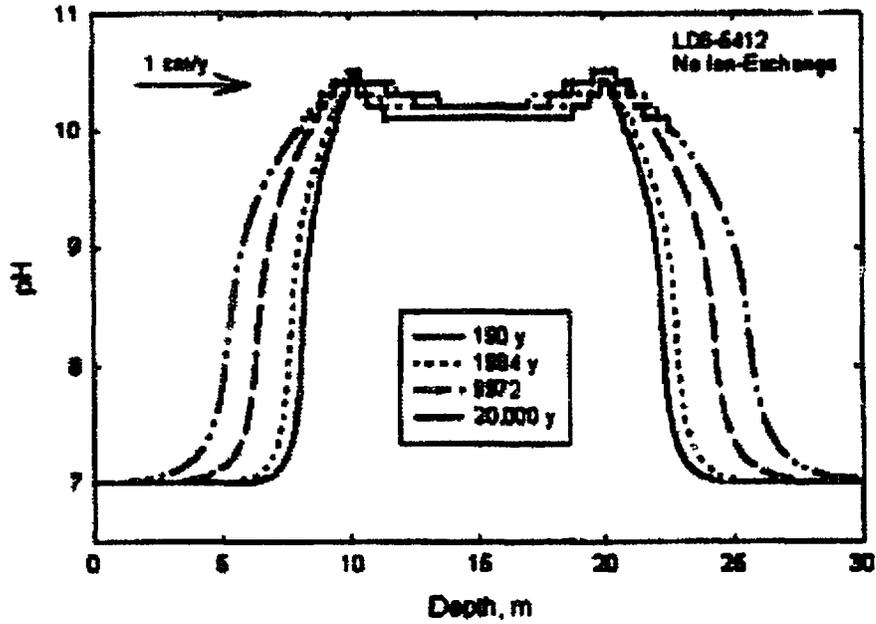
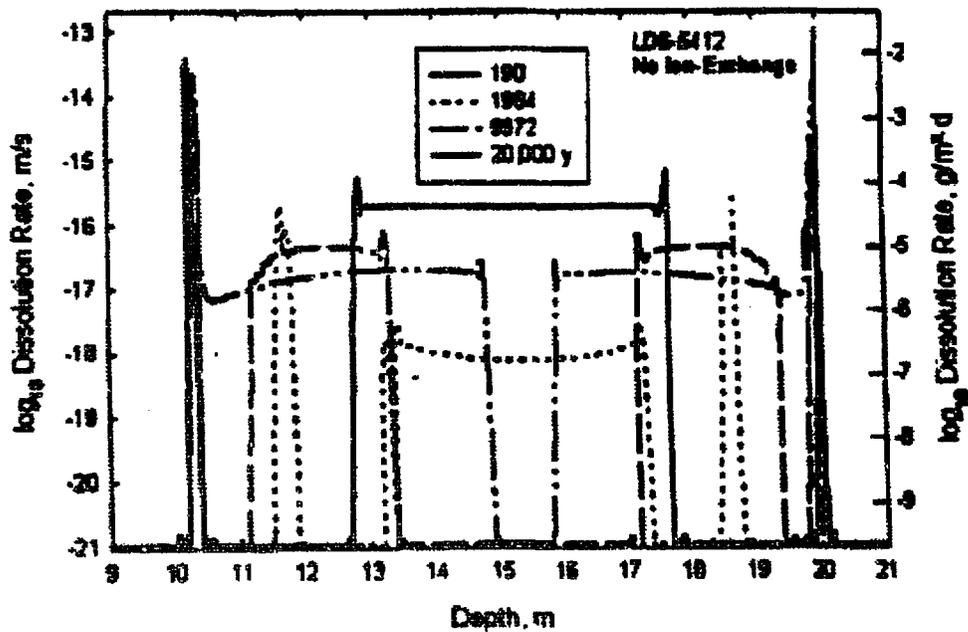


Figure E-10. Glass Dissolution Rate as a Function of Time and Space when NOT Considering Ion Exchange Reaction.



orders of magnitude lower than the forward rate of reaction for LD6-5412 glass at this temperature and average pH in the vault.

Figure E-11 shows the calculated ^{99}Tc concentrations as a function of time and space. Unlike the complex time and spatial dependence found for the glass corrosion rate, the ^{99}Tc concentrations appear smooth and regular, with only a slight peak near the vault edges where the glass reaction rate is highest. The smooth spatial profile for ^{99}Tc results because under the oxidizing conditions in the vault, ^{99}Tc is highly soluble as a pertechnetate (TcO_4^-) anion. With no solid phase precipitation to affect the concentration profile, the radionuclide is subject to dispersion by diffusion and advection, which tends to smooth concentration gradients.

The simulation results presented in Figures E-8 through E-11 neglected the ion-exchange Reaction (10). The inclusion of this reaction has a dramatic effect on the computed pH profile in the vault, as illustrated in Figure E-12. With ion exchange included, the computed pH in the vault rises to over 12, nearly two pH units higher than in the simulations without the reaction (Figure E-9). LD6-5412 glass is less stable at pH >12; this is reflected by a marked increase in the calculated glass corrosion rate, as shown in Figure 4-22. With ion exchange included in the simulation, the overall rate of glass corrosion in the vault increases by several orders of magnitude. Although it will not be shown here, the increase in glass corrosion rate increases proportionately the release rate of an element such as ^{99}Tc , which is highly soluble under these conditions. The release rates of less soluble radionuclides increase or even decrease depending on whether the solubility of any secondary phases that contain the elements increase or decrease at the higher pH.

The large increase in the computed glass corrosion rate in the vault from the ion-exchange reaction mechanism is a clear example in which a computer simulation has identified a significant performance assessment issue that is not observable from laboratory test results. In typical water-saturated, low-temperature, batch tests with LD6-5412 glass, the sodium ion-exchange reaction was identified as a minor secondary reaction that contributed to an enhanced rate of sodium release as compared with the other major glass components, including boron and silicon. The importance of this reaction mechanism to the overall performance of the disposal system was only revealed through computer simulations that properly couple chemical reactions and transport. Now that the importance of this mechanism has been identified, new glasses can be formulated that either eliminate or minimize the sodium ion exchange, and thus significantly improve the overall performance of the disposal system.

Figure E-11. Calculated Total Aqueous ⁹⁹Tc Concentration as a Function of Time and Space.

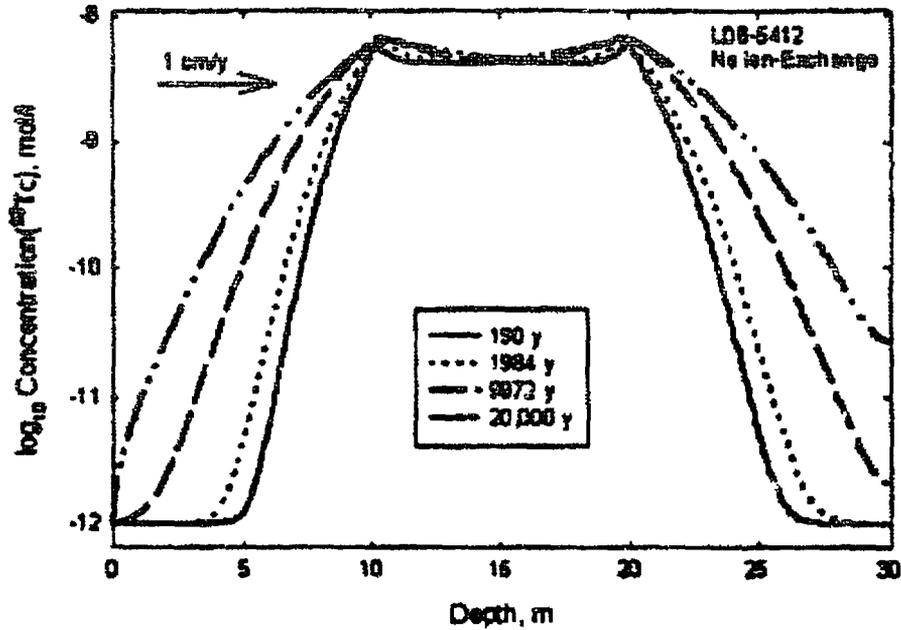
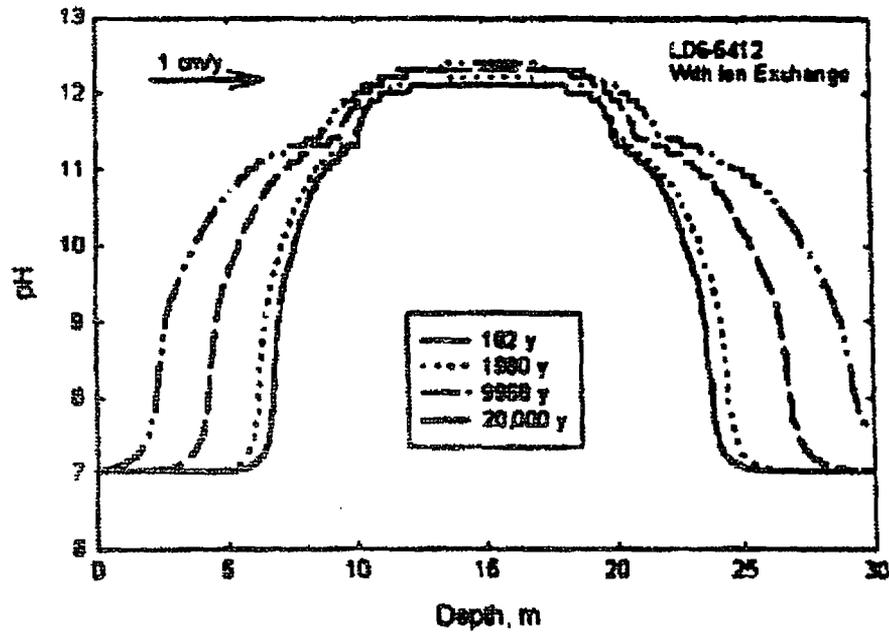


Figure E-12. Computed pH in Disposal Vault When Ion Exchange Is Included.



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**Westinghouse Hanford Company
 Tank Waste Remediation system
 Milestone Description Sheet**

Page 1 of 2
 Rev 0

ORIGINAL

Milestone Control No T34-96-016
 WBS Number 1.01.01.03.04.01.0003.0001

Revision/CIN: 0
 Due Date: 9/30/96
 ADS No: 1250
 Schedule ID: S1W03000B

Title: ISSUE INTERIM PERFORMANCE
 ASSESSMENT FOR INTERNAL REVIEW

Scheduler: VL Armstrong

| Milestone Level: | Deliverables | Addressed To: |
|--|--|--|
| <input type="checkbox"/> TPA | <input checked="" type="checkbox"/> Report | <input type="checkbox"/> DOE-HQ |
| <input type="checkbox"/> DOE-HQ | <input type="checkbox"/> Letter | <input checked="" type="checkbox"/> DOE-RL |
| <input type="checkbox"/> DOE-FO | <input type="checkbox"/> Drawing | <input type="checkbox"/> Other (Specify) |
| <input checked="" type="checkbox"/> DOE-RL | <input type="checkbox"/> Other (Specify) | |
| <input type="checkbox"/> Contractor | | |

Description of this Commitment:

Prepare (for internal review) the Hanford LLW Interim PA as a letter report to the Project Office. The contents, format, computer codes and date to be used in the preparation of this report are defined in "Data Packages for the Interim Performance Assessment," WHC-SD-WM-RPT-166. The interim PA is more fully described in Activity 2 in the SOW, WHC-SD-WM-PAP-062, Rev. 1

Description of what Constitutes Completion of the Commitment:

See above.

Acceptance Criteria:

Project Office accepts the report as being ready for internal review.

MDS APPROVAL

COMPLETION APPROVAL

R. J. Murkowski *[Signature]*
 WHC Responsible Manager/Date

9-16-96
 Date Milestone Was Completed
G. E. Williamson *[Signature]*
 WHC Responsible Manager/Date

DOE Manager/Date

DOE Manager/Date

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February 9, 1997

Mr. Donald D. Modrich
Office of Tank Waste Remediation System
U.S. Department of Energy
Richland Operations Office
P.O. Box 550 MSIN S7-50
Richland, WA 99352

SUBJECT: REQUEST FOR ADDITIONAL INFORMATION - HANFORD INCIDENTAL WASTE
CLASSIFICATION

Dear Mr. Modrich:

U.S. Nuclear Regulatory Commission staff along with our contractor, the Center for Nuclear Waste Regulatory Analyses, are in the process of reviewing the "Technical Basis for Classification of Low-Activity Waste Fraction from Hanford Site Tanks" (Technical Basis), WMC-SD-WM-TI-699, Rev. 2, as requested in the November 7, 1996, letter from J. Kinzer, U.S. Department of Energy (DOE), to C. Paperiallo, U.S. Nuclear Regulatory Commission. In the process of reviewing the Technical Basis, we have also examined several of the supporting references, including the "Hanford Low-Level Tank Waste Interim Performance Assessment" (Interim PA), WMC-EP-0884, dated September 16, 1996. With respect to the Interim PA, we have identified several issues that need to be resolved before NRC staff can fully evaluate your request for agreement that the Hanford tank waste planned for disposal on-site is incidental waste that would not be subject to NRC licensing authority. These comments address the effects of certain assumptions, models, or parameters on dose calculations with respect to meeting the third of the incidental waste classification criteria set forth in the March 2, 1993, letter from R. Bernero, NRC, to J. Lytle, DOE. The comments are listed in the Enclosure.

In order to facilitate the expedited review schedule requested in the November 7 letter, we would like to attempt to resolve these issues in a meeting (face-to-face, or through telecon or videocon) with you and with the PA staff that authored the Interim PA document. Please contact either Jennifer Davis at (301) 415-5874, or Richard Weller at (301) 415-7287 to set up a meeting. We would appreciate it if the meeting could be held very soon, as we are working to meet your scheduled completion date of April 1997.

Sincerely,


Michael J. Bell, Chief
Engineering and Geosciences Branch
Division of Waste Management
Office of Nuclear Material Safety
and Safeguards

Enclosure: As stated
cc: J. Kinzer (w/encl)

SPECIFIC COMMENTS FROM REVIEW OF THE
"HANFORD LOW-LEVEL TANK WASTE INTERIM PERFORMANCE
ASSESSMENT," WNC-EP-0884, REVISION 0

1. The Interim PA provides a value of an initial fractional radionuclide release rate of 4.4×10^{-6} for all radionuclides except ^{99}Tc , which has a rate of 8.8×10^{-7} (pp. iv and 3-32). These values for the fractional radionuclide release rate may be unrealistically low for the disposal facility. The Interim PA assumes that the fractional radionuclide release rates are limited by the fractional bulk dissolution rate of the glass. However, it is not clear how the fractional release rates for ^{99}Tc , a highly soluble nuclide, could be much smaller than the other isotopes in the glass. These values should be justified. For example, Kerrisk (1984) presents a detailed model for calculating fractional radionuclide release rates for vitrified pressurized water reactor high-level waste for 10 important radionuclides expected in the waste, based on nuclide solubilities, recharge rates, background concentrations of silica, and other factors. A similar evaluation would be appropriate for the Tank Waste Remediation System waste.

Additionally, the bulk dissolution rate for glass does not necessarily determine the dissolution rate for high-solubility fission products in the glass (such as ^{99}Tc and ^{129}I), because many of these nuclides may have the ability to diffuse out of the glass, and may, therefore, have high release rates. These processes are not included in the Interim PA.

2. The K_d value for I (p. 3-27, Table 3-5) appears to be nonconservative. As standard practice, I is generally considered to be unretarded, i.e., $K_d = 1$ L/kg. (See also Sheppard and Thibault, 1990.) The value presented in the Interim PA, $K_d = 3$ L/kg is somewhat higher. This difference is expected to significantly affect the results. The value used should be altered or justified.
3. Some of the all-pathways dose conversion factors (DCFs) in the Interim PA (p. B-56, Table B-3) appear to be low compared with DCFs for other arid sites (LaPlante, et al., 1995). The Interim PA should include a more detailed technical justification for the selection of the DCFs, because evaluations of disposal facility performance are expected to be very sensitive to the values selected.

Enclosure

4. The derivation of the relative radionuclide release rate (pp. 3-33 and 3-34) may require modification. The equation in the center of page 3-33 describes the absolute radionuclide release rate (in Ci/yr) for the waste form as:

$$RRR(t) = C * S(t) * I(t)/V(t)$$

where:

- RRR(t) = the radionuclide release rate (Ci/t)
- t = the time
- C = the constant corrosion rate (1/t)
- S(t) = the surface area of the waste form as a function of time (1²)
- I(t) = the radionuclide inventory in the waste form as a function of time (Ci)
- V(t) = the volume of the waste form as a function of time (1³)

Assuming that this equation is correct, the relative (or fractional) radionuclide release rate, FRRR(t), i.e., the fraction of radionuclide inventory release rate per unit time would be given by:

$$FRRR(t) = RRR(t)/I(t) = C * S(t)/V(t)$$

The waste area to volume ratio is expected to increase with time due to corrosion of the waste form and cracking due to formation of corrosion products. Because FRRR(t) is directly proportional to the waste area to volume ratio, this quantity would be expected to increase with time. On page 3-34, there is an expression for FRRR(t) that decreases with time. These considerations should be included in the Interim PA, because performance is likely to be highly sensitive to radionuclide release rate.

5. The Interim PA methodology is deterministic, and single values (sometimes best values) of parameters are used. The reviewers are concerned that if the range of measured parameter values were incorporated into the Interim PA, some performance limits might be exceeded. Uncertainty analyses should be performed in addition to the sensitivity analyses presented in the Interim PA.
6. There is insufficient justification for the assumption that the capillary barrier will be intact for 1000 years. The performance of this barrier will degrade with time. Similarly, the Interim PA assumes that the concrete vaults will be intact for 500 years. This assumption seems to be based on a U.S. Nuclear Regulatory Commission Branch Technical Position which specifies that the maximum credit that can be allowed for concrete structures is 70 years. A site-specific justification should be provided for this assumption, since occurrence of earthquakes and other natural events must be accounted for.

7. The infiltration rate of 0.5 mm/yr for the first 1000 years and 3mm/yr thereafter has not been adequately justified. These values may be unrealistically low, and contribution from lateral subsurface flow during storms has been neglected.
8. The release rate calculation appears unrealistic in that the dissolution time for the entire inventory is based on dissolution in still water. In flowing water, waste dissolution will be faster because the fresh water will provide for continuous attack on the waste form. The Interim PA acknowledges that performance results are dependent upon the release rate (pp. 3-32 and 3-35). The dissolution time calculations should be justified or altered.
9. The Interim PA uses an equation which appears to consider that the quantity of radionuclides transported to the base of the vadose zone is dissolved in a volume of water equal to the annual recharge (p. 3-61). This would be unrealistic and nonconservative, particularly for the second design option in which the vaults are interspersed by soil. The volume of water will be the portion of annual recharge that actually flows over the waste. The concentration calculated by the flow and transport code would appear to be more justifiable.
10. Flow and transport modeling neglects heterogeneity within layers, thereby omitting consideration of spatially distributed flow.

REFERENCES

Kerrisk, J.F., "Solubility Limits on Radionuclide Dissolution at a Yucca Mountain Repository," LA-9995-MS, Los Alamos National Laboratory, Los Alamos, NM, 1984.

LaPlante, P.A., S.J. Maneras, and M.S. Jarzempa, "Initial Analysis of Selected Site Specific Dose Assessment Parameters and Exposure Pathways Applicable to the Groundwater Release Scenario at Yucca Mountain," CMWRA 95-018, Center for Nuclear Waste Regulatory Analyses, San Antonio, TX, 1995.

Sheppard, M.I., and D.H. Thibault, "Default Soil/Solid Liquid Partition Coefficients, K_d , for Four Major Soil Types: A Compendium," Health Physics, Vol. 59, No. 4, pp. 471-482, 1990.