Systems Study on Engineered Barriers

**A Reference Analysis on the
Use of Engineered Barriers for
Isolation of Spent Nuclear
Fuel in Granite and Basalt**

**M. O. Cloninger
C. R. Cole**

August 1981

**Prepared for the
Office of Nuclear Waste Isolation,
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Errata A Priori

This report has been referenced by M. O. Cloninger in two documents, PNL-SA-8706 and PNL-3540, as being published in 1980. The material for these two documents was taken from an earlier draft of this report. Since that time, some change in the referenced material has occurred. Though most of the changes are not of major consequence, they should be noted by those using this document for reference.

The most important change is that the significance of a 10^{-3} per year release rate as a point of sensitivity to consequence was found only in the reference salt site analysis and not in the non-salt analysis reported here (see the section on "Reference Salt versus Non-salt Sites" in this document).

Other changes have no significant impact on the conclusions of the above documents.

FOREWORD AND EXECUTIVE SUMMARY

If the geologic setting for a deep permanent repository for spent nuclear fuel is appropriately chosen, there is little technical reason to design a nuclear waste package and other engineered barriers to a ensured performance level other than that required for transportation and emplacement of the waste into a repository. If placed in highly plastic media, the waste package must also be engineered to withstand short periods of backfilling and settling to overburden pressure, and must be retrievable. Because the remote possibility exists that humans might accidentally come in contact with the waste through the ground- and surface-water system, considerations should be made to engineering the disposal system to reduce the consequences of such an occurrence.

The "as low as reasonably achievable" (ALARA) portion of the waste-disposal-system licensing process can be based on the results of systems analyses of engineered barriers (e.g., this report), performance modeling of proposed waste packages and systems, and predictions of the capital and operating expenses for the candidate systems. These three sources can also help provide a basis for meeting or revising regulated performance criteria, which are usually expressed in terms of allowable consequences or actual in situ performance levels for the engineered barriers themselves.

When the ALARA cost/benefit work is sufficiently rigorous, and the regulated minimum performance parameters are met, the application of utility curves from decision theory to the cost/benefit analysis may lead to new insights as to how good is good enough.

SUMMARY

This report evaluates the effectiveness of engineered barriers in delaying or reducing the rate of release of radionuclides from spent fuel in geologic repositories in granite and basalt. We assumed that the major exposure pathway from the repository to humans would be the ground-water system overlying or underlying a site. Hence, this report focuses on ground-water pathways. A geosphere transport model, GETOUT, and the biosphere transport/dose models, ALLDOS and PABLM, were integrated and used to calculate the potential radiological dose that might be received by humans at various times after repository closure. Presumably, radioactive material would reach humans if they drank contaminated water; used contaminated water for irrigation and stock water; ate contaminated aquatic organisms; or swam in affected waters.

Because the geology of a waste disposal site may retard radionuclide migration, the model was used to simulate the relative retardation capacity of granite and basalt. Release of radionuclides to the environment can also be a function of 1) the rate of release of radionuclides from the repository, 2) the time it takes for leaching to begin, 3) the aquifer flow velocity, and 4) the flow pathlength to the biosphere.

The results of this study pertain to the performance of engineered barriers in reference spent-fuel repositories located in granite and basalt. The following conclusions have been drawn from our work:

- Regional geology is the most effective barrier to the release of radionuclides to the biosphere. For long-lived isotopes of carbon, technetium, and iodine, however, the geology is not very effective once leaching and transport have started, because these elements are poorly sorbed onto geologic media.
- The most effective function of engineered barriers is to reduce the rate at which radionuclides are released in a repository. For the reference granite and basalt sites, a release rate of less

than 10^{-5} yr^{-1} (fractional) is necessary to reduce potential doses from ^{14}C , ^{99}Tc and ^{129}I to a baseline level below that of the actinides. Beyond this level, a rate of considerably less than 10^{-5} yr^{-1} is required before the potential dose from the actinide chains can be further lowered by this mechanism. Only in extreme cases of the intrusion water well case (ground water travel time less than 500 yr) is there a linear relationship between release rate from the repository and release to the biosphere for the actinide chain daughters.

Below a 10^{-6} per year repository release rate, the radiological consequences due to even the actinide daughters are generally linear with repository release rate, and any reduction in release rate would lead to a reduction in dose. Thus, an "as low as reasonably achievable" (ALARA) cost/benefit approach is appropriate for determining the optimal release rate. Such an approach would balance predicted performance versus consequences versus cost and should include reasonable probabilities, account for geochemical limits to release rate, and the 2-D effects of the flow field.

- Containers, sealants and other engineered barriers will not significantly reduce radiological doses unless they delay the start of leaching for more than 100,000 years.
- Specific nuclides of concern for extreme conditions of the general case (early, fast release from the repository, short ground-water transport times) are the fission products ^{14}C , ^{99}Tc and ^{129}I . For the more likely and moderate conditions of the general case, the important nuclides are ^{241}Am as a source of ^{237}Np and its daughters (^{233}U , ^{229}Th , ^{225}Ra); ^{234}U and ^{238}U primarily as a source of ^{226}Ra but also as dose contributors themselves; and ^{226}Ra and its daughters (especially ^{210}Pb and ^{210}Po). For extreme conditions of the intrusion well case, the dominant nuclides were ^{14}C , ^{241}Am , ^{243}Am , ^{79}Se , and ^{239}Pu .

This one-dimensional, deterministic analysis is quite conservative and ignores several phenomena that tend to reduce both the magnitude of potential dose consequences from a deep geologic repository and the sensitivity of those consequences to the performance of engineered barriers.

The technical incentives for providing the above functions via engineered systems can only be reduced from those described above if the actual limitations to mass transport in a backfilled deep geologic repository, the geochemical kinetics, thermodynamic equilibria, and the three-dimensional hydrologic system are rigorously taken into account and if, additionally, the natural biological saturation limits are used in the dose model.

Calculating absolute dose estimates is not the main intent of this work (evaluating relative potential dose reductions via engineered barriers performance is), but this discussion would not be complete without some estimate of the result for expected conditions. Even in a highly disrupted, deep geology, the natural limitations of volumetric flow restrictions, transport distances and geochemical interactions will likely by themselves limit the bulk release rate to 10^{-4} per year or less and provide a ground-water travel time on the order of 5000 yr or more. Given these parameters, our very conservative calculations for the reference granite site predict that the maximum individual would receive an incremental lifetime critical organ dose (cumulative) of one rem or less and a lifetime average annual total body dose of nominally 10 mrem per year from the entire repository. The average individual would receive substantially less. Furthermore, even though it has not been rigorously demonstrated, it appears that under the most conservative conditions, the transport analysis methodology used in this work overestimates resultant consequences by at least an order of magnitude; thus, these calculated absolute dose estimates are likely quite a bit higher than what can actually occur. The methodology is particularly conservative for the analysis of the intrusion well case, because 3-dimensional dispersion effects, which can be very important for short transport distances, are not considered.

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CONTENTS

FOREWORD	v
SUMMARY	vii
ACKNOWLEDGMENTS	xi
1.0 INTRODUCTION	1.1
2.0 METHODOLOGY	2.1
2.1 THE SCENARIO	2.1
2.2 THE MODELS	2.3
3.0 REFERENCE REPOSITORY SITES	3.1
3.1 ISOLATION EFFECTIVENESS AND GEOHYDROLOGIC PARAMETERS	3.2
3.2 DESCRIPTION OF A REFERENCE REPOSITORY IN GRANITE	3.3
3.2.1 Generic Description of the Granite Geohydrology	3.4
3.2.2 Permeability (Hydraulic Conductivity) and Porosity	3.6
3.2.3 Ground Water Flows and Ages	3.11
3.2.4 Hydrologic Parameter Estimates for Transport Calculations	3.12
3.2.5 Sorption Estimates for the Reference Granite Site	3.14
3.3 DESCRIPTION OF A REFERENCE REPOSITORY IN BASALT	3.20
3.3.1 Generic Description of Basalt Geohydrology	3.21
3.3.2 Permeability (Hydraulic Conductivity and Porosity)	3.22
3.3.3 Hydrologic Parameter Estimates and Transport Calculations	3.22
3.3.4 Reference Basalt Repository Hydrologic Parameters	3.25
3.3.5 Sorption Estimates for the Reference Basalt Site	3.26

4.0	RESULTS AND DISCUSSION	4.1
4.1	REFERENCE GRANITE SITE RESULTS	4.1
4.1.1	General Scenario	4.1
4.1.2	Intrusion Well Scenario	4.7
4.2	REFERENCE BASALT SITE RESULTS	4.23
4.2.1	General Scenario	4.23
4.2.2	Intrusion Well Scenario	4.27
4.4	REFERENCE SALT VERSUS NON-SALT SITES	4.30
5.0	PERSPECTIVE	5.1
6.0	ASSUMPTIONS AND CONCLUSIONS	6.1
6.1	SUMMARY OF ASSUMPTIONS AND APPROACH	6.1
6.2	CONCLUSIONS	6.2
7.0	REFERENCES	7.1
APPENDIX A -	REFERENCE GRANITE SITE EXPANDED DOSE SUMMARY TABLES	A.1
APPENDIX B -	REFERENCE BASALT SITE EXPANDED DOSE SUMMARY TABLES	B.1

FIGURES

1	Schematic of Fractured Rock	3.5
2	Ranges in Permeability for Crystalline Rock as a Function of Depth	3.8
3	Variation in Three Types of Porosity	3.9
4	Hydraulic Conductivity Values for Selected Zones	3.20
5	Hydraulic Conductivity Across Flow Contacts Within the Wanapum Basalts	3.21
6	Range of Hydraulic Conductivity Across Low-Density Zones	3.21
7	Theoretical Relationship Between Local, Intermediate and Regional Ground-Water Flow Systems	3.23
8	Potentiometric Map for and Inferred Flow Directions of Ground Water Within the Mabton Interbed Beneath the Hanford Site	3.24
9	Sensitivity of Consequence to Repository Release Rate for the General Scenario in Granite	4.2
10	Sensitivity of Consequences to Delay of Leach Initiation (Containment) for the General Scenario in Granite	4.3
11	Sensitivity of Consequences to Ground-Water Travel Time to Biosphere for the General Scenario in Granite	4.5
12	Sensitivity of Consequences to Repository Release Rate for the Intrusion Well Scenario in Granite	4.8
13	Result by Significant Isotope for $t = 50$ Yr Line of Figure 12	4.9
14	Result by Significant Isotope for $t = 500$ yr Line of Figure 12	4.12
15	Result by Significant Isotope for $t = 10^6$ yr Line of Figure 12	4.13
16	Sensitivity of Consequences to Delay of Leach Initiation (Containment) for the Intrusion Well Scenario in Granite	4.17
17	Sensitivity of Consequences to Ground-Water Travel Time to Biosphere for the Intrusion Well Scenario in Granite	4.19

18	Result by Significant Isotope for the $t = 1$ yr, $1 = 100$ yr Line of Figure 17	4.20
19	Result by Significant Isotope for the $t = 1$ yr, $1 = 10^6$ yr Line of Figure 17	4.21
20	Sensitivity of Consequences to Repository Release Rate for the General Scenario in Basalt	4.24
21	Sensitivity of Consequences to Delay of Leach Initiation (Containment) for the General Scenario in Basalt	4.25
22	Sensitivity of Consequences to Ground-Water Travel Time to Biosphere for the General Scenario in Basalt	4.26
23	Sensitivity of Consequences to Repository Release Rate for the Intrusion Well Scenario in Basalt	4.27
24	Sensitivity of Consequences to Delay of Leach Initiation (Containment) for the Intrusion Well Scenario in Basalt	4.28
25	Sensitivity of Consequences to Ground-Water Travel Time to Biosphere for the Intrusion Well Scenario in Basalt	4.29
26	General Effect of Repository Release Rate on Resultant Consequences for the Reference Salt Site	4.31
27	General Effect of Repository Release Rate on Resultant Consequences for the Reference Non-Salt Sites	4.32

TABLES

1	Repository Nuclide Inventories in Curies at Various Times After Closure in Year 2050	2.4
2	Reference Site Parameter Summary	3.1
3	Degrees of Permeability of Various Rock Types	3.7
4	Hydraulic Properties of Different Hydrologic Structures for the Reference Reporting Site Area in Granite	3.10
5	Reference Granite Site Equilibrium Sorption Coefficients K _d , ml/g	3.14
6	Reference Granite Site Retardation Coefficients K(dimensionless)	3.16
7	Reference Basalt Site K _d and K Values	3.27

1.0 INTRODUCTION

The development and characterization of waste forms, containers, and other engineered barriers destined for use in the disposal of nuclear waste in deep geologic repositories has progressed to the point where there are several options among the combinations of barrier systems that are available to help ensure safe disposal of nuclear wastes. However, a rigorous basis has not yet been developed to define whether various concepts or products are required or desirable, or how durable they should be for how long. This analysis is a consequence analysis designed to contribute to that basis. The intent of the study is to determine what incentives exist for providing highly effective engineered barriers for the isolation of spent fuel in a deep geologic repository, based on what effect, if any, the engineered barrier may have on the ultimate potential dose to humans living in the future.

Engineered barriers as used here are considered to be anything that man places in the repository to enhance the containment of radioactive material, including the waste form, containers, and backfill materials.

Potential dose commitments were calculated using an integrated geosphere transport and biosphere transport/dose model. The geosphere transport model simulates the release of radionuclides from a repository through contact with and leaching by flowing ground water, subsequent transport of nuclides in the ground water (including the effects of convection, hydrodynamic dispersion, reversible sorption and mineralization, and radioactive decay), and ultimate release of the nuclides to the surface water (lake or river) or to an intrusion water well borehole. Output of the geosphere model is the input for the biosphere model. The biosphere model predicts the radiation dose to humans from the nuclide release to surface waters via several pathways, including direct ingestion of water, aquatic foods, and irrigated food products, as well as irradiation from shoreline deposition and swimming. Food chain reconcentration/accumulation effects are included.

A sensitivity analysis was performed by varying four important system parameters: the waste radionuclide release rate, the delay prior to

ground-water contact with the waste (leach initiation), aquifer flow velocity, and flow pathlength to the biosphere. The first two parameters represent the net effectiveness of the near-field repository system and the latter two are partially representative of the far field effectiveness.

The radionuclide release rate was varied from 10^{-2} to 10^{-6} fraction per year of the entire repository contents. Delay prior to leach initiation was varied from one to one million years after repository closure. Combinations of aquifer flow velocity and pathlength were varied such that the ground-water travel time from the repository to the biosphere ranged from 500 yr to 10^6 yr for the general scenario in granite and 500 to 2×10^6 yr in basalt. Ground-water travel time from the repository to the water well borehole varied from a minimum of 50 yr up to 10^6 yr in granite and 2×10^6 yr in basalt.

This analysis is limited to looking only at engineered barriers whose net effect is either to delay ground-water contact with the waste form or to limit the rate of release of radionuclides into the ground water once contact has occurred. It does not address the effectiveness of engineered barriers that provide other functions, such as altering the characteristics of the near-field ground-water system (Eh, pH), except as they might reduce release rate or delay the onset of leaching, or barriers that provide warning of the existence of the waste to future generations. Furthermore, the analysis considers only leach scenarios, including a water well intrusion into the ground water near a repository. This report does not consider other human intrusion events (e.g., excavation) or extreme, disruptive events (e.g., volcanic action affecting the repository or sudden thrusting of the repository to the surface).

The analysis documented here is a supplement to a more detailed study (Cloninger, Cole and Washburn 1980) of the effectiveness of engineered barriers in reducing potential long-term radiological consequences from a reference salt site repository.

Past consequence analyses of generic repositories (Burkholder and Cloninger 1978; Burkholder, Cloninger, Baker, and Jansen 1976; Burkholder

1976; Cloninger, Cole, and Washburn 1980) developed a methodology for assessing potential consequences of nuclide release from a repository. Similar methodology is used in this analysis and is described in detail in the next section.

2.0 METHODOLOGY

The analysis is based on predicting the potential releases from a deep geologic repository due to a process involving ground-water intrusion into the repository, leaching and transport of nuclides to the surface, and transport of the nuclides in the biosphere where they cause radiological dose to humans. Releases to the biosphere are converted to a dose to a maximally exposed individual ("maximum individual") in order to determine, through parametric analysis, what effects the properties of engineered barriers may have on that resultant dose over a range of geohydrologic conditions.

2.1 THE SCENARIO

Ground-water leaching and transport are assumed to be the highest-risk pathways enabling radionuclides to migrate from the storage site through the geosphere to the biosphere. This assumption is made even though the relative risks of all of the various pathways have not been evaluated. The scenario on which this study was based involves the following steps:

- penetration of the repository by ground water
- failure of the waste container or containment function
- leaching of the radionuclides from the waste form
- transport of the nuclides through the surrounding geology to the biosphere
- transport of the nuclides through the biosphere to man
- interaction of the nuclides with man.

The geologic repository system provides barriers to the first four steps in the process. The transport of nuclides from the repository to the biosphere is limited by several factors, such as the dissolution rate of the waste form at repository conditions; the chemical composition of the ground water, especially its pH, Eh, ionic strength, and its content of complexing

agents; and the sorption capability of the repository media and all geologic media along the ground-water flow path. These factors are, of course, inter-related. For example, water velocity and flow direction are a function of aquifer porosity, effective permeability, and hydraulic gradient. They can also be affected by the thermal gradient near the repository. Also, the solubility of the waste form and the net sorptive selectivity of the geologic media can be greatly affected by the pH, Eh, and ionic strength of the ground water.

Through these factors, the geologic repository system provides two general means of protection from radioactive waste. The first means is containment of the waste for a sufficient length of time for the hazardous nuclides to decay to innocuous levels such that unrestricted release to the environment presents no radiological hazard. The second means is to limit the rate at which nuclides are released to the biosphere such that their concentration in the constantly renewed local surface water and air never exceed acceptable limits. Actual repository systems will provide protection using some effective balance of these two means.

The available system components that provide the means for this protection can be reduced to 1) the waste form, 2) the containment package, and 3) the geology (including hydrology). Engineered barriers such as nonhomogeneous waste forms (e.g., micro-encapsulation), overpacks, and special backfill can be considered part of one of these components.

The scenario involving human-caused intrusion through a water well can essentially short-circuit the protection from nuclides already dissolved in the ground water that the far-field geologic system provides. The intrusion well scenario is chosen as a limiting case of the leach incident pathway.

The radionuclide inventory used in the analysis represents one-fifth of the total spent, unprocessed fuel (no-recycle case) accumulated in the U.S. through the year 2050 that was used in the Commercial Waste Management Generic Impact Statement, CWM/GEIS (DOE 1979). The assumption is that there would be five operating repositories, each containing an equal fraction of the total

U.S. spent-fuel accumulation. The inventories of the radionuclides in the repository are shown in Table 1 for various times after repository sealing in the year 2050.

2.2 THE MODELS

The geosphere transport model is a second-generation Fortran version of the GETOUT code (DeMier, Cloninger, Burkholder, and Liddell 1979), a one-dimensional analytical model that simulates the release of radionuclides from a repository through contact and leaching by flowing ground water, subsequent transport of the nuclides in the ground water (including the effects of convection, hydrodynamic dispersion, reversible sorption and mineralization, and radioactive decay), and predicts the ultimate time and rate of release of the nuclides to the surface water (lake or river) or water well intake.

To simplify the analysis, a multitude of parameters is reduced to terms representing the net effect of several more complex phenomena. The release rate of nuclides into the flowing ground water (source term) is a constant rate approximation of what may, in reality, be a more complex release function. The model parameter representing the rate-limiting capacity of the engineered barriers is the inverse of the release rate (fraction/yr), or the constant rate release duration in years. The model parameter representing the combined effectiveness of the engineered barrier's containment ability and the stability (or integrity) of the surrounding geology is the delay (years) in the start of a release from the repository, measured from the date of repository closure.

The major hydrologic parameters are the dispersivity, ground-water flow rates, and total pathlength to the biosphere, which are functions of the porosity, permeability, net hydraulic head and gradient, and fracture patterns of the geologic media. For this analysis, these parameters have been reduced to net ground-water flow velocity, total migration pathlength, and a net dispersion coefficient. The flow velocity and pathlength, though modeled separately, are combined for graphic presentation into a single parameter: ground-water travel time (pathlength/flow velocity). A minor degree of

TABLE 1. Repository Nuclide Inventories in Curies at Various Times After Closure in Year 2050

Isotope	Time (years)									
	1.00+000	100 1.00+002	300 3.00+002	1000 1.00+003	3000 3.00+003	10,000 1.00+004	30,000 3.00+004	100,000 1.00+005	300,000 3.00+005	1,000,000 1.00+006
³ H	4.38+006	1.57+004	7.22-004	1.53-018	0.00	0.00	0.00	0.00	0.00	0.00
⁹⁹ Tc	9.64+005	9.64+005	9.62+005	9.60+005	9.54+005	9.32+005	8.72+005	6.92+005	3.58+005	3.56+004
¹²⁹ I	2.48+003	2.48+003	2.48+003	2.48+003	2.48+003	2.46+003	2.46+003	2.46+003	2.44+003	2.38+003
¹⁴ C	2.50+004	2.46+004	2.38+004	2.22+004	1.74+004	7.46+003	6.64+002	1.40-001	4.44-012	0.00
⁹³ Mo	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
⁴¹ Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
⁷⁹ Se	2.62+004	2.62+004	2.62+004	2.60+004	2.54+004	2.36+004	1.90+004	9.04+003	1.07+003	6.18-001
⁹⁰ Sr	2.02+009	1.71+008	1.05+005	3.96-002	1.53-023	0.00	0.00	0.00	0.00	0.00
¹⁰ Be	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
⁶⁰ Co	8.34+006	1.59+001	1.11-016	0.00	0.00	0.00	0.00	0.00	0.00	0.00
⁵⁹ Ni	2.30+005	2.30+005	2.28+005	2.28+005	2.24+005	2.10+005	1.77+005	9.66+004	1.71+004	3.98+001
⁶³ Ni	2.72+007	1.28+007	1.34+006	1.47+004	4.22-003	5.46-026	0.00	0.00	0.00	0.00
⁸⁷ Rb	1.29+000	1.29+000	1.29+000	1.29+000	1.29+000	1.29+000	1.29+000	1.29+000	1.29+000	1.29+000
¹³⁵ Cs	2.00+004	2.00+004	2.00+004	2.00+004	2.00+004	2.00+004	1.99+004	1.96+004	1.87+004	1.59+004
¹³⁷ Cs	2.88+009	2.86+008	2.80+005	2.70-001	2.38-021	0.00	0.00	0.00	0.00	0.00
¹⁰⁷ Po	7.32+003	7.32+003	7.32+003	7.32+003	7.32+003	7.32+003	7.30+003	7.26+003	7.10+003	6.64+003
¹²⁶ Sn	3.54+004	3.54+004	3.54+004	3.52+004	3.48+004	3.32+004	2.88+004	1.63+004	4.44+003	3.50+001
¹⁵¹ Sm	6.36+007	2.86+007	2.62+006	2.22+004	2.68+003	1.68-027	0.00	0.00	0.00	0.00
¹⁶⁶ Mho	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
¹⁵² Eu	1.33+005	4.14+002	1.25-005	1.14-020	0.00	0.00	0.00	0.00	0.00	0.00
¹⁵⁴ Eu	9.02+007	1.19+006	2.72+000	1.42-011	0.00	0.00	0.00	0.00	0.00	0.00
⁹³ Zr	1.24+005	1.24+005	1.24+005	1.24+005	1.24+005	1.24+005	1.23+005	1.19+005	1.08+005	7.84+004
¹¹³ McdM	1.10+005	7.84+002	2.80-004	3.58-017	0.00	0.00	0.00	0.00	0.00	0.00
²⁴⁸ Cm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
²⁴⁴ Pu	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
²⁴⁴ Cm	2.38+007	5.18+005	5.30+000	0.00	0.00	0.00	0.00	0.00	0.00	0.00
²⁴⁰ Pu	3.38+007	3.34+007	3.24+007	3.04+007	2.48+007	1.21+007	1.56+006	1.19+003	1.47-006	0.00
²³⁶ U	1.69+004	1.70+004	1.73+004	1.78+004	1.88+004	2.30+004	2.46+004	2.64+004	2.62+004	2.58+004
²³² Th	2.04-005	8.66-005	3.16-004	1.30-003	1.99-003	1.01-002	7.30-002	1.88-001	2.84-001	1.27+000
²³² U	1.01+003	3.88+002	2.16+001	6.68-002	2.90-010	0.00	0.00	0.00	0.00	0.00
²⁴⁵ Cm	1.30+004	1.29+004	1.25+004	1.19+004	1.01+004	5.60+003	1.05+003	2.96+000	1.53-007	4.86-033

TABLE 1. (contd)

[illegible]

accuracy is lost in combining pathlength and flowrate parameters due to somewhat different net hydrodynamic dispersion effects at different flow velocity and pathlength combinations; however, it does allow the presentation of results from a multitude of transport calculations to be presented, keyed to a single parameter.

Output data of the geosphere model are the input data for the biosphere codes PABLM (Napier, Kennedy and Soldat 1980) and ALLDOS (Streng, Napier, Peloquin, and Zimmerman 1980). The biosphere model predicts the radiation dose to humans from the nuclide release to surface waters via several pathways, including direct ingestion of water, aquatic foods, and irrigated food products, as well as irradiation from shoreline deposition and swimming. Food chain reconcentration/accumulation effects are included. For the general scenario, the biosphere parameters are the same as were used in CWM/GEIS, and have been held constant throughout the analysis. The intrusion well scenario parameters are the same as used in Cloninger, Cole and Washburn (1980), with exceptions as noted in following sections.

3.0 REFERENCE REPOSITORY SITES

The models were applied to simulate a leach incident release from a repository in two reference sites having potential ranges of characteristics as listed in Table 2. The ranges for the reference salt site are also listed in Table 2. The 100-year constant rate leach duration was set as a minimum, representing the fastest possible release of nuclides (1%/yr) from the repository due to solubility and mass transfer limitations in a backfilled repository and assumes no credit for any rate-limiting capacity of the engineered system. Actual solubility-limited release rates for most elemental ions of interest are probably much lower. The 100-year value is not based on

TABLE 2. Reference Sites Parameter Summary

Range Used for Reference-Site Calculations

Parameter	Salt (a)	Granite	Basalt
Release Rate (yr^{-1})	1.0E-2 to 1.0E-9	1.0E-2 to 1.0E-6	1.0E-2 to 1.0E-6
Migration Pathlength (km)			
-General scenario	5.6E+0 to 6.4E+1	1.0E+0 to 1.5E+1	1.6E+1 to 3.2E+1
-Intrusion well scenario	1.6E-1 to 6.4E+1	1.0E-1 to 1.5E+1	1.6E+0 to 3.2E+1
Ground-Water Velocity (m/yr)	1.7E-1 to 1.1E+1	1.5E-2 to 2.0E+0	1.6E-2 to 3.1E+1
Ground-Water Travel Time (yr)			
-General scenario	5.0E+2 to 3.7E+5	5.0E+2 to 1.0E+6	5.0E+2 to 2.0E+6
-Intrusion well scenario	1.4E+1 to 3.7E+5	5.0E+1 to 1.0E+6	5.0E+1 to 2.0E+6
Leach Initiation Delay (yr)	1.0E+0 to 1.0E+6	1.0E+0 to 1.0E+6	1.0E+0 to 1.0E+6
Dispersion Coefficient (m^2/yr)	1.6E-2 to 4.2E+1	2.6E+0 to 1.3E+1	7.4E-4 to 3.7E+1

(a) Cloninger, Cole, and Washburn 1980.

any actual solubility or volumetric flow data.. The "delay prior to leach initiation" parameter range is arbitrarily chosen in order to cover a very wide range of possibilities without regard to initiating events or processes. The remaining site parameters and parameter ranges in Table 2 are based on measured and estimated data from characterization efforts at various sites as discussed in the following subsections.

3.1 ISOLATION EFFECTIVENESS AND GEOHYDROLOGIC PARAMETERS

Determination of a reasonable range of geohydrologic parameters for a reference repository site in various geologic settings is a difficult task because of the complex interactions between the various geohydrologic parameters. The process of determining an expected value and range for the major parameters that control the effectiveness of geohydrologic system involves not only knowing the geohydrologic properties and waste-water-media interaction properties of the host rock but also the kinds of values for these properties of the media that lie between the host rock and the biosphere. One must also know what kind of environment and climate the site or sites are located in and many other factors such as the location of the recharge and discharge sites of the aquifer above and below the host rock, as well as the size, interconnection and extent of these aquifer systems.

Three principal geohydrologic quantities determine the effectiveness of the geohydrologic system in minimizing the impact of releases from a breached repository on man. These parameters are ground water travel time, the variation in travel time, and the sorption selectivity of the geologic media.

$$\text{Travel time} = \int_{\text{source}}^{\text{discharge}} \frac{\theta(s)}{K(s)G(s)} ds$$

where:

s = position along the flow path from the repository to the discharge site

$\theta(s)$ = porosity at position s

$K(s)$ = hydraulic conductivity at position s

$G(s)$ = gradient in potential along the flow path at position s .

The variation in the travel time from the repository to the biosphere can result from various sources. Variation in travel time is a function of:

- 1) the character of the flow field, geometry of discharge site, and type of release scenario
- 2) distribution of the source in the hydrologic system
- 3) the hydrodynamic dispersion caused by the tortuosity and heterogeneity of the geologic media.

The effect of variation in travel time that occurs from (1) and (2) above is generally many times greater than from (3). The effects of (1) and (2) are omitted in a one-dimensional analysis; however, the significance of any errors due to ignoring such effects is large only when the dimensions of the repository are large compared to the flow path to the biosphere entry point as in the case of the extreme water well scenario. Thus, the extreme well scenario is quite conservative. The importance of these effects is discussed more fully in the "Perspective" section and Appendix D of (Cloninger et al. 1980).

3.2 DESCRIPTION OF A REFERENCE REPOSITORY IN GRANITE

Granite is a viable host rock for nuclear waste repositories because of its many suitable characteristics (KBS 1978, INFCE 7/41 1979, INFCE 7/13 1979, INFCE/DEP 7/21 1979). As one of the most abundant rock types in the earth's crust, granite occurs at the surface in large, tectonically stable platforms and monotonous, uniform units. At depth, granite is generally a poor source of water. Granite masses have good mechanical strength and can be mined in a relatively safe and economical manner. Granite masses rarely contain significant ore deposits, which reduces the chance of human intrusion.

Some of the potential disadvantages result from the presence of some water at depth and the low thermal conductivity of the rock. Water presence is generally of little concern since the flow rates and velocities at

repository depths are believed to be very low. The low thermal conductivity, while of concern, can be accommodated by proper emplacement design.

3.2.1 Generic Description of the Granite Geohydrology

A granite site would typically be in a flat, low-lying, stable platform area where erosion has reached a mature stage. The surface would consist of granite outcrop and surficial deposits of till and clay a few meters to a few tens of meters thick. Beyond this upper layer of till, the stratigraphy would be granitic or gneissic. Regional tilt would be on the order of 10^{-3} m/m, and local topographic variations would be approximately 10^{-1} m/m. Hydrologic discharge sites would consist of the lakes, rivers, and streams that drain the area. Recharge is typically from rainfall and possibly from lakes, rivers, and streams. Repository sites would typically be located below recharge zones, which are as distant as possible from discharge sites. This would ensure that waters entering the repository would move downward through the repository into deeper, more regional circulation systems enroute to the biosphere.

The granite masses consist of solid rock blocks and contain only micro-fracture systems in or between mineral grains (hydraulic conductivity $<10^{-11}$ m/sec), surrounded by fracture planes or joints. These joints are discontinuous in their own planes, and flow in these rock masses is dominated by the flow in the more or less interconnected joint sets. Fractures or joints in these large rock masses, in most cases, are continuous over distances that are about three to four times the average fracture spacing. These larger masses of rock, where flow is dominated by the joint systems, frequently contain more highly interconnected discrete fracture zones, which can be identified via various geophysical methods. Fracture zones are generally much more permeable than the surrounding rock masses, varying from a meter or so in width to tens of meters in width and hundreds to thousands of meters in length. The hydrologic properties of discrete fracture zones are dependent on the stresses that formed these systems, as well as the stresses which now exist in the rock masses. Shear zones, for example, are generally filled with broken or crushed rock and may be embedded in clay. Figure 1 illustrates a fractured rock mass

FIGURE 1. Schematic of Fractured Rock

having joints and discrete fracture zones. While the microfracture systems in the solid rock blocks do not contribute significantly to the flow of ground water, they allow the diffusion of nuclides from the active fractures and joints--thus delaying transport times. This kinetic effect is discussed in a report by Neretnieks (1979).

The upper portion of the granitic systems, which can extend from the surface up to, in some cases, a few hundred meters, is often characterized by higher permeabilities due to the more extensive and coherent network of fissures. With increasing depth, there is a transition to larger spacings between fractures or joints that are less interconnected.

Sites deep in a granite system can make excellent repositories, because these sites contain blocks of solid rock that are very massive and distant from major fracture and discharge zones. Massive blocks of solid rock ensure greater isolation of wastes.

3.2.2 Permeability (Hydraulic Conductivity) and Porosity

As already discussed, flow in granite systems is dominated by flow in fractures. In these large areas of rock mass away from the discrete fracture zones, it is the degree and nature of the fracture's or joint's interconnection with other fractures or joints which determine the permeability of the

rock mass. Since laboratory studies (Gale 1975, Iwai 1976) indicate that, for single fractures, hydraulic conductivity is a function of the aperture squared and the flux is a function of the aperture cubed, it is understandable that analysis of field data on permeability and porosity of hard rock systems suggests a logarithmic variation with depth (Davis and Turk 1964, Snow 1968). Fractures represent the most deformable component of crystalline rock, thus accounting for the rapid decrease in permeability and porosity with depth due to the increasing normal stresses.

Table 3 and Figure 2 illustrate the range of measured permeabilities for granitic and other crystalline rock. Figure 3 illustrates the ranges in matrix porosity data that have been measured. Table 4 illustrates the values for permeability and porosity used in the INFCE release consequence analysis (INFCE 7/21 1979).

In the INFCE study, the porosities and hydraulic conductivity were assumed to vary linearly on a log-log plot of conductivity or porosity with depth. The slope used is implied from the values given at 1 and 500 meters in Table 4. Data cited on effective porosity measurements via a variety of methods and for various granitic rocks (KBS 1978) indicate values for porosity between 0.028 and 0.001 (m^3/m^3). The three-dimensional ground-water flow modeling of the Finnsjo area of Sweden (KBS 1978, Stockes and Thunvick 1978) indicates that a 1-km^2 repository would fit in an area where ground water takes longer than 3,000 years to reach the surface. In these studies the hydraulic conductivity of the rock blocks dominated by flow through joint systems varied with depth according to

$$K = 10^{-0.003Z-6} \text{ (m/sec)}$$

where Z is the depth in meters below the surface. The porosity value was constant in the KBS study at 0.0001. The above variation of K with depth corresponds to a value of 10^{-6} m/sec at the surface and $10^{-7.5}$ m/sec at 500 m below surface. The discrete, high-conductivity fracture zones that were included in the model had conductivity that varied as

TABLE 3. Ranges of Permeability for Various General Rock Types

Hydraulic Conductivity, m/s	1.0	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}	10^{-10}	10^{-11}
Permeability, Darcies	10^5	10^4	10^3	10^2	10^1	1.0	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
Degree of Permeability	Very High		High		Moderate			Low		Very Low		
Rock Type

FIGURE 2. Ranges in Permeability for Crystalline Rock as a Function of Depth. (The ordinate in this figure is permeability--in kilodarcies--or hydraulic conductivity--in m/sec. Bar for each site shows the range of measured values.)

$$K_p = 10^{-0.003Z-4} \text{ (m/sec)}$$

where Z = depth below the surface in meters.

It should be noted that the solid rock blocks in the massive areas, where the dominant flow is through joint systems, have permeabilities $<10^{-11}$ m/sec. Thus, water that comes in contact with waste implaced in these non-transmissive solid rock blocks would have much greater travel times since water flow

FIGURE 3. Variation in Three Types of Porosity

through only a few meters of this non-transmissive rock can take thousands to hundreds of thousands of years.

3.2.3 Ground-Water Flows and Ages

Data reported on ages of ground waters (KBS 1978) indicate a range of 3,000 to 11,000 years for waters at an average depth of 380 m (average age of 5,300 years). Some age determinations for waters from the Stripa mine give values up to 30,000 years. These ages correlate well with the Swedish modeling study estimates.

Another important factor in the siting of a waste repository deals with ground-water flow volumes. If flow volumes are small enough, even short travel times to the biosphere are of little importance since only trivial amounts of waste can be transported. Flow estimates from the INCFE study (INCFE 7/21 1979) indicate a total flow rate through a 1-km² repository of

TABLE 4. Hydraulic Properties of Different Hydrogeologic Structures for the Reference Repository Site Area in Granite

Description	Width (m)	Depth (m)	Conductivity (m/s)	Porosity	Velocity (Unit Gradient) (m/s)	Water Travel Time for 1 km Under 0.001 Gradient (y)
Rock Mass		1	10^{-7}	3×10^{-3}	3.33×10^{-5}	951
		500	10^{-10}	10^{-5}	1×10^{-5}	3170
First-Order Fracture Zones (tension)	50	1	10^{-5}	3×10^{-2}	3.33×10^{-4}	95
		500	10^{-8}	10^{-4}	10^{-4}	317
Second-Order Fracture Zones (tension)	10	1	10^{-5}	3×10^{-2}	3.33×10^{-4}	95
		500	10^{-8}	10^{-4}	10^{-4}	317
Second-Order Fracture Zones (shear)	20	1	5×10^{-7}	5×10^{-3}	1×10^{-4}	317
		500	5×10^{-10}	1.7×10^{-5}	3×10^{-5}	1057
Second-Order Fracture Zones (compression)	5	1	10^{-6}	5×10^{-3}	2×10^{-4}	159
		500	10^{-9}	1.7×10^{-5}	6×10^{-5}	529

only $2.6 \text{ m}^3/\text{yr}$ (or $2.6 \times 10^{-3} \text{ } \mu/\text{m}^2\text{-yr}$). This value coincides with estimates for the Karlshamn area (KBS 1978) of $1.5 \times 10^{-3} \text{ } \mu/\text{m}^2\text{-yr}$ at the repository level. Even at higher values for conductivity and porosity, flow values less than $0.1 - 0.15 \text{ } \mu/\text{m}^2\text{-yr}$ are obtained.

3.2.4 Hydrologic Parameter Estimates for Transport Calculations

Travel time cannot be estimated as easily in the granite systems because conductivity and porosity vary with depth and because water flow in granite is determined by fracture systems. Data from the INFCE (7/21/1979) and Swedish modeling studies, as well as age determination data, will be used in estimating travel time, path length, velocity, and dispersion.

Age determination data indicate that water at the average depth of 380 m required an average of 5,300 years with a range between 3,000 and 11,000 years to travel from the recharge area to the surface. INFCE modeling studies

indicate an average travel time of $11,700 \pm 1,300$ years for water exiting a 1-km^2 repository. The average length of the travel path was 7,100 m and average velocity was 0.61 m/yr. Swedish modeling of a 5-by-6-km portion of the Finnsjö Lake area shows that a 1-km^2 rock repository located at the 500 m level could be contained in an area for which flow times to the surface were in excess of 3,000 years. Travel time predictions vary from 3,000 to greater than 10^6 years, and velocities vary from 10^{-3} m/yr to 1.5 m/yr. Path lengths range from one to four kilometers. It is evident from both the INFCE and Swedish modeling studies that large variations in travel time occur even for a repository of only 1 km^2 in area. This variation in water travel time is important in dispersing any nuclides that might be released from a repository.

Another factor that might affect the time it takes for waste to leave an emplacement in a repository is the nature of the rock's microstructure. Water-flow studies and water-age determinations really represent estimates for waters moving in the interconnected fracture or joint systems and discrete, highly-fractured zones of a granite system. Water movement in solid rock blocks, where flow is through a system of microfractures, is much slower. Under typical ground-water gradients and at the conductivities measured at Karlshamn of $<2 \times 10^{-12}$ m/sec, movement of water through only 1 m of this rock can take over 15,000 years.

Based on the results of the Swedish water-age data and the Swedish and INFCE 3-D ground-water modeling efforts for granite systems, along with the arguments for water transit times in blocks of solid rock, the following hydrologic transport parameters are used to represent a range for the reference repository in granite:

Travel time	min. 3,000 yr
	avg. 10,000 yr
	max. 10^6 yr
Path lengths	min. 1 km
	avg. 5 km
	max. 15 km

Averaged velocities over the path	min. 10^{-3} m/yr avg. 0.5 m/yr max. 2 m/yr
Dispersion in arrival time for a 1 km ² repository	min. 1,000 yrs max. 10^6 yrs

The above values should be considered a reasonable range for the reference granite repository, general transport scenario. Ground-water travel times as low as 500 years for the general scenario were used (Table 2) in order to compare results with the reference salt site analysis already completed (Cloninger, Cole, and Washburn 1980). A ground-water travel time of as low as 50 years was used for the intrusion water-well transport scenario in order to represent the partial short-circuiting of the far-field geohydrologic system's protection from the repository wastes.

In the previous reference salt site analysis, the volumetric flow through the entire repository was assumed to be 3.14×10^{-3} m³/sec, subsequently diluted (after exiting the salt) to 0.91 m³/sec in order to approach potable saline content limits for well-water use. The same 3.14×10^{-3} m³/sec assumption is used here for the reference granite site analysis, but no further dilution is assumed, since water drawn from granitic aquifers is usually quite potable. The volumetric flow assumptions are somewhat arbitrary since they can only be established for a particular, real site. The value used here was chosen to be consistent with the reference salt site analysis and is also used in the reference basalt site descriptions that follows.

Assuming that solubility limits are not exceeded, resultant doses from the intrusion water-well scenario are essentially linearly and inversely proportional to the assumed volumetric flow rate through the repository, so they can be easily adjusted for any assumed rate. More important than the absolute dose values calculated, however, are the relative doses resulting from different degrees of engineered barrier efficacy. This important effect is not changed by volumetric flow assumptions, as long as the same flow exiting the repository is used throughout the analysis.

The important effects of an engineered barrier that may restrict this flow volume (water exclusion backfill, for instance) can still be measured in representative effect of release rate reduction or delay in leach initiation, as used in this analysis, without actually using a lower volumetric flow rate in the calculations. Relating these effects to any particular engineered barrier in a particular repository requires establishing the solubility limits or release mechanisms, or both, in the near-field repository.

3.2.5 Sorption Estimates for the Reference Granite Site

The effect of sorption is modeled explicitly. However, the sorption equilibrium coefficients (K_d) for any particular reference site were held constant as an overall characteristic of each site and were not varied parametrically. The relative effect of the various reference sites' sorption properties could be determined from the data in the appendices of the reference salt site analysis (Cloninger, Cole, and Washburn 1980) and the appendices of this report. K_d values for the reference granite site are listed in Table 5 for both oxic and anoxic conditions. The more conservative oxic conditions' K_d 's were chosen for this analysis in order to maximize any incentives for engineered barriers.

Applying of the sorption coefficients in the GETOUT model requires consideration of the specific ratio of geologic material to pore volume available for saturated ground-water flow. The GETOUT code was originally designed to model flow through porous media.

Transport through fractured systems is a relatively new field for which a considerable amount of research will be required before it is as well understood as the more familiar porous media. Two basic approaches to hydrology in fractured media have been put forth. One relies upon the observed regularity of many fracture systems to consider the rock mass as a network of interconnected discrete fractures. In this approach, each fracture must be separately identified. The other approach treats the rock mass as if it were a porous medium, in which the hydraulic characteristics of the fracture are averaged. The first approach is reasonably applied only in the near field, where the

TABLE 5. Reference Granite Site Equilibrium Sorption Coefficients
 K_d , ml/g^(a,b)

Element	Oxic Condition (0.2 ATM O_2)	Anoxic Condition (Negligible O_2)
H	0	0
Se	2.4*	10
Kr	0	0
Rb	200	200
Sr	5 to 20* (12)	5 to 20
Y	50	50
Zr	1000	1000
Tc	0*	10
Ru	20	20
Pd	500	500
Sn	100	200
Te	100	100
I	0	0
Xe	0	0
Cs	500*	500
Ba	20	20
Ce, Pr, Nd, Pm, Sm, Gd,		400
Tb, Eu	400	400
C	0	0
Ni	20	20
Co	100	100
Th	500*	500
Pa	300	300
U	6 to 10* (8)	50
Np	20	50
Pu	60	300
Am	500	500
Cm	500	500
Ra	80	80

- (a) Assumption: (1) Geologic medium is a hybrid of Swedish bed-rock and Nevada Test Site Climax stock "granite" quartz monzonite
(2) Water is similar to Swedish and LASL's analysis of Climax Stock
(3) Room temperature and 70°C have been measured for some isotopes. Values with * are measured, others are educated guess.
(4) K_d 's are reported for crushed granite rock; for fracture flow a surface area to mass correction must be made.

(b) KBS36, PNL-SA-6957

(c) () = value used where range given

detailed identification of fracture flowpaths is sometimes feasible. A mixed fracture-porous hybrid medium is approximated for the reference granite site analysis by the method of Allard, Kipatsi and Torstenfelt (1980) in KBS-98.

Normally, for porous flow, the K_d values are incorporated as "K-values" or retardation coefficients, K, according to the equation

$$K = 1 + \beta K_d$$

where β represents the ratio of geologic material available for sorption to the specific volume available for saturated ground-water flow. K is then the average ratio of the ground-water velocity divided by the nuclide transport velocity in the direction of ground-water flow. The pseudo-porous approximation for crack flow used here is based on the equation

$$K = 1 + K_a \cdot a \frac{(1 - \epsilon)}{\epsilon}$$

where:

$K_a = \frac{K_d}{A_2}$ = surface distribution coefficient

A_2 = conversion factor from experimental data, m^2/kg

ϵ = porosity of the rock

a = specific area of the fissure surfaces per unit volume of rock, m^{-1}

such that

$$\beta = \frac{a(1-\epsilon)}{A_2\epsilon}$$

Specific values used for the conversion from the measured and estimated equilibrium sorption coefficients to the pseudo-porous fracture flow retardation coefficients are

$$\epsilon = 2.0 \times 10^{-4}$$

$$a = 67 \text{ m}^2/\text{m}^3 \quad \text{Source: (INFCE 7/21 1979)}$$

and A_2 (Allard, Kipatsi, and Torstenfelt 1978):

<u>Element</u>	<u>A_2 (m^2/kg)</u>
Sr, Ra	2
Cs	3
Am + all others	10

Resultant retardation coefficients for the reference granite site are listed in Table 6.

TABLE 6. Reference Granite Site Retardation Coefficients, K (dimensionless)

<u>Element</u>	<u>K</u>
H	1.0E+0
Se	8.0E+1
Kr	1.0E+0
Rb	6.7E+3
Sr	2.0E+3
Zr	3.3E+4
Tc	1.0E+0
Ru	6.7E+2
Pd	1.7E+4
Sn	3.3E+3
Te	3.3E+3
I	1.0E+0
Xe	1.0E+0
Cs	5.6E+4
Ba	6.7E+2
Ce	1.3E+4
Pr	1.3E+4
Nd	1.3E+4

TABLE 6. (contd)

<u>Element</u>	<u>K</u>
Pm	1.3E+4
Sm	1.3E+4
Gd	1.3E+4
Tb	1.3E+4
Eu	1.3E+4
C	1.0E+0
Co	3.3E+3
Ni	6.7E+2
Th	1.7E+4
Pa	1.0E+4
U	2.7E+2
Np	6.7E+2
Pu	2.0E+3
Am	1.7E+4
Cm	1.7E+4
Ra	1.3E+4

3.3 DESCRIPTION OF A REFERENCE REPOSITORY IN BASALT

The Columbia Plateau basalts, a large expanse of flood basalts lying in southeastern Washington, western Idaho, and northern Oregon, are being investigated as a host rock for a waste repository. Although other areas of basalts exist, very few quantitative data are available. Therefore, the data reported in this document will be primarily for the Columbia Plateau basalts.

The values for a reference repository site in basalt were derived from the preliminary data available on the tholeiitic flood basalts of the Columbia Plateau within the Pasco Basin. Due to the preliminary nature of the data, these estimates should be viewed only as rough estimates in travel time that can be expected. These estimates were made from simple, one-dimensional considerations alone and should not be viewed as representative of flows through

the Columbia Basalts, since more data and more detailed analyses are required. The maximal and minimal travel times, however, represent conservative estimates.

Although the basalts consist of many flows with interbeds, some of the flows are quite dense and massive. Total depth of the Columbia Plateau basalts is largely unknown, since few wells have completely penetrated these flows. A well at Rattlesnake Mountain over 10,000 feet deep did not exit the basalt; however, a well near Ephrata encountered basement rock near 5,000 ft.

The proposed repository would be developed within one of the thick, dense basalt flows at a depth of 2,000 to 2,500 ft. Such basalts have good mechanical strength for mine stability. Significant mineral deposits are extremely rare, offering a low incentive for direct human intrusion.

Although the region has been tectonically inactive in recent history, it was produced by traumatic events, including the lava flows that produced the flood basalts. Several potential disadvantages result from the presence of water in the interbed material and in the brecciated basalt zones. These areas act as ground-water aquifers. Basalts, like granites, exhibit a low thermal conductivity, a factor that will have to be considered in repository design.

3.3.1 Generic Description of Basalt Geohydrology

All of the information in this section relates to the region centered in the Pasco Basin due to the paucity of data available on basalt in other regions. Site characterization for the Columbia Plateau basalts is continuing. The reference site description here is based on information available in the literature as of 1979. Basalt flows range in thickness from a few tens of centimeters to more than 100 m, averaging 30 to 40 m. The thick flows result from ponding in pre-basalt valleys. Layers of sediment, called interbeds, were deposited between the separate basalt flows. The beds of sediment and the highly-fractured interflow zones, because of their higher conductivity, conduct most of the water on a regional scale.

Although basalt flows are usually highly fractured, some are relatively contiguous. An analysis of a basalt core from Core Hole DH-5 located six

miles to the east of Sentinel Gap, Washington led to the following observations (Gephart et al. 1979):

- Eighty-three percent of the 1,454 fractures that were logged were filled with secondary minerals consisting primarily of montmorillonite clays; the remaining fractures were open.
- Unfilled fractures had apertures less than 0.01 cm wide; however, some open or partially-filled fractures were 0.5 to 1.0 cm wide.
- Primary cooling fractures were larger than 0.02 cm and occurred at a frequency less than 14 fractures/m.
- Secondary cooling fractures occur with the same frequency as above and had widths less than 0.02 m.
- Maximum fracture lengths were 0.9 m in the DH-5, while exposed basalt had maximum fracture length of 24 m as measured at Sentinel Gap. Therefore, even though the basalt is highly fractured, most of the fractures are filled and many may be dead-end cracks that do not conduct water at fracture velocities.

Many trade-offs may occur here, but a repository will be placed in a thick, relatively contiguous flow as close to a recharge (ground-water divide) boundary as possible. This will ensure good containment in the basalt and maximal travel times should a breach occur.

3.3.2 Permeability (Hydraulic Conductivity and Porosity)

The interbeds and interflow zones dominate the ground-water flow within the basalts. Therefore, flow is predominantly horizontal. Hydraulic conductivities within these zones for the Saddle Mountain Basalt are shown in Figure 4. Of the seventeen values reported for the interbeds, all but four fall between 1 and 100 ft/day regardless of the interbed tested (Gephart et al. 1979). Within the Wanapum Basalts, the hydraulic conductivities reported for the Priest Rapids member vary between 10^{-2} to 10^{+4} ft/day as shown in Figure 5 (Gephart et al. 1979).

Figure 6 (Gephart et al. 1979) shows the distribution of hydraulic conductivity for all basalt zones tested in the Grand Ronde containing zones of

FIGURE 4. Hydraulic Conductivity Values for Selected Zones Within the Saddle Mountains Basalt

low-density basalt or vesicular, vuggy, brecciated basalt. Values range between 10^2 and 10^{-5} ft/day with only two of the thirty-six reported values 1 ft/day or larger. The remaining values are grouped between 10^{-1} and 10^{-5} ft/day.

FIGURE 5. Hydraulic Conductivity Across Flow Contacts Within the Wanapum Basalts

FIGURE 6. Range of Hydraulic Conductivity Across Low-Density Zones Within the Grande Ronde Basalt

Values for porosities are reported for Grand Ronde vesicular basalt between 9.8 and 25.4% and a single fracture core sample of 2.1%. Basalt cores from the Bacon Siphon and Tunnel-Second Unit near Coulee City, Washington, had porosities ranging from 0.6 to 13%. The uppermost confined aquifer in the Lower Ringold sediments are estimated to have porosities from 5 to 20%.

3.3.3 Hydrologic Parameter Estimates and Transport Calculations

The layered stratigraphy of the flood basalts makes it difficult to determine paths of possible contaminant migration and travel times. The preliminary nature of the data is made evident by the different and sometimes conflicting conceptual models of the regional hydrology of the basalts (Gephart et al. 1979, LaSala et al. 1973, Deju and Fecht 1979). Areas or points of discharge to the environment from the confined aquifers within the basalts are the subject of much investigation. One conceptual model visualizes a horizontal movement in the interflow (regional) zones similar to Figure 7 (Gephart et al. 1979) and a slower widespread upward leakage through the basalt flows to the uppermost confined aquifer, then to the unconfined aquifer (local), and to the river. Total distance from the reference basalt repository site to a discharge point is estimated to be 20 miles. Using this concept and one-dimensional calculations, some travel times can be estimated.

3.3.3.1 Intermediate and Upper Confined Flow Zone

Using the potentiometric surface shown in Figure 8 (Gephart et al. 1979), a 20-mile flow path, and the range of hydrologic values for the uppermost confined system, travel times were calculated as follows:

- Distance 20 miles
- Hydraulic conductivity (ft/day) Low 0.1, avg 2, high 7
- Hydraulic gradient (ft/ft) Low 0.0005, avg 0.001, high 0.002
- Porosity Low 0.05, avg 0.1, high 0.2

$$\text{Travel time} = \frac{\text{distance} \times \text{porosity}}{\text{hydraulic conductivity} \times \text{hydraulic gradient}}$$

$$\text{Minimum travel time} = \frac{(20 \times 5280) \times 0.05}{7.0 \times 0.002} \times \frac{1 \text{ year}}{365 \text{ days}} = 1,000 \text{ years}$$

- LOCAL SYSTEM OF GROUND-WATER FLOW
- INTERMEDIATE SYSTEM OF GROUND-WATER FLOW
- REGIONAL SYSTEM OF GROUND-WATER FLOW

FIGURE 7. Theoretical Relationship Between Local, Intermediate, and Regional Ground-Water Flow Systems

$$\text{Average travel time} = \frac{(20 \times 5280) \times 0.10}{2 \times 0.001} \times \frac{1}{365} = 14,500 \text{ years}$$

$$\text{Maximum travel time} = \frac{(20 \times 5280) \times 0.20}{0.1 \times 0.0005} \times \frac{1}{365} = 1.16\text{E}6 \text{ years}$$

3.3.3.2 Deeper Regional Confined Flow Zone

To opt toward conservatism, hydrologic parameters for all the basalt sequences' more permeable interbeds and brecciated zones were used. The travel-time estimates are based on the 20-mile path length and the ranges of hydrologic parameters shown below:

- Distance 20 miles
- Hydraulic conductivity (ft/day) Low 0.01, avg 1, high 2
- Hydraulic gradient (ft/ft) Low 0.005, avg 0.001, high 0.002
- Porosity Low 0.01, avg 0.02, high 0.04

FIGURE 8. Potentiometric Map for and Inferred Flow Directions of Ground Water Within the Mabton Interbed Beneath the Hanford Site

$$\text{Minimum travel time} = \frac{(20 \times 5280) \times 0.01}{2 \times 0.002} \times \frac{1}{365} = 720 \text{ years}$$

$$\text{Average travel time} = \frac{(20 \times 5280) \times 0.02}{1 \times 0.001} \times \frac{1}{365} = 5760 \text{ years}$$

$$\text{Maximum travel time} = \frac{(20 \times 5280) \times 0.04}{0.01 \times 0.0005} \times \frac{1}{365} = 2.3\text{E}6 \text{ years}$$

3.3.4 Reference Basalt Repository Hydrologic Parameters

Travel time ranges from a minimum of 700 years to a maximum of 2.3 million years and a conservative, realistic estimate of approximately 17,000 years. Velocities range from a maximum of 0.28 ft/day through an average of around 3×10^{-2} ft/day to a minimum of $1.25\text{E}-4$ ft/day in the more permeable basalt interbeds and brecciated zones.

Reference site parameters:

Nominal Distance	20 miles
Hydraulic conductivity (ft/day)	1
Hydraulic gradient (ft/ft)	0.001
Porosity	0.02
Travel time range	700 years to 2.3E6 years
Velocity range	0.28 ft/day to $1.25\text{E}-4$ ft/day

All travel times must be treated as preliminary and conservative. Modeling studies of the Columbia Basin basalts are currently being conducted by PNL, Rockwell Hanford Operations, and the United States Geological Survey. These studies will yield a much better understanding of the system's hydrology, as well as significantly improved estimates of travel time. This analysis is not in any way an evaluation of the Columbia Basin basalts as a possible repository site.

The above values should be considered a reasonable range for the reference basalt repository, general transport scenario. Ground-water travel times as low as 500 years were used for the general scenario (Table 2) in order to compare results with the past reference salt site analysis. As with the reference granite site, a travel time as low as 50 years was used for the basalt intrusion water-well transport scenario.

Volumetric flow through the entire basalt repository was assumed to be the same as that used for the reference granite site, $3.14 \times 10^{-3} \text{ m}^3/\text{sec}$.

3.3.5 Sorption Estimates for the Reference Basalt Site

The K_d (equilibrium sorption constant) values used for the reference basalt site calculations are listed in Table 7 along with the resultant K -values (retardation coefficients) based on a $\beta = 10$. The treatment for the basalt site is based on the assumption that a particulate media exists, because conversion factors (A_2 and a) were not available for the pseudo-porous approximation of crack flow that was used for the reference granite site treatment.

TABLE 7. Reference Basalt Site K_d and K Values^(a,b)

Element	Equilibrium Sorption Coefficient K_d (ml/g) ^(c)	Retardation Coefficient K(dimensionless)
H	0	1.0
Se	15*	150
Kr	0	1.0
Rb	200	2000
Sr	100*	1000
Zr	200	2000
Tc	10*	100
Ru	50	500
Pd	200	2000
Sn	100	1000
Te	100	1000
I	5*	51
Xe	0	1.0
Cs	800*	8000
Ba	50	500
Ce, Pr, Nd, Gd, Tb, Eu, Pm, Sm, Ro	200 (200)	2000
C	0	1.0
Ni	50	500
Co	450*	4500
Th	200	2000
Pa	200	2000
U	10*	100
Np	5*	51
Pu	20 to 100* (60)	600
Am	6*	61
Ra	850*	8500

- (a) Assumptions:
- (1) Geologic medium is Umtanum Flow Columbia Plateau Basalt
 - (2) Ground water as reported in Ames 1978
 - (3) Only room temperature K_d values have been measured
 - (4) K_d 's are for crushed basalt. For fracture flow, a surface-area-to-mass correction must be made
 - (5) Values with * are measured, others are educated guesses
 - (6) $\beta = 10$

(b) Ames 1978 and Barney et al. 1978

(c) () = value used where range is given

4.0 RESULTS AND DISCUSSION

The methodology described in Section 2 was applied to the two reference sites defined in Section 3. The calculations were not done to the same degree of detail as in the analysis for the reference salt site (Cloninger, Cole, and Washburn 1980), but were performed in combinations of extreme values of the descriptive parameters (release rate, delay prior to leach initiation, ground-water velocity and pathlength). Limited intermediate values were used to better define trends in order to determine whether an analysis of other reference repository sites indicates any significant change in the general conclusions that were developed from the reference salt site study.

4.1 REFERENCE GRANITE SITE RESULTS

Results for the reference granite site are presented in two parts. The first part is a brief description of the overall results for the general scenario. The second part includes the more detailed results for the intrusion well scenario plus an explanation of the nuclide transport phenomena that led to the results observed in both the general case and the intrusion well case.

4.1.1 General Scenario

The relationship between release to the biosphere in terms of resultant dose and net release rate from the repository is shown in Figure 9 for four combinations of the other two descriptive parameters (ground-water travel time and leach initiation time) at their extreme values. Overall, the resultant dose commitment is fairly sensitive to release rate from the repository, although there is not a one-to-one relationship between repository release rate and biosphere entry rate and resultant dose. The effect ranges from approximately a three orders-of-magnitude reduction in dose via a four orders-of-magnitude reduction in repository release rate (four orders-of-magnitude increase in release duration) at the most conservative values of the ground-water travel time and leach initiation time (top line, Figure 9) to about two

FIGURE 9. Sensitivity of Consequences to Repository Release Rate for the General Scenario in Granite

orders-magnitude-dose reduction for four orders magnitude release rate reduction for the least conservative value of ground-water travel time, regardless of leach initiation time (lower line Figure 9).

This sensitivity to release rate from the repository is characteristic of non-sorbed, single nuclides (not daughters of decay chains) and, in this case, the dose is dominated by the long-lived, non-sorbed fission products ⁹⁹Tc, ¹⁴C, and ¹²⁹I until the release duration exceeds 10⁵ year (repository release rate falls below 10⁻⁵ per year), at which point the actinide chain daughters dominate. This single nuclide result would be exactly linear over the range of release duration from 100 to 10⁵ yr, except for the spreading effect of

hydrodynamic dispersion, which distributes the release band considerably, especially for fast release (10^{-4} year or less) and long ground-water travel time combinations. A more detailed explanation of these observations is provided in the presentation of the well scenario results.

Figure 10 shows the sensitivity of resultant dose to the delay prior to leach initiation at four combinations of the extreme values of the other two descriptive parameters, release rate and ground-water travel time. There isn't much to say about this result except that there is very little effect. Even for fast releases (1% per year) and short (500 yr) ground-water travel time, there is no benefit (maximal dose reduction) in delaying the initiation

FIGURE 10. Sensitivity of Consequences to Delay of Leach Initiation (Containment) for the General Scenario in Granite

of leaching by a period of time that could be reasonably ensured by engineered systems, 10^4 years or less. This is because the nuclides that dominate the dose, either themselves or their source parents, have half-lives far in excess of 10^4 years. The only exception is a slight reduction in resultant dose over 10^4 years in the top and third lines of Figure 10 (500 yr ground-water travel time) due to decay of ^{14}C (half life ~ 5730 yr). The greatest overall effect is a one-half order-of-magnitude reduction in dose via a six order-of-magnitude delay in time of leach initiation due to ^{14}C and ^{99}Tc decay over one million years.

The effect of ground-water travel time (the combined parameters of path-length and net ground-water velocity) on resultant dose for four combinations of extreme values of the other two descriptive parameters is shown in Figure 11. Overall, the effect of ground-water travel time is less than that of release rate but considerably greater than that of delay prior to leach initiation. The greatest effect is an approximately 1.5 order-of-magnitude reduction in dose via a 3.5 order-of-magnitude increase in ground-water travel time.

As might be expected, this maximum effect is observed at the most conservative constant values of the other two descriptive parameters, shown in the top line of Figure 11. In this case, there is an immediate, fast release from the repository resulting in a high, narrow band of contamination in the ground-water plume. Thus, dispersion has some effect in spreading the narrow band more and more with increasing ground-water travel time. Furthermore, as the transport time increases, the decay of ^{14}C and then ^{99}Tc leads to further dose reduction. In fact, the only difference between the top line and second line in Figure 11 is that the second line represents delaying initiation of leaching 10^6 yr such that essentially all of the ^{14}C and most of the ^{99}Tc have decayed away before transport begins and only ^{129}I (half life ~ 16 million yr) remains to dominate the dose. Thus, the top line shows the combined effect of decay during transport plus dispersion, while the second line shows the effect of dispersion only, since the ^{129}I does not decay significantly during the million-year transport time to the biosphere.

FIGURE 11. Sensitivity of Consequences to Ground-Water Travel Time to Biosphere for the General Scenario in Granite

The lower two lines in Figure 11 represent the effect of ground-water travel time when the release rate is very low, 10^{-6} fraction per year (10^6 yr release duration). This results in a broad, low-level band of contamination in the plume exiting the repository, which is not notably affected by hydrodynamic dispersion, but can be greatly affected by the spreading due to differential sorption of actinide chain members. The uppermost of the lower two lines of Figure 11 is the result for leach initiation immediately after repository closure, but at a very low rate. The early part of the line, up to about a 10^4 -yr ground-water travel time is dominated by the actinide chain

$^{241}\text{Am} \rightarrow ^{237}\text{Np} \rightarrow$ chain daughters (^{233}U , ^{229}Th , ^{225}Ra) with a slight reconcentration effect evident (this is more obvious in the well scenario results following this section). Beyond a 10^5 -yr travel time, the dose is controlled mainly by ^{226}Ra from the ^{238}U parent and is generally insensitive to release rate or delay of leach initiation as well as ground-water travel time in this range.

The lower line of Figure 11 represents the result when the start of leaching is delayed one million years and the repository release rate is 10^{-6} per year. For this case, the resultant dose is dominated by ^{226}Ra from ^{238}U over the entire range of ground-water travel time and is, for all practical purposes, insensitive to any change in release rate or ground-water travel time in this range but is a function of relative sorption effects and half-lives among the chain members.

Calculating absolute dose consequence estimates is not the intent of this work, but this discussion would not be complete without some estimate of the result for expected conditions. Even allowing for the conservative methodology and models (see "Perspective" section of Cloninger, Cole, and Washburn 1980), and allowing that even in a highly disrupted, deep geology (itself an incredible thought for deep granite systems), the natural limitations of volumetric flow restrictions, transport distances, and geochemical interactions will likely by themselves limit the bulk release rate to 10^{-4} per year or less and provide a ground-water travel time on the order of 5000 yr or more. Given even these conservative parameters, the maximum individual would receive an incremental lifetime critical organ dose (cumulative) of one rem or less and a lifetime average annual total body dose of nominally 10 mrem per year. The average individual would receive substantially less. Furthermore, although it has not been rigorously demonstrated, it appears that under the most conservative conditions, the transport analysis methodology used in this work overestimates resultant consequences by at least an order of magnitude. Thus, these calculated, absolute dose estimates are likely quite a bit higher than what can actually occur. The methodology is particularly conservative for the analysis of the intrusion well scenario, because the 3-dimensional dispersion

effects (which can be very important for short transport distances) are not considered and may lead to dose estimates three or more orders of magnitude too high.

4.1.2 Intrusion Well Scenario

The calculations for the reference granite site intrusion well case were done in somewhat more detail, especially regarding the effect of ground-water transport time from the repository to the biosphere. A more detailed explanation of the observed results is thus possible. Most of the explanation applies equally to the results for the general case, except where noted in the following discussion.

Figure 12 shows the general results for the effect of release rate from the repository for extreme combinations of the other two descriptive parameters. The shapes of the graphs for the well case are similar to those for the general case in Figure 9. However, the overall magnitude of calculated resultant dose is higher and there is a slightly higher (and expected) sensitivity to release rate for the very short ground-water travel time (from repository to well intake) of 50 yr (second line from the top, Figure 12).

Figure 13 shows the contribution by isotope for the ($t=50$, $r=1$) graph of Figure 12. The consequences from the non-sorbed single nuclides (as opposed to primarily chain daughters in inventory) ^{129}I , ^{14}C and ^{99}Tc are essentially inversely linear with repository release duration (linear with repository release rate) over the entire range of release duration used in the analysis, since even at the shortest release duration of 100 years (release rate of 1% per year), the release band extends twice the time (and space) of the ground-water travel time (which in this case is the same as the nuclide transport time) and extends several more multiples of the dispersion length in time and space. If these nuclides were sorbed on the geologic media sufficiently that their transport time was reduced below that of the time expression of the dispersion length, then the resultant release band would be narrower than the sorption-modified dispersion length, and an effective lowering of the contaminant peak would be accomplished, acting like a lowered release rate as viewed at the entry to the biosphere. This is observed for the sorbed nuclide, ^{234}U ,

FIGURE 12. Sensitivity of Consequences to Repository Release Rate for the Intrusion Well Scenario in Granite

in Figure 13 where dispersion effects magnified by sorption act like a 10^3 -yr release duration. Only when the repository release duration exceeds 10^3 yr (release rate falls below 10^{-3} per yr) is there significant effect. Dispersion effects over very long ground-water travel times can also nonlinearize the result for non-sorbed nuclides, as is observed in the ^{129}I graph of Figure 15, which will be discussed further below.

FIGURE 13. Result by Significant Isotope for $t=50$ yr Line of Figure 12

An additional factor acting on the result for ^{234}U and ^{237}Np in Figure 13 is that they act like actinide chain daughters for short repository release durations (fast release). As release duration increases and release rate decreases, most of the short-lived parents (^{238}Pu and ^{241}Am , respectively, in this case) have decayed to the daughter before a significant fraction of parent or daughter has been released from the waste package, or whatever containment boundary is used. Thus, the resultant primary release from the

repository is that of the daughter and not the parent, so it acts like a single nuclide release and the resultant release to the biosphere is controlled more by release rate from the repository than by the subsequent transport phenomena enroute. In the case of Figure 13, this transition from chain daughter behavior to primary single nuclide behavior occurs at a release duration of about 10^3 yr for ^{234}U from ^{238}Pu (half-life ~ 88 yr), and more gradually but completely at 10^4 yr for ^{237}Np from ^{241}Am (half-life ~ 433 yr).

Different parent half-lives and relative sorption differences between parent and daughter between the two chains account for the difference in transition to single nuclide behavior. In the case of ^{234}U , ^{238}Pu is the early source of most of the ^{234}U in the repository. Over a 1000-yr release, over half of the ^{238}Pu has decayed to ^{234}U in the first 100 years, at which point 90% of the combined ^{238}Pu and ^{234}U is still in the containment package or zone. At the end of 200 years, about 80% of the ^{238}Pu has decayed to ^{234}U , and 80% of the combined inventory (64% of the ^{234}U from ^{238}Pu that will be released) is still contained. This material will be released over the next 800 yr. Thus, the character of the ^{234}U release from the waste form is more ^{234}U alone than $^{238}\text{Pu} \rightarrow ^{234}\text{U}$. At a release duration of 10^4 yr, the nature of the release is, for all practical purposes, that of ^{234}U alone. The same effect exists for longer ground-water travel times than that of Figure 13 (50 yr), but becomes overshadowed by the transport dispersion effects on the long-term source of ^{234}U , ^{238}U . This is because the uranium migrates at a net rate 270 times slower than the ground water (K-value, Table 6) in the reference granite site. As ground-water travel times get long (transport distance gets long or velocity gets slow, or both), the transport time of uranium gets very long with respect to the half-lives of the ^{238}Pu and ^{234}U , such that the only ^{234}U that exits the geosphere is that created from the decay of the very long-lived ^{238}U very near the outlet to the biosphere. The release of ^{234}U to the biosphere is thus not overly sensitive to release rate from the repository (Figure 15). This result is typical of chain migration (with one modification in the case of $^{238}\text{U} \rightarrow ^{234}\text{U}$), and will be discussed further below.

The same phenomena, at a different rate, control the ^{237}Np result in Figure 13 (^{241}Am is the ultimate source of $\sim 75\%$ of total ^{237}Np in the reference

inventory, except that, unlike the ^{234}U , ^{237}Np has no significant longer-lived parent. As a result, at very long ground-water travel times, ^{237}Np decays away before reaching the biosphere entry point. For this reason, ^{237}Np is absent from Figure 15.

The release to the biosphere of subsequent members of the actinide chains $^{238}\text{Pu} \rightarrow ^{234}\text{U}$, $^{238}\text{U} \rightarrow ^{234}\text{U}$ and $^{241}\text{Am} \rightarrow ^{237}\text{Np}$, namely $^{234}\text{U} \rightarrow ^{226}\text{Ra}$ and its daughters and $^{237}\text{Np} \rightarrow ^{233}\text{U}$, ^{229}Th and ^{225}Ra behaves quite differently in the sensitivity to repository release rate as seen in the bottom two lines of Figure 13. The parent nuclides, ^{238}U , ^{234}U and ^{237}Np , all have long half-lives relative to release durations of up to a million yr, such that the total inventory of parent nuclides is not reduced greatly over the release period, and the daughter nuclides that are created from the parents' decay are mostly created during transport to the biosphere, especially at longer ground-water travel times and large retardation coefficients (effective K).

The result of this behavior can be seen as a sequentially reduced sensitivity to release duration for the ^{226}Ra + daughters and ^{237}Np daughters graphs in Figures 13 (ground-water travel time, $t = 50$ yr), 14 ($t = 500$ yr), and 15 ($t = 10^6$ yr). In Figure 13, with a relatively short ground water travel time, the daughters that were created while still in the containment package at longer release durations begin to act more like single nuclides as a greater fraction of their ultimate (equilibrium) inventory is released as daughter and not parent, thus causing the initial bending of the lower two lines in Figure 13.

However, the greatest phenomenon affecting the sensitivity of the actinide daughters behavior to release rate is the relative transport retardation ("sorption") among chain members, which tends to spread them in time and space much as a greatly reduced initial release rate would. Only when the release rate from the repository is so low that its spreading effect exceeds that of the sorption differences is any effect observed. This release-rate effect is seen to occur in Figure 13 at a release duration of about 10^5 yr for the ^{226}Ra + daughter and ^{237}Np daughters results. As the ground-water travel time is increased, the transport phenomena, particularly differential sorption, become

more important such that, finally, there is almost no sensitivity to release rate at the repository. This is seen sequentially in the actinide chain results in Figures 13 through 15. In Figure 15, the net sorption effects for the ^{237}Np and daughters provide enough delay that these nuclides decay before reaching the biosphere.

It is not possible within the scope of this document to describe the entire theoretical basis for these results. An introduction to that theory is

FIGURE 14. Result by Significant Isotope for $t = 500$ yr Line of Figure 12

FIGURE 15. Result by Significant Isotope for $t = 10^6$ yr Line of Figure 12

contained in Appendix D of Cloninger, Cole, and Washburn 1980, which goes somewhat beyond the one-dimensional results presented here.

Another effect that is apparent but not dominant in Figures 13 and 14 is a degree of reconcentration phenomena that, under certain pathlengths, ground-water velocities, relative half-lives, and sorption effects among chain members, can cause local secular disequilibrium in the other direction and

actually result in a much higher daughter concentration (and thereby release rate to the biosphere) than would be predicted by secular equilibrium and rate of parent release only. This phenomenon is nonlinear and sometimes inverse with release rate from the repository but is mitigated somewhat by one-dimensional hydrodynamic dispersion (accounted for in these results) and can be mitigated entirely by three-dimensional dispersion effects due to the character of the regional flow field (not accounted for in these results). An introduction to the theory and some analysis of maximum effect of this phenomenon are in Burkholder and Cloninger 1977, Rodgers 1978, and Giuffre and Ross 1978. The effect of the phenomenon can be seen in Figure 13 as a slight increase in dose consequence (due to increased rate of release to the biosphere) with decreasing repository release rate (increasing release duration) from a release duration of 100 yr to a peak at about 10^4 yr for both the ^{226}Ra + daughters and ^{237}Np daughters. This reconcentration effect is apparently what causes the dose consequence in Figure 12 at the 10^6 -yr release duration and ground-water travel time, $t = 500$ yr (upper line Figure 12) to be higher than the resultant dose for the same release duration at $t = 50$ yr (second line, Figure 12), since the phenomena can be inverse with transport time also. This will be addressed somewhat further in a later discussion regarding the effect of ground-water travel time.

Figures 14 and 15 show the sensitivity by isotope of dose consequences to repository release rate for ground-water travel times of 500 yr and 10^6 yr, respectively, corresponding to the uppermost and lowest lines of Figure 12. Many of the effects evident in Figures 14 and 15 have already been discussed relative to Figure 13, but there are a few remaining points of importance to understanding the observed results.

The results for the non-sorbed single nuclides-- ^{14}C , ^{99}Tc , and ^{129}I --are virtually the same for Figures 14 and 13 throughout the range of release duration analyzed, since the only two effects that can reduce their release rate to the biosphere other than reduced release rate from the repository are hydrodynamic dispersion (in the one-dimensional model) and radioactive decay. Neither effect is great enough over a 500-yr ground-water travel time to have

significant impact on the release rate to the biosphere and proportional consequences, because these nuclides travel at the ground-water velocity.

In Figure 14, the effect of reconcentration for the 500-yr ground-water travel time raises the resultant consequences from the ^{237}Np daughters over the entire range of release durations such that the overall consequence result at large release durations is higher at $t = 500$ than at $t = 50$ (Figure 12), as previously mentioned.

The transitions from release-rate-insensitive, chain-like behavior to release-rate-sensitive, single-nuclide behavior for the ^{234}U and ^{237}Np lines of Figure 14 occur at a somewhat higher release duration than in Figure 13, and the resultant dose consequences for the shorter release durations (faster release rates) in Figure 14 begin at somewhat lower values than in Figure 13. This is due to greater dispersion effects at the longer ground-water travel time represented in Figure 14, coupled with the same retardation coefficient as in Figure 13 (and held constant for each isotope for the entire granite site analysis). The combined dispersion and retardation, as previously mentioned, act like a lowered release rate in effect.

Figure 15 shows the result by isotope for the lower line of Figure 12. The ground-water travel time here is 10^6 yr, an extreme value, but not out of the reasonable range for granite systems. This very long ground-water travel time eliminates any consequence from ^{14}C , since even though it is transported at the ground water velocity, its half-life is small compared to the transit time, and it decays entirely before it can enter the biosphere. Net sorption effects coupled with the long ground-water travel time also eliminate the entire $^{241}\text{Am} + ^{237}\text{Np} + \text{daughters}$ chain, since all of the radiologically significant daughters decay before they can enter the biosphere. The remaining nuclides that endure the journey to the biosphere are either themselves long-lived or are from long-lived parents.

The upper line in Figure 15 shows the result for ^{129}I sensitivity to repository release duration. The moderate dispersion effect is due to the long transport time, which acts like a reduced release rate of about 5×10^{-4} per year (release duration $\sim 2 \times 10^3$ yr) as viewed from the biosphere entry

point. When the repository release duration exceeds 2×10^3 yr, the sensitivity is again essentially linear with release rate. Radioactive decay is negligible for ^{129}I over the 10^6 -yr transport time.

While the behavior of ^{99}Tc in Figure 15 is very similar to iodine, the magnitude of the ^{99}Tc dose is overall much less because of ^{99}Tc 's 10^6 -yr travel time. This travel time represents a significant fraction of the ^{99}Tc half-life.

The sensitivity of the ^{226}Ra + daughters dose consequence to release rate from the repository for the 10^6 -yr ground-water transport time of Figure 15 is virtually nil over the range investigated. This is because, for this case, the only ^{226}Ra that ever reaches the biosphere is that which came from original ^{238}U via a complex chain. Dispersion and sorption effects totally control the release to the biosphere.

Somewhat greater--though slight--sensitivity exists for the ^{234}U results of Figure 15. The only ^{234}U that exits to the biosphere in this case is that which was created from the original ^{238}U . Geochemically, the two isotopes of uranium act identically (except for slight solubility differences due to α -recoil energies upon decay and creation in the "sorbed" state, which are not accounted for here), and their combined transport together is effectively that of a single nuclide. The release of ^{234}U to the biosphere in this case is controlled by sorption-enhanced dispersion effects during transport, and the resultant sensitivity to release rate from the repository is essentially negligible even when it exceeds 10^{-5} per year.

The same sensitivity trends were apparent in the earlier salt site analysis (Cloninger, Cole, and Washburn 1980) except that, in the reference salt site, the net actinide chain sorption was less substantial which, coupled with higher overall ground-water velocities than the reference granite system, allowed the actinide chains (especially ^{226}Ra daughter) to dominate the dose even when the release rate of long-lived fission products was as high as 10^{-3} per year. On the other hand, the reference granite site properties are such that the non-sorbed, long-lived fission products had the same behavior as in the reference salt site, but due to greater overall sorption and relative

intra-chain sorption (thus greater spreading) the actinide chains were held to orders-of-magnitude-lower release rates to the biosphere, regardless of release rate from the repository. Thus, the long-lived fission products dominate the dose over nearly the entire range of release rates analyzed and are the source of the higher overall sensitivity to release rate for the granite site as compared to the salt site. There may be some incentive to eliminate ^{129}I , ^{14}C , and possibly ^{99}Tc (if truly non-sorbed) from the waste and dispose of it somewhere other than a geologic repository.

Figure 16 shows the sensitivity of dose consequence to delaying initiation of leaching. The result again indicates that maximum release rates

FIGURE 16. Sensitivity of Consequences to Delay of Leach Initiation (Containment) for the Intrusion Well Scenario in Granite

to the biosphere and the resultant doses are not affected by any delay in leach expected to be provided by engineered containment other than proper site selection. Only after the delay in leach initiation exceeds 10^5 yr is there any resultant reduction in maximum release rate. While any delay in the start of leaching results in nominally the same delay in time of occurrence of maximum dose (all other considerations being unchanged with time), merely delaying a dose so that it will be received by a future generation is not considered to be of any net positive value in this analysis.

Even if the ground-water pathlength and velocity parameters are taken to the extreme values that were used in the reference salt site analysis, resulting in a ground-water travel time of only 14 yr, there still would be no incentive to provide long-term containment to reduce the potential dose from ^{90}Sr and ^{137}Cs , because these elements are strongly sorbed on the reference granite media and decay before they can move but a few tens of centimeters down the aquifer, even at maximum ground-water velocity. Thus, there appears to be no incentive at all for providing an engineered delay function, or engineered containment, to delay the initiation of ground-water contact with, and leaching from, the waste form in the granite system.

Figure 17 shows the sensitivity of dose consequences to ground-water travel time from the repository to the biosphere at extreme value combinations of the other two performance parameters. The top two lines of Figure 17 represent, respectively, immediate and delayed fast release (1% per year) and are dominated by non-sorbed fission product doses. The bottom two lines represent immediate and delayed slow release (10^{-6} fraction per year) and are dominated by an actinide chain daughter dose due to the low release rate, as previously discussed. The relative sensitivity between these two general cases is shown in Figures 18 and 19.

Figure 18 contains the breakdown of dose contribution by isotope for the top line ($t=1$ yr, $\lambda=100$ yr) of Figure 17. The non-sorbed fission products ^{99}Tc , ^{14}C , and ^{129}I dominate the result. Ground-water travel times exceeding 10^3 yr are required before any consequence reduction due to radioactive decay of ^{14}C (top line Figure 18) is observed. The travel time must exceed 10^4

FIGURE 17. Sensitivity of Consequences to Ground-Water Travel Time to Biosphere for the Intrusion Well Scenario in Granite

years before significant decay of ^{99}Tc occurs. Dispersion effects begin to reduce the consequence at a ground-water travel time of about 10^3 yr, as seen in the ^{129}I result of Figure 18 (3rd line from top), which is not affected notably by radioactive decay over the 10^6 -yr transport time.

The intermediate behavior of the ^{234}U and ^{237}Np in Figure 18 is typical of daughter isotopes with short half-lived parents up to a ground-water travel

FIGURE 18. Result by Significant Isotope for the $t = 1$ yr, $l = 100$ yr
Line of Figure 17

time of about 3×10^3 years, at which point the ^{234}U changes to behavior typical of a well-sorbed, single nuclide and the ^{237}Np continues its same behavior. This is because at longer ground-water travel times, the ^{234}U that eventually exits to the biosphere is no longer that from the short-lived ^{238}Pu , but is from decay equilibrium with the longer-lived ^{238}U parent, which transports nominally at the same rate as ^{234}U , thus acting like the release of a single nuclide inventory of ^{234}U .

FIGURE 19. Result by Significant Isotope for the $t = 1$ yr, $\lambda = 10^6$ yr
Line of Figure 17

On the other hand, since it has no alternate long-lived parent, the ^{237}Np continues its behavior typical of a two-member chain with short-lived parent (^{241}Am), longer-lived daughter, and significant sorption difference between parent and daughter, such that any increase in ground-water travel time leads to a greater sorption-enhanced spreading between parent and daughter as the daughter is being formed via radioactive decay, resulting in significant reduction in release rate of the daughter to the biosphere. After the ground-

water travel time exceeds about 4000 yr, the behavior of the ^{237}Np is that of a well-sorbed single nuclide.

The behavior of the ^{226}Ra + daughters in Figure 18 is relatively insensitive to ground-water travel time due to the complexity of the decay chains contributing to the total ^{226}Ra release up to a ground-water travel time of about 10^4 years (these contributing chains mainly include the original inventory of ^{238}Pu , ^{238}U , ^{234}U , and ^{230}Th), after which point it is mainly a function of ^{226}Ra from only the long-lived parent, ^{238}U , and is somewhat more sensitive to ground-water travel time due to magnification of sorption differences and their spreading effects at longer ground-water travel times.

The result for the ^{237}Np daughters somewhat tracks the result for ^{237}Np since all members of the chain, including the ^{237}Np parent, are well-sorbed and have half-lives that are small compared to their respective and collective transport times at longer ground-water travel times.

Figure 19 shows the result by significant isotope for the third line of Figure 17 ($t=1$ yr, $\lambda = 10^6$ yr). As mentioned in the discussion of Figure 17, the entire result in this case is dominated by the two major actinide chain daughters since the biosphere release rate of and resultant dose from the non-sorbed fission products are now held at a lower value due to the low release rate from the repository. The reconcentration effect with increasing ground-water travel time for the $^{241}\text{Am} \rightarrow ^{237}\text{Np} \rightarrow$ daughters chain is seen most clearly now in the top line of Figure 19, peaking at a ground-water travel time of about 10^3 years and then converging with the ^{237}Np trend (bottom line, Figure 19) as radioactive decay and other dispersion effects become important at long ground-water travel times.

The broad release band of 10^6 yr reduces the sensitivity to ground-water travel time of the actinide chains contributing to the ^{226}Ra + daughters result even at travel times of up to 10^6 yr, as indicated by the second line in Figure 19, and totally eliminates any sensitivity for the non-sorbed ^{129}I result, because the initial dispersion due to the reduced release rate is much greater than that from hydrodynamic dispersion even at the maximum ground-water travel time.

The result for ^{234}U is now essentially parallel to the result for ^{226}Ra , because both isotopes are basically the result of ^{238}U decay to daughters both prior to leaching from the waste form (at short ground-water travel times) and while being transported to the biosphere.

Behavior of both ^{14}C and ^{99}Tc in Figure 19 is dominated primarily by radioactive decay of the isotopes prior to leaching from the waste form (at short ground-water travel times) due to the long release duration (low release rate) plus decay during transport at longer travel times. The absolute magnitude of their dose contribution is determined by the low release rate from the repository as previously discussed.

4.2 REFERENCE BASALT SITE RESULTS

Results for the reference basalt site are presented in terms of the general scenario case and the intrusion well case. The transport phenomena that affect the overall results are similar to those detailed in the previous discussion on the reference granite site well scenario, although to different relative degrees, and won't be presented in such detail for the reference basalt results. One significant difference between the reference granite and reference basalt sites is that ^{99}Tc and ^{129}I are moderately retarded by the reference basalt media (K-values from Table 7 are 51 for I and 100 for Tc). This has considerable effect on the sensitivity of the results to ground-water travel time, as will be discussed later.

4.2.1 General Scenario

Figure 20 shows the sensitivity of resultant dose to repository release duration (release rate⁻¹) for the reference basalt site. The upper two lines in Figure 20 represent the result for early and late (10^6 yr) leach initiation at a ground-water travel time of only 500 yr, the minimum for the general case. Both of these lines show a linearity with release rate down to a release rate of about 10^{-5} per yr (release duration of 10^5 yr), at which point the consequences are dominated by nuclides from the actinide chains which show less sensitivity to release rate than the single fission product nuclides which dominate at higher release rates. The explanation is identical to that

FIGURE 20. Sensitivity of Consequences to Repository Release Rate for the General Scenario in Basalt

for the reference granite site and involves the same isotopes, though to different degrees under different conditions.

The lower line of Figure 20 represents the result for the maximum ground-water travel time for the reference basalt site (2×10^6 yr) with leach initiation at either 1 or 10^6 yr. The entire result is dominated by ^{226}Ra + daughters from the original ^{238}U parent. The release of ^{226}Ra to the biosphere is controlled mostly by transport phenomena after the ^{238}U leaves the repository and is, therefore, generally insensitive to release rate from the waste package or repository.

Figure 21 shows the result of delaying the initiation of leaching for the reference basalt site. There is virtually no benefit from delay in this case.

FIGURE 21. Sensitivity of Consequences to Delay of Leach Initiation (Containment) for the General Scenario in Basalt

Figure 22 shows the resultant consequence sensitivity to ground-water travel time in basalt. The top two lines of Figure 22 represent a fast release rate (10^{-2} per year) beginning early (top line) and late (second line).

At a 500-yr ground-water travel time, the upper line is dominated by ^{14}C , which decays away significantly during transport at a ground-water travel time of 5×10^4 yr or more, after which point the result is dominated by ^{226}Ra from the ^{238}U parent. The second line is dominated by dose from the ^{237}Np daughters, ^{233}U , ^{229}Th and ^{225}Ra , at short ground-water travel times and again by ^{226}Ra from ^{238}U at the longer travel times. This increased sensitivity to

FIGURE 22. Sensitivity of Consequences to Ground-Water Travel Time to Biosphere for the General Scenario in Basalt

ground-water travel time, as compared to the reference granite site, is due to the moderate retardation of Tc and I on the reference basalt media versus no retardation of either on the reference granite media. This retardation both enhances hydrodynamic dispersion effects and delays the release of the isotopes to the biosphere to such a degree that even the very long-lived ^{129}I is not released to the biosphere for over six half-lives at the 2×10^6 ground-water travel time.

The difference in relative sensitivity to ground-water travel time between the reference granite and basalt sites due to differences in retardation of Tc and I can be visualized by comparing the top two lines of Figures 11 and 22 for the general case and Figures 17 and 25 for the intrusion well case. The lower two lines of Figure 22 are the result for slow release from the repository, 10^{-6} per year (release duration, $l = 10^6$ yr) with early

and late leach initiation, respectively. Both these lines are generally dominated by ^{226}Ra and its daughter isotope, ^{210}Pb . The sensitivity is not great, since the initial spreading due to low release rate is large, even compared to the spreading effects of the chain transport phenomena mentioned earlier.

4.2.2 Intrusion Well Scenario

Figure 23 shows the sensitivity of consequences to repository release rate for the intrusion well case in basalt. The curves have basically the

FIGURE 23. Sensitivity of Consequences to Repository Release Rate for the Intrusion Well Scenario in Basalt

same shape as those for the general case, although with some differences and, of course, have a higher overall magnitude of resultant dose.

Figure 24 shows the result of delaying initiation of leaching. Under some conditions, as in the top two lines of Figure 24, there is some benefit in providing containment for 10^3 yr and somewhat more benefit if delay is extended to 10^4 yr.

The curves of Figure 25 show the sensitivity of consequences to ground-water travel time for the intrusion well case in basalt. There is a similarity in shape to those for the general case, although the absolute potential dose is higher.

FIGURE 24. Sensitivity of Consequences to Delay of Leach Initiation (Containment) for the Intrusion Well Scenario in Basalt

FIGURE 25. Sensitivity of Consequences to Ground-Water Travel Time to Biosphere for the Intrusion Well Scenario in Basalt

One difference between the reference basalt site results and the others is that ^{241}Am and ^{243}Am dominate the dose consequences for very extreme cases of the intrusion well scenario (ground-water travel time = 50 yr, early and fast release). This is mainly due to the different sorption (retardation) capabilities of the various reference geologic media.

The reference basalt and granite sites also differ in that the basalt retards T_c and I better, making the release rate from the repository a factor in how sensitive the dose is to ground-water travel time. This relationship

is not observed in the reference granite case. Again, this can be seen by comparing first the two upper versus two lower lines of Figure 22 for basalt, then the two upper versus two lower lines of Figure 11 for granite. In both cases, the magnitude of dose is higher at the higher release rates (upper lines) than at the lower release rates (lower lines), but only in the case of the basalt site is the sensitivity to ground-water travel time greater at the higher release rates. At the lower release rates, the sensitivity to ground-water travel time is about the same for both granite and basalt since in these cases the actinide daughters dominate the dose. Although there are differences between granite and basalt, the actinides are strongly retarded in both media (Tables 6 and 17.)

4.4 REFERENCE SALT VERSUS NON-SALT SITES

The reference salt site analysis (Cloninger, Cole, and Washburn 1980) and the non-salt site analysis reported here differ in two main respects. First, the relative calculated dose consequences from the intrusion well case in the salt site were generally lower than those from like or similar cases in the non-salt site analysis (the entire scenario is much less likely for the salt site as well). This is because the radioactivity-contaminated saline plume exiting the salt repository was assumed to undergo sufficient salt dilution to allow its unrestricted use in agriculture. The means by which this dilution is attained was not specified, but the only obvious means is by mixing with the fresh aquifer. (The question of how this can occur at very short distances from the salt repository indicates considerably low probability for extreme intrusion well scenarios in salt media.) The ground water exiting the non-salt repositories was assumed to be totally potable, except for the radioactive isotope content.

Ground-water volumetric flow through the repository was estimated (see Methodology section) and held constant for all four reference sites. Since the calculated dose results for the well scenario are nominally proportional to isotope concentration in the ground water at the point of borehole penetration, the large dilution assumed for the salt site results in the overall lower dose in the well case.

The second apparent difference between the reference salt and non-salt site results is that the effective bulk retardation of the actinide chains was generally less in the salt case than in the non-salt, resulting in a higher significance of the actinides to the overall potential dose consequences in the salt case. This can be seen by comparing Figures 26 (repeated here from Cloninger, Cole, and Washburn 1980) and 27. These figures show the general sensitivity of consequences for the reference salt and non-salt cases, respectively, to release rate (release duration⁻¹) from the repository.

FIGURE 26. General Effect of Repository Release Rate on Resultant Consequences for the Reference Salt Site

The upper line of Figure 26 represents such an extreme scenario--a ground-water travel time of only 14 years from a salt site--that this scenario, given the very conservative limitations of the methodology, is mainly of academic interest. When the lower two lines of Figure 26 are compared with the two lines of Figure 27, the relative significance of the actinide chain daughters is apparent.

FIGURE 27. General Effect of Repository Release Rate on Resultant Consequences for the Reference Non-Salt Sites

5.0 PERSPECTIVE

From a hydrologic transport standpoint, the assumptions used here tend to ignore (due to the mathematical difficulty of simulation or the unavailability of pertinent data) limiting phenomena that, if considered, would both lower the calculated nuclide release rates to the biosphere (and thereby the resultant dose) and reduce the calculated sensitivity of that release to the performance of engineered barriers in the repository. Thus, the treatment here is quite conservative.

The absolute dose estimates and dose sensitivity to performance parameters, especially release rate from the repository, that were calculated for extreme cases of the intrusion well scenario are likely to be so conservative as to be nearly academic in value. The ultraconservatism is due to the nature of our limited application of the geologic transport model in only one physical dimension. Application of the model along typically distributed source and point discharge flow lines for a hydrologic system of appropriate scale for the reference repository is possible for these cases, but is beyond the scope of this analysis and is not very valuable in a reference analysis. A brief introduction to the possible significance of these two-dimensional effects is presented elsewhere (Appendix D of Cloninger, Cole, and Washburn 1980).

Further conservatism occurs with the application of the biosphere transport model to determine estimated dose for high nuclide concentrations. The dose transfer via food chain reconcentration was considered linear with ground-water concentration at levels far exceeding the intended useful range of the model, ignoring any biological saturation limitations that exist throughout the natural system. This may be particularly significant for the calculated ^{129}I doses, which were dominated by the thyroid receiver, probably well beyond the capacity of the thyroid to retain iodine. Definition of such biological limits was far beyond our scope; thus, the linear extrapolation is used.

Aside from dispersion effects enhanced by sorption, the release rate of single nuclides to the biosphere is generally proportional to their release rate from the repository and, if they are not strongly sorbed or otherwise retarded, the sensitivity is great. Thus, for fast releases, nearly without regard to delay in leach initiation or ground-water travel time, the poorly-sorbed, long-lived fission products dominate the dose consequences. On the other hand, for isotopes created via decay of a parent largely after their release from the repository, the sensitivity to the release rate of the parent is not great, especially if the degree of geochemical retardation is quite different between parent and daughter isotope.

In Figure 26, the nearly linear sensitivity to release rate (inverse linearity with release duration) of the single fission products dominates the result down to a release rate of only 10^{-3} fraction per year (constant-rate release duration of only 10^3 yr), at which point the actinide chains dominate, finally becoming sensitive to release rate when it falls below 10^{-5} per year (release duration 10^5 yr).

The same behavior exists for the non-salt sites, but the sensitivity of the single nuclides, especially the long-lived, non-sorbed fission products, dominates down to a release rate of nearly 10^{-5} per yr (release duration of nearly 10^5 yr). Below the 10^{-5} rate, the actinide chains again dominate, because the consequence from single nuclides is now held below the transport-dictated actinide chain level by the low release rate. At a slightly lower release rate, the actinide chain begins to become more linear with release rate as the spread in time and space due to reduced release rate exceeds that due to different degrees of retardation among chain members, coupled with sorption-enhanced convective dispersion.

Even in view of the very conservative result and its overestimation of resultant dose from the intrusion well scenario, the result suggests that ground-water contamination potential is a valid consideration for site selection criteria, even though the probability of significant contamination is expected to be low.

Two reasons exist for locating repositories in regions that drain to a large river. (It is not practical to locate deep enough to avoid all aquifer regions.) First, the dilution potential for radioisotopes reaching the surface water is great. Second, the ground-water system near a large river is not as important to the general population since the river itself is the primary source of municipal and agricultural water supply. In regions where the deep aquifer is the primary or only source of water, the potential consequence of aquifer contamination is higher.

In the past, few people populated arid regions in which the ground-water system was the primary water source. However, recent technological advances have allowed larger populations to flourish in arid areas, and the trend is increasing. Continued technological advance may relieve the dependence of these populations on the aquifers for a primary water supply, but it is always unclear what the future will hold. Technological decline could also occur (although historical evidence does not strongly support that possibility), and the arid regions' population would decrease, reducing the population at risk.

It should be noted that the ever-increasing populations of the arid regions in the southwestern United States have so far shown no statistically significant health effects due to the already higher-than-average natural radioactivity content of their ground water.

6.0 ASSUMPTIONS AND CONCLUSIONS

Several assumptions were made to perform the analysis. The conclusions are, of course, based on the validity of the assumptions and are limited to the reference systems and real systems whose properties are within or near the range of the reference site parameters and constants.

6.1 SUMMARY OF ASSUMPTIONS AND APPROACH

1. The radionuclide source is one-fifth of the spent nuclear fuel accumulated in the U.S. through the year 2000, as defined in CWM/GEIS (DOE 1979a).
2. The release pathways with the greatest risk to man originate from the waste after disposal.
3. The highest risk pathway from the repository to the biosphere is the ground-water transport pathway.
4. All nuclides are soluble in ground water, and the dissolved nuclides do not change speciation during migration.
5. The migrating nuclides are in reversible sorption equilibrium at all points.
6. The water velocity and the axial dispersion coefficient are constant for any single parametric calculation.
7. Estimates of the sorption equilibrium constants are used in most cases.
8. Transverse convection and dispersion are neglected.
9. The nuclides are dissolved in the ground water in trace concentrations such that there is no inter- or intra-species competition for sorption, nor are solubility limits ever approached in the far-field hydrology.

10. The release of nuclides from the repository is a constant rate band (fraction per year) term, except for the effect of radioactive decay (decaying band release).
11. Doses are calculated for a "maximum" individual.
12. For all dose calculations, the discharging nuclides accumulate in the biosphere for 70 yr; the "maximum individual" is exposed to that accumulation during those 70 yr, and the nuclides are subsequently dispersed into the biosphere with no dose after the exposure period.
13. Humans' dietary and living habits will remain constant throughout geologic time.
14. If the "maximum individual" is adequately protected, all individuals are adequately protected. This ignores any statistical consequences due to integrated population doses based on a linear population consequences approach.
15. A mrem dose received by a person living in the year 2051 is equivalent to a mrem dose received by a person living in the year 1,002,051 (10^6 yr later). Dose value is not discounted with time of dose occurrence.

6.2 CONCLUSIONS

Even in view of the uncertainty and conservatism inherent in the analysis, these results show trends that are not overly sensitive to a reasonable variation in geohydrologic properties.

- In nearly all cases, the regional geology is the most effective barrier to release of radionuclides to the biosphere; however, for long-lived isotopes of carbon, technetium and iodine, which were poorly sorbed on the geologic media, the geology is not very effective once leaching and transport are initiated.
- While the need for and the effectiveness of a release-rate-limiting barrier are dependent on the sorption properties of the geologic

media, generally, a release rate of less than 10^{-5} yr^{-1} (fractional) is necessary to reduce the potential dose from ^{14}C , ^{99}Tc and ^{129}I to a baseline level below that of the actinides. Beyond that, a release rate of considerably less than 10^{-5} yr^{-1} is required before the potential dose from the actinide chains can be further lowered by this mechanism. This is because the distribution of actinide chain members in time and space, due to their different sorption properties and the characteristics of the groundwater flow field, has the same effect as a release rate of between 10^{-5} to 10^{-6} yr^{-1} . Only in extreme cases of the intrusion water well scenario is there a direct relationship between release rate from the repository and release to the biosphere for the actinide chain daughters.

- The 10^4 yr (or less) delay in leach initiation that an engineered barrier, container, or sealant might provide is insufficient to accomplish any maximum potential dose reduction. Only the delay provided by a stable geology for 10^5 yr or more can accomplish this.
- Specific nuclides of concern for extreme conditions of the general case (early, fast release from the repository, short ground-water transport times) are the fission products ^{14}C , ^{99}Tc and ^{129}I . For the more likely and moderate conditions of the general case, the important nuclides are ^{241}Am as a source of ^{237}Np , ^{237}Np , and its daughters (^{233}U , ^{229}Th , ^{225}Ra); ^{234}U and ^{238}U primarily as a source of ^{226}Ra (and also as dose contributors themselves); and ^{226}Ra and its daughters (especially ^{210}Pb and ^{210}Po). For extreme conditions of the intrusion well case, the dominant nuclides were ^{14}C , ^{241}Am , ^{243}Am , ^{79}Se , and ^{239}Pu .

If actual limitations to mass transport in a backfilled repository, the geochemical limits in the hydrogeologic far field, and the three-dimensional hydrologic system were rigorously taken into account, and natural biological

saturation limits were used, the technical incentive for providing the above functions via engineered systems could possibly be reduced from that described above.

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A fundamental question here is, how far do we want to take this? Somewhere between the naivety of trusting mother earth to receive our errors, protecting us in her infinite way, and the skepticism of analysis forever paralyzed in dwelling on fear, there is a balanced path, but only if both reason and risk are accepted.

APPENDIX A

REFERENCE GRANITE SITE
EXPANDED DOSE SUMMARY TABLES

REFERENCE GRANITE SITE EXPANDED DOSE SUMMARY TABLES

A.1 SUMMARY TABLES FOR GENERAL LEACH INCIDENT SCENARIOS

The following tables are expanded summaries of the consequence calculations for the granite-site parametric sets. These tables list the nuclides in descending order of dose commitment to a critical organ, along with the associated total body dose and time of maximum dose occurrence. Tables A.1.1 through A.1.9 contain the results for the general leach incident scenario. All tables are arbitrarily cut off at the 20 most dose-significant (to critical organ) nuclides in order to save space. Very little information is lost, since generally only a few isotopes dominate the dose and all others are orders of magnitude less significant. In several cases, less than 20 nuclides survived the transport time from the repository to the biosphere; thus, fewer than 20 appear in the dose tables for those cases.

TABLE A.1.1. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case GRT001G

Parametric Data

Release duration = 1.0E+02; delay prior to release = 1.0E+00 yr;
ground-water velocity = 2.00E+00 m/yr; ground-water pathlength = 1.00E+03 m;
ground-water travel time = 5.0E+02 yr; dispersion coefficient = 1.3E+01 m²/yr.

Nuclide	Time After Closure, yr	Seventy-year dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
¹⁴ C	0.54E+03	1.4+001	7.2+001	1.4+001	1.4+001	1.4+001
⁹⁹ Tc	0.54E+03	4.6-001	1.1+000	1.4-001	3.5-006	6.2+001
¹²⁹ I	0.54E+03	5.4-002	3.1-002	1.9-002	2.7+001	2.1-002
²³⁷ Np	0.33E+06	3.8-002	5.8-001	1.3-002	1.3-002	1.3-002
²³⁴ U	0.14E+06	3.1-002	5.0-001	1.5-004	1.5-004	4.1-002
²²⁶ Ra	0.33E+06	3.0-001	4.0-001	4.2-004	4.2-004	4.2-004
²²⁹ Th	0.33E+06	8.7-003	1.6-001	7.7-004	7.7-004	7.7-004
²³⁸ U	0.14E+06	9.2-003	1.2-001	2.1-003	2.1-003	1.2-002
²³⁶ U	0.14E+06	7.2-003	1.2-001	1.0-006	1.0-006	1.0-006
²²⁵ Ra	0.33E+06	2.0-002	1.0-001	0.0	0.0	0.0
²¹⁰ Pb	0.33E+06	6.7-004	1.7-002	9.5-008	9.5-008	9.5-008
²³³ U	0.33E+06	7.7-004	1.2-002	2.7-006	2.7-006	2.7-006
²¹⁰ Po	0.33E+06	2.6-003	1.1-002	1.1-011	1.1-011	1.1-011
²⁴² Pu	0.10E+07	2.5-004	5.2-003	7.1-007	7.1-007	1.4-003
²³⁰ Th	0.14E+06	4.5-005	1.5-003	1.0-007	1.0-007	1.0-007
⁵⁹ Ni	0.33E+06	1.5-004	9.0-004	4.9-009	4.9-009	4.9-009
²²⁵ Ac	0.33E+06	5.7-004	7.4-004	5.5-004	5.5-004	5.5-004
²³⁵ U	0.14E+06	6.0-005	5.1-004	3.0-005	3.0-005	8.3-005
²²⁷ Ac	0.14E+06	5.4-007	7.9-006	4.6-008	4.6-008	4.6-008
²³¹ Pa	0.14E+06	2.6-007	4.1-006	9.5-008	9.5-008	9.5-008

TABLE A.1.2. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case GRT002G

Parametric Data

Release duration = 1.0E+06; delay prior to release = 1.0E+00 yr;
ground-water velocity = 2.00E+00 m/yr; ground-water pathlength = 1.00E+03 m;
ground-water travel time = 5.0E+02 yr; dispersion coefficient = 1.3E+01 m²/yr.

Nuclide	Time After Closure, yr	Seventy-year dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
²²⁹ Th	0.60E+06	3.3-003	6.1-002	2.9-004	2.9-004	2.9-004
²²⁵ Ra	0.60E+06	7.6-003	3.8-002	0.0	0.0	0.0
²²⁶ Ra	0.35E+06	2.2-002	2.9-002	3.2-005	3.2-005	3.2-005
²³⁷ Np	0.35E+06	5.0-004	7.5-003	1.7-004	1.7-004	1.7-004
¹⁴ C	0.54E+03	1.4-003	7.2-003	1.4-003	1.4-003	1.4-003
⁹⁹ Tc	0.54E+03	4.6-005	1.1-004	1.4-005	3.5-010	6.2-003
²³³ U	0.60E+06	2.9-004	4.7-003	1.0-006	1.0-006	1.0-006
²³⁴ U	0.15E+06	2.4-004	3.9-003	1.1-006	1.1-006	3.2-004
²¹⁰ Pb	0.35E+06	1.2-004	3.2-003	1.8-008	1.8-008	1.8-008
¹²⁹ I	0.54E+03	5.4-006	3.1-006	1.9-006	2.8-003	2.1-006
²¹⁰ Po	0.35E+06	4.9-004	2.0-003	2.1-012	2.1-012	2.1-012
²³⁶ U	0.15E+06	6.7-005	1.1-003	9.4-009	9.4-009	9.4-009
²³⁸ U	0.60E+06	6.1-005	8.0-004	1.4-005	1.4-005	7.8-005
²²⁴ Ac	0.60E+06	2.1-004	2.8-004	2.1-004	2.1-004	2.1-004
²³⁰ Th	0.35E+06	6.6-006	2.2-004	1.5-008	1.5-008	1.5-008
²⁴² Pu	0.10E+07	6.4-006	1.3-004	1.8-008	1.8-008	3.6-005
⁵⁹ Ni	0.35E+06	2.2-006	1.3-005	7.0-011	7.0-011	7.0-011
²²⁸ Ra	0.88E+07	6.0-006	5.5-006	2.7-009	2.7-009	2.7-009
²³⁵ U	0.60E+06	4.2-007	3.6-006	2.2-007	2.2-007	5.9-007
²²⁷ Ac	0.60E+06	5.8-008	8.5-007	5.0-009	5.0-009	5.0-009

TABLE A.1.3. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case GRT003G

Parametric Data

Release duration = 1.0E+06; delay prior to release = 1.0E+06 yr;
ground-water velocity = 2.00E+00 m/yr; ground-water pathlength = 1.00E+03 m;
ground-water travel time = 5.0E+02 yr; dispersion coefficient = 1.3E+01 m²/yr.

Nuclide	Time After Closure, yr	Seventy-year dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
²²⁶ Ra	0.14E+07	9.8-003	1.3-002	1.4-005	1.4-005	1.4+005
²³⁷ Np	0.14E+07	3.6-004	5.4-003	1.2-004	1.2-004	1.2-004
²³³ U	0.13E+07	2.5-004	4.0-003	8.8-007	8.8-007	8.8-007
¹²⁹ I	0.10E+07	5.2-006	3.0-006	1.8-006	2.7-003	2.0-006
²¹⁰ Pb	0.14E+07	5.5-005	1.4-003	7.9-009	7.9-009	7.9-009
²²⁹ Th	0.13E+07	6.2-005	1.2-003	5.5-006	5.5-006	5.5-006
²³⁴ U	0.11E+07	7.3-005	1.2-003	3.4-007	3.4-007	9.6-005
²³⁶ U	0.13E+07	6.4-005	1.0-003	9.1-009	9.1-009	9.1-009
²¹⁰ Po	0.14E+07	2.2-004	9.1-004	9.5-013	9.5-013	9.5-013
²³⁸ U	0.16E+07	6.1-005	8.0-004	1.4-005	1.4-005	7.8-005
²²⁵ Ra	0.13E+07	1.4-004	7.2-004	0.0	0.0	0.0
⁹⁹ Tc	0.10E+07	1.7-006	4.3-006	5.4-007	1.3-011	2.3-004
²³⁰ Th	0.13E+07	2.9-006	9.8-005	6.9-009	6.9-009	6.9-009
²³⁵ U	0.16E+07	8.9-006	7.6-005	4.5-006	4.5-006	1.2-005
²⁴² Pu	0.20E+07	1.0-006	2.1-005	2.9-009	2.9-009	5.7-006
²²⁷ Ac	0.16E+07	1.2-006	1.7-005	1.0-007	1.0-007	1.0-007
²²⁸ Ra	0.98E+07	1.8-005	1.6-005	7.9-009	7.9-009	7.9-009
²³¹ Pa	0.16E+07	5.8-007	9.0-006	2.1-007	2.1-007	2.1-007
²²⁵ Ac	0.13E+07	4.1-006	5.3-006	4.0-006	4.0-006	4.0-006
²³² Th	0.98E+07	2.2-008	3.8-007	9.5-009	9.5-009	2.3-008

TABLE A.1.4. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case GRT004G

Parametric Data

Release duration = 1.0E+02; delay prior to release = 1.0E+06 yr;
ground-water velocity = 2.00E+00 m/yr; ground-water pathlength = 1.00E+03 m;
ground-water travel time = 5.0E+02 yr; dispersion coefficient = 1.3E+01 m²/yr.

Nuclide	Time After Closure, yr	Seventy-year dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
¹²⁹ I	0.10E+07	5.2-002	3.0-002	1.8-002	2.6+001	2.0-002
⁹⁹ Tc	0.10E+07	1.7-002	4.3-002	5.4-003	1.3-007	2.3+000
²³⁷ Np	0.13E+07	2.1-002	3.3-001	7.4-003	7.4-003	7.4-003
²³³ U	0.11E+07	1.4-002	2.3-001	5.0-005	5.0-005	5.0-005
²³⁴ U	0.11E+07	1.1-002	1.7-001	5.1-005	5.1-005	5.1-002
²³⁶ U	0.11E+07	9.4-003	1.5-001	1.3-006	1.3-006	1.3-006
²²⁶ Ra	0.13E+07	1.1-001	1.4-001	1.6-004	1.6-004	1.6-004
²³⁸ U	0.11E+07	9.2-003	1.2-001	2.1-003	2.1-003	1.2-002
²²⁹ Th	0.11E+07	9.5-004	1.8-002	8.4-005	8.4-005	8.4-005
²³⁵ U	0.11E+07	1.3-003	1.1-002	6.7-004	6.7-004	1.8-003
²²⁵ Ra	0.11E+07	2.2-003	1.1-002	0.0	0.0	0.0
²¹⁰ Pb	0.13E+07	2.6-004	6.8-003	3.7-008	3.7-008	3.7-008
²¹⁰ Po	0.13E+07	1.0-003	4.3-003	4.5-012	4.5-012	4.5-012
²⁴² Pu	0.20E+07	4.1-005	8.5-004	1.2-007	1.2-007	2.3-004
²³⁰ Th	0.11E+07	1.8-005	5.9-004	4.1-008	4.1-008	4.1-008
²²⁷ Ac	0.11E+07	1.2-005	1.8-004	1.0-006	1.0-006	1.0-006
²³¹ Pa	0.11E+07	5.9-006	9.1-005	2.1-006	2.1-006	2.1-006
²²⁵ Ac	0.11E+07	6.2-005	8.1-005	6.1-005	6.1-005	6.1-005
²²⁸ Ra	0.93E+07	2.9-005	2.7-005	1.3-008	1.3-008	1.3-008
²³² Th	0.93E+07	3.6-008	6.1-007	1.5-008	1.5-008	3.8-008

TABLE A.1.5. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case GRT005G

Parametric Data

Release duration = 1.0E+02; delay prior to release = 1.0E+06 yr;
ground-water velocity = 1.50E-02 m/yr; ground-water pathlength = 1.50E+04 m;
ground-water travel time = 1.0E+06 yr; dispersion coefficient = 5.3E-03 m²/yr.

Nuclide	Time After Closure, yr	Seventy-year dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
¹²⁹ I	0.20E+07	4.1-003	2.4-003	1.4-003	2.1+000	1.6-003
²²⁶ Ra	0.27E+09	1.5-002	1.9-002	2.1-005	2.1-005	2.1-005
⁹⁹ Tc	0.20E+07	5.3-005	1.3-004	1.6-005	4.0-010	7.1-003
²³⁴ U	0.27E+09	1.8-004	2.9-003	8.5-007	8.5-007	2.4-004
²³⁸ U	0.27E+09	1.8-004	2.3-003	4.1-005	4.1-005	2.3-004
²¹⁰ Pb	0.27E+09	8.2-005	2.1-003	1.2-008	1.2-008	1.2-008
²¹⁰ Po	0.27E+09	3.3-004	1.4-003	1.4-012	1.4-012	1.4-012
²³⁵ U	0.27E+09	2.1-005	1.8-004	1.1-005	1.1-005	2.9-005
²³⁰ Th	0.27E+09	4.5-006	1.5-004	1.0-008	1.0-008	1.0-008
²²⁷ Ac	0.27E+09	2.5-006	3.7-005	2.1-007	2.1-007	2.1-007
²³¹ Pa	0.27E+09	1.2-006	1.9-005	4.4-007	4.4-007	4.4-007
²³⁶ U	0.27E+09	6.7-008	1.1-006	9.4-012	9.4-012	9.4-012
²²⁸ Ra	0.17E+11	3.0-007	2.8-007	1.3-010	1.3-010	1.3-010
²¹⁰ Bi	0.27E+09	4.6-009	8.0-009	7.5-012	7.5-012	7.5-012
²³² Th	0.17E+11	3.7-010	6.3-009	1.6-010	1.6-010	3.9-010
²²⁴ Ra	0.17E+11	5.7-010	2.9-009	4.2-013	4.2-013	4.2-013
²²⁸ Th	0.17E+11	1.0-010	2.0-009	3.6-011	3.6-011	3.6-011
⁸⁷ Rb	0.67E+10	4.2-010	5.0-017	5.0-017	5.0-017	5.0-017

TABLE A.1.6. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case GRT006G

Parametric Data

Release duration = 1.0E+06; delay prior to release = 1.0E+06 yr;
ground-water velocity = 1.50E-02 m/yr; ground-water pathlength = 1.50E+04 m;
ground-water travel time = 1.0E+06 yr; dispersion coefficient = 5.3E-03 m²/yr.

Nuclide	Time After Closure, yr	Seventy-year dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
²²⁶ Ra	0.27E+09	6.7-003	8.9-003	9.8-006	9.8-006	9.8-006
¹²⁹ I	0.20E+07	5.0-006	2.9-006	1.7-006	2.5-003	1.9-006
²¹⁰ Pb	0.27E+09	3.8-005	9.7-004	5.4-009	5.4-009	5.4-009
²³⁴ U	0.27E+09	6.0-005	9.5-004	2.8-007	2.8-007	7.9-005
²³⁸ U	0.27E+9	5.9-005	7.6-004	1.3-005	1.3-005	7.4-005
²¹⁰ Po	0.27E+09	1.5-004	6.2-004	6.5-013	6.5-013	6.5-013
²³⁰ Th	0.27E+09	2.0-006	6.8-005	4.8-009	4.8-009	4.8-009
²³⁵ U	0.27E+09	6.8-006	5.8-005	3.5-006	3.5-006	9.5-006
²²⁷ Ac	0.27E+09	9.0-007	1.3-005	7.7-008	7.7-008	7.7-008
⁹⁹ Tc	0.20E+07	6.7-008	1.7-007	2.1-008	5.0-013	9.0-006
²³¹ Pa	0.27E+09	4.4-007	6.8-006	1.6-007	1.6-007	1.6-007
²²⁸ Ra	0.17E+11	4.3-007	4.0-007	1.9-010	1.9-010	1.9-010
²³⁶ U	0.27E+09	2.1-008	3.4-007	3.0-012	3.0-012	3.0-012
²³² Th	0.17E+11	5.4-010	9.1-009	2.3-010	2.3-010	5.6-010
²²⁴ Ra	0.17E+11	8.2-010	4.1-009	6.1-013	6.1-013	6.1-013
²¹⁰ Bi	0.27E+09	2.1-009	3.7-009	3.4-012	3.4-012	3.4-012
²²⁸ Th	0.17E+11	1.5-010	2.8-009	5.2-011	5.2-011	5.2-011
⁸⁷ Rb	0.67E+10	3.9-010	4.7-017	4.7-017	4.7-017	4.7-017

TABLE A.1.7. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case GRT007G

Parametric Data

Release duration = 1.0E+06; delay prior to release = 1.0E+00 yr;
ground-water velocity = 1.50E-02 m/yr; ground-water pathlength = 1.50E+04 m;
ground-water travel time = 1.0E+06 yr; dispersion coefficient = 5.3E-03 m²/yr.

Nuclide	Time After Closure, yr	Seventy-year dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
²²⁶ Ra	0.27E+09	6.7-003	8.9-003	9.8-006	9.8-006	9.8-006
¹²⁹ I	0.10E+07	5.2-006	3.0-006	1.8-006	2.7-003	2.0-006
²¹⁰ Pb	0.27E+09	3.8-005	9.7-004	5.4-009	5.4-009	5.4-009
²³⁴ U	0.27E+09	6.0-005	9.5-004	2.8-007	2.8-007	7.9-005
²³⁸ U	0.27E+09	5.9-005	7.6-004	1.3-005	1.3-005	7.4-005
²¹⁰ Po	0.27E+09	1.5-004	6.2-004	6.5-013	6.5-013	6.5-013
⁹⁹ Tc	0.10E+07	1.8-006	4.4-006	5.5-007	1.3-011	2.4-004
²³⁰ Th	0.27E+09	2.0-006	6.8-005	4.8-009	4.8-009	4.8-009
²³⁵ U	0.27E+09	3.4-007	2.9-006	1.7-007	1.7-007	4.7-007
²²⁷ Ac	0.27E+09	4.4-008	6.4-007	3.7-009	3.7-009	3.7-009
²³⁶ U	0.27E+09	2.2-008	3.5-007	3.1-012	3.1-012	3.1-012
²³¹ Pa	0.27E+09	2.1-008	3.3-007	7.7-009	7.7-009	7.7-009
²²⁸ Ra	0.17E+11	1.8-007	1.6-007	7.9-011	7.9-011	7.9-011
²³² Th	0.17E+11	2.2-010	3.8-009	9.5-011	9.5-011	2.3-010
²¹⁰ Bi	0.27E+09	2.1-009	3.7-009	3.4-012	3.4-012	3.4-012
²²⁴ Ra	0.17E+11	3.4-010	1.7-009	2.5-013	2.5-013	2.5-013
²²⁸ Th	0.17E+11	6.0-011	1.2-009	2.1-011	2.1-011	2.1-011
⁸⁷ Rb	0.67E+10	3.9-010	4.7-017	4.7-017	4.7-017	4.7-017

TABLE A.1.8. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case GRT008G

Parametric Data

Release duration = 1.0E+02; delay prior to release = 1.0E+00 yr;
ground-water velocity = 1.50E-02 m/yr; ground-water pathlength = 1.50E+04 m;
ground-water travel time = 1.0E+06 yr; dispersion coefficient = 5.3E-03 m²/yr.

Nuclide	Time After Closure, yr	Seventy-year dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
¹²⁹ I	0.10E+07	4.3-003	2.5-003	1.5-003	2.2+000	1.7-003
⁹⁹ Tc	0.10E+07	1.5-003	3.7-003	4.6-004	1.1-008	2.0-001
²²⁶ Ra	0.27E+09	1.5-002	1.9-002	2.1-005	2.1-005	2.1-005
²³⁴ U	0.27E+09	1.8-004	2.9-003	8.5-007	8.5-007	2.4-004
²³⁸ U	0.27E+09	1.8-004	2.3-003	4.1-005	4.1-005	2.3-004
²¹⁰ Pb	0.27E+09	8.2-005	2.1-003	1.2-008	1.2-008	1.2-008
²¹⁰ Po	0.27E+09	3.3-004	1.4-003	1.4-012	1.4-012	1.4-012
²³⁰ Th	0.27E+09	4.5-006	1.5-004	1.1-008	1.1-008	1.1-008
²³⁵ U	0.27E+09	1.0-006	8.7-006	5.2-007	5.2-007	1.4-006
²²⁷ Ac	0.27E+09	1.2-007	1.8-006	1.0-008	1.0-008	1.0-008
²³⁶ U	0.27E+09	6.7-008	1.1-006	9.4-012	9.4-012	9.4-012
²³¹ Pa	0.27E+09	6.0-008	9.3-007	2.2-008	2.2-008	2.2-008
²²⁸ Ra	0.17E+11	4.3-008	4.0-008	1.9-011	1.9-011	1.9-011
²¹⁰ Bi	0.27E+09	4.6-009	8.0-009	7.5-012	7.5-012	7.5-012
²³² Th	0.17E+11	5.4-011	9.1-010	2.3-011	2.3-011	5.6-011
²²⁴ Ra	0.17E+11	8.2-011	4.1-010	6.1-014	6.1-014	6.1-014
²²⁸ Th	0.17E+11	1.5-011	2.8-010	5.2-012	5.2-012	5.2-012
⁸⁷ Rb	0.67E+10	4.2-010	5.0-017	5.0-017	5.0-017	5.0-017

TABLE A.1.9. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case GRT009G

Parametric Data

Release duration = 1.0E+04; delay prior to release = 1.0E+00 yr;
ground-water velocity = 1.50E-02 m/yr; ground-water pathlength = 1.5E+04 m;
ground-water travel time = 1.0E+06 yr; dispersion coefficient = 5.3E-03 m²/yr.

Nuclide	Time After Closure, yr	Seventy-year dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
¹²⁹ I	0.10E+07	5.2-004	3.0-004	1.8-004	2.6-001	2.0-004
⁹⁹ Tc	0.10E+07	1.8-004	4.4-004	5.5-005	1.3-009	2.4-002
²²⁶ Ra	0.27E+09	1.5-002	1.9-002	2.1-005	2.1-005	2.1-005
²³⁴ U	0.27E+09	1.8-004	2.9-003	8.5-007	8.5-007	2.4-004
²³⁸ U	0.27E+09	1.8-004	2.3-003	4.1-005	4.1-005	2.3-004
²¹⁰ Pb	0.27E+09	8.2-005	2.1-003	1.2-008	1.2-008	1.2-008
²¹⁰ Po	0.27E+09	3.3-004	1.4-003	1.4-012	1.4-012	1.4-012
²³⁰ Th	0.27E+09	4.5-006	1.5-004	1.1-008	1.1-008	1.1-008
²³⁵ U	0.27E+09	1.0-006	8.7-006	5.2-007	5.2-007	1.4-006
²²⁷ Ac	0.27E+09	1.2-007	1.8-006	1.0-008	1.0-008	1.0-008
²³⁶ U	0.27E+09	6.7-008	1.1-006	9.4-012	9.4-012	9.4-012
²³¹ Pa	0.27E+09	6.0-008	9.3-007	2.2-008	2.2-008	2.2-008
²²⁸ Ra	0.17E+11	4.5-008	4.1-008	2.0-011	2.0-011	2.0-011
²¹⁰ Bi	0.27E+09	4.6-009	8.0-009	7.5-012	7.5-012	7.5-012
²³² Th	0.17E+11	5.6-011	9.5-010	2.4-011	2.4-011	5.9-011
²²⁴ Ra	0.17E+11	8.6-011	4.3-010	6.3-014	6.3-014	6.3-014
²²⁸ Th	0.17E+11	1.5-011	3.0-010	5.4-012	5.4-012	5.4-012
⁸⁷ Rb	0.67E+10	4.2-010	5.0-017	5.0-017	5.0-017	5.0-017

A.2 SUMMARY TABLES FOR INTRUSION WATER WELL SCENARIO

The following tables are expanded summaries of the consequence calculations for the intrusion water-well scenario. The nuclides are listed in decreasing dose commitment to critical organs, along with the associated total body dose commitment and time of peak dose occurrence. All tables are arbitrarily cut off at the 20 most dose-significant isotopes in order to save space. Very little information is lost since generally only a few isotopes dominate the dose and all others are orders of magnitude less significant. In several cases less than 20 nuclides survived the transport from the repository to the biosphere; thus, fewer than 20 appear in the dose tables for those cases. In some cases, ^{79}Se was added as the twentieth nuclide due to its strong contribution to the "total body" dose even though it is insignificant as a critical organ dose contributor.

TABLE A.2.1. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case GRT001W

Parametric Data

Release duration = 1.0E+02 yr; delay prior to release = 1.0E+00 yr;
ground-water velocity = 2.00E+00 m/yr; ground-water pathlength = 1.00E+03 m;
ground-water travel time = 5.0E+02 yr; dispersion coefficient = 1.3E+01 m²/yr.

Nuclide	Time After Closure, yr	Seventy-Year Dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
¹⁴ C	0.54E+03	5.4+005	2.7+006	5.4+005	5.4+005	5.4+005
⁹⁹ Tc	0.54E+03	1.7+004	4.3+004	5.4+003	0.0	2.3+006
¹²⁹ I	0.54E+03	1.3+003	4.7+002	0.0	1.0+006	7.1+001
²³⁴ U	0.14E+06	9.2+002	1.5+004	0.0	0.0	1.2+003
²³⁷ Np	0.33E+06	3.0+002	6.8+003	0.0	0.0	0.0
²²⁶ Ra	0.33E+06	4.2+003	5.4+003	0.0	0.0	0.0
²³⁶ U	0.14E+06	2.1+002	3.4+003	0.0	0.0	0.0
²³⁸ U	0.14E+06	2.0+002	3.3+003	0.0	0.0	2.7+002
²²⁹ Th	0.33E+06	8.4+001	1.7+003	0.0	0.0	0.0
²²⁵ Ra	0.33E+06	2.2+002	1.1+003	0.0	0.0	0.0
²¹⁰ Pb	0.33E+06	2.0+001	5.0+002	0.0	0.0	0.0
²³³ U	0.33E+06	2.3+001	3.7+002	0.0	0.0	0.0
²⁴² Pu	0.10E+07	5.9+000	1.2+002	0.0	0.0	3.3+001
⁵⁹ Ni	0.33E+06	4.1+000	2.4+001	0.0	0.0	0.0
²³⁰ Th	0.14E+06	4.7-001	1.6+001	0.0	0.0	0.0
²³⁵ U	0.14E+06	8.3-001	1.3+001	0.0	0.0	1.5+000
²¹⁰ P	0.33E+06	7.7-001	3.2+000	0.0	0.0	0.0
²²⁵ Ac	0.33E+06	4.6-002	6.9-001	0.0	0.0	0.0
²³¹ Pa	0.14E+06	3.9-003	9.3-002	0.0	0.0	0.0
²²⁷ Ac	0.14E+06	2.8-003	4.4-002	0.0	0.0	0.0

TABLE A.2.2. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case GRT002W

Parametric Data

Release duration = 1.0E+06 yr; delay prior to release = 1.0E+00 yr;
ground-water velocity = 2.00E+00 m/yr; ground-water pathlength = 1.00E+03 m;
ground-water travel time = 5.0E+02 yr; dispersion coefficient = 1.3E+01 m²/yr.

Nuclide	Time After Closure, yr	Seventy-Year Dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
²²⁹ Th	0.60E+06	3.1+001	6.4+002	0.0	0.0	0.0
²²⁶ Ra	0.35E+06	3.1+002	4.1+002	0.0	0.0	0.0
²²⁵ Ra	0.60E+06	8.1+001	4.1+002	0.0	0.0	0.0
¹⁴ C	0.54E+03	5.4+001	2.7+002	5.4+001	5.4+001	5.4+001
⁹⁹ Tc	0.54E+03	1.7+000	4.4+000	5.4-001	0.0	2.3+002
²³³ U	0.60E+06	8.6+000	1.4+002	0.0	0.0	0.0
²³⁴ U	0.15E+06	7.2+000	1.1+002	0.0	0.0	9.5+000
¹²⁹ I	0.54E+03	1.3-001	4.7-002	0.0	1.0+002	7.1-003
²¹⁰ Pb	0.35E+06	3.7+000	9.3+001	0.0	0.0	0.0
²³⁷ Np	0.35E+06	3.9+000	8.8+001	0.0	0.0	0.0
²³⁶ U	0.15E+06	2.0+000	3.2+001	0.0	0.0	0.0
²³⁸ U	0.60E+06	1.3+000	2.2+001	0.0	0.0	1.8+000
²⁴² Pu	0.10E+07	1.5-001	3.1+000	0.0	0.0	8.3-001
²³⁰ Th	0.35E+06	7.0-002	2.3+000	0.0	0.0	0.0
²¹⁰ Po	0.35E+06	1.4-001	5.9-001	0.0	0.0	0.0
⁵⁹ Ni	0.35E+06	5.8-002	3.4-001	0.0	0.0	0.0
²²⁵ Ac	0.60E+06	1.7-002	2.6-001	0.0	0.0	0.0
²³⁵ U	0.60E+06	5.9-003	9.6-002	0.0	0.0	1.1-002
²²⁸ Ra	0.88E+07	8.1-002	7.4-002	0.0	0.0	0.0
²³¹ Pa	0.60E+06	4.2-004	1.0-002	0.0	0.0	0.0

TABLE A.2.3. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case GRT003W

Parametric Data

Release duration = 1.0E+06 yr; delay prior to release = 1.0E+06 yr;
ground-water velocity = 2.00E+00 m/yr; ground-water pathlength = 1.00E+03 m;
ground-water travel time = 5.0E+02 yr; dispersion coefficient = 1.3E+01 m²/yr.

Nuclide	Time After Closure, yr	Seventy-Year Dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
²²⁶ Ra	0.14E+07	1.4+002	1.8+002	0.0	0.0	0.0
²³³ U	0.13E+07	7.2+000	1.2+002	0.0	0.0	0.0
¹²⁹ I	0.10E+07	1.3-001	4.5-002	0.0	9.8+001	6.8-003
²³⁷ Np	0.14E+07	2.8+000	6.3+001	0.0	0.0	0.0
²¹⁰ Pb	0.14E+07	1.6+000	4.2+001	0.0	0.0	0.0
²³⁴ U	0.11E+07	2.1+000	3.4+001	0.0	0.0	2.8+000
²³⁶ U	0.13E+07	1.9+000	3.0+001	0.0	0.0	0.0
²³⁸ U	0.16E+07	1.3+000	2.2+001	0.0	0.0	1.8+000
²²⁹ Th	0.13E+07	6.0-001	1.2+001	0.0	0.0	0.0
⁹⁹ Tc	0.10E+07	6.5-002	1.6-001	2.0-002	0.0	8.8+000
²²⁵ Ra	0.13E+07	1.5+000	7.7+000	0.0	0.0	0.0
²³⁵ U	0.16E+07	1.2-001	2.0+000	0.0	0.0	2.2-001
²³⁰ Th	0.13E+07	3.1-002	1.0+000	0.0	0.0	0.0
²⁴² Pu	0.20E+07	2.4-002	5.0-001	0.0	0.0	1.3-001
²¹⁰ Po	0.14E+07	6.3-002	2.6-001	0.0	0.0	0.0
²²⁸ Ra	0.98E+07	2.4-001	2.2-001	0.0	0.0	0.0
²³¹ Pa	0.16E+07	8.5-003	2.0-001	0.0	0.0	0.0
²²⁷ Ac	0.16E+07	6.2-003	9.7-002	0.0	0.0	0.0
²²⁵ Ac	0.13E+07	3.3-004	4.9-003	0.0	0.0	0.0
²³² Th	0.98+07	1.1-004	3.3-003	0.0	0.0	1.2-004

TABLE A.2.4. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case GRT004W

Parametric Data

Release duration = 1.0E+02 yr; delay prior to release = 1.0E+06 yr;
ground-water velocity = 2.00E+00 m/yr; ground-water pathlength = 1.00E+03 m;
ground-water travel time = 5.0E+02 yr; dispersion coefficient = 1.3E+01 m²/yr.

Nuclide	Time After Closure, yr	Seventy-Year Dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
¹²⁹ I	0.10E+07	1.3+003	4.5+002	0.0	9.8+005	6.8+001
⁹⁹ Tc	0.10E+07	6.5+002	1.6+003	2.0+002	0.0	8.8+004
²³³ U	0.11E+07	4.1+002	6.7+003	0.0	0.0	0.0
²³⁴ U	0.11E+07	3.2+002	5.1+003	0.0	0.0	4.2+002
²³⁶ U	0.11E+07	2.8+002	4.4+003	0.0	0.0	0.0
²³⁷ Np	0.13E+7	1.7+002	3.8+003	0.0	0.0	0.0
²³⁸ U	0.11E+07	2.0+002	3.3+003	0.0	0.0	2.7+002
²²⁶ Ra	0.13E+07	1.5+003	2.0+003	0.0	0.0	0.0
²³⁵ U	0.11E+07	1.8+001	3.0+002	0.0	0.0	3.3+001
²¹⁰ Pb	0.13E+07	7.8+000	2.0+002	0.0	0.0	0.0
²²⁹ Th	0.11E+07	9.2+000	1.9+002	0.0	0.0	0.0
²²⁵ Ra	0.11+07	2.4+001	1.2+002	0.0	0.0	0.0
²⁴² Pu	0.20E+07	9.7-001	2.0+001	0.0	0.0	5.4+000
²³⁰ Th	0.11E+07	1.9-001	6.3+000	0.0	0.0	0.0
²³¹ Pa	0.11E+07	8.7-002	2.1+000	0.0	0.0	0.0
²¹⁰ Po	0.13E+07	3.0-001	1.3+000	0.0	0.0	0.0
²²⁷ Ac	0.11E+07	6.3-002	9.9-001	0.0	0.0	0.0
²²⁸ Ra	0.93E+07	3.9-001	3.6-001	0.0	0.0	0.0
²²⁵ Ac	0.11E+07	5.0-003	7.5-002	0.0	0.0	0.0
²³² Th	0.93E+07	1.9-004	5.3-003	0.0	0.0	2.0-004

TABLE A.2.5. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case GRT005W

Parametric Data

Release duration = 1.0E+02 yr; delay prior to release = 1.0E+06 yr;
ground-water velocity = 1.50E-02 m/yr; ground-water pathlength = 1.50E+04 m;
ground-water travel time = 1.0E+06 yr; dispersion coefficient = 5.3E+03 m²/yr.

Nuclide	Time After Closure, yr	Seventy-Year Dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
¹²⁹ I	0.20E+07	9.9+001	3.6+001	0.0	7.8+004	5.4+000
²²⁶ Ra	0.27E+09	2.1+002	2.7+002	0.0	0.0	.0
⁹⁹ Tc	0.20E+07	2.0+000	5.0+000	6.2-001	0.0	2.7+002
²³⁴ U	0.27E+09	5.3+000	8.5+001	0.0	0.0	7.1+000
²³⁸ U	0.27E+09	3.9+000	6.4+001	0.0	0.0	5.2+000
²¹⁰ Pb	0.27E+09	2.4+000	6.2+001	0.0	0.0	0.0
²³⁵ U	0.27E+09	2.9-001	4.7+000	0.0	0.0	5.2-001
²³⁰ Th	0.27E+09	4.7-002	1.6+000	0.0	0.0	0.0
²³¹ Pa	0.27E+09	1.8-002	4.3-001	0.0	0.0	0.0
²¹⁰ Po	0.27E+09	9.5-002	3.9-001	0.0	0.0	0.0
²²⁷ Ac	0.27E+09	1.3-002	2.0-001	0.0	0.0	0.0
²³⁶ U	0.27E+09	2.0-003	3.2-002	0.0	0.0	0.0
²²⁸ Ra	0.17E+11	4.1-003	3.7-003	0.0	0.0	0.0
²¹⁰ Bi	0.27E+09	1.3-004	2.3-004	0.0	0.0	0.0
²³² Th	0.17E+11	1.9-006	5.5-005	0.0	0.0	2.1-006
²²⁴ Ra	0.17E+11	3.7-006	1.8-005	0.0	0.0	0.0
²²⁸ Th	0.17E+11	5.9-007	1.7-005	0.0	0.0	0.0
⁸⁷ Rb	0.67E+10	2.5-006	0.0	0.0	0.0	0.0

TABLE A.2.6. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case GRT006W

Parametric Data

Release duration = 1.0E+06; delay prior to release = 1.0E+06 yr;
ground-water velocity = 1.50E-02 m/yr; ground-water pathlength = 1.50E+04 m;
ground-water travel time = 1.0E+06 yr; dispersion coefficient = 5.3E-03 m²/yr.

Nuclide	Time After Closure, yr	Seventy-year dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
²²⁶ Ra	0.27E+09	9.5+001	1.3+002	0.0	0.0	0.0
¹²⁹ I	0.20E+07	1.2-001	4.3-002	0.0	9.4+001	6.5-003
²¹⁰ Pb	0.27E+09	1.1+000	2.8+001	0.0	0.0	0.0
²³⁴ U	0.27E+09	1.7+000	2.8+001	0.0	0.0	2.3+0.0
²³⁸ U	0.27E+09	1.3+000	2.1+001	0.0	0.0	1.7+000
²³⁵ U	0.27E+09	9.4-002	1.5+000	0.0	0.0	1.7-001
²³⁰ Th	0.27E+09	2.2-002	7.2-001	0.0	0.0	0.0
⁹⁹ Tc	0.20E+07	2.6-003	6.3-003	7.9-004	0.0	3.4-001
²¹⁰ Po	0.27E+09	4.4-002	1.8-001	0.0	0.0	0.0
²³¹ Pa	0.27E+09	6.4-003	1.5-001	0.0	0.0	0.0
²²⁷ Ac	0.27E+09	4.7-003	7.3-002	0.0	0.0	0.0
²³⁶ U	0.27E+09	6.3-004	1.0-002	0.0	0.0	0.0
²²⁸ Ra	0.17E+11	5.8-003	5.3-003	0.0	0.0	0.0
²¹⁰ Bi	0.27E+09	6.2-005	1.1-004	0.0	0.0	0.0
²³² Th	0.17E+11	2.7-006	7.9-005	0.0	0.0	3.2-006
²²⁴ Ra	0.17E+11	5.3-006	2.7-005	0.0	0.0	0.0
²²⁸ Th	0.17E+11	8.5-007	2.5-005	0.0	0.0	0.0
⁸⁷ Rb	0.67E+10	2.4-006	0.0	0.0	0.0	0.0

TABLE A.2.7. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case GRT007W

Parametric Data

Release duration = 1.0E+06; delay prior to release = 1.0E+00 yr;
ground-water velocity = 1.5E-02 m/yr; ground-water pathlength = 1.5E+04 m;
ground-water travel time = 1.0E+06 yr; dispersion coefficient = 5.3E-03 m²/yr.

Nuclide	Time After Closure, yr	Seventy-year dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
²²⁶ Ra	0.27E+09	9.5+001	1.3+002	0.0	0.0	0.0
¹²⁹ I	0.10E+07	1.3-001	4.5-002	0.0	9.8+001	6.8-003
²¹⁰ Pb	0.27E+09	1.1+000	2.8+001	0.0	0.0	0.0
²³⁴ U	0.27E+09	1.7+000	2.8+001	0.0	0.0	2.3+000
²³⁸ U	0.27E+09	1.3+000	2.1+001	0.0	0.0	1.7+000
⁹⁹ Tc	0.10E+07	6.7-002	1.7-001	2.1-002	0.0	9.1+000
²¹⁰ Th	0.27E+09	2.2-002	7.2-001	0.0	0.0	0.0
²¹⁰ Po	0.27E+09	4.4-002	1.8-001	0.0	0.0	0.0
²³⁵ U	0.27E+09	4.7-003	7.6-002	0.0	0.0	8.4-003
²³⁶ U	0.27E+09	6.5-004	1.0-002	0.0	0.0	0.0
²³¹ Pa	0.27E+09	3.1-004	7.5-003	0.0	0.0	0.0
²²⁷ Ac	0.27E+09	2.3-004	3.6-003	0.0	0.0	0.0
²²⁸ Ra	0.17E+11	2.4-003	2.2-003	0.0	0.0	0.0
²¹⁰ Bi	0.27E+09	6.2-005	1.1-004	0.0	0.0	0.0
²³² Th	0.17E+11	1.1-006	3.3-005	0.0	0.0	1.2-006
²²⁴ Ra	0.17+11	2.2-006	1.1-005	0.0	0.0	0.0
²²⁸ Th	0.17E+11	3.5-007	1.0-005	0.0	0.0	0.0
⁸⁷ Rb	0.67+10	2.4-006	0.0	0.0	0.0	0.0

TABLE A.2.8. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case GRT008W

Parametric Data

Release duration = 1.0E+02; delay prior to release = 1.0E+00 yr;
ground-water velocity = 1.50E-02 m/yr; ground-water pathlength = 1.50E+04 m;
ground-water travel time = 1.0E+06 yr; dispersion coefficient = 5.3E-03 m²/yr.

Nuclide	Time After Closure, yr	Seventy-year dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
¹²⁹ I	0.10E+07	1.0+002	3.8+001	0.0	8.2+004	5.7+000
⁹⁹ Tc	0.10E+07	5.6+001	1.4+002	1.8+001	0.0	7.6+003
²²⁶ Ra	0.27E+09	2.1+002	2.7+002	0.0	0.0	0.0
²³⁴ U	0.27E+09	5.3+000	8.5+001	0.0	0.0	7.1+000
²³⁸ U	0.27E+09	3.9+000	6.4+001	0.0	0.0	5.2+000
²¹⁰ Pb	0.27E+09	2.4+000	6.2+001	0.0	0.0	0.0
²³⁰ Th	0.27E+09	4.8-002	1.6+000	0.0	0.0	0.0
²¹⁰ Po	0.27E+09	9.5-002	3.9-001	0.0	0.0	0.0
²³⁵ U	0.27E+09	1.4-002	2.3-001	0.0	0.0	2.5-002
²³⁶ U	0.27E+09	2.0-003	3.2-002	0.0	0.0	0.0
²³¹ Pa	0.27E+09	8.8-004	2.1-002	0.0	0.0	0.0
²²⁷ Ac	0.27E+09	6.4-004	1.0-002	0.0	0.0	0.0
²²⁸ Th	0.17E+11	5.8-004	5.3-004	0.0	0.0	0.0
²¹⁰ Bi	0.27E+09	1.3-004	2.3-004	0.0	0.0	0.0
²³² Th	0.17E+11	2.7-007	7.9-006	0.0	0.0	3.0-007
²²⁴ Ra	0.17E+11	5.3-007	2.6-006	0.0	0.0	0.0
²²⁸ Th	0.17E+11	8.5-008	2.5-006	0.0	0.0	0.0
⁸⁷ Rb	0.67E+10	2.5-006	0.0	0.0	0.0	0.0

TABLE A.2.9. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case GRT009W

Parametric Data

Release duration = 1.0E+04; delay prior to release = 1.0E+00 yr;
ground-water velocity = 1.5E-02 m/yr; ground-water pathlength = 1.50E+04 m;
ground-water travel time = 1.0E+06 yr; dispersion coefficient = 5.3E-03 m²/yr.

Nuclide	Time After Closure, yr	Seventy-year dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
¹²⁹ I	0.10E+07	1.3+001	4.5+000	0.0	9.8+003	6.8-001
⁹⁹ Tc	0.10E+07	6.7+000	1.7+001	2.1+000	0.0	9.1+002
²²⁶ Ra	0.27E+09	2.1+002	2.7+002	0.0	0.0	0.0
²³⁴ U	0.27E+09	5.3+000	8.5+001	0.0	0.0	7.1+000
²³⁸ U	0.27E+09	3.9+000	6.4+001	0.0	0.0	5.2+000
²¹⁰ Pb	0.27E+09	2.4+000	6.2+001	0.0	0.0	0.0
²³⁰ Th	0.27E+09	4.8-002	1.6+000	0.0	0.0	0.0
²¹⁰ Po	0.27E+09	9.5-002	3.9-001	0.0	0.0	0.0
²³⁵ U	0.27E+09	1.4-002	2.3-001	0.0	0.0	2.5-002
²³⁶ U	0.27E+09	2.0-003	3.2-002	0.0	0.0	0.0
²³¹ Pa	0.27E+09	8.8-004	2.1-002	0.0	0.0	0.0
²²⁷ Ac	0.27E+09	6.4-004	1.0-002	0.0	0.0	0.0
²²⁸ Ra	0.17E+11	6.1-004	5.5-004	0.0	0.0	0.0
²¹⁰ Bi	0.27E+09	1.3-004	2.3-004	0.0	0.0	0.0
²³² Th	0.17E+11	2.9-007	8.3-006	0.0	0.0	3.1-007
²²⁴ Ra	0.17E+11	5.5-007	2.8-006	0.0	0.0	0.0
²²⁸ Th	0.17E+11	8.9-008	2.6-006	0.0	0.0	0.0
⁸⁷ Rb	0.67E+10	2.5-006	0.0	0.0	0.0	0.0

TABLE A.2.10. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case GRT010W

Parametric Data

Release duration = 1.0E+02; delay prior to release = 1.0E+00 yr;
ground-water velocity = 2.00E+00 m/yr; ground-water pathlength = 1.00E+02 m;
ground-water travel time = 5.0E+01 yr; dispersion coefficient = 2.6E+00 m²/yr.

Nuclide	Time After Closure, yr	Seventy-year dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
¹⁴ C	0.53E+02	5.9+005	2.9+006	5.9+005	5.9+005	5.9+005
⁹⁹ Tc	0.53E+02	1.7+004	4.3+004	5.4+003	0.0	2.3+006
¹²⁹ I	0.53E+02	1.3+003	4.7+002	0.0	1.0+006	7.1+001
²³⁴ U	0.14E+05	1.7+004	2.7+005	0.0	0.0	2.2+004
²³⁷ Np	0.33E+05	2.4+003	5.5+004	0.0	0.0	0.0
²³⁸ U	0.14E+05	2.4+003	3.9+004	0.0	0.0	3.2+003
²³⁶ U	0.14E+05	2.3+003	3.6+004	0.0	0.0	0.0
²⁴² Pu	0.10E+06	3.6+002	7.5+003	0.0	0.0	2.0+003
²²⁶ Ra	0.33E+05	4.1+003	5.4+003	0.0	0.0	0.0
¹⁵⁹ Ni	0.33E+05	6.8+002	4.1+003	0.0	0.0	0.0
²²⁹ Th	0.33E+05	1.3+002	2.6+003	0.0	0.0	0.0
²²⁵ Ra	0.33E+05	3.3+002	1.6+003	0.0	0.0	0.0
²¹⁰ Pb	0.33E+05	4.9+001	1.2+003	0.0	0.0	0.0
²³³ U	0.33E+05	3.2+001	5.2+002	0.0	0.0	0.0
²³⁹ Pu	0.10E+06	1.4+001	3.0+002	0.0	0.0	7.6+001
¹²⁶ Sn	0.17E+06	6.3+000	2.2+002	0.0	1.3+000	0.0
²³⁵ U	0.14E+05	1.0+001	1.6+002	0.0	0.0	1.8+001
³ H	0.53E+02	1.4+002	0.0	1.4+002	1.4+002	1.4+002
²⁴⁰ Pu	0.10E+06	3.3+000	7.1+001	0.0	0.0	1.8+001
⁷⁹ Se	0.42E+04	4.7+004	0.0	0.0	0.0	0.0

TABLE A.2.11. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case GRT011W

Parametric Data

Release duration = 1.0E+04; delay prior to release = 1.0E+00 yr;
ground-water velocity = 2.00E+00 m/yr; ground-water pathlength = 1.00E+02 m;
ground-water travel time = 5.0E+01 yr; dispersion coefficient = 2.6E+00 m²/yr.

Nuclide	Time After Closure, yr	Seventy-year dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
¹⁴ C	0.53E+02	5.9+003	2.9+004	5.9+003	5.9+003	5.9+003
⁹⁹ Tc	0.53E+02	1.7+002	4.3+002	5.4+001	0.0	2.3+004
²³⁴ U	0.15E+05	9.9+002	1.6+004	0.0	0.0	1.3+003
²³⁷ Np	0.35E+05	4.5+002	1.0+004	0.0	0.0	0.0
¹²⁹ I	0.53E+02	1.3+001	4.7+000	0.0	1.0+004	7.1-001
²²⁶ Ra	0.35E+05	4.7+003	6.2+003	0.0	0.0	0.0
²²⁹ Th	0.35E+05	1.4+002	2.8+003	0.0	0.0	0.0
²³⁶ U	0.15E+05	1.4+002	2.2+003	0.0	0.0	0.0
²³⁸ U	0.15E+05	1.3+002	2.2+003	0.0	0.0	1.8+002
²²⁵ Ra	0.35E+05	3.6+002	1.8+003	0.0	0.0	0.0
²⁴² Pu	0.10E+06	7.6+001	1.6+003	0.0	0.0	4.2+002
²¹⁰ Pb	0.35E+05	5.6+001	1.4+003	0.0	0.0	0.0
²³³ U	0.35E+05	3.9+001	6.3+002	0.0	0.0	0.0
⁵⁹ Ni	0.35E+05	9.0+001	5.3+002	0.0	0.0	0.0
¹²⁶ Sn	0.17E+06	3.7+000	1.3+002	0.0	7.6-001	0.0
²³⁹ Pu	0.10E+06	3.3+000	7.1+001	0.0	0.0	1.8+001
²³⁰ Th	0.35E+05	1.1+000	3.7+001	0.0	0.0	0.0
²⁴⁰ Pu	0.10E+06	6.7-001	1.4+001	0.0	0.0	3.8+000
²³⁵ U	0.15E+05	5.5-001	9.1+000	0.0	0.0	1.0+000
⁷⁹ Se	0.42E+04	5.6+002	0.0	0.0	0.0	0.0

TABLE A.2.12. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case GRT012W

Parametric Data

Release duration = 1.0E+06; delay prior to release = 1.0E+00 yr;
ground-water velocity = 2.00E+00 m/yr; ground-water pathlength = 1.0E+02 m;
ground-water travel time = 5.0E+01 yr; dispersion coefficient = 2.6E+00 m²/yr.

Nuclide	Time After Closure, yr	Seventy-year dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
²²⁶ Ra	0.17E+06	3.9+002	5.1+002	0.0	0.0	0.0
²²⁹ Th	0.67E+06	2.0+001	4.1+002	0.0	0.0	0.0
¹⁴ C	0.53E+02	5.9+001	2.9+002	5.9+001	5.9+001	5.9+001
²²⁵ Ra	0.67E+06	5.2+001	2.6+002	0.0	0.0	0.0
⁹⁹ Tc	0.53E+02	1.7+000	4.4+000	5.4-001	0.0	2.3+002
²³⁴ U	0.15E+05	9.9+000	1.6+002	0.0	0.0	1.3+001
²¹⁰ Pb	0.17E+06	4.6+000	1.2+002	0.0	0.0	0.0
²³⁷ Np	0.35E+05	4.6+000	1.0+002	0.0	0.0	0.0
¹²⁹ I	0.53E+02	1.3-001	4.7-002	0.0	1.0+002	7.1-003
²³³ U	0.67E+06	5.7+000	9.3+001	0.0	0.0	0.0
²³⁶ U	0.56E+05	2.0+000	3.2+001	0.0	0.0	0.0
²⁴² Pu	0.17E+06	1.3+000	2.7+001	0.0	0.0	7.4+000
²³⁸ U	0.60E+05	1.3+000	2.2+001	0.0	0.0	1.8+000
⁵⁹ Ni	0.35E+05	9.0-001	5.3+000	0.0	0.0	0.0
²³⁰ Th	0.17E+06	8.7-002	2.9+000	0.0	0.0	0.0
²³⁹ Pu	0.17E+06	7.1-002	1.5+000	0.0	0.0	3.9-001
¹²⁶ Sn	0.17E+06	4.1-002	1.4+000	0.0	8.3-003	0.0
²¹⁰ Po	0.17E+06	1.8-001	7.4-001	0.0	0.0	0.0
¹³⁵ Cs	0.29E+07	1.7-001	4.3-001	4.5-002	0.0	0.0
⁷⁹ Se	0.60E+05	6.0+000	0.0	0.0	0.0	0.0

APPENDIX B

REFERENCE BASALT SITE
EXPANDED DOSE SUMMARY TABLES

REFERENCE BASALT SITE EXPANDED DOSE SUMMARY TABLES

B.1 SUMMARY TABLES FOR GENERAL LEACH INCIDENT SCENARIOS

The following tables are expanded summaries of the consequence calculations for the basalt site parametric sets. These tables list the nuclides in descending order of dose commitment to a critical organ, along with the associated total body dose and time of maximum dose occurrence. Tables B.1.1 through B.1.8 contain the results for the general leach-incident scenario. All tables are arbitrarily cut off at the 20 most dose-significant (to critical organ) nuclides in order to save space. Very little information is lost since generally only a few isotopes dominate the dose and all others are orders of magnitude less significant. In several cases, ^{79}Se is shown as the twentieth nuclide due to its strong contribution to the "total body" dose even though it is insignificant as a critical-organ dose contributor.

TABLE B.1.1. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case BST001G

Parametric Data

Release duration = 1.0E+02 yr; delay prior to release = 1.0E+00 yr;
ground-water velocity = 3.11E+01 m/yr; ground-water pathlength = 1.6E+04 m;
ground-water travel time = 5.0E+02 yr; dispersion coefficient = 3.7E+01 m²/yr.

<u>Nuclide</u>	<u>Time After Closure, yr</u>	<u>Seventy-year dose, rem</u>				
		<u>Total Body</u>	<u>Bone</u>	<u>Lungs</u>	<u>Thyroid</u>	<u>GI-LLI</u>
¹⁴ C	0.52E+03	1.4+001	7.2+001	1.4+001	1.4+001	1.4+001
²⁴³ Am	0.32E+05	1.6+000	3.2+001	3.2-001	3.2-001	3.2-001
²³⁷ Np	0.26E+05	1.6+000	2.4+001	5.6-001	5.6-001	5.6-001
¹²⁹ I	0.26E+05	2.1-002	1.2-002	7.2-003	1.1+001	7.9-003
⁹⁹ Tc	0.52E+05	7.7-002	1.9-001	2.4-002	5.8-007	1.0+001
²³⁴ U	0.52E+05	5.7-001	9.1+000	2.7-003	2.7-003	7.6-001
²³⁸ U	0.52E+05	1.2-001	1.6+000	2.7-002	2.7-002	1.5-001
²³⁶ U	0.52E+05	8.4-002	1.3+000	1.2-005	1.2-005	1.2-005
²⁴² Pu	0.30E+06	1.5-002	3.1-001	4.2-005	4.2-005	8.2-002
²²⁶ Ra	0.78E+05	1.5-001	1.9-001	2.1-004	2.1-004	2.1-004
²²⁹ Th	0.32E+05	9.5-003	1.8-001	8.4-004	8.4-004	8.4-004
²²⁵ Ra	0.32E+05	2.2-002	1.1-001	0.0	0.0	0.0
²⁴⁵ Cm	0.52E+05	3.9-003	8.2-002	5.7-004	5.7-004	5.7-004
²⁴¹ Am	0.52E+05	3.2-003	7.7-002	1.1-004	1.1-004	6.6-003
²¹⁰ Pb	0.78E+05	8.2-004	2.1-002	1.2-007	1.2-007	1.2-007
¹²⁶ Sn	0.52E+06	3.4-003	1.6-002	3.0-003	3.1-003	3.0-003
²³³ U	0.32E+05	8.7-004	1.4-002	3.1-006	3.1-006	3.1-006
²¹⁰ Po	0.78E+05	3.3-003	1.4-002	1.4-011	1.4-011	1.4-011
⁵⁹ Ni	0.26E+06	1.9-003	1.2-002	6.3-008	6.3-008	6.3-008
²³⁰ Th	0.78E+05	2.9-004	9.8-003	6.9-007	6.9-007	6.9-007

TABLE B.1.2. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case BST002G

Parametric Data

Release duration = 1.0E+06 yr; delay prior to release = 1.0E+02 yr;
ground-water velocity = 3.11E+01 m/yr; ground-water pathlength = 1.6E+04 m;
ground-water travel time = 5.0E+02 yr; dispersion coefficient = 3.7E+01 m²/yr.

Nuclide	Time After Closure, yr	Seventy-year dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
²²⁹ Th	0.52E+06	1.7-003	3.2-002	1.5-004	1.5-004	1.5-004
²²⁶ Ra	0.26E+06	1.6-002	2.1-002	2.3-005	2.3-005	2.3-005
²²⁵ Ra	0.52E+06	4.0-003	2.0-002	0.0	0.0	0.0
²⁴³ Am	0.33E+05	5.0-004	1.0-002	1.0-004	1.0-004	1.0-004
²³⁷ Np	0.26E+05	5.8-004	8.8-003	2.0-004	2.0-004	2.0-004
¹⁴ C	0.52E+03	1.4-003	7.2-003	1.4-003	1.4-003	1.4-003
⁹⁹ Tc	0.53E+05	3.9-005	9.6-005	1.2-005	2.9-010	5.2-003
²³⁴ U	0.53E+05	3.1-004	5.0-003	1.5-006	1.5-006	4.1-004
¹²⁹ I	0.53E+05	5.4-006	3.1-006	1.9-006	2.8-003	2.1-006
²³³ U	0.52E+06	1.6-004	2.5-003	5.6-007	5.6-007	5.6-007
²¹⁰ Pb	0.26E+06	9.1-005	2.3-003	1.3-008	1.3-008	1.3-008
²¹⁰ Po	0.26E+06	3.6-004	1.5-003	1.6-012	1.6-012	1.6-012
²³⁶ U	0.78E+05	6.7-005	1.1-003	9.4-009	9.4-009	9.4-009
²³⁰ Th	0.26E+06	2.4-005	8.1-004	5.7-008	5.7-008	5.7-008
²³⁸ U	0.53E+05	6.1-005	8.0-004	1.4-005	1.4-005	7.8-005
²⁴² Pu	0.40E+06	3.7-005	7.7-004	1.1-007	1.1-007	2.1-004
²²⁵ Ac	0.52E+06	1.1-004	1.5-004	1.1-004	1.1-004	1.1-004
¹²⁶ Sn	0.52E+06	1.6-005	7.7-005	1.4-005	1.5-005	1.4-005
¹³⁵ Cs	0.44E+07	2.0-005	4.8-005	5.0-006	9.9-013	9.9-013
²⁴⁵ Cm	0.53E+05	1.9-006	3.9-005	2.7-007	2.7-007	2.7-007

TABLE B.1.3. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case BST003G

Parametric Data

Release duration = 1.0E+06 yr; delay prior to release = 1.0E+06 yr;
ground-water velocity = 3.11E+01 m/yr; ground-water pathlength = 1.6E+04 m;
ground-water travel time = 5.0E+02 yr; dispersion coefficient = 3.7E+01 m²/yr.

Nuclide	Time After Closure, yr	Seventy-year dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
²²⁶ Ra	0.13E+07	6.6-003	8.7-003	9.6-006	9.6-006	9.6-006
²³⁷ Np	0.11E+07	3.9-004	6.0-003	1.4-004	1.4-004	1.4-004
¹²⁹ I	0.11E+07	5.2-006	3.0-006	1.8-006	2.7-003	2.0-006
²³³ U	0.11E+07	1.5-004	2.4-003	5.3-007	5.3-007	5.3-007
²²⁹ Th	0.11E+07	1.2-004	2.2-003	1.0-005	1.0-005	1.0-005
²²⁵ Ra	0.11E+07	2.7-004	1.4-003	0.0	0.0	0.0
²³⁴ U	0.11E+07	7.5-005	1.2-003	3.5-007	3.5-007	1.0-004
²³⁶ U	0.11E+07	6.4-005	1.0-003	9.1-009	9.1-009	9.1-009
²¹⁰ Pb	0.13E+07	3.7-005	9.5-004	5.3-009	5.3-009	5.3-009
²³⁸ U	0.11E+07	6.1-005	8.0-004	1.4-005	1.4-005	7.8-005
²¹⁰ Po	0.13E+07	1.5-004	6.1-004	6.4-013	6.4-013	6.4-013
²³⁰ Th	0.13E+07	1.1-005	3.5-004	2.5-008	2.5-008	2.5-008
⁹⁹ Tc	0.11E+07	1.4-006	3.6-006	4.5-007	1.1-011	1.9-004
²⁴² Pu	0.14E+07	6.0-006	1.2-004	1.7-008	1.7-008	3.3-005
²³⁵ U	0.11E+07	8.9-006	7.6-005	4.5-006	4.5-006	1.2-005
¹³⁵ Cs	0.54E+07	1.6-005	3.8-005	4.0-006	7.9-013	7.9-013
²²⁷ Ac	0.15E+07	2.3-006	3.3-005	2.0-007	2.0-007	2.0-007
²³¹ Pa	0.15E+07	1.1-006	1.7-005	4.0-007	4.0-007	4.0-007
²²⁸ Ra	0.21E+07	1.3-005	1.2-005	5.8-009	5.8-009	5.8-009
²²⁵ Ac	0.11E+07	7.6-006	9.8-006	7.4-006	7.4-006	7.4-006

TABLE B.1.4. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case BST004G

Parametric Data

Release duration = 1.0E+02 yr; delay prior to release = 1.0E+06 yr;
ground-water velocity = 3.11E+01 m/yr; ground-water pathlength = 1.6E+04 m;
ground-water travel time = 5.0E+02 yr; dispersion coefficient = 3.7E+01 m²/yr.

Nuclide	Time After Closure, yr	Seventy-year dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
²³⁷ Np	0.10E+07	1.5+000	2.3+001	5.3-001	5.3-001	5.3-001
¹²⁹ I	0.10E+07	2.0-002	1.2-002	6.9-003	1.0+001	7.6-003
²³³ U	0.11E+07	2.6-001	4.3+000	9.5-004	9.5-004	9.5-004
²³⁴ U	0.11E+07	1.5-001	2.4+000	7.0-004	7.0-004	2.0-001
²³⁶ U	0.11E+07	1.3-001	2.0+000	1.8-005	1.8-005	1.8-005
²³⁸ U	0.11E+07	1.2-001	1.6+000	2.7-002	2.7-002	1.5-001
⁹⁹ Tc	0.11E+07	2.8-003	7.0-003	8.8-004	2.1-008	3.8-001
²³⁵ U	0.11E+07	1.7-002	1.5-001	8.8-003	8.8-003	2.4-002
²²⁹ Th	0.11E+07	5.8-003	1.1-001	5.1-004	5.1-004	5.1-004
²²⁶ Ra	0.11E+07	5.6-002	7.3-002	8.1-005	8.1-005	8.1-005
²²⁵ Ra	0.11E+07	1.4-002	6.7-002	0.0	0.0	0.0
²⁴² Pu	0.13E+07	2.5-003	5.1-002	6.9-006	6.9-006	1.4-002
²¹⁰ Pb	0.11E+07	3.1-004	8.0-003	4.5-008	4.5-008	4.5-008
²¹⁰ Po	0.11E+07	1.2-003	5.1-003	5.4-012	5.4-012	5.4-012
²³⁰ Th	0.11E+07	1.1-004	3.5-003	2.5-007	2.5-007	2.5-007
²²⁸ Ra	0.20E+07	1.2-003	1.1-003	5.4-007	5.4-007	5.4-007
¹³⁵ Cs	0.53E+07	4.0-004	9.7-004	1.0-004	2.0-011	2.0-011
^{93m} Nb	0.20E+07	5.8-005	6.8-004	2.7-006	2.7-006	2.7-006
²²⁵ Ac	0.11E+07	3.8-004	4.9-004	3.7-004	3.7-004	3.7-004
²²⁷ Ac	0.11E+07	3.1-005	4.6-004	2.7-006	2.7-006	2.7-006

TABLE B.1.5. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case BST005G

Parametric Data

Release duration = 1.0E+02 yr; delay prior to release = 1.0E+06 yr;
ground-water velocity = 1.60E-02 m/yr; ground-water pathlength = 3.22E+04 m;
ground-water travel time = 2.0E+06 yr; dispersion coefficient = 7.4E-04 m²/yr.

Nuclide	Time After Closure, yr	Seventy-year dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
²²⁶ Ra	0.20E+09	1.5-002	1.09-002	2.1-005	2.1-005	2.1-005
²³⁴ U	0.20E+09	8.3-004	1.3-002	3.9-006	3.9-006	1.1-003
²³⁸ U	0.20E+09	8.2-004	1.1-002	1.9-004	1.9-004	1.0-003
²¹⁰ Pb	0.20E+09	8.2-005	2.1-003	1.2-008	1.2-008	1.2-008
²¹⁰ Po	0.20E+09	3.3-004	1.4-003	1.4-012	1.4-012	1.4-012
¹²⁹ I	0.10E+09	1.9-006	1.1-006	6.4-007	9.5-004	7.1-007
²³⁵ U	0.20E+09	1.0-004	8.7-004	5.2-005	5.2-005	1.4-004
²³⁰ Th	0.20E+09	2.5-005	8.3-004	5.8-008	5.8-008	5.8-008
²²⁷ Ac	0.20E+09	1.3-005	1.9-004	1.1-006	1.1-006	1.1-006
²³¹ Pa	0.20E+09	6.3-006	9.7-005	2.3-006	2.3-006	2.3-006
²³⁶ U	0.20E+09	2.3-006	3.7-005	3.2-010	3.2-010	3.2-010
²²⁸ Ra	0.40E+10	7.2-006	6.5-006	3.2-009	3.2-009	3.2-009
²³² Th	0.40E+10	8.9-009	1.5-007	3.8-009	3.8-009	9.3-009
²²⁴ Ra	0.40E+10	1.4-008	6.8-008	1.0-011	1.0-011	1.0-011
²²⁸ Th	0.40E+10	2.4-009	4.7-008	8.5-010	8.5-010	8.5-010
²¹⁰ Bi	0.20E+09	4.6-009	8.0-009	7.5-012	7.5-012	7.5-012
²³⁷ Np	0.10E+09	1.1-016	1.6-015	3.7-017	3.7-017	3.7-017
⁸⁷ Rb	0.40E+10	2.4-009	2.8-016	2.8-016	2.8-016	2.8-016
²³³ U	0.10E+09	2.9-018	4.7-017	1.0-020	1.0-020	1.0-020
²²⁹ Th	0.10E+09	1.3-018	2.4-017	1.1-019	1.1-019	1.1-019

**TABLE B.1.6. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case BST006G**

Parametric Data

Release duration = 1.0E+06 yr; delay prior to release = 1.0E+06 yr;
ground-water velocity = 1.60E-02 m/yr; ground-water pathlength = 3.22E+04 m;
ground-water travel time = 2.0E+06 yr; dispersion coefficient = 7.4E-04 m²/yr.

Nuclide	Time After Closure, yr	Seventy-year dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
²²⁶ Ra	0.20E+09	2.9-003	3.9-003	4.3-006	4.3-006	4.3-006
²³⁴ U	0.20E+09	6.0-005	9.5-004	2.8-007	2.8-007	7.9-005
²³⁸ U	0.20E+09	5.9-005	7.6-004	1.3-005	1.3-005	7.4-005
²¹⁰ Pb	0.20E+09	1.6-005	4.2-004	2.4-009	2.4-009	2.4-009
²¹⁰ Po	0.20E+09	6.5-005	2.7-004	2.8-013	2.8-013	2.8-013
²³⁰ Th	0.20E+09	4.6-006	1.5-004	1.1-008	1.1-008	1.1-008
²³⁵ U	0.20E+09	7.2-006	6.2-005	3.7-006	3.7-006	1.0-005
¹²⁹ I	0.10E+09	6.7-008	3.9-008	2.3-008	3.4-005	2.5-008
²²⁷ Ac	0.20E+09	1.7-006	2.5-005	1.4-007	1.4-007	1.4-007
²³¹ Pa	0.20E+09	8.2-007	1.3-005	3.0-007	3.0-007	3.0-007
²²⁸ Ra	0.40E+10	9.4-006	8.6-006	4.2-009	4.2-009	4.2-009
²³⁶ U	0.20E+09	1.6-007	2.6-006	2.3-011	2.3-011	2.3-011
²³² Th	0.40E+10	1.2-008	2.0-007	5.0-009	5.0-009	1.2-008
²²⁴ Ra	0.40E+10	1.8-008	9.0-008	1.3-011	1.3-011	1.3-011
²²⁸ Th	0.40E+10	3.2-009	6.2-008	1.1-009	1.1-009	1.1-009
²¹⁰ Bi	0.20E+09	9.2-010	1.6-009	1.5-012	1.5-012	1.5-012
⁸⁷ Rb	0.40E+10	2.1-009	2.5-016	2.5-016	2.5-016	2.5-016
²³⁷ Np	0.10E+09	3.7-018	5.6-017	1.3-018	1.3-018	1.3-018
²³³ U	0.10E+09	2.6-019	4.2-018	9.2-022	9.2-022	9.2-022
²²⁹ Th	0.10E+09	1.7-019	3.2-018	1.5-020	1.5-020	1.5-020

TABLE B.1.7. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case BST007G

Parametric Data

Release duration = 1.0E+06 yr; delay prior to release = 1.0E+00 yr;
ground-water velocity = 1.60E-02 m/yr; ground-water pathlength = 3.22E+04 m;
ground-water travel time = 2.0E+06 yr; dispersion coefficient = 7.4E-04 m²/yr.

Nuclide	Time After Closure, yr	Seventy-year dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
²²⁶ Ra	0.20E+09	2.9-003	3.9-003	4.3-006	4.3-006	4.3-006
²³⁴ U	0.20E+09	6.0-005	9.5-004	2.8-007	2.8-007	7.9-005
²³⁸ U	0.20E+09	5.9-005	7.6-004	1.3-005	1.3-005	7.4-005
²¹⁰ Pb	0.20E+09	1.6-005	4.2-004	2.4-009	2.4-009	2.4-009
²¹⁰ Po	0.20E+09	6.5-005	2.7-004	2.8-013	2.8-013	2.8-013
²³⁰ Th	0.20E+09	4.6-006	1.5-004	1.1-008	1.1-008	1.1-008
¹²⁹ I	0.10E+09	6.9-008	4.0-008	2.4-008	3.5-005	2.6-008
²³⁵ U	0.20E+09	3.6-007	3.1-006	1.8-007	1.8-007	5.0-007
²²⁸ Ra	0.40E+10	3.3-006	3.0-006	1.4-009	1.4-009	1.4-009
²³⁶ U	0.20E+09	1.7-007	2.7-006	2.3-011	2.3-011	2.3-011
²²⁷ Ac	0.20E+09	8.3-008	1.2-006	7.1-009	7.1-009	7.1-009
²³¹ Pa	0.20E+09	4.0-008	6.3-007	1.5-008	1.5-008	1.5-008
²³² Th	0.40E+10	4.1-009	6.9-008	1.8-009	1.8-009	4.3-009
²²⁴ Ra	0.40E+10	6.3-009	3.1-008	4.6-012	4.6-012	4.6-012
²²⁸ Th	0.40E+10	1.1-009	2.2-008	3.9-010	3.9-010	3.9-010
²¹⁰ Bi	0.20E+09	9.2-010	1.6-009	1.5-012	1.5-012	1.5-012
⁸⁷ Rb	0.40E+10	2.1-009	2.5-016	2.5-016	2.5-016	2.5-016
²³⁷ Np	0.10E+09	5.0-018	7.6-017	1.8-018	1.8-018	1.8-018
²²⁹ Th	0.10E+09	3.9-018	7.3-017	3.5-019	3.5-019	3.5-019
²²⁵ Ra	0.10E+09	9.2-018	4.6-017	0.0	0.0	0.0

TABLE B.1.8. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case BST008G

Parametric Data

Release duration = 1.0E+02 yr; delay prior to release = 1.0E+00 yr;
ground-water velocity = 1.60E-02 m/yr; ground-water pathlength = 3.22E+04 m;
ground-water travel time = 2.0E+06 yr; dispersion coefficient = 7.4E-04 m²/yr.

Nuclide	Time After Closure, yr	Seventy-year dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
²²⁶ Ra	0.20E+09	1.5-002	1.9-002	2.1-005	2.1-005	2.1-005
²³⁴ U	0.20E+09	8.3-004	1.3-002	3.9-006	3.9-006	1.1-003
²³⁸ U	0.20E+09	8.2-004	1.1-002	1.9-004	1.9-004	1.0-003
²¹⁰ Pb	0.20E+09	8.2-005	2.1-003	1.2-008	1.2-008	1.2-008
²¹⁰ Po	0.20E+09	3.3-004	1.4-003	1.4-012	1.4-012	1.4-012
¹²⁹ I	0.10E+09	1.9-006	1.1-006	6.4-007	9.5-004	7.1-007
²³⁵ U	0.20E+09	1.0-004	8.7-004	5.2-005	5.2-005	1.4-004
²³⁰ Th	0.20E+09	2.5-005	8.3-004	5.8-008	5.8-008	5.8-008
²²⁷ Ac	0.20E+09	1.3-005	1.9-004	1.1-006	1.1-006	1.1-006
²³¹ Pa	0.20E+09	6.3-006	9.7-005	2.3-006	2.3-006	2.3-006
²³⁶ U	0.20E+09	2.3-006	3.7-005	3.2-010	3.2-010	3.2-010
²²⁸ Ra	0.40E+10	7.2-006	6.5-006	3.2-009	3.2-009	3.2-009
²³² Th	0.40E+10	8.9-009	1.5-007	3.8-009	3.8-009	9.3-009
²²⁴ Ra	0.40E+10	1.4-008	6.8-008	1.0-011	1.0-011	1.0-011
²²⁸ Th	0.40E+10	2.4-009	4.7-008	8.5-010	8.5-010	8.5-010
²¹⁰ Bi	0.20E+09	4.6-009	8.0-009	7.5-012	7.5-012	7.5-012
²³⁷ Np	0.10E+09	1.1-016	1.6-015	3.7-017	3.7-017	3.7-017
⁸⁷ Rb	0.40E+10	2.4-009	2.8-016	2.8-016	2.8-016	2.9-016
²³³ U	0.10E+09	2.9-018	4.7-017	1.0-020	1.0-020	1.0-020
²²⁹ Th	0.10E+09	1.3-018	2.4-017	1.1-019	1.1-019	1.1-019

B.2 SUMMARY TABLES FOR INTRUSION WATER WELL SCENARIO IN BASALT

The following tables are expanded summaries of the consequence calculations for the intrusion water well scenario. The nuclides are listed in decreasing dose commitment to critical organs, along with the associated total body dose commitment and time of peak dose occurrence. All tables are arbitrarily cut off at the 20 most dose-significant isotopes in order to save space. Very little information is lost since generally only a few isotopes dominate the dose and all others are orders of magnitude less significant. In several cases, ^{79}Se is shown as the twentieth nuclide due to its strong contribution to the "total body" dose, even though it is insignificant as a critical organ dose contributor.

TABLE B.2.1. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case BST001W

Parametric Data

Release duration = 1.0E+02 yr; delay prior to release = 1.0E+00 yr;
ground-water velocity = 3.11E+01 m/yr; ground-water pathlength = 1.60E+04 m;
ground-water travel time = 5.0E+02 yr; dispersion coefficient = 3.7E+01 m²/yr.

Nuclide	Time After Closure, yr	Seventy-year dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
¹⁴ C	0.52E+03	5.4+005	2.7+006	5.4+005	5.4+005	5.4+005
¹²⁹ I	0.26E+05	5.0+002	1.8+002	0.0	3.9+005	2.7+001
⁹⁹ Tc	0.52E+05	2.9+003	7.2+003	9.1+002	0.0	3.9+005
²³⁷ Np	0.26E+05	1.3+004	2.8+005	0.0	0.0	0.0
²³⁴ U	0.52E+05	1.7+004	2.7+005	0.0	0.0	2.2+004
²⁴³ Am	0.32E+05	6.6+003	1.7+005	0.0	0.0	0.0
²³⁸ U	0.52E+05	2.6+003	4.3+004	0.0	0.0	3.5+003
²³⁶ U	0.52E+05	2.5+003	4.0+004	0.0	0.0	0.0
²⁴² Pu	0.30E+06	3.5+002	7.2+003	0.0	0.0	1.9+003
²²⁶ Ra	0.78E+05	2.1+003	2.7+003	0.0	0.0	0.0
²²⁹ Th	0.32E+05	9.2+001	1.9+003	0.0	0.0	0.0
²²⁵ Ra	0.32E+05	2.4+002	1.2+003	0.0	0.0	0.0
²¹⁰ Pb	0.78E+05	2.4+001	6.2+002	0.0	0.0	0.0
²⁴⁵ Cm	0.52E+05	2.0+001	4.8+002	0.0	0.0	0.0
²³³ U	0.32E+05	2.6+001	4.2+002	0.0	0.0	0.0
²⁴¹ Am	0.52E+05	1.6+001	4.0+002	0.0	0.0	3.4+001
⁵⁹ Ni	0.26E+06	5.2+001	3.1+002	0.0	0.0	0.0
²³⁵ U	0.52E+05	1.1+001	1.7+002	0.0	0.0	1.9+001
²³⁰ Th	0.78E+05	3.1+000	1.0+002	0.0	0.0	0.0
⁷⁹ Se	0.78E+05	6.4+003	0.0	0.0	0.0	0.0

TABLE B.2.2. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case BST002W

Parametric Data

Release duration = 1.0E+06 yr; delay prior to release = 1.0E+02 yr;
ground-water velocity = 3.11E+01 m/yr; ground-water pathlength = 1.60E+04 m;
ground-water travel time = 5.0E+02 yr; dispersion coefficient = 3.7E+01 m²/yr.

Nuclide	Time After Closure, yr	Seventy-year dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
²²⁹ Th	0.52E+06	1.7+001	3.4+002	0.0	0.0	0.0
²²⁶ Ra	0.26E+06	2.3+002	3.0+002	0.0	0.0	0.0
¹⁴ C	0.52E+03	5.4+001	2.7+002	5.4+001	5.4+001	5.4+001
²²⁵ Ra	0.52E+06	4.3+001	2.2+002	0.0	0.0	0.0
⁹⁹ Tc	0.53E+05	1.5+000	3.7+000	4.6-001	0.0	2.0+002
²³⁴ U	0.53E+05	9.2+000	1.5+002	0.0	0.0	1.2+001
¹²⁹ I	0.53E+05	1.3-001	4.7-002	0.0	1.0+002	7.1-003
²³⁷ Np	0.26E+05	4.5+000	1.0+002	0.0	0.0	0.0
²³³ U	0.52E+06	4.6+000	7.5+001	0.0	0.0	0.0
²¹⁰ Pb	0.26E+06	2.7+000	6.8+001	0.0	0.0	0.0
²⁴³ Am	0.33E+05	2.1+000	5.2+001	0.0	0.0	0.0
²³⁶ U	0.78E+05	2.0+000	3.2+001	0.0	0.0	0.0
²³⁸ U	0.53E+05	1.3+000	2.2+001	0.0	0.0	1.8+000
²⁴² Pu	0.40E+06	8.8-001	1.8+001	0.0	0.0	4.9+000
²³⁰ Th	0.26E+06	2.6-001	8.6+000	0.0	0.0	0.0
⁵⁹ Ni	0.26E+06	1.3-001	7.5-001	0.0	0.0	0.0
²¹⁰ Po	0.26E+06	1.0-001	4.3-001	0.0	0.0	0.0
²³⁹ Pu	0.53E+05	1.7-002	3.7-001	0.0	0.0	9.4-002
¹³⁵ Cs	0.44E+07	1.1+001	2.8+001	2.9-002	0.0	0.0
²⁴⁵ Cm	0.53E+05	9.3-003	2.2-001	0.0	0.0	0.0
⁷⁹ Se	0.12E+06	3.2+000	0.0	0.0	0.0	0.0

**TABLE B.2.3. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case BST003W**

Parametric Data

Release duration = 1.0E+06 yr; delay prior to release = 1.0E+06 yr;
ground-water velocity = 3.11E+01 m/yr; ground-water pathlength = 1.60E+04 m;
ground-water travel time = 5.0E+02 yr; dispersion coefficient = 3.7E+01 m²/yr.

Nuclide	Time After Closure, yr	Seventy-year dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
²²⁶ Ra	0.13E+07	9.3+001	1.2+002	0.0	0.0	0.0
¹²⁹ I	0.11E+07	1.3-001	4.5-002	0.0	9.8+001	6.8-003
²³³ U	0.11E+07	4.4+000	7.1+001	0.0	0.0	0.0
²³⁷ Np	0.11E+07	3.1+000	7.0+001	0.0	0.0	0.0
²³⁴ U	0.11E+07	2.2+000	3.5+001	0.0	0.0	2.9+000
²³⁶ U	0.11E+07	1.9+000	3.0+001	0.0	0.0	0.0
²¹⁰ Pb	0.13E+07	1.1+000	2.8+001	0.0	0.0	0.0
²²⁹ Th	0.11E+07	1.1+000	2.3+001	0.0	0.0	0.0
²³⁸ U	0.11E+07	1.3+000	2.2+001	0.0	0.0	1.8+000
²²⁵ Ra	0.11E+07	2.9+000	1.4+001	0.0	0.0	0.0
⁹⁹ Tc	0.11E+07	5.5-002	1.4-001	1.7-002	0.0	7.4+000
²³⁰ Th	0.13E+07	1.1-001	3.7+000	0.0	0.0	0.0
²⁴² Pu	0.14E+07	1.4-001	2.9+000	0.0	0.0	7.8-001
²³⁵ U	0.11E+07	1.2-001	2.0+000	0.0	0.0	2.2-001
²³¹ Pa	0.15E+07	1.6-002	3.9-001	0.0	0.0	0.0
¹³⁵ Cs	0.54E+07	9.0-002	2.2-001	2.3-002	0.0	0.0
²²⁷ Ac	0.15E+07	1.2-002	1.9-001	0.0	0.0	0.0
²¹⁰ Po	0.13E+07	4.3-002	1.8-001	0.0	0.0	0.0
²²⁸ Ra	0.21E+07	1.8-001	1.6-001	0.0	0.0	0.0
⁷⁹ Se	0.11E+07	7.7-005	0.0	0.0	0.0	0.0

TABLE B.2.4. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case BST004W

Parametric Data

Release duration = 1.0E+02 yr; delay prior to release = 1.0E+06 yr;
ground-water velocity = 3.11E+01 m/yr; ground-water pathlength = 1.60E+04 m;
ground-water travel time = 5.0E+02 yr; dispersion coefficient = 3.7E+01 m²/yr.

Nuclide	Time After Closure, yr	Seventy-year dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
¹²⁹ I	0.10E+07	4.8+002	1.7+002	0.0	3.8+005	2.6+001
²³⁷ Np	0.10E+07	1.2+004	2.7+005	0.0	0.0	0.0
²³³ U	0.11E+07	7.8+003	1.3+005	0.0	0.0	0.0
²³⁴ U	0.11E+07	4.4+003	7.0+004	0.0	0.0	5.8+003
²³⁶ U	0.11E+07	3.7+003	6.0+004	0.0	0.0	0.0
²³⁸ U	0.11E+07	2.6+003	4.3+004	0.0	0.0	3.5+003
⁹⁹ Tc	0.11E+07	1.1+002	2.7+002	3.3+001	0.0	1.4+004
²³⁵ U	0.11E+07	2.4+002	3.9+003	0.0	0.0	4.4+002
²⁴² Pu	0.13E+07	5.7+001	1.2+003	0.0	0.0	3.2+002
²²⁹ Th	0.11E+07	5.6+001	1.1+003	0.0	0.0	0.0
²²⁶ Ra	0.11E+07	7.8+002	1.0+003	0.0	0.0	0.0
²²⁵ Ra	0.11E+07	1.4+002	7.2+002	0.0	0.0	0.0
²¹⁰ Pb	0.11E+07	9.2+000	2.4+002	0.0	0.0	0.0
²³⁰ Th	0.11E+07	1.1+000	3.7+001	0.0	0.0	0.0
²²⁸ Ra	0.20E+07	1.6+001	1.5+001	0.0	0.0	0.0
¹³⁵ Cs	0.53E+07	2.3+000	5.6+000	5.9-001	0.0	0.0
²³¹ Pa	0.11E+07	2.2-001	5.3+000	0.0	0.0	0.0
²²⁷ Ac	0.11E+07	1.6-001	2.6+000	0.0	0.0	0.0
²¹⁰ Po	0.11E+07	3.6-001	1.5+000	0.0	0.0	0.0
⁷⁹ Se	0.11E+07	1.5-001	0.0	0.0	0.0	0.0

TABLE B.2.5. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case BST005W

Parametric Data

Release duration = 1.0E+02 yr; delay prior to release = 1.0E+06 yr;
ground-water velocity = 1.6E-02 m/yr; ground-water pathlength = 3.22E+04 m;
ground-water travel time = 2.0E+06 yr; dispersion coefficient = 7.4E-04 m²/yr.

Nuclide	Time After Closure, yr	Seventy-year dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
²³⁴ U	0.20E+09	2.4+001	3.9+002	0.0	0.0	3.2+001
²³⁸ U	0.20E+09	1.8+001	2.9+002	0.0	0.0	2.4+001
²²⁶ Ra	0.20E+09	2.1+002	2.7+002	0.0	0.0	0.0
²¹⁰ Pb	0.20E+09	2.4+000	6.2+001	0.0	0.0	0.0
¹²⁹ I	0.10E+09	4.5-002	1.6-002	0.0	3.5+001	2.4-003
²³⁵ U	0.20E+09	1.4+000	2.3+001	0.0	0.0	2.6+000
²³⁰ Th	0.20E+09	2.6-001	8.8+000	0.0	0.0	0.0
²³¹ Pa	0.20E+09	9.3-002	2.2+000	0.0	0.0	0.0
²³⁶ U	0.20E+09	6.7-002	1.1+000	0.0	0.0	0.0
²²⁷ Ac	0.20E+09	6.7-002	1.1+000	0.0	0.0	0.0
²¹⁰ Po	0.20E+09	9.5-002	3.9-001	0.0	0.0	0.0
²²⁸ Ra	0.40E+10	9.6-002	8.8-002	0.0	0.0	0.0
²³² Th	0.40E+10	4.5-005	1.3-003	0.0	0.0	4.9-005
²²⁴ Ra	0.40E+10	8.8-005	4.4-004	0.0	0.0	0.0
²²⁸ Th	0.40E+10	1.4-005	4.1-004	0.0	0.0	0.0
²¹⁰ Bi	0.20E+09	1.3-004	2.3-004	0.0	0.0	0.0
²³⁷ Np	0.10E+09	8.4-013	1.9-011	0.0	0.0	0.0
²³³ U	0.10E+09	8.6-014	1.4-012	0.0	0.0	0.0
²²⁹ Th	0.10E+09	1.2-014	2.5-013	0.0	0.0	0.0
²²⁵ Ra	0.10E+09	3.2-014	1.6-013	0.0	0.0	0.0

TABLE B.2.6. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case BST006W

Parametric Data

Release duration = 1.0E+06 yr; delay prior to release = 1.0E+06 yr;
ground-water velocity = 1.60E-02 m/yr; ground-water pathlength = 3.22E+04 m;
ground-water travel time = 2.0E+06 yr; dispersion coefficient = 7.4E-04 m²/yr.

Nuclide	Time After Closure, yr	Seventy-year dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
²²⁶ Ra	0.20E+09	4.1+001	5.4+001	0.0	0.0	0.0
²³⁴ U	0.20E+09	1.7+000	2.8+001	0.0	0.0	2.3+000
²³⁸ U	0.20E+09	1.3+000	2.1+001	0.0	0.0	1.7+000
²¹⁰ Pb	0.20E+09	4.9-001	1.2+001	0.0	0.0	0.0
²³⁵ U	0.20E+09	1.0-001	1.6+000	0.0	0.0	1.8-001
²³⁰ Th	0.20E+09	4.8-002	1.6+000	0.0	0.0	0.0
¹²⁹ I	0.10E+09	1.6-003	5.8-004	0.0	1.3+000	8.8-005
²³¹ Pa	0.20E+09	1.2-002	2.9-001	0.0	0.0	0.0
²²⁷ Ac	0.20E+09	8.8-003	1.4-001	0.0	0.0	0.0
²²⁸ Ra	0.40E+10	1.3-001	1.2-001	0.0	0.0	0.0
²¹⁰ Po	0.20E+09	1.9-002	7.8-002	0.0	0.0	0.0
²³⁶ U	0.20E+09	4.8-003	7.7-002	0.0	0.0	0.0
²³² Th	0.40E+10	6.0-005	1.7-003	0.0	0.0	6.5-005
²²⁴ Ra	0.40E+10	1.1-004	5.8-004	0.0	0.0	0.0
²²⁸ Th	0.40E+10	1.9-005	5.4-004	0.0	0.0	0.0
²¹⁰ Bi	0.20E+09	2.7-005	4.7-005	0.0	0.0	0.0
²³⁷ Np	0.10E+09	2.9-014	6.5-013	0.0	0.0	0.0
²³³ U	0.10E+09	7.6-015	1.2-013	0.0	0.0	0.0
²²⁹ Th	0.10E+09	1.6-015	3.3-014	0.0	0.0	0.0
²²⁵ Ra	0.10E+09	4.2-015	2.1-014	0.0	0.0	0.0

TABLE B.2.7. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case BST007W

Parametric Data

Release duration = 1.0E+06 yr; delay prior to release = 1.0E+00 yr;
ground-water velocity = 1.6E-02 m/yr; ground-water pathlength = 3.22E+04 m;
ground-water travel time = 2.0E+06 yr; dispersion coefficient = 7.4E-04 m²/yr.

Nuclide	Time After Closure, yr	Seventy-year dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
²²⁶ Ra	0.20E+09	4.1+001	5.4+001	0.0	0.0	0.0
²³⁴ U	0.20E+09	1.7+000	2.8+001	0.0	0.0	2.3+000
²³⁸ U	0.20E+09	1.3+000	2.1+001	0.0	0.0	1.7+000
²¹⁰ Pb	0.20E+09	4.9-001	1.2+001	0.0	0.0	0.0
²³⁰ Th	0.20E+09	4.8-002	1.6+000	0.0	0.0	0.0
¹²⁹ I	0.10E+09	1.7-003	6.0-004	0.0	1.3+000	9.0-005
²³⁵ U	0.20E+09	5.0-003	8.2-002	0.0	0.0	9.0-003
²³⁶ U	0.20E+09	4.9-003	7.8-002	0.0	0.0	0.0
²¹⁰ Po	0.20E+09	1.9-002	7.8-002	0.0	0.0	0.0
²²⁸ Ra	0.40E+10	4.4-002	4.0-002	0.0	0.0	0.0
²³¹ Pa	0.20E+09	6.0-004	1.4-002	0.0	0.0	0.0
²²⁷ Ac	0.20E+09	4.3-004	6.8-003	0.0	0.0	0.0
²³² Th	0.40E+10	2.1-005	6.0-004	0.0	0.0	2.3-005
²²⁴ Ra	0.40E+10	4.0-005	2.0-004	0.0	0.0	0.0
²²⁸ Th	0.40E+10	6.5-006	1.9-004	0.0	0.0	0.0
²¹⁰ Bi	0.20E+09	2.7-005	4.7-005	0.0	0.0	0.0
²³⁷ Np	0.10E+09	3.9-014	8.9-013	0.0	0.0	0.0
²²⁹ Th	0.10E+09	3.8-014	7.7-013	0.0	0.0	0.0
²²⁵ Ra	0.10E+09	9.8-014	4.9-013	0.0	0.0	0.0
²³³ U	0.10E+09	1.0-014	1.7-013	0.0	0.0	0.0

TABLE B.2.8. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case BST008W

Parametric Data

Release duration = 1.0E+02 yr; delay prior to release = 1.0E+00 yr;
ground-water velocity = 1.6E-02 m/yr; ground-water pathlength = 3.22E+04 m;
ground-water travel time = 2.0E+06 yr; dispersion coefficient = 7.4E-04 m²/yr.

Nuclide	Time After Closure, yr	Seventy-year dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
²³⁴ U	0.20E+09	2.4+001	3.9+002	0.0	0.0	3.2+001
²³⁸ U	0.20E+09	1.8+001	2.9+002	0.0	0.0	2.4+001
²²⁶ Ra	0.20E+09	2.1+002	2.7+002	0.0	0.0	0.0
²¹⁰ Pb	0.20E+09	2.4+000	6.2+001	0.0	0.0	0.0
¹²⁹ I	0.10E+09	4.7-002	1.7-002	0.0	3.7+001	2.6-003
²³⁰ Th	0.20E+09	2.6-001	8.8+000	0.0	0.0	0.0
²³⁶ U	0.20E+09	6.7-002	1.1+000	0.0	0.0	0.0
²³⁵ U	0.20E+09	6.5-002	1.1+000	0.0	0.0	1.2-001
²¹⁰ Po	0.20E+09	9.5-002	3.9-001	0.0	0.0	0.0
²³¹ Pa	0.20E+09	4.3-003	1.0-001	0.0	0.0	0.0
²²⁷ Ac	0.20E+09	3.1-003	4.9-002	0.0	0.0	0.0
²²⁸ Ra	0.40E+10	3.6-003	3.2-003	0.0	0.0	0.0
²¹⁰ Bi	0.20E+09	1.3-004	2.3-004	0.0	0.0	0.0
²³² Th	0.40E+10	1.7-006	4.8-005	0.0	0.0	1.8-006
²²⁴ Ra	0.40E+10	3.2-006	1.6-005	0.0	0.0	0.0
²²⁸ Th	0.40E+10	5.2-007	1.5-005	0.0	0.0	0.0
²³⁷ Np	0.10E+09	1.2-012	2.6-011	0.0	0.0	0.0
²²⁹ Th	0.10E+09	4.4-013	9.0-012	0.0	0.0	0.0
²²⁵ Ra	0.10E+09	1.1-012	5.6-012	0.0	0.0	0.0
²³³ U	0.10E+09	1.2-013	1.9-012	0.0	0.0	0.0

TABLE B.2.9. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case BST009W

Parametric Data

Release duration = 1.0E+02 yr; delay prior to release = 1.0E+00 yr;
ground-water velocity = 3.11E+01 m/yr; ground-water pathlength = 1.56E+03 m;
ground-water travel time = 5.0E+01 yr; dispersion coefficient = 5.3E-01 m²/yr.

Nuclide	Time After Closure, yr	Seventy-year dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
²⁴¹ Am	0.32E+04	8.2+005	2.0+007	0.0	0.0	1.7+006
²⁴³ Am	0.32E+04	3.4+005	8.5+006	0.0	0.0	0.0
¹⁴ C	0.52E+02	5.9+005	2.9+006	5.9+005	5.9+005	5.9+005
⁹⁹ Tc	0.51E+04	1.7+004	4.2+004	5.2+003	0.0	2.2+006
²³⁴ U	0.51E+04	8.4+004	1.3+006	0.0	0.0	1.1+005
²⁴⁰ Pu	0.29E+05	6.3+004	1.3+006	0.0	0.0	3.5+005
¹²⁹ I	0.26E+04	1.3+003	4.7+002	0.0	1.0+006	7.1+001
²³⁷ Np	0.26E+04	2.5+004	5.7+005	0.0	0.0	0.0
²³⁸ U	0.51E+04	1.3+004	2.1+005	0.0	0.0	1.7+004
²³⁶ U	0.51E+04	1.2+004	1.9+005	0.0	0.0	0.0
²⁴⁵ Cm	0.51E+04	4.5+003	1.1+005	0.0	0.0	0.0
²⁴² Pu	0.29E+05	4.5+003	9.3+004	0.0	0.0	2.5+004
⁵⁹ Ni	0.25E+05	3.2+003	1.9+004	0.0	0.0	0.0
¹²⁶ Sn	0.50E+05	1.6+002	5.5+003	0.0	3.2+001	0.0
²²⁶ Ra	0.11E+05	3.3+003	4.3+003	0.0	0.0	0.0
²²⁹ Th	0.32E+04	9.6+001	1.9+003	0.0	0.0	0.0
²²⁵ Ra	0.32E+04	2.5+002	1.2+003	0.0	0.0	0.0
²¹⁰ Pb	0.11E+05	3.9+001	9.9+002	0.0	0.0	0.0
²³⁹ Pu	0.29E+05	4.2+001	9.1+002	0.0	0.0	2.3+002
⁷⁹ Se	0.76E+04	5.1+004	0.0	0.0	0.0	0.0

TABLE B.2.10. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case BST010W

Parametric Data

Release duration = 1.0E+04 yr; delay prior to release = 1.0E+00 yr;
ground-water velocity = 3.11E+01 m/yr; ground-water pathlength = 1.56E+03 m;
ground-water travel time = 5.0E+01 yr; dispersion coefficient = 5.3E-01 m²/yr.

Nuclide	Time After Closure, yr	Seventy-year dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
²⁴¹ Am	0.32E+04	8.2+003	2.0+005	0.0	0.0	1.7+004
²⁴³ Am	0.32E+04	3.4+003	8.5+004	0.0	0.0	0.0
¹⁴ C	0.52E+02	5.9+003	2.9+004	5.9+003	5.9+003	5.9+003
²⁴⁰ Pu	0.29E+05	1.2+003	2.5+004	0.0	0.0	6.6+003
⁹⁹ Tc	0.52E+04	1.7+002	4.3+002	5.4+001	0.0	2.3+004
²³⁴ U	0.52E+04	9.9+002	1.6+004	0.0	0.0	1.3+003
²³⁷ Np	0.32E+04	4.5+002	1.0+004	0.0	0.0	0.0
¹²⁹ I	0.52E+04	1.3+001	4.7+000	0.0	1.0+004	7.1+001
²²⁶ Ra	0.10E+06	5.8+003	7.6+003	0.0	0.0	0.0
²⁴² Pu	0.39E+05	1.7+002	3.4+003	0.0	0.0	9.3+002
²³⁶ U	0.11E+05	1.8+002	2.9+003	0.0	0.0	0.0
²³⁹ Pu	0.39E+05	1.0+002	2.2+003	0.0	0.0	5.7+002
²³⁸ U	0.52E+04	1.3+002	2.2+003	0.0	0.0	1.8+002
²¹⁰ Pb	0.10E+06	6.8+001	1.7+003	0.0	0.0	0.0
²²⁹ Th	0.11E+05	8.0+001	1.6+003	0.0	0.0	0.0
²⁴⁵ Cm	0.52E+04	4.6+001	1.1+003	0.0	0.0	0.0
²²⁵ Ra	0.11E+05	2.0+002	1.0+003	0.0	0.0	0.0
⁵⁹ Ni	0.25E+05	9.5+001	5.6+002	0.0	0.0	0.0
²³³ U	0.11E+05	2.3+001	3.8+002	0.0	0.0	0.0
⁷⁹ Se	0.11E+05	9.8+002	0.0	0.0	0.0	0.0

TABLE B.2.11. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case BST011W

Parametric Data

Release duration = 1.0E+06 yr; delay prior to release = 1.0E+00 yr;
ground-water velocity = 3.11E+01 m/yr; ground-water pathlength = 1.56E+03 m;
ground-water travel time = 5.0E+01 yr; dispersion coefficient = 5.3E-01 m²/yr.

Nuclide	Time After Closure, yr	Seventy-year dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
²²⁶ Ra	0.23E+06	1.9+003	2.5+003	0.0	0.0	0.0
²⁴¹ Am	0.32E+04	8.2+001	2.0+003	0.0	0.0	1.7+002
²⁴³ Am	0.32E+04	3.4+001	8.5+002	0.0	0.0	0.0
²¹⁰ Pb	0.23E+06	2.3+001	5.8+002	0.0	0.0	0.0
²²⁹ Th	0.43E+06	1.8+001	3.7+002	0.0	0.0	0.0
¹⁴ C	0.52E+02	5.9+001	2.9+002	5.9+001	5.9+001	5.9+001
²⁴⁰ Pu	0.29E+05	1.2+001	2.5+002	0.0	0.0	6.6+001
⁹⁹ Tc	0.52E+04	1.7+000	4.3+000	5.4+001	0.0	2.3+002
²²⁵ Ra	0.43E+06	4.6+001	2.3+002	0.0	0.0	0.0
²³⁴ U	0.52E+04	9.9+000	1.6+002	0.0	0.0	1.3+001
²³⁷ Np	0.32E+04	4.6+000	1.0+002	0.0	0.0	0.0
¹²⁹ I	0.52E+04	1.3+001	4.7+002	0.0	1.0+002	7.1+003
²³³ U	0.43E+06	4.9+000	8.0+001	0.0	0.0	0.0
²³⁰ Th	0.23E+06	2.3+000	7.6+001	0.0	0.0	0.0
²⁴² Pu	0.50E+05	1.7+000	3.4+001	0.0	0.0	9.3+000
²³⁶ U	0.25E+05	2.1+000	3.3+001	0.0	0.0	0.0
²³⁸ U	0.52E+04	1.3+000	2.2+001	0.0	0.0	1.8+000
²³⁹ Pu	0.51E+05	6.3+001	1.3+001	0.0	0.0	3.4+000
²⁴⁵ Cm	0.52E+04	4.6+001	1.1+001	0.0	0.0	0.0
⁷⁹ Se	0.11E+05	9.8+000	0.0	0.0	0.0	0.0

TABLE B.2.12. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case BST012W

Parametric Data

Release duration = 1.0E+02 yr; delay prior to release = 1.0E+03 yr;
ground-water velocity = 3.11E+01 m/yr; ground-water pathlength = 1.56E+03 m;
ground-water travel time = 5.0E+01 yr; dispersion coefficient = 5.3E-01 m²/yr.

Nuclide	Time After Closure, yr	Seventy-year dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
²³⁹ Pu	0.30E+05	3.9+005	8.4+006	0.0	0.0	2.1+006
²⁴³ Am	0.42E+04	3.0+005	7.7+006	0.0	0.0	0.0
²⁴¹ Am	0.42E+04	1.6+005	3.9+006	0.0	0.0	3.3+005
¹⁴ C	0.11E+04	5.2+005	2.6+006	5.2+005	5.2+005	5.2+005
⁹⁹ Tc	0.61E+04	1.7+004	4.1+004	5.2+003	0.0	2.2+006
²³⁴ U	0.61E+04	9.2+004	1.5+006	0.0	0.0	1.2+005
²⁴⁰ Pu	0.30E+05	5.6+004	1.2+006	0.0	0.0	3.1+005
¹²⁹ I	0.36E+04	1.3+003	4.7+002	0.0	1.0+006	7.1+001
²³⁷ Np	0.36E+04	3.9+004	8.9+005	0.0	0.0	0.0
²³⁸ U	0.61E+04	1.3+004	2.1+005	0.0	0.0	1.7+004
²³⁶ U	0.61E+04	1.2+004	2.0+005	0.0	0.0	0.0
²⁴⁵ Cm	0.61E+04	4.2+003	1.0+005	0.0	0.0	0.0
²⁴² Pu	0.30E+05	4.5+003	9.3+004	0.0	0.0	2.5+004
⁵⁹ Ni	0.26E+05	3.2+003	1.9+004	0.0	0.0	0.0
²³⁵ U	0.61E+04	7.7+002	1.3+004	0.0	0.0	1.4+003
²²⁶ Ra	0.10E+06	6.6+003	8.7+003	0.0	0.0	0.0
¹²⁶ Sn	0.51E+05	1.6+002	5.5+003	0.0	3.2+001	0.0
²³³ U	0.61E+04	1.9+002	3.2+003	0.0	0.0	0.0
²¹⁰ Pb	0.10E+06	7.8+001	2.0+003	0.0	0.0	0.0
⁷⁹ Se	0.86E+04	5.1+004	0.0	0.0	0.0	0.0

TABLE B.2.13. Seventy-Year Cumulative Dose Commitment (Maximum-Individual)
Expanded Summary for Case BST013W

Parametric Data

Release duration = 1.0E+02 yr; delay prior to release = 1.0E+04 yr;
ground-water velocity = 3.11E+01 m/yr; ground-water pathlength = 1.56E+03 m;
ground-water travel time = 5.0E+01 yr; dispersion coefficient = 5.3E-01 m²/yr.

Nuclide	Time After Closure, yr	Seventy-year dose, rem				
		Total Body	Bone	Lungs	Thyroid	GI-LLI
²³⁹ Pu	0.39E+05	3.0+005	6.4+006	0.0	0.0	1.6+006
²⁴³ Am	0.13E+05	1.3+005	3.3+006	0.0	0.0	0.0
⁹⁹ Tc	0.15E+05	1.6+004	4.0+004	5.0+003	0.0	2.2+006
²³⁴ U	0.15E+05	9.2+004	1.5+006	0.0	0.0	1.2+005
¹²⁹ I	0.13E+05	1.3+003	4.7+002	0.0	1.0+006	7.1+001
²³⁷ Np	0.13E+05	4.3+004	9.7+005	0.0	0.0	0.0
¹⁴ C	0.10E+05	1.7+005	8.7+005	1.7+005	1.7+005	1.7+005
²⁴⁰ Pu	0.39E+05	2.2+004	4.7+005	0.0	0.0	1.2+005
²³⁶ U	0.15E+05	1.6+004	2.6+005	0.0	0.0	0.0
²³⁸ U	0.15E+05	1.3+004	2.1+005	0.0	0.0	1.7+004
²⁴² Pu	0.39E+05	4.4+003	9.0+004	0.0	0.0	2.4+004
²²⁶ Ra	0.11E+06	5.2+004	6.8+004	0.0	0.0	0.0
²⁴⁵ Cm	0.15E+05	2.0+003	4.8+004	0.0	0.0	0.0
²³³ U	0.15E+05	2.5+003	4.1+004	0.0	0.0	0.0
²⁴¹ Am	0.15E+05	1.6+003	4.0+004	0.0	0.0	3.4+003
⁵⁹ Ni	0.35E+05	2.9+003	1.7+004	0.0	0.0	0.0
²¹⁰ Pb	0.11E+06	6.1+002	1.5+004	0.0	0.0	0.0
²³⁵ U	0.15E+05	8.8+002	1.4+004	0.0	0.0	1.6+003
²³⁰ Th	0.11E+06	2.2+002	7.2+003	0.0	0.0	0.0
⁷⁹ Se	0.18E+05	4.7+004	0.0	0.0	0.0	0.0

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