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**MASTER
BEDDED-SALT REPOSITORY
ANALYSIS:
FINAL REPORT**

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ABSTRACT

This report contains a description of an analysis of a generic nuclear waste repository in bedded salt. This analysis was performed by TASC for inclusion in a major Lawrence Livermore Laboratory report to NRC; this report therefore should be viewed as providing more complete and detailed information about this analysis than was possible to include in the LLL report.

The analysis is performed with the NUTRAN computer codes which are described in the report. The model to be analyzed is defined, and the results of a series of possible waste migration scenarios are presented. Several of these scenarios are used as the basis for a sensitivity analysis, and an uncertainty analysis utilizing Monte Carlo techniques is also performed. A new method for defining the consequences to users of a well drilled near the repository is also described, and results are presented based on two of the waste migration scenarios.

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1.

INTRODUCTION

1.1 PURPOSE AND OUTLINE OF THIS REPORT

Lawrence Livermore Laboratory (LLL) has been engaged by the Nuclear Regulatory Commission (NRC) to study the potential effects of nuclear waste repositories on the public health and safety. LLL has subcontracted a portion of their work to The Analytic Sciences Corporation (TASC). TASC's principal contribution to this effort has been the development of NUTRAN, a computer model of long-term hazards from waste repositories (see Ch. 2), and the subsequent use of NUTRAN in the analysis of the environmental impact of a repository located in various media.

This report is an account of the repository failure scenario analysis performed by TASC for inclusion in a major LLL report (Ref. 1) to NRC on the subject of repositories located in bedded salt. The LLL report contains the results and conclusions of the TASC study. This volume may be viewed as both a detailed report of TASC's efforts and, possibly, as an appendix to LLL's report containing more information for the interested reader.

Because one function of this document is to be a report of TASC's effort, a brief description of the inputs for the NUTRAN model is also included. These inputs - descriptions of the salt basin, waste form, failure scenarios, etc. - are presented in detail in the LLL report. We hope that the reader using this document as an appendix to LLL's report will excuse this circularity which is made necessary by the dual function served by the present volume.

The following outline of the work is offered to help the reader identify those portions of the report which are of most interest. Chapter 2 contains a description of NUTRAN. In Chapter 3 a brief description of the waste form, repository, salt basin, and failure scenarios is provided.

Chapters 4 through 7 are the heart of the report. Chapter 4 provides results on the environmental impacts both of an unflawed repository and of repositories with various failure modes present. Several repository failure models were chosen for sensitivity and uncertainty analyses. These studies are reported in Chapters 5 and 6 respectively. Chapter 7 contains a description of work done to assess the biological consequences of wells drilled into the aquifer near the repository. A new methodology for conceptualizing the hazard to the public from wells is presented.

The entire report is summarized in Chapter 8 where the principal conclusions are listed.

Several appendices have been included. They contain the more quantitative and analytic aspects of the discussion.

1.2 ACKNOWLEDGEMENTS

The work described in this report was performed in phases over a period of several months. As each phase was completed, a report was written at TASC on the results and sent to LLL in a form suitable as input for their Bedded Salt Report (Ref. 1) to NRC. As a consequence LLL had a large influence on the form of these short reports. In general, these short reports are being used as the chapters of this

report. Consequently, we at TASC owe a debt to LLL for the presentation and content of material presented here.

We specifically acknowledge the contributions of Mr. William O'Connell of LLL. Mr. O'Connell implemented LLL responsibilities by providing the basis for the discussions of modeling philosophy and scenario selection presented in Chapter 3. He also suggested that simplified qualitative analysis is an appropriate method for prescreening scenarios in order to select those for detailed analysis. This concept is the basis for material presented in Section 4.1 and Appendix C.

2. OVERVIEW OF THE NUTRAN COMPUTER CODE

TASC's analysis of the repository failure scenarios was performed using the NUTRAN computer codes. This chapter describes the codes and their most important features.

The TASC-developed NUTRAN system of computer codes calculates doses to humans from radioactivity carried out of deep geologic nuclear waste repositories by groundwater. A series of barriers will impede the escape of waste from a repository; NUTRAN evaluates their combined effect. Among the phenomena whose effects are incorporated into the calculation are:

- The refilling of the repository cavity with water
- Leaching of the waste matrix
- Dissolution of the radioactive elements in the waste
- Transport of waste by groundwater through the repository, surrounding strata, and adjacent aquifers
- Withdrawal of contaminated groundwater through wells
- Transport of waste in surface waters and associated ecosystems
- Human exposure and dose mechanisms.

The most complex aspect of a repository risk assessment is the calculation of the transport of radionuclides by groundwater. In NUTRAN, these computations are simplified by treating the groundwater flow field as a network of flow pathways

which correspond to stream tubes. The output of each path segment is the input to the subsequent segments. This approach makes computer execution more efficient, simplifies interpretation of results, and permits the modeling of small flaws such as unsealed shafts or boreholes.

NUTRAN is composed of four computer programs, as illustrated in Fig. 2-1. The ORIGEN code, developed at Oak Ridge National Laboratory (Ref. 2) is used to calculate the inventory of radionuclides in the waste as a function of time. WASTE models the release of radionuclides from the repository and their transport in the subsurface, and BIODOSE computes the doses to humans which result from any releases of radioactivity into the biosphere. WASTE calculates releases in units of MWe-yr of waste, and BIODOSE calculates the dose per MWe-yr released at any time. The output of these two programs must be multiplied together to obtain doses; this is done by the program WPLOT.

2.1 ESCAPE OF WASTE FROM THE REPOSITORY AND SUBSURFACE TRANSPORT

The subsurface waste transport code WASTE represents the mass transport of radionuclides due to flow in groundwater. The model incorporates the effects of advective transport, hydrodynamic dispersion, and chemical interactions between waste components and rock. Changes in groundwater movement can be modeled for both natural and man-related events.

Because the characteristics of possible waste repository sites and engineering designs are not always well defined, the model is constructed to facilitate handling various hydrogeologic characteristics and performing sensitivity studies.

Figure 2-1 The Programs Which Comprise NUTRAN

In order to make this flexibility possible, procedures which divide the region of interest into a lattice of cells, such as finite element and finite difference methods, are avoided. Instead, the three-dimensional flow field is modeled as a network of one-dimensional flow paths or "stream tubes," which follow the stream flow lines. A derivation of the one-dimensional transport equation for stream tubes is presented in Ref. 3.

The stream tube approach results in a high degree of computational efficiency and allows a relatively straightforward representation of small discontinuities (e.g., faults, boreholes), avoiding the difficulties which are encountered in

solving time-dependent solute migration problems by finite-element or finite-difference methods (Refs. 4 and 5). Furthermore, large scale regional flow patterns are easily and directly represented by means of spatial averaging.

The groundwater flow pattern can be calculated within the program using a resistor network approach to solve for the pressures along the network of stream tubes. When appropriate, the details of flow near the waste storage rooms can be accounted for by a more detailed model. The groundwater flow can also be ascertained outside the program, using finite elements or other methods, and input to it.

The waste migration calculation begins with the computation of the length of time required for the repository to refill with water and repressurize after decommissioning. (The age of the waste at decommissioning and the time required for canister corrosion are inputs to the program.) This time is found by calculating the inflow to the repository from adjacent aquifers, using the same stream tube model as is used for the waste transport modeling, but with the repository initially at atmospheric pressure. The pressure of the repository remains atmospheric until the cavity has refilled, and then rises as water enters the surrounding rock in a quantity determined by its "specific storage." The time required for the entire resaturation process can be input to the program when this model is inappropriate.

When the repository has resaturated, waste begins to leave the storage rooms. The rate at which any element is released is given by the slowest of three processes:

- The leaching of the matrix in which the waste is incorporated (typically glass for waste from a reprocessing plant, or uranium oxide for spent fuel).

- The solubility of the element in the water flowing near the waste canister.

When the release of any element is limited by its solubility, the quantity which has been leached from the waste matrix, but has not dissolved, is recorded as a reserve of what may be thought of as precipitate. The precipitate is released as soon as its solubility permits.

Only the most abundant isotope of each element is checked against its solubility, and other isotopes are assumed to move in a constant proportion. This approach is conservative because the total concentration of an element will exceed that of any single isotope. Isotopes with radically different half-lives, such as ^{135}Cs and ^{137}Cs , are treated independently. The decay-product daughters of nuclides affected by solubility are assumed to be formed from their parents shortly before they reach the biosphere.

Transport of dissolved radionuclides in groundwater is modeled by treating each path segment independently. The output of each segment is calculated from the input using a Green's function approach. This output, as a function of time, is used as the input to the next segment. When paths branch, the waste is divided in proportion to the amount of water entering each stream tube, except at waste storage rooms where a more detailed model can be used.

Radionuclides can reach the surface either by flow to surface water bodies or by withdrawal through wells. Radionuclide concentrations in well water are calculated using a two-dimensional equation for a homogeneous aquifer. Water withdrawn from the well can either not affect the aquifer flow

field or, taking the opposite limit, can remove all contamination in the aquifer. These two limits represent the worst cases for individual and population doses respectively.

The model does not calculate the motion of decay-product daughter nuclides separately from their parents. There exists, however, a "reconcentration effect" (Ref. 6) which causes the release rates of daughter and parent nuclides to differ if their motion is retarded unequally by sorption effects. This is accounted for by applying a correction factor to the release rates of daughter nuclides. The correction factor is usually the ratio of the ionic velocities of daughter and parent nuclides in the groundwater, but takes a more complicated form in certain cases.

2.2 BIOSPHERE TRANSPORT AND DOSES

Doses to humans will depend on the movement of waste to wells or surface waters, concentration in the ecosystem, human diets and living habits, and the biochemistry of the waste nuclides in the human body. These factors are modeled in the TASC-developed BIODOSE code.

Environmental assessment of future releases requires consideration of the cycling of long-lived radionuclides in the biosphere and the possibility of local build-up and concentration. Due to the vast uncertainty about future conditions, the basis of model predictions for times far into the future must be defined carefully. The basic philosophy of BIODOSE is to provide tools for evaluating the consequences of radionuclide release under conditions not too far removed from those experienced today.

Transport in surface water systems is calculated using a compartment or box model. Because the release of waste is expected to occur over long time periods, the surface water system is assumed to be in dynamic equilibrium with the input flow of the waste. This simplification permits the calculation of doses per unit input flow of waste independently of the WASTE program.

The transport model computes the concentrations of each radionuclide in soil, sediment and water systems. The model is composed of compartments for each system and assumes uniform mixing within each compartment. The following dynamic processes which affect concentration are considered; dilution by mixing, diffusion between sediment and water, sedimentation, removal of water and food products by man, ion exchange, biogeochemical processes, and radioactive decay. The potential for accumulating radionuclides in the topsoil due to irrigation of crop lands is also modeled. The complexity of this model is limited by the accuracy with which the transfer coefficients between the compartments can be modeled (Ref. 7).

The concentrations calculated for the sediment, topsoil and water subsystems are used with a simple ecosystem model based on that developed by J.K. Soldat (Ref. 8) to give radionuclide dose rates to man. Doses are assumed to be received by ingestion and external exposure. The ingestion pathways modeled are drinking water, aquatic foods, irrigated crops and farm animals. External exposure to both the water subsystems and the topsoil is considered. The pathways considered are summarized in Fig. 2.2-1.

Doses are computed for individuals and populations as a function of living habits and usage. Although estimates of the local demography are not possible far into the future, it

Figure 2.2-1 Pathways Modeled in BIODOSE.

is possible to develop reasonable limits to the potential population exposure. The population dose from the aquatic food pathway, for example, depends on the net harvest and not on the size of the local population. Similarly, the vegetable and animal pathways depend primarily on the irrigation rate. Since these pathways are dominant, the potential population dose from a river system is relatively independent of the local demography. Population doses were therefore based on estimates of the usage rates of the water system rather than on population.

A dosimetry subprogram is used to compute hazard on the basis of length of exposure and period of dose commitment.

Doses are computed for the whole body and seven body organs. In addition, an effective "whole-body-equivalent" dose commitment is computed by aggregating these doses according to their contribution to cancer risk.

2.3 PROBABILISTIC CALCULATIONS

Future events, such as faulting or failure of engineered seals, can effect the movement of groundwater and dissolved radionuclides. In NUTRAN a number of geologic states can be defined, such as fault open and fault closed. Geologic events then become transitions between states. The times at which such events occur can usually be predicted only on a probabilistic basis. The WASTE model can take these future events into account in three different ways:

- Scenarios in which events occur at specified times can be modeled
- Events can be taken to occur at times specified by random numbers. The resulting scenarios are then modeled and the outputs analyzed statistically
- Expected values of doses and radionuclide concentrations can be calculated directly using the occurrence rates of the events.

The direct calculation of expected values uses a statistical method derived in Ref. 9. In this approach, a quantity is calculated which is equal to the expected value of the rate at which waste enters each pathway segment if the system is in a given geologic state, multiplied by the probability of being in that state. An amount of waste which enters a segment in one state is placed in other states when it leaves the segment in proportion to the probability that the system has made

a transition between the two states while the waste was traveling through the segment.

Use of this method rests on two principal assumptions (Ref. 9):

- The operator describing waste transport must be linear. This excludes cases in which release of some radionuclides is solubility-limited
- The transitions between geologic states must be represented by a first-order Markov process.

When these assumptions are not met, either of the other methods of modeling future events may be used.

The NUTRAN computer codes are discussed in detail in Reference 10.

3. DESCRIPTION OF THE REPOSITORY AND BASIN

The NUTRAN computer codes require a detailed description of the repository and its environment in order to calculate the consequences to the public health and safety caused by the repository. In this chapter the principal portions of the description required by NUTRAN are described and the parameter values required for computation are presented.

It is important to note that the salt basin used in this analysis is generic and does not represent any particular basin or group of basins. It is based on the large volume of findings reported in Ref. 1, and was chosen by LLL as were the values of the model parameters presented in this report.

We wish to acknowledge LLL's assistance in describing the modeling philosophy which led them to the selection of the basin model and to the choice of the scenarios for analysis.

3.1 MODELING PHILOSOPHY

A generic model of a bedded salt basin was constructed and a series of waste migration scenarios for a hypothetical nuclear waste repository located in the basin were analyzed. The purposes of this analysis were to:

- Demonstrate an analysis methodology, which could be used with real input data to analyze a specific site.

- Identify processes and parameters which are important to the ultimate repository performance under various conditions.
- Clarify where further model improvements are needed.

The generic model includes the main features typically found in salt basins, but is not an attempt to model more than the most obvious characteristics of these geological formations. The generic model is not a particular basin, nor is it representative of some well-defined group of basins. Rather, it is a reasonable model having characteristics which are within the range of those found in real basins.

The generic basin for the present analysis is based on Naymik and Thorson's basin model (Ref. 11) used in their analysis of regional groundwater hydrology and waste transport. It is considered to be flawed on a basin-wide scale. However, the repository is assumed to be placed in a region, termed the local area, which is essentially unflawed. The flaws that do exist in the local area are assumed to be isolated. These flaws may have been undiscovered in the exploration process, have been caused by exploration, excavation, or emplacement of waste or have been the results of geologic changes in the region. In any case it is waste migration through these isolated flaws which is studied in the scenarios.

The basin parameter values are regional averages. Salt may be essentially impermeable on a local scale (e.g., in the local area). On a larger scale, there will be interconnections of the aquifer layers through the barrier rock and salt layers, due to joints, faults, breccia pipes, etc. Consequently, there will be little vertical piezometric head difference between the two aquifer layers over a wide area in the basin.

The rock parameters in the local area around the repository will differ from the regional averages both because variability over the region is to be expected, and because the repository site exploration program will arrange that the repository is placed in an area with competent barrier rock and salt. The local area, for purposes of repository performance evaluation, will extend for several kilometers beyond the repository. For our generic site model we assume that we have a region of highly competent salt and shale extending 5 km in the direction of groundwater flow on either side of the repository. This region is bounded by flaws which provide very low resistance vertical connections for groundwater flow.

This generic basin is different from that used in earlier work (Ref. 12) in two ways:

- It has different parameters on the local and regional scale, and a local high-integrity zone extending 5 km from the edge of the repository.
- It has a much lower vertical head difference (3.6 m maximum in the region, versus 60 m), but nearly the same horizontal gradient.

Because of the second difference, horizontal motion of the waste will assume greater importance than in earlier studies (Ref. 13). The horizontally moving waste will reach the edge of the high-integrity region and flow quickly upward through the low resistance flaws forming the boundary of the local area. Thus, the reduction in vertical head difference is not necessarily unconservative.

3.2 SCENARIO ANALYSIS

The scenario analysis is designed to answer the following questions:

- 1) What are the expected consequences of a representative set of scenarios? (Baseline Consequence Analysis)
- 2) What parameters have the most influence on the values of the performance measures for each scenario? (Sensitivity Analysis)
- 3) What effects do uncertainties in the input parameters have on the repository performance measures? (Uncertainty Analysis).

Potential scenarios whereby groundwater may enter or exit a repository in bedded salt have been identified and grouped in Ref. 14. The present work considers waste migration in these generic paths with driving forces due to hydraulic gradients and diffusion.

In order to evaluate the environmental impact of a nuclear waste repository scenario NUTRAN requires a numerical description of the waste form, the repository, and its geological milieu including flaws. In this section the required numerical values are provided for the scenarios studied. An attempt is also made to help the reader visualize the spatial arrangement of the elements of the scenarios.

The parameters dealing with the waste form are described in Section 3.2.1. The salt basin, repository, and upper aquifer are discussed in the following section, and the flaws which are modeled are described in Section 3.2.3. The final section describes the scenarios which were modeled.

The values of the parameters are generally taken from the Data Base Handbook (Ref. 15). The choice of parameters describing the local area is described in Ref. 16.

3.2.1 The Waste Form

For the scenarios modeled in this study it is assumed that the repository contains 2×10^6 MWe-yr of ten-year-old spent fuel. This quantity of waste requires that approximately 1.5×10^5 canisters are buried.

The geometry of the niche for each canister is depicted in Fig. 3.2-1. The spent fuel canister is placed inside a stainless steel sleeve which is then filled with overpack and covered with a concrete plug. The entire assembly is placed in a niche which is slightly larger than the assembly.

The waste dissolution model used in this study was developed entirely by LLL and is described in Ref. 17. Qualitatively, the model is based on computing the maximum amount of UO_2 , the principal component of the waste, which can dissolve in the water passing through the pathway between the sleeve and the edge of the niche. Waste transport through the overpack is also considered.

The lengths of those features used in the dissolution model are explicitly labeled in Fig. 3.2-1. Other parameters needed by the model are the void volume of the canister (0.044 m^3), longitudinal dispersivity of the overpack (0.01 m) and the molecular diffusion constant ($0.03 \text{ m}^2/\text{yr}$). The saturation concentration of UO_2 is set at 9.0 gm/m^3 .

The dissolution rate of the waste also depends on the flow rate of water through the niche. It was assumed that 10%

of all water flowing through the repository flows through a niche. Since there are about 1.5×10^5 canisters in the repository, the flow rate through each niche is the flow rate through the entire repository divided by 1.5×10^6 .

NOTE: HORIZONTAL AND VERTICAL SCALES DIFFER

Figure 3.2-1 Canister Niche

The water flow rate through the repository depends on the scenario. However, the approximate dissolution rate as a function of the flow rate Q , through the repository is given in Table 3.2-1.

TABLE 3.2-1
DISSOLUTION RATE AS A FUNCTION OF FLOW RATE

FLOW RATE, Q (m ³ /yr)	DISSOLUTION RATE (fraction of waste per year)
$0 < Q < 40$	1.2×10^{-8}
$40 \leq Q < 5000$	$\frac{1.45 \times 10^{-11} Q}{1 - \exp(-1.21 \times 10^{-3} Q)}$
$Q \geq 5000$	$1.45 \times 10^{-11} Q$

The dissolution rates of all nuclides in the spent fuel matrix are given by Table 3.2-1. However, 10% of ^{129}I , ^{99}Tc , and ^{14}C present originally in the waste are assumed to be located on the cladding. These nuclides on the cladding are dissolved immediately and are released from the canister niche at a rate about 10^6 times faster than the rest of the waste. A detailed explanation of this assumption may be found in Ref. 17.

The solubility of UO_2 determines the dissolution rate of the waste. The concentration of one other isotope, ^{93}Zr , is also checked against its solubility, $5.0 \times 10^{-6} \text{ gm/m}^3$, during these analyses.

The waste canister is assumed to protect the waste from water for a period of 500 years. Thus, the dissolution of the waste cannot be initiated for at least this length of time.

3.2.2 Description of the Salt Basin and Repository

The repository is assumed to be placed in a salt basin similar to that studied in Ref. 11. Figure 3.2-2 shows a simplified view of the basin. The basin consists of five layers. The central layer consists of bedded salt and is the least permeable layer in the basin. It is sandwiched between two shale layers which are essentially identical to each other. The outer layers are two sandstone layers which are identical to each other except for thickness. The distance from the repository to the hypothesized river is 52 km.

Figure 3.2-2 Stratigraphic Column, Showing Basin Geometry

A vertical head difference between the aquifers of 3.6 m and a horizontal head gradient of 0.006 is assumed throughout the basin. Table 3.2-2 summarizes the hydrologic parameters for each of the five layers.

TABLE 3.2-2
HYDROLOGICAL PARAMETER VALUES FOR REGIONAL AREA

T-3545

NOMINAL MATERIAL	THICKNESS	HYDRAULIC CONDUCTIVITY		EFFECTIVE POROSITY	DISPERSIVITY		HYD. GRADIENT	RETARDATION FACTORS	
		HORIZONTAL	VERTICAL		LONGIT.	TRANSVERSE		FIS. PROD.	ACT.
	(m)	(cm/s)	(cm/s)				(m/m)		
Sandstone	177.	6.3E-4	6.3E-4	0.10	50.	5.	0.006	10 ²	10 ⁴
Shale	177.	6.3E-5	6.3E-5	0.05	30.	5.	0.006	10	10 ²
Salt	221.	3.2E-6	3.2E-6	0.05	30.	10.	0.006	1	1
Shale	177.	6.3E-5	6.3E-5	0.05	30.	5.	0.006	1	1
Sandstone	210.	6.3E-4	6.3E-4	0.10	50.	5.	0.006	10	10 ²

The repository is located in a portion of the basin which is somewhat more impermeable than the regional average. The choice of such a region will be made after site exploration is completed. The hydrological parameter values for the local area of the repository are provided in Table 3.2-3.

TABLE 3.2-3
HYDROLOGICAL PARAMETER VALUES FOR LOCAL AREA

T-3546

NOMINAL MATERIAL	THICKNESS	HYDRAULIC CONDUCTIVITY		EFFECTIVE POROSITY	DISPERSIVITY		HYD. GRADIENT	RETARDATION FACTORS	
		HORIZONTAL	VERTICAL		LONGIT.	TRANSVERSE		FIS. PROD.	ACT.
	(m)	(cm/s)	(cm/s)				(m/m)		
Sandstone	177.	6.3E-4	6.3E-4	0.10	50.	10.	0.006	10 ²	10 ⁴
Shale	177.	5.E-7	1.E-7	0.05	50.	10.	0.006	1	1
Salt	221.	1.E-8	1.E-10	0.01	50.	10.	0.006	1	1
Shale	177.	5.E-7	1.E-7	0.05	50.	10.	0.006	1	1
Sandstone	210.	6.3E-4	6.3E-4	0.10	50.	10.	0.006	10	10 ²

In this study the repository is located at two different depths depending on the permeability of the bedded salt. In scenarios with impermeable salt, the repository is located 177 m below the top of the salt layer. If the salt is assumed permeable the repository is placed 104 m below the top of the salt layer (see Fig. 3.2-2).

The repository is assumed to have a planar area of $5 \times 10^6 \text{ m}^2$ and the storage rooms are about 6 m high. The waste is buried below the storage room floors as depicted in Fig. 3.2-1.

There are three shaft locations used in the scenarios. The shaft may be upstream of, lateral to, or downstream of the repository. The three positions are illustrated in Fig. 3.2-3. Given the assumed gradient in the aquifer (0.006) and the distances, the head distance between consecutive shaft locations is about 10 m.

R-50860

Figure 3.2-3 Shaft Locations

The upper sandstone layer is often identified as the upper aquifer in waste migration studies. However, the assumption that the basin has an 0.006 horizontal gradient in each layer means that the flow rate of water to the river in a layer is proportional to the horizontal permeability of the layer. Consequently, the water flow rate through the upper shale layer is about 10% of the flow rate through the upper sandstone layer. This fact suggests that the upper shale layer should not be ignored in defining the aquifer. This suggestion is reinforced by a study of material transport in the basin using a two-dimensional finite element code (Ref. 11).

The method employed to construct a flow path equivalent to both the upper sandstone and shale layers is based on the Aris Moment Method (Ref. 18). The resulting homogenized upper aquifer has a horizontal permeability of 4.41×10^{-4} cm/sec, a longitudinal dispersivity of 1866 m, and an effective porosity of 0.075. The aquifer length is 52 km.

Nuclide retardation values in the homogenized upper aquifer are 1 for the unretarded nuclides (^{129}I , ^{99}Tc , and ^{14}C , which are called nuclide group I), 30 for the fission products (nuclide group II), and 1000 for the actinides (nuclide group III) except for ^{210}Pb , ^{210}Po , and all Ra isotopes which have a retardation factor of 200.

3.2.3 Flaw Descriptions

A flaw is a pathway in which groundwater flows through the salt and shale layers. An unflawed repository has waste migration by molecular diffusion only. Except for a single unflawed repository case, all waste migration scenarios analyzed for this study involve waste transport in flowing groundwater and, hence, require that flaws be included in the repository

model. The types of flaws considered in the analysis are described in this section. For each flaw, the length, permeability, porosity, and dispersion constant of the resulting flow path are in the direction of groundwater flow; the cross-sectional area is measured perpendicular to the direction of flow. The length of those flaws passing through the salt layer depends on the repository location in the scenario. The lengths in Table 3.2-4 refer to the permeable salt cases. The lengths of those flaws through impermeable salt are 73 m longer than stated in the table.

In all flawed scenarios the repository shaft and tunnel (S/T) provide a flow path for groundwater. In most scenarios the flow path is through the shaft/tunnel fracture zone created during excavation. This flow path consists of four segments: two each in the shaft and tunnel. The hydraulic properties of these four segments are presented in Table 3.2-4 as flow path types C1, C2, D1, and D2.

The flow path types, based on the scenario paths described in Ref. 12, are listed in Table 3.2-4. The values of these input parameters are highly uncertain. We are considering in most cases a far-future degraded condition of an engineered barrier, or a future disruptive event such as breccia pipe development or earthquake fault movement. The parameters were chosen to represent large flaws with rather high hydraulic conductivity, but we presently cannot determine what might be worst-case parameters. The parameters and analyses are presented in the spirit of raising issues, exploring hypothetical cases to determine where the consequences might be most significant, and indicating areas where further research or site-specific exploration may be important.

TABLE 3.2-4
PARAMETERS FOR VARIOUS 1-D FLOW PATH TYPES

	LENGTH (m)	CROSS-SEC. AREA (m ²)	HYDRAULIC CONDUCTIVE (cm/s)	EFFECTIVE POROSITY	DISPERSION (m)	RETARDATION FACTORS FIS. PROD. ACT.	
A: Porous Flow, Salt, Vertical	104. ^a	5E6	1E-10	.01	50	1	1
B: Shale, Porous Flow, Vertical	177	5E6	1E-7	.05	50	1	1
Tunnel Fracture Zone:							
C1: Inside Repos.	1200.	3300.	1E-6	1E-3	50	1	1
C2: Outer Tunnel	440	198.	1E-6	1E-3	50	1	1
Shaft Fracture Zone:							
D1: In Salt	110.	60	1E-6	1E-3	50	1	1
D2: In Shale	177.	5.	1E-4	1E-3	50	1	1
Upper Aquifer:							
E1: Local Area	5.E3	3.8E5	6.3E-4	.10	50	10 ²	10 ⁴
E2: Regional Area	47.E3	3.8E5	6.3E-4	.10	50	10 ²	10 ⁴
F: Shale, Fracture Flow, Vertical	177.	5E6	1E-6	1E-4	50.	1	1
G: Salt, Fracture Flow, Vertical	104. ^a	5E6	1E-8	1E-4	50.	1	1
H: Tunnel, Failed Backfill							
H1: Inside repos.	1200.	3300.	1E-4	1E-2	50.	1	1
H2: Outer tunnel	440.	150.	1E-4	1E-2	50.	1	1
J: Shaft, Failed Backfill	281. ^a	64.	1E-4	1E-2	50.	1	1
K: Fault, Old, Residual:							
K1: Salt Layer	104. ^a	10 ⁵	1E-9	1E-3	50.	1	1
K2: Shale Layer	177.	10 ⁵	1E-6	1E-3	50.	1	1
L: Fault, Reactivated:							
L1: Salt Layer	104. ^a	10 ⁵	1E-3	1E-4	50.	1	1
L2: Shale Layer	177.	10 ⁵	1E-4	1E-3	50.	1	1
M: Breccia Pipe, Up to Aquifer Layer:	281. ^a	1E5	1E-2	0.3	50.	1	1
N: Breccia Pipe Up To Repository Level:	104. ^a	1E4	1E-2	0.3	50.	1	1
P: Failed Seals of Boreholes:							
P1: 0-500 yr	281. ^a	0.1	1E-4	1E-2	50.	1	1
P2: 500-1000 yr		0.3	1E-4	1E-2	50.	1	1
P3: 1000 yr.		0.5	1E-4	1E-2	50.	1	1
Q: Future Boreholes (Several)	281. ^a	0.1	1E-4	1E-2	50.	1	1
R: Interbeds. R1: Up to 1 km (Scenario Dependent)		3.8E5	1E-8	.01	50.	1	1
R2: 2-5 km, Base Case	(")	3.8E5	1E-9	.01	50.	1	1
R3: 2-5 km, High Case	(")	3.8E5	1E-6	.01	50	1	1
S: Facies Change (Connected to Salt Interbeds)	(")	3.8E5	1E-7	.01	50.	1	1
T: Facies Change (Connected to Shale Layer)	(")	3.0E5	5E-6	.08	50	1	10

^a Increase length by 2m for impermeable salt cases, for paths above repository; decrease length by 2m for impermeable salt cases, for paths below repository.

The parameters for the water flow path types A, B, and E are based on Tables 3.2-2 and 3.2-3. The parameters for C, D and F through Q are basically taken from previous work, (Ref. 12), which may have a limited data base or may be an expert estimate in the absence of data. Much further research is needed in defining rates and site-specific values.

The parameters for the interbeds (path type R) use the full thickness of the salt-plus-interbeds layer, and hydrologic parameters which are averages of the salt and interbed values. It is assumed that there is 1% (by thickness) of conductive sandstone-like interbeds, 5% of relatively non-conductive interbeds and the rest salt. Over a longer distance (2-5 km) the interbeds are assumed to have some variations in thickness and connectivity.

3.2.4 The Flow Scenarios

Unflawed Case - The base case has the repository in an unflawed salt and shale sequence with a perfect shaft seal, but with an inevitable fractured zone around the tunnels and shaft. This fracture zone may be due to excavation methods or to the stress change due to creating an underground opening. There is some controversy on whether intact salt can conduct a steady state water flow. Thus we will analyze two alternatives: a strictly zero permeability in salt, as is found in some of the measurements collected in Ref. 15, and a small positive permeability which is within the range of the nonzero results reported in the same reference.

The base case, with an impermeable salt layer, has only one hydraulic path: the shaft fracture zone. Because there is no through-going path the only driving force for waste migration is diffusion. The results for this case are covered in Section 4.2, and the methodology used to obtain them in Appendix B.

Flawed Repository/Failure Modes - The flawed repository scenarios are divided into two groups depending on whether the salt layer is assumed to be impermeable or not. The impermeable salt scenarios all contain a single flaw plus the tunnel/shaft fracture zone. Either an upstream shaft serves as the inflow path for groundwater to the repository and waste leaves the repository via the flaw, or a lateral shaft serves as an exit path for waste and inflow is provided by the flaw. Figures 3.2-4 and 3.2-5 are schematic representation of the impermeable salt flow paths. The shaft is upstream in Fig. 3.2-5 and exit via a flaw and an interbed/flaw system is depicted. The shaft is lateral in Fig. 3.2-4 and the various flaw combinations are depicted.

N.B. DRAWINGS ARE NOT TO SCALE

Figure 3.2-4 Impermeable Salt Scenarios with Lateral Shaft

N.B. DRAWINGS ARE NOT TO SCALE

Figure 3.2-5 Impermeable Salt Scenarios with Upstream Shaft

Table 3.2-5 contains a listing of the impermeable salt scenarios. In this table, a "small" borehole has a 0.1 m^2 cross section, a "large" borehole has a 0.3 m^2 cross section, an "increasing" borehole has a cross section which increases from 0.1 m^2 to 0.5 m^2 in a 1000 year period (pipe type P of Table 3.2-4) and then stays constant at the larger value. "Healing" faults begin as new faults (pipe type L of Table 3.2-4) and heal (pipe type K of Table 3.2-4) with a transition probability of 10^{-4} per yr.

The permeable salt scenarios include porous flow through the salt layer as well as flow through either the shaft fracture zone or the backfill in the shaft and tunnel in case the backfill is assumed to have failed, and flow through various possible additional flaws.

TABLE 3.2-5
IMPERMEABLE SALT SCENARIOS

INFLOW PATH	OUTFLOW PATH
Jointing (L)*	Lateral Shaft
New Fault (L)	Lateral Shaft
Jointing (L)/Interbed	Lateral Shaft
New Fault (L)/Interbed	Lateral Shaft
Jointing (U)/Interbed	Lateral Shaft
Old Fault (U)/Interbed	Lateral Shaft
Breccia Pipe (U)/Interbed	Lateral Shaft
Small Borehole (U)/Interbed	Lateral Shaft
Increasing Borehole (U)/Interbed	Lateral Shaft
Facies Change (L)/Interbed	Lateral Shaft
Healing Fault (U)/Interbed	Lateral Shaft
Healing Fault (L)/Interbed	Lateral Shaft
Upstream Shaft (U)	Jointing
Upstream Shaft (U)	New Fault
Upstream Shaft (U)	Breccia Pipe
Upstream Shaft (U)	Small Borehole
Upstream Shaft (U)	Large Borehole
Upstream Shaft (U)	Increasing Borehole
Upstream Shaft (U)	Lateral Shaft
Upstream Shaft (U)	Facies Change
Upstream Shaft (U)	Interbed/Any Flaw

*U denotes inflow from the upper aquifer
L denotes inflow from the lower aquifer

For the scenarios with permeable unfractured salt the waste flow through the upper shale layer is predominately horizontal because of the small vertical gradient across the layer. This horizontal flow is modeled and it is assumed that this waste moves quickly upward into the upper aquifer when it meets the flaws defining the edges of the local areas (see discussion of the local area in Section 3.2).

Table 3.2-6 contains a listing of the permeable salt scenarios which were analyzed. Several of these scenarios are depicted schematically in Fig. 3.2-6. The permeable salt scenarios analyzed by computer were chosen after preliminary screening of the possible scenarios using qualitative calculations. The method used for these calculations and the results for various scenarios are presented in Appendix C.

TABLE 3.2-6
PERMEABLE SALT SCENARIOS

T-3548

INFLOW PATHS	OUTFLOW PATHS
*Porous Flow	Porous Flow and Lateral Shaft
Porous Flow	Porous Flow and Downstream Shaft
Porous Flow	Porous Flow and Lateral Shaft and Failed Backfill
Porous Flow	Porous Flow and Downstream Shaft with Failed Backfill
Porous Flow	Porous Flow and Lateral Shaft and Large Borehole
*Porous Flow and Upstream New Fault	Porous Flow and Downstream Shaft
Porous Flow and Upstream Shaft	Porous Flow and New Fault
*Porous Flow and Upstream Shaft	Fractured Salt and Shale
Porous Flow and Upstream Shaft	Porous Flow and Old Fault
Porous Flow and Upstream Shaft	Porous Flow and Large Borehole
*Porous Flow and Upstream Shaft and a New Fault/Breccia Pipe System	Porous Flow and Breccia Pipe
Fractured Salt and Shale and Upstream Shaft	Fractured Salt and Shale
Porous Flow and Upstream Shaft and New Fault	Porous Flow and New Fault

*These scenarios are illustrated in Fig. 3.2-6.

R-50863

N.B. DRAWINGS ARE NOT TO SCALE

Figure 3.2-6 Selected Permeable Salt Scenarios

3.3 POSSIBLE EFFECTS OF CHANGES TO PARAMETERS DESCRIBING ENGINEERED FEATURES

Most of the parameters used in the waste migration scenario analysis are descriptive of the geology and hydrology of the salt basin. Consequently, the repository designer can exert control on their values only by choosing the location of the repository. However, certain of the parameters describe man-made portions of the waste disposal system. The values of these parameters can be controlled by the designers to reduce the health consequence of the repository. This section contains an example of a parameter which can be changed to reduce the doses calculated in the scenario analysis.

The parameter varied in this example is the void volume of the waste canister (see Section 3.2.1). This quantity affects the release rate of the 10% of the unretarded nuclides which are present on the spent fuel cladding rather than in the fuel. The release rate is inversely proportional to the void volume.

It was discovered in the scenario analysis (Chapter 4) that the peak individual doses are determined by the quickly-released nuclides on the cladding. An increase in the canister void volume should reduce the release rate of these nuclides, and therefore, reduce the calculated peak doses.

In order to test this hypothesis the scenario with impermeable salt, an upstream shaft, and a large borehole for outflow was again analyzed with the void volume increased from 0.044 m^3 , the value used in the original scenario analysis, to 0.44 m^3 . With the new value of void volume peak doses were 15% lower than in the original model.

The scenario mentioned above was also used in the well analysis (Chapter 7). Three well scenarios were reanalyzed with the larger value for void volume. The peak doses were significantly reduced. The amount of the reduction varied with the distance between the well and the borehole. This variation is shown in Table 3.3-1.

TABLE 3.3-1
REDUCTION OF PEAK DOSE AS A FUNCTION OF
DISTANCE BETWEEN THE WELL AND BOREHOLE

DISTANCE BETWEEN WELL AND BOREHOLE (m)	PERCENT REDUCTION IN PEAK DOSE
2,000	50%
25,000	24%
50,400	18%

The percent reduction in peak dose decreases with distance because of the extremely large dispersion of the double-layer aquifer. Dispersion in the aquifer reduces the height of the nuclide pulse. The longer the path in the aquifer, the more dispersion is experienced by the pulse. This reduction in pulse height by dispersion "masks" the effect of the reduction in pulse height by the increase in void volume, and hence, the longer the aquifer path, the smaller the percent reduction in peak dose.

These results are but one example of how large decreases in the dose to the public are obtainable through the use of engineering design.

4. WASTE MIGRATION SCENARIO ANALYSIS

This chapter contains the results of the waste migration scenario analysis performed by TASC based on the generic salt basin model described in the last chapter. Results are presented for unflawed and flawed repositories. The more mathematical portions of the discussion are presented in Appendices B and C.

The biological impact of each scenario was calculated using several different measures for three million years after the emplacement of the waste. This time scale was chosen because at three million years the spent fuel will have decayed to about the same level of radioactivity that the uranium ore used to fabricate the fuel would have had if it had been left in the ground. Whole-body-equivalent doses were calculated: a fifty year dose for an average individual, and the yearly dose for the entire population. The whole-body-equivalent dose is computed by aggregating the doses to the whole body and seven body organs according to their contribution to cancer risk. (Ref. 19).

Two simulated river ecosystems were employed in the dose calculations. These river systems are labeled "Colorado" and "Columbia". It is important to note that while each river system is roughly based on the river named they are not meant to be exact models of those two rivers. The parameters used for the simulated river systems are amalgamations of data for the western and northwestern United States respectively. It would be more correct to refer to the simulated river as "Colorado-like" and "Columbia-like" but this phraseology is

not employed in the interest of more succinct expression (See Ref. 13 for details on the "Columbia-like" system and Ref. 20 for the "Colorado-like" system.)

It is important to note that dose values are lower for the Columbia River ecosystem than for the Colorado River ecosystem. This is due to the shallower depth of irrigation assumed in the Columbia system model compared to that used in the Colorado. Also, the rate of rainfall is assumed to equal the rate of evapotranspiration in the Columbia River system, which allows percolation of all contaminated irrigation water drawn from wells back to the river (and hence, eventually out of the ecosystem). In the Colorado River system, however, the only loss of irrigation water occurs via crop intake, resulting in the retention of most of the contaminated water within the ecosystem. The Colorado model is designed to represent a "worst case" for rivers in the continental United States.

An overview section is presented which amalgamates the findings of the computer analyses with the results of the qualitative analysis in Appendix C. The results of the analyses are presented in the following four sections which contain a review of the principal findings followed by information on the unflawed repository, flawed repositories with impermeable salt, and the flawed repositories with permeable salt, respectively. The more technical discussions needed to understand these results have been placed in Appendices B and C.

4.1 OVERVIEW OF THE SCENARIO ANALYSIS RESULTS

This section contains a review of the basic description of waste migration gleaned from both the results of the NUTRAN scenario analyses reported in this chapter and the qualitative

analysis of the scenarios reported in Appendix C. This summarization is presented here both to allow the cursory reader to review the conclusions without having to read through the many results in this chapter or the mathematical detail of the appendix, and to provide the more thorough reader with a road map to what follows.

In this study two types of radiation doses are considered: either peak doses to an individual or population, or integrated doses to a population over the repository lifetime (three million years). The peak doses are primarily produced by the 10% of quick-leaching unretarded nuclides which originally reside on the cladding. These nuclides are initially released at a rate one million times faster than the nuclides in the waste form, and, consequently, produced a fairly short-duration but high-intensity input pulse which produces the peak dose when it reaches the biosphere. The integrated doses are determined principally by the dissolution rate of the waste. The faster the waste form dissolves the more contaminant reaches the biosphere during the three-million year period considered.

The flow of waste to the biosphere is retarded by four barriers: the refill barrier, the dissolution barrier, the local flow barrier, and the regional flow barrier. The waste transport in the basin can be understood by consideration of these barriers.

The refill barrier prevents the initiation of waste flow. It produces a time delay during which waste remains in the canister. It has little effect on the doses unless the time delay is on the order of several hundred thousand years. The peak doses are determined by the ^{129}I on the cladding. This isotope has a sixteen million year half-life, and hence does not decay appreciably in the repository life-time. The

actinides and fission products may have substantial decay during the refill time delay, but this time delay is generally only a very small fraction of the transport time for these species to the biosphere and hence does not contribute to a large reduction in the environmental impact of the repository.

The dissolution barrier limits the amount of waste leaving the source after waste migration has begun. The barrier is dependent both on waste form properties and the flow rate of ground water through the repository. When the flow rate of ground water is large, the dissolution rate of the waste will greatly increase and, thereby, greatly increase the integrated dose. This barrier has little effect on the peak dose. Release time for the pulse of nuclides from the cladding is at most 85 years in the case where no ground water flow exists and dissolution is by molecular diffusion only. The large dispersion of the upper aquifer masks the difference between the various possible leach times sufficiently that no difference in output is discernable.

The local flow barrier slows the transport of the waste from the repository to the aquifer. Very long local flow times are possible. In some scenarios these flow times are longer than the three million year repository lifetime so no waste reaches the biosphere. In other scenarios, these times are long enough to reduce the amount of waste reaching the biosphere, and thus to reduce the integrated dose. The local barrier reduces peak dose by dispersion. The pulse width at the aquifer is about one-half of the local flow time. Hence when flow times are fairly large, the pulse of nuclides which cause the peak dose will be significantly dispersed even though decay has not greatly reduced the total amount of nuclides present.

Analysis of the local flow barrier is complicated because there may be several pathways between the repository and aquifer. These pathways carry different amounts of waste to the aquifer at different speeds. A borehole carries ground water to the aquifer very quickly because of its small porosity. A permeable salt pathway carries ground water to the aquifer very slowly because of its larger porosity and the subsequent horizontal flow through the shale. If a borehole provides the only pathway to the aquifer, the waste pulse will not be significantly dispersed by the local barrier and large peak doses will result. If a permeable salt pathway is also present with the borehole, only 2% of the waste flowing from the repository will enter the borehole, and the remainder of the waste will enter the salt. The waste in the salt will be highly dispersed and will not contribute to the peak dose. Consequently, a large reduction in peak dose is produced by the presence of the permeable salt. This reduction is not an isolated phenomenon. The presence of a permeable salt layer often significantly mitigates the affect of flaws, and rarely increases dose more than a very small amount.

The regional flow barrier slows the transport of waste in the aquifer. This barrier provides both a time delay and a very large dispersion. Retardation of the fission products and actinides greatly increases the effectiveness of this barrier to flow by these nuclides. The fission products are delayed long enough that these most dangerous species have decayed before entering the biosphere. The retarded actinide travel time in the aquifer is about five million years. However, the large dispersion in the aquifer causes some actinides to reach the biosphere in less than three million years by spreading of the actinide wave front. This same dispersion causes a large reduction in the amplitude of the quick-leaching nuclide pulse, and, consequently, is one of the principal reasons why the peak doses found in this study are small.

The largest peak doses occur for impermeable salt scenarios with a single fast exit path such as a borehole. In such a scenario, the repository refills slowly and has a minimum waste dissolution rate. However, the unretarded nuclides on the cladding always leach fairly quickly and are almost undisturbed by the local barrier due to the fast flow times. The pulse is dispersed in the aquifer. However, all scenarios have this same dispersion and, consequently, the poor performance of the local barrier produces the largest peak doses. Integrated doses for such a case are small.

The largest integrated doses occur for cases with a continuous low resistance flow path between the aquifers and passing through the repository. In such a case the dissolution rate of the waste is very large and produces a large "steady-state" flow to the biosphere. The peak doses are still produced by the quick-leaching nuclides and generally flow through the low-resistance flaw. Almost all of the waste will flow through this path even in the presence of permeable salt. Flow through a low resistance flaw is generally fairly slow and hence does not produce as large a dose as a borehole.

The smallest doses occurred for the unflawed case. In this scenario waste transport occurred by molecular diffusion only. It suffices to say that all doses were extremely low.

4.2 THE UNFLAWED REPOSITORY

The flow of water into an unflawed bedded salt repository after resaturation is insignificant if the permeability is taken to be in the vicinity of 10^{-12} cm/sec. In that event, flow of waste from canisters through the repository and shafts to an aquifer is by molecular diffusion only.

The diffusion model, which is discussed in detail in Appendix B, assumes that water in proximity to waste canisters is saturated. Only the waste in the fuel pellet matrix is considered. The fast-dissolving 10% of Group I nuclides on the cladding is not considered. Waste is allowed to flow first through the overpack between the canisters and the repository floor. The repository is depicted as a one-dimensional pipe with a uniform (spatially) source of nuclides from the canisters below the floor. The transport of waste through the repository is then determined from the diffusion equation with a boundary condition imposed that the exit tunnels and shaft provide a severe constriction due to their smaller flow area. Finally, the waste flow along these exterior pipes is estimated using infinite medium Green's functions. The result of these calculations is the fraction of waste per year entering the aquifer.

Qualitatively, the results of the diffusion model indicate that waste requires of the order of a few million years or longer to traverse the repository exit tunnel and shaft. Because the repository becomes saturated with waste rapidly and saturation retards flow from canisters, dissolution of the waste canisters is extremely slow; the dissolution time is about 10^{15} years. Thus, there is a very small leakage rate of waste into an overlying aquifer.

The results of NUTRAN code calculations based on the diffusion model are presented in the tables below. Table 4.2-1 gives peak release rates and peak times for each of three nuclide groups to surface waters from a 5.2×10^4 m long aquifer. Table 4.2-2 shows maximum individual, peak population, and integrated population doses due to contamination of the Colorado River. Table 4.2-3 presents the same information for the Columbia River.

Figure 4.2-1 illustrates the time behavior of population dose for the Colorado River. Note that doses increase markedly from 10^5 years onward.

TABLE 4.2-1
PEAK RELEASE RATES

GROUP	RELEASE RATES (Ci/yr)	TIME (yr)
I (I, Tc, C)	2.7×10^{-9}	8.7×10^5
II (Fission Products)	1.6×10^{-7}	2.1×10^6
III (Actinides)	9.3×10^{-13}	3.0×10^6
TOTAL	1.6×10^{-7}	2.1×10^6

TABLE 4.2-2
COLORADO RIVER WHOLE-BODY-EQUIVALENT DOSES

DOSE TYPE	VALUE	TIME (yr)
Max. 50 Yr Individual	1.9×10^{-10} rem	2.9×10^6
Peak Population	5.9×10^{-5} man-rem/y	2.9×10^6
Integrated Population	113 man-rem	-

TABLE 4.2-3
COLUMBIA RIVER WHOLE-BODY-EQUIVALENT DOSES

DOSE TYPE	VALUE	TIME (yr)
Max. 50 Yr Individual	7.4×10^{-13} rem	2.3×10^6
Peak Population	1.0×10^{-7} man-rem/y	2.9×10^6
Integrated Population	0.19 man-rem	-

Figure 4.2-1 Unflawed Salt Repository Diffusion Model
Population Dose

4.3 THE FLAWED REPOSITORY WITH IMPERMEABLE SALT

In order to focus the discussion of the results, the scenarios have been divided into four groups labeled 1A, 1B, 2A, and 2B. The first factor used to classify scenarios is whether the salt layer is assumed to be impermeable. All scenarios with impermeable salt are placed in group 1; those scenarios with permeable salt are placed in group 2. In every scenario the pathway through the tunnel and shaft between the repository and the upper aquifer is assumed to be permeable. In the majority of cases the flow path is assumed to be in the

fracture zones formed during construction of the shaft and tunnel. In a few cases the backfill material in the shaft and tunnel is assumed to have failed and this failed material forms the pathway. In either case a secondary classification of the scenarios is made into subgroup A if the shaft and tunnel form an outflow path for contaminated water from the repository and subgroup B if the shaft and tunnel form an inflow path for water to the repository. One scenario (a repository with two shaft systems: one an inflow, the other an outflow) was arbitrarily placed in group 1B.

The results of the impermeable salt scenarios (group 1) are discussed in this section. The results of the permeable salt scenarios (group 2) are discussed in the following section.

4.3.1 Scenarios with Outflow through the Shaft

The results for the group 1A scenarios are presented in Table 4.3.1. For each scenario, the peak fifty year individual dose, the peak population dose, and the integrated population dose for the Colorado River system are presented. In each case the whole-body-equivalent dose is used. The time of occurrence of the peaks is noted (both peaks occur simultaneously) and the time at which the doses first reach 10% of their peak value is also given. For the Columbia River system only the peak population dose is presented. The peak Columbia River dose is always smaller than the Colorado River dose. The value of peak fifty year individual dose and integrated population dose for the Columbia River system can be roughly approximated (to within an order of magnitude) by scaling the Colorado River doses in the same way that the peak population doses scale. Unless otherwise noted the Columbia and Colorado River doses peak simultaneously. The amount of radioactivity from each nuclide group reaching the biosphere is also listed for each scenario.

TABLE 4.3-1
IMPERMEABLE SALT: OUTFLOW VIA LATERAL SHAFT

I-3024

INLET: (C.R. 1 FOR CONNECTION TO LOWER ADDITION, 0 FOR CONNECTION TO UPPER ADDITION)	COLORADO RIVER					COLUMBIA RIVER	PEAK RADIOACTIVE OUTPUT		
	PEAK 50 YR. INDIVIDUAL DOSE (rem)	PEAK POPULATION DOSE (man-rem/yr)	INTEGRATED POPULATION DOSE (man-rem)	TIME OF PEAK DOSE (yr)	TIME OF PEAK DOSE/10 (yr)	PEAK POPULATION DOSE (man-rem/yr)	PEAK DOSE GROUP I (Ci/yr)	PEAK DOSE GROUP II (Ci/yr)	PEAK DOSE GROUP III (Ci/yr)
Jointing (I)	1.2×10^{-2}	5.0×10^3	1.1×10^3	2.5×10^4	1.6×10^4	1.7	5.5	9.5×10^{-4}	2.3×10^{-4}
New Fault (I)	1.2×10^{-2}	5.0×10^3	1.1×10^3	2.5×10^4	1.6×10^4	1.7	5.5	9.5×10^{-4}	2.3×10^{-4}
Jointing (I)/Interbed	4.6×10^{-2}	1.0×10^4	1.1×10^3	9.5×10^3	6.9×10^3	8.5	2.1×10^1	1.1×10^{-3}	2.4×10^{-4}
New Fault (I)/Interbed	4.6×10^{-2}	1.0×10^4	1.1×10^3	9.5×10^3	6.9×10^3	8.5	2.1×10^1	1.1×10^{-3}	2.4×10^{-4}
Jointing (II)/Interbed	2.3×10^{-2}	9.6×10^3	1.1×10^3	1.6×10^4	1.0×10^4	3.6	1.1×10^1	1.0×10^{-3}	2.4×10^{-4}
Old Fault (II)/Interbed	1.0×10^{-2}	7.7×10^3	1.1×10^3	2.0×10^4	1.4×10^4	2.7	8.5	9.9×10^{-4}	2.4×10^{-4}
Recess Pipe (III)/Interbed	2.3×10^{-2}	9.6×10^3	1.1×10^3	1.6×10^4	1.0×10^4	3.6	1.1×10^1	1.0×10^{-3}	2.4×10^{-4}
Small Borehole (III)/Interbed	1.4×10^{-3}	1.5×10^3	9.4×10^2	7.2×10^4	4.3×10^4	4.6×10^{-1}	1.5	6.9×10^{-4}	2.0×10^{-4}
Increasing Borehole (III)/Interbed	1.1×10^{-2}	4.0×10^3	1.0×10^3	3.0×10^4	2.0×10^4	1.6	5.2	9.3×10^{-4}	2.3×10^{-4}
Facies Change (I)/Interbed	9.4×10^{-3}	4.0×10^3	1.0×10^3	3.0×10^4	1.9×10^4	1.3	4.4	9.3×10^{-4}	2.3×10^{-4}
Healing Fault (II)/Interbed	2.3×10^{-2}	9.6×10^3	1.1×10^3	1.6×10^4	1.0×10^4	3.6	1.1×10^1	3.2×10^{-3}	2.4×10^{-4}
Healing Fault (I)/Interbed	4.6×10^{-2}	1.0×10^4	1.1×10^3	9.5×10^3	6.5×10^3	8.5	2.1×10^1	3.1×10^{-3}	2.4×10^{-4}

The following sections contain qualitative discussions of the results and a statement of conclusions for the study. A more detailed discussion of the qualitative analysis is contained in Appendix C.

In these scenarios the salt layer is impermeable. Water enters the repository through flaws that provide a flow path from either the lower or upper aquifer and leaves through the shaft/tunnel fracture zone. Two types of inflow connections to the lower aquifer were analyzed. Either the flaw goes directly from the aquifer into the repository or the flaw enters the salt layer 3 km upstream and moves through the salt layer via an interbed to the repository. All inflow connections to the upper aquifer are through a flaw intersecting the salt layer about 1.5 km upstream with the water flowing in an interbed to the repository. The various configurations are depicted in Fig. 3.2-4. The inflow path for each scenario is given in the left-hand column of Table 4.3-1.

The following general observations may be made from the results:

- The individual and population doses produced by a flaw are highest if the flaw is connected to the lower aquifer by an interbed and lowest if the flaw is located directly below the repository
- A large amount of nuclide group I escapes and the amount varies with location of the flaw in the same way as the individual and population doses
- The integrated population dose shows little variation with scenario
- Nuclide group II shows little variation with scenario and Nuclide group III shows even less.

The following qualitative arguments are offered to better understand the causes of these observations.

The variation of inflow paths with the shaft/tunnel fracture zone outflow path affects both the time necessary for waste flow to begin and the amount of water flowing through the repository in the steady-state hydrology.

In order for waste flow to begin two independent conditions must be met. First, the canisters must have corroded sufficiently for water to contact the waste. In all scenarios the canister corrosion time is 500 yr. Second, the repository must have refilled with water. The repository refill time depends on the resistance of the inflow path. These times range from a few years for very low resistance flaws such as a new fault directly beneath the repository to about 8000 years for extremely high resistance flaws such as a very small borehole. Waste flow is initiated at the refill time unless that is less than the canister corrosion time in which case waste begins to flow at 500 years.

The steady-state flow rate of water through the repository depends on both the resistance of the flaw and the hydraulic head where the flaw intersects the aquifer. The interbeds are moderately resistive features, however the flaws they intersect meet the aquifers upstream of the repository thereby providing much larger hydraulic driving forces. The net result is that the flow rates are higher for a flaw intersecting an upstream interbed than for a similar flaw directly below the repository.

The flow rate of water determines the dissolution rate of the waste and also the time required for waste to flow from the repository to the upper aquifer through the tunnel/shaft fracture zone. In all these scenarios the steady-state

flow rate is less than $2.0 \text{ m}^3/\text{yr}$. At these small flow rates, molecular diffusion dominates in the dissolution process and the waste dissolution rate is essentially constant in all scenarios, with about 1.2×10^{-8} of the total inventory dissolving per year. The flow time of the waste to the aquifer varies directly with steady-state water flow rate. The flow times for these scenarios range from about 4000 years for a joint located 3 km upstream from the repository to about 66,000 years for the small borehole located 1.5 km upstream. Dispersion in the local area is proportional to flow time.

The total time required for waste to reach the biosphere is the sum of the flow initiation time, the flow time to the aquifer and the flow time through the aquifer to the river. Chemical processes in the aquifer retard some of the nuclides so that their velocities are less than that of the groundwater. Retardation of the fission products (nuclide group II) and the actinides (nuclide group III) greatly increases the time they spend in the aquifer. The unretarded nuclides (nuclide group I) spend about 4.7×10^3 years in the aquifer while the corresponding times for fission products and actinides are 1.4×10^5 years and 4.7×10^6 years respectively. Consequently, the effect of the flaw on total travel time to the river is small for group II nuclides and practically negligible for group III nuclides.

The peak doses are produced by 10% of the group I nuclides which are assumed to dissolve with the cladding, and thus, for a short time after waste flow begins, leach at a much higher rate than the rest of the waste. The passage of this pulse of waste through the basin and into the biosphere defines the peak doses. The integrated population doses are essentially constant because the initial pulse always reaches the biosphere and the slow constant output from the waste is not sensitive to the small variations in travel times for the scenarios.

Figure 4.3-1 shows the population dose to an individual for input through a fault/interbed system from the lower aquifer. The "pulse" of unretarded nuclides arrives at about 10,000 years. The small rise at about 2×10^5 yr is due to the arrival of group II. The large increase at about 2×10^6 yr is the beginning of the group III arrival. If the graph were extended beyond 3×10^6 yr group III doses would continue to increase for about two million more years. The peak dose from the actinides would be between one and two orders of magnitude higher than the dose at three million years.

Figure 4.3-1 Impermeable Salt/Lateral Shaft Outflow Through Fault/Interbed System: Population Dose

4.3.2 Scenarios with Inflow through the Shaft

The results for the impermeable salt scenarios with inflow through the shaft (group 1B) are presented in Table 4.3-2.

TABLE 4.3-2
IMPERMEABLE SALT: INFLOW VIA UPSTREAM SHAFT

I-3025

CONTINENT	CONRADIA RIVER				CONRADIA RIVER				PEAK RADIOACTIV. OUTPUT	
	PEAK 50 YR. INDIVIDUAL DOSE (rem)	PEAK POPULATION DOSE (man-rem/yr)	INDIVIDUAL DOSE (man-rem)	TIME OF PEAK DOSE (yr)	TIME OF PEAK DOSE (yr)	TIME OF PEAK DOSE (yr)	PEAK 50 YR. INDIVIDUAL DOSE (man-rem/yr)	PEAK 50 YR. INDIVIDUAL DOSE (man-rem/yr)	NUCLEID GROUP (Ct/yr)	NUCLEID GROUP (Ct/yr)
Atlantic	2.0×10^{-9}	0.2×10^3	5.2×10^7	3.4×10^5	1.3×10^5	1.9×10^{-3}	6.3×10^{-2}	2.0×10^{-4}	8.6×10^{-6}	8.6×10^{-6}
	1.0×10^{-3}	4.5×10^2	8.0×10^7	9.3×10^8	3.9×10^8	5.0×10^{-1}	4.5×10^{-1}	4.6×10^{-4}	2.3×10^{-4}	2.3×10^{-4}
New York	0.0	0.0	0.0	---	---	0.0	0.0	0.0	0.0	0.0
	6.3×10^{-2}	2.6×10^4	1.2×10^8	1.1×10^4	9.0×10^3	1.0×10^1	2.9×10^1	1.1×10^{-3}	3.2×10^{-4}	3.2×10^{-4}
Small Borehole	6.5×10^{-2}	2.6×10^4	1.2×10^8	9.5×10^3	7.7×10^3	1.2×10^1	3.0×10^1	1.1×10^{-3}	3.3×10^{-4}	3.3×10^{-4}
	1.4×10^{-2}	2.6×10^4	1.2×10^8	9.0×10^3	6.9×10^3	1.2×10^1	3.0×10^1	1.1×10^{-3}	3.3×10^{-4}	3.3×10^{-4}
Large Borehole	1.0×10^{-2}	6.6×10^1	1.0×10^8	2.3×10^4	1.6×10^4	2.3	7.3	9.4×10^{-4}	1.0×10^{-4}	1.0×10^{-4}
	0.0	0.0	0.0	---	---	0.0	0.0	0.0	0.0	0.0
Federal Shaft	0.0	0.0	0.0	---	---	0.0	0.0	0.0	0.0	0.0
	0.0	0.0	0.0	---	---	0.0	0.0	0.0	0.0	0.0
Factors Change	0.0	0.0	0.0	---	---	0.0	0.0	0.0	0.0	0.0
	0.0	0.0	0.0	---	---	0.0	0.0	0.0	0.0	0.0
Interlock/Any Case	0.0	0.0	0.0	---	---	0.0	0.0	0.0	0.0	0.0
	0.0	0.0	0.0	---	---	0.0	0.0	0.0	0.0	0.0

in these scenarios, water enters the repository through the tunnel/shaft fracture zone. Contaminated water leaves the repository either through a flaw connecting to the aquifer directly above, or through 3 km-long interbeds that intersect a flaw which leads to the upper aquifer. The various configurations are depicted in Fig. 3.2-5. In each case the outflow path is listed in the left-hand column of Table 4.3-2.

The following general observations are based on these results:

- The doses from the borehole cases are the highest for the impermeable salt scenarios
- There is no outflow through the breccia pipe, facies changes, or in a scenario involving flow through the 3 km interbed within our 3-million year period
- Very low resistance flaws such as jointing or new faults do not produce large doses.

The comments concerning refill time, resaturation time, and steady-state flow rate made with respect to the group 1A scenarios also hold for the group 1B scenarios. The waste will begin to flow in as little as 500 years for a low resistance flaw or as much as 8000 years for a high resistance flaw. The steady-state flow rate increases as the resistance of the flaw decreases, but in no case does as much as $2.0 \text{ m}^3/\text{yr}$ flow through the repository. The fractional dissolution rate of the waste is about $1.2 \times 10^{-8} \text{ yr}^{-1}$.

Despite these similarities the results for groups 1A and 1B differ. The disparity is caused by the differing capacities (void volumes) of the outflow paths in the 1B scenarios. The total flow time in an outflow path is equal to the capacity

of the path divided by the volumetric flow rate of water. Two outflow paths with the same resistance will produce identical steady-state water flow rates, but have substantially different transit times if they have substantially different capacities. This is true for the joint and new fault outflow paths (see Table 4.3-2). They have essentially equal resistances, but the capacity of the joint system is about five times greater than the capacity of the fault. Hence, the flow time in the fault is much shorter than in the fracture system, so the fault produces higher doses.

The concept of capacity was not mentioned for the group 1A scenarios because the outflow path was always the same. The two shaft repository scenario in group 1B can be used to compare the shaft outflow path to the other possible outflow paths.

The very large capacities of the breccia pipe, facies changes, and interbeds prevent any output from reaching the rivers in these scenarios. The flow times are larger than three million years. This result is especially striking in the case of the breccia pipe which is a very low resistance flaw.

The very small capacity of the boreholes causes them to have the shortest transit time to the aquifer of any of the scenarios. Thus, even though the boreholes are highly resistive to water flow (causing a slow repository refill and a small volumetric flow rate) their low capacity produces the largest doses of the impermeable salt failure scenarios.

The radioactive outputs for group II and III nuclides now show variations with scenario both because the flow time from the repository to the upper aquifer may be an appreciable

fraction of the transit times of the nuclides in the aquifer, and because the very short flow times in some scenarios significantly reduce dispersion of the waste.

Figure 4.3-2 shows the population dose for the large borehole outflow path. The peak dose occurs at about 10^4 years due to the long refill time (about 5000 years) for this scenario. The waste enters the aquifer only six years after leaving the repository and then takes 4500 years to reach the river. The small rise in dose associated with the fission products occurs as in Fig. 4.3-1 as does the late increase in dose caused by the actinides.

Figure 4.3-2 Impermeable Salt/Upstream Shaft Outflow
Through Large Borehole: Population Dose

4.4 THE FLAWED REPOSITORY WITH PERMEABLE SALT

4.4.1 Scenarios with Outflow Through the Shaft

The results for the permeable salt scenarios with outflow through the shaft (Group 2A) are presented in Table 4.4-1. In these scenarios, water enters the repository through the porous rock and possibly another flaw. A variety of exit paths are modeled. In addition to outflow through the porous rock, either a shaft/tunnel fracture zone or a failed shaft/tunnel backfill is used as an outlet path in each scenario. The shaft/tunnel system is located either lateral to or downstream of the repository. In addition, exits through other flaws are also modeled. Some typical configurations are depicted in Fig. 3.2-6. The left-hand column of Table 4.4-1 lists the inflow paths included in each scenario, states the position of the shaft, notes whether the shaft has failed and describes any additional outflow paths.

In the scenarios with permeable salt, the repository is assumed to be located in the center of the salt layer. As a consequence the lengths of the flaws studied in these scenarios and the length of the shaft differ from those in the impermeable salt scenarios by about 25%. In the following, direct comparisons are made between scenarios with permeable and impermeable salt having otherwise analogous flaws in spite of the differences in lengths. The large effect of the permeable pathway through the salt tends to mask the changes caused by the differences in length sufficiently that these comparisons are reasonable.

The results support the following observations:

- The doses obtained with impermeable salt are reduced when a permeable salt pathway is added to similar scenarios

TABLE 4.4-1
PERMEABLE SALT: OUTFLOW VIA LATERAL (LAT) OR DOWNSTREAM (DOWN)
SHAFT AND POROUS ROCK

I-3826

INFLOW: (Porous Rock and ...)	COLORADO RIVER					COLUMBIA RIVER	PEAK RADIOACTIVE OUTFLOW		
	PEAK 50 YR. INDIVIDUAL DOSE (rem)	PEAK POPULATION DOSE (man-rem/yr)	INTEGRATED POPULATION DOSE (man-rem)	TIME OF PEAK DOSE (yr)	TIME OF PEAK DOSE/10 (yr)	PEAK POPULATION DOSE (man-rem/yr)	PEAK DOSE I (Ci/yr)	PEAK DOSE II (Ci/yr)	PEAK DOSE III (Ci/yr)
Porous Only (lat)	4.6×10^{-4}	2.0×10^2	1.9×10^7	3.9×10^4	2.1×10^4	6.3×10^{-2}	2.1×10^{-1}	9.2×10^{-5}	1.3×10^{-5}
Porous Only (down)	2.0×10^{-3}	8.1×10^2	1.7×10^7	1.0×10^4	7.3×10^3	1.6×10^{-1}	9.2×10^{-1}	7.7×10^{-5}	1.3×10^{-5}
Porous Only; Failed Shaft (lat)	1.7×10^{-2}	7.1×10^3	8.5×10^7	1.0×10^4	1.2×10^4	7.6	7.9	8.4×10^{-4}	1.2×10^{-4}
Porous Only; Failed Shaft (down)	5.8×10^{-2}	2.3×10^4	1.2×10^8	6.9×10^3	4.5×10^3	1.2×10^1	2.8×10^1	1.3×10^{-3}	3.3×10^{-4}
New Fault/Interbed (lat)	5.9×10^{-4}	2.5×10^2	2.8×10^7	2.1×10^4	1.3×10^4	8.7×10^{-2}	2.7×10^{-1}	1.6×10^{-4}	2.9×10^{-5}
Porous Only/Shaft (lat) and an Additional Exit via a Large Borehole	9.0×10^{-3}	3.6×10^3	3.6×10^7	1.0×10^4	6.2×10^3	1.6	4.1	2.6×10^{-4}	4.9×10^{-5}
New Fault Upstream; Shaft (down)	8.5×10^{-4}	3.5×10^2	4.1×10^7	1.2×10^4	8.1×10^3	1.8×10^{-1}	3.9×10^{-1}	3.6×10^{-4}	7.9×10^{-5}

- The doses from a downstream shaft are larger than from a lateral shaft
- The failed downstream shaft scenario produces doses comparable to the worst of the impermeable salt scenarios.

The addition of porous flow causes several changes in all scenarios. First, the repository is refilled in less than 500 years through the permeable pathways. Consequently, the waste begins to flow at 500 years, when the canisters have corroded, in all of the permeable salt scenarios. Second the presence of the porous rock increases the steady-state water flow rate through the repository. Flow rates for these scenarios range from about $3 \text{ m}^3/\text{yr}$ for the case with porous flow and lateral shaft only to about $25 \text{ m}^3/\text{yr}$ for the scenario with the slightly upstream fault and downstream shaft. These flow rates are not large enough to significantly change the dissolution rate of the waste.

Despite the increased flow rate of water through the repository the presence of the porous flow pathway tends to reduce the peak doses. The permeability used for the salt in this study is 10^{-10} cm/sec . At this permeability the flow path through the salt has a moderate resistance (0.66 yr/m^2 as compared to $6.0 \times 10^{-5} \text{ yr/m}^2$ for a new fault and 37.5 yr/m^2 for a large borehole). Branching flow paths carry water away roughly in inverse proportion to their resistance. Hence, the porous flow path is able to carry a large portion of the water leaving the repository in many cases. The porous rock has an extremely large capacity so flow times to the aquifer range from 5×10^5 to over 2×10^6 years.

In these scenarios waste leaving the repository can flow to the aquifer either through the permeable salt (resistance of about 0.66 yr/m^2), the shaft/tunnel fracture zone

(resistance of about 15 yr/m^2), the failed shaft/tunnel backfill (resistance of about 0.24 yr/m^2) or a borehole (resistance of about 30.0 yr/m^2). Thus the porous rock will "compete" effectively for the waste except in the failed backfill scenarios. The long flow times will allow for significant decay and dispersion of the waste while in the porous rock.

Flow rates are much larger with the shaft downstream rather than lateral because the downstream shaft reduces the head of the repository, thereby increasing the steady-state inflow. The failed downstream shaft scenario reduces the repository head sufficiently that water flows down into the repository from the upper aquifer in the steady state. This leads to large doses because of this large inflow and because the failed shaft has a lower resistance than the porous rock so it transports a larger portion of the waste.

In two cases (the new fault/interbed scenario and the slightly upstream fault scenario) the repository head is raised due to the low resistance flaws with relatively large hydraulic driving forces. The resulting steady-state flow paths have waste flowing downward from the repository into the lower aquifer in addition to the usual upward flow. The hydraulic driving force is very small for the downward-moving waste so none of it is able to reach the river in three million years.

Figure 4.4-1 shows the population dose for the new fault/interbed inflow scenario. This scenario is the direct analog of the impermeable scenario which produces Fig. 4.3-1. The initial peak is reduced by approximately two orders of magnitude in the permeable case because only about 4.0% of the water leaving the repository goes through the shaft. This reduction in water flow produces a proportional reduction in the amount of waste leaving the repository via the shaft and also produces an increase in the flow time through the shaft.

Figure 4.4-1 Permeable Salt/Lateral Shaft New Fault/
Interbed Inflow from Lower Aquifer
Population Dose

The flow time of waste through the porous rock is about one million years. The second peak in dose in Fig. 4.4-1 is produced by the fast dissolving unretarded nuclides that have travelled through the porous rock. The long travel time has reduced and spread the pulse through decay and dispersion. The final small rise at about three million years is caused by the actinides which flowed through the shaft.

4.4.2 Scenarios with Inflow through the Shaft

Group 2B - In this group of scenarios water enters the repository through the porous rock and an upstream tunnel/shaft fracture zone and leaves through a variety of possible flaws. In the last three scenarios listed in Table 4.4-2 an

TABLE 4.4-2
PERMEABLE SALT: INFLOW VIA POROUS ROCK AND UPSTREAM SHAFT

1-3827

GIFTLIME: (Porous Flow and ...)	COLORADO RIVER					COLUMBIA RIVER	PEAK RADIOACTIVE CONCENTRATION		
	PEAK 50 YR. INDIVIDUAL DOSE (rem)	PEAK POPULATION DOSE (man-rem/yr)	INTEGRATED POPULATION DOSE (man-rem)	TIME OF PEAK DOSE (yr)	TIME OF PEAK DOSE/10 (yr)	PEAK POPULATION DOSE (man-rem/yr)	NUCLIDE GROUP I (Ci/yr)	NUCLIDE GROUP II (Ci/yr)	NUCLIDE GROUP III (Ci/yr)
New Fault	2.1×10^{-2}	8.5×10^3	1.0×10^8	1.1×10^4	6.2×10^3	3.7	9.7	1.0×10^{-3}	1.4×10^{-4}
Fractured Rock	4.1×10^{-3}	1.7×10^3	1.0×10^8	3.0×10^4	1.2×10^4	5.6×10^{-1}	1.9	9.1×10^{-4}	2.2×10^{-4}
Old Fault	2.8×10^{-4}	1.2×10^2	2.6×10^7	5.8×10^4	2.2×10^4	5.0×10^{-2}	1.3×10^{-1}	1.0×10^{-4}	2.2×10^{-5}
Large Borehole	1.2×10^{-3}	4.7×10^2	1.7×10^7	5.3×10^3	3.3×10^3	2.9×10^{-1}	6.2×10^{-1}	8.5×10^{-5}	8.9×10^{-6}
New Fault with an Additional Inflow via a New Fault	5.9×10^{-2}	2.3×10^4	8.6×10^8	5.0×10^3	3.1×10^3	1.4×10^1	3.0×10^1	1.3×10^{-1}	5.5×10^{-3}
Breccia Pipe with an Additional Inflow via a New Fault/Breccia Pipe System	6.0×10^{-2}	2.3×10^4	1.4×10^9	5.3×10^3	3.5×10^3	2.5×10^1	3.0×10^1	1.6×10^{-1}	1.1×10^{-2}
Fractured Rock with an Additional Inflow via Fractured Rock	5.9×10^{-2}	2.3×10^4	2.1×10^8	5.9×10^3	3.7×10^3	1.3×10^1	2.9×10^1	3.9×10^{-3}	2.9×10^{-4}

*This peak occurs at 3×10^6 yrs.

additional low resistance inflow path has been added. Typical configurations are depicted in Fig. 3.2-6. The left-hand column of the table gives the outflow path plus any additional inflow paths included in the scenario.

The following observations can be derived from these results:

- The doses for a low resistance outflow path are slightly increased when the salt is permeable
- The doses for the large borehole are significantly decreased when the salt has non-zero permeability
- Both a low resistance inflow and outflow path must be added to the permeable salt to approach the worst case for impermeable salt
- There are large variations in integrated population dose and in radioactive output from nuclide groups II and III in the worst cases.

The comments regarding the ability of the permeable salt to compete for waste with other flaws made concerning group 2A are equally true for these scenarios. In the new fault case, the porous rock is much more resistive than the new fault so the waste flows predominantly through the fault. Because of the permeable salt the amount of water flowing through the repository is about 20 times larger than in the corresponding impermeable salt case. Not surprisingly, the peak doses have increased in the permeable salt scenario.

For the cases involving the old fault and large borehole, most of the waste flows through the salt; the smaller capacity of the borehole accounts for the higher doses in that

scenario. The results of the permeable salt scenarios with inflow through the shaft are presented in Table 4.4-2.

The last three scenarios listed in Table 4.4.2 each has a low resistance flow path from the lower aquifer to the upper aquifer. These flow paths can accommodate very large steady-state flow rates. These flow rates are large enough to affect the dissolution rate of the waste. Table 4.4-3 summarizes these flow rates and dissolution rates.

TABLE 4.4-3
WASTE DISSOLUTION RATES FOR LARGE FLOW SCENARIOS

OUTFLOW PATH	FLOW RATE (m^3/vr)	DISSOLUTION RATE (yr^{-1})
New Fault	6.3×10^4	1.1×10^{-6}
Breccia Pipe	3.0×10^4	2.3×10^{-6}
Fractured Rock	2.7×10^2	7.5×10^{-7}

These variable flow rates cause the peak radioactivities from nuclide groups II and III to vary because of the different amounts of radioactivity released per unit time. The group I and dose peaks are still determined by the initial pulse of unretarded nuclides. The integrated population doses also increase in these cases because of the much larger amount of waste entering into transport each year.

In each of these cases the waste is almost 100% committed to the flaw since all of the output flaws have a much lower resistance than the salt (see Appendix C). The flow times through the flaws are very short, and thus the peak doses are about the same for these scenarios.

Figure 4.4-2 shows the population dose for the large borehole scenario. This scenario is analogous to the scenario that produced Fig. 4.3-2. The peak dose is reduced by a factor of 50 since only two percent of the waste enters the borehole when the salt is permeable. The second rise in dose in Fig. 4.4-2 is caused by the initial pulse which has passed through the porous media. The actinides flowing through the borehole are responsible for the increased dose at three million years.

Figure 4.4-2 Permeable Salt/Upstream Shaft Outflow Through Large Borehole: Population Dose

Figure 4.4-3 shows the population dose for the scenario with breccia pipe outflow and a new fault and breccia pipe system below the repository. The dose after the peak passes is much higher than usual because about 100 times more waste is dissolving per year than in the previously examined

scenarios. The large drop in dose at about one million years is because the waste had dissolved by this point in time. The unretarded nuclides have already entered the biosphere and the major contributor to dose are the fission products. Eventually the actinides begin to enter the biosphere and the dose again rises.

Figure 4.4-3 Permeable Salt/Upstream Shaft Outflow Through Breccia Pipe Inflow Through New Fault/Breccia Pipe: Population Dose

5.

SENSITIVITY ANALYSIS

Sensitivity analysis is a method for determining the effect of changes in parameter values on dose predictions. The value of a single parameter is changed in each case and the other parameters retain their original values. Two types of sensitivity analyses can be considered. In one type only small parameter changes are allowed. The results give a measure of the sensitivity of the model near its nominal configuration. The other type of analysis changes parameter values to the limits of their range. The results give a measure of the effect of the uncertainty in parameter values on the nominal performance of the repository. Both types of analysis are discussed in the following.

Sensitivity analysis was performed on four waste migration scenarios:

- Scenario 1: repository located in impermeable salt with new fault/interbed inflow and outflow from a lateral shaft
- Scenario 2: repository located in impermeable salt with inflow through an upstream shaft and outflow from a large borehole
- Scenario 3: repository located in fractured salt, with shale above and below and inflow through an upstream shaft
- Scenario 4: repository located in permeable salt, with inflow through an upstream shaft and outflow through a large borehole.

For ease of discussion the scenarios will be referred to by number within this chapter. The NUTRAN computer code was used to generate the outputs of the waste release scenarios in terms of curie releases, rather than dose to man. This was done in order to circumvent testing the sensitivity of the biological uptake model concurrently with that of the nuclide transport model. The term "output" will be used synonymously with "released curies" within this chapter.

For each sensitivity case the value of a single parameter was changed from its baseline value. All four scenarios had a set of parameters which was increased by 10% of its baseline value. In addition, the last two scenarios had the same set of parameters changed to maximally detrimental values which were still credible. These changes varied between a fraction of the baseline value to a difference of several orders of magnitude. (These will be referred to as "range" changes.) Curie releases were computed for each sensitivity case. The fractional change in peak and integrated curies from the baseline case were computed as follows:

$$\text{Change in Peak Curies} = \frac{C(j) - C_o(j)}{C_o(j)}$$

$$\text{Change in Integrated Curies} = \frac{T(j) - T_o(j)}{T_o(j)}$$

where

$C(j)$ = peak curies for nuclide group j ,
sensitivity case

$C_o(j)$ = peak curies for nuclide group j ,
baseline case

$T(j)$ = integrated curies for nuclide group j ,
sensitivity case

$T_0(j)$ = integrated curies for nuclide group j ,
baseline case

The sets of varied parameters for each scenario were then ranked according to the magnitude of change in the peak curies and integrated curies for all nuclides. These results are discussed on a scenario-by-scenario basis.

The change in peak curies and integrated curies due to the range change were also computed with a modification factor to make them more comparable despite the wide variation in the amount by which the input value was altered; i.e., they were multiplied by:

$$\frac{I_0}{I - I_0}$$

where

I_0 = baseline input value of parameter

I = sensitivity input value of parameter

The modification factor has the effect of diminishing the change in output if the range change is more than 100% of the baseline value and increasing it if it is under 100% of the baseline value. To obtain the modified change in curies for 10% change in input values, multiply the numbers in Table 5-1, 5-2, 5-4, and 5-7 by 10.

The precise meaning of the modified values can be understood as follows. For the integrated curies, the

modified factor is

$$\frac{T - T_0}{T - T_0} \bigg/ \frac{T_0}{T_0}$$

This quantity represents the marginal rate of change of dose with respect to the parameter varied.

Scenario 1: The relative impeturbability of total integrated output to 10% changes in selected parameters is evident from Table 5-1. In this and the other tables of this chapter, "nuclide group" and "nuclide class" are synonymous. No change in any of the parameters results in more than a 1.4% change in the total integrated curies. For this scenario, increasing the gradient of the aquifer caused the greatest overall change in the outputs. No other factor had more than a 1% change in integrated curies or a 5% change in the peak curies of Nuclide group I.

Nuclide groups II and III represent a relatively small portion of the total output, hence large changes in release from these nuclides may not be reflected in the total. Group II nuclides are most affected by changes in the solubility of uranium (9.6% increase in the integrated curies and 9.9% increase in peak curies). Nuclide group III may undergo large fluctuations, i.e., 156% or 125% (due to 10% increases in the permeability of sandstone and the gradient of the aquifer respectively). This results from the output of this group just beginning to rise three million years, the cutoff point for this study. Any change in the time of the peak can radically change the integrated curies or peak curies for nuclide group three. However, these changes are so overshadowed by output of Nuclide group I, that these changes are barely reflected in the total output.

TABLE 5-1
CHANGE IN CURIES DUE TO 10% INCREASE IN SELECTED PARAMETERS
IN SCENARIO WITH IMPERMEABLE SALT, LATERAL SHAFT
AND AN UNHEALED UPSTREAM FAULT

1-3035

RANK ON PEAK CURIES	VARIED PARAMETER AND BARRIER*	CHANGE IN CURIES							
		INTEGRATED CURIES				PEAK CURIES			
		ALL NUCLIDES	CLASS 1	CLASS 2	CLASS 3	ALL NUCLIDES	CLASS 1	CLASS 2	CLASS 3
1	Gradient of Aquifer (RI)	0.014	0.012	0.032	1.250	0.105	0.105	0.126	1.050
3	Length of Interbed (LI)	0.007	0.007	0.004	0.002	0.038	0.038	0.006	0.002
9	Permeability of Sandstone (RI)	0.006	0.004	0.024	1.560	0.018	0.018	0.091	1.210
5	Length of Aquifer (RI)	-0.005	-0.005	-0.026	-0.696	-0.030	-0.030	0.099	-0.652
6	Length of First Tunnel Segment (LI)	-0.004	-0.004	-0.001	-0.001	-0.028	0.028	-0.004	-0.001
2	Porosity of First Tunnel Segment (LI)	-0.004	-0.004	-0.001	-0.001	-0.048	-0.048	0.004	-0.001
13	Saturation Concentration of UO_2 (R)	0.004	0.003	0.096	0.096	0	0	0.099	0.100
8	Porosity of Sandstone (RI)	-0.002	-0.002	-0.010	-0.343	-0.023	-0.023	-0.046	-0.300
12	Piezometric Level Repository (LI)	0.001	0.001	-0.001	-0.001	0.002	0.002	0	0
10	Transmissivity of Interbed (LI)	0.001	0.001	0.001	-0.001	0.007	0.007	0.001	-0.001
7	Dispersion of First Tunnel Segment (LI)	-0.001	-0.001	-0.001	-0.001	-0.023	-0.023	-0.001	0
11	Permeability of First Tunnel Segment (LI)	-0.001	-0.001	-0.001	-0.001	0.003	0.003	0	0
14	Actinide Retardation (RI)	-0.001	0	0	-0.576	0	0	0	-0.541
15	Fission Product Retardation (RI)	-0.001	0	-0.027	0	0	0	-0.113	0
16	Lateral Dispersivity of Sandstone (RI)	-0.001	-0.001	-0.001	0.000	-0.001	-0.001	-0.001	0.005
4	Permeability of Shale (RI)	-0.001	-0.001	0.002	-0.182	0.036	0.036	-0.027	-0.135

* D: Dissolution LI: Local Hydrology RI: Regional Hydrology
TABLE

CHANGE IN CURIES DUE TO 10% INCREASE IN SELECTED PARAMETERS
IN SCENARIO WITH IMPERMEABLE SALT, LATERAL SHAFT AND AN
UNHEALED UPSTREAM FAULT.

Scenario 2: The fraction of iodine released with the dissolution of the cladding has the largest effect on the integrated curies for all nuclides and group I nuclides (Table 5-2). Since the iodine peak determines the peak curies for all nuclides, a ten percent increase in the fraction of iodine released results in a ten percent increase in the peak curies for these groups. With the exception of this parameter, no other parameter altered the integrated curies for all nuclides more than two percent.

Nuclide groups II and III are directly affected by the solubility of uranium; both the integrated and peak curies are increased by ten percent when the solubility is equally increased. Changes in the gradient of the aquifer and the permeability of the sandstone can have marked effects on the integrated and peak curies for nuclide group III for reasons already mentioned.

Scenario 3: The baseline and range values for the parameters analyzed in this scenario are given in Table 5-3. The changes in curies for 10%, range and modified range changes are given in Tables 5-4 through 5-6. Under the ten percent and modified range changes, the fraction of iodine released most strongly affects the integrated curies for Group I and all nuclide groups and strongly affects the peak curies for these outputs. The saturation concentration of uranium dominates the change in the integrated curies for the unmodified range change, but when modified, drops to sixth in rank. As already mentioned, factors affecting the travel time of the actinides can greatly affect the peak and integrated curies for nuclide group III; changes in the length and gradient of the aquifer, retardation and permeability of unfractured shale (shale located in the basin away from the repository) create marked increases in the output of the actinides. But, as seen before, even these increases barely affect the outputs for all nuclides combined.

TABLE 5-2
CHANGES IN CURIES DUE TO 10% INCREASE IN SELECTED PARAMETERS
IN SCENARIO WITH IMPERMEABLE SALT, UPSTREAM SHAFT
AND OUTFLOW THROUGH LARGE BOREHOLE

T-3834

RANK ON PEAK CURIES	VARIED PARAMETER AND BARRIER ¹	CHANGE IN CURIES							
		INTEGRATED CURIES				PEAK CURIES			
		ALL NUCLIDES	CLASS 1	CLASS 2	CLASS 3	ALL NUCLIDES	CLASS 1	CLASS 2	CLASS 3
2	Fraction of Indine (D)	0.096	0.097	0	0	0.100	0.100	0	0
1	Gradient of Aquifer (RH)	0.018	0.016	0.030	1.140	0.119	0.119	0.123	0.938
8	Permeability of 2nd Tunnel Segment (LH)	0.015	0.015	0.030	0.004	0.002	0.002	0.008	0.003
4	Length of Aquifer (RH)	-0.005	-0.005	-0.027	-0.681	-0.053	-0.053	-0.104	-0.631
6	Permeability of Sandstone (RH)	0.006	0.004	0.025	1.380	0.034	0.034	0.007	1.090
7	Piezometric Level of Repository (LH)	0.005	0.015	0.001	0.001	0.009	0.009	0.003	0.001
11	Saturation Concentration of UO_2 (D)	0.004	0.003	0.100	0.100	0	0	0.100	0.100
5	Porosity of Sandstone (RH)	-0.002	-0.002	-0.010	-0.322	-0.038	-0.038	-0.040	-0.286
9	Cross-Section of Borehole (LH)	0.002	0.002	-0.001	-0.001	-0.002	-0.002	0.001	-0.001
12	Actinide Retardation (RH)	-0.001	0	0	-0.550	0	0	0	-0.511
13	Fission Product Retardation (RH)	-0.001	0	-0.027	0	0	0	-0.117	0
14	Radium Retardation (RH)	-0.001	0	0	-0.063	0	0	0	-0.056
10	Lateral Dispersivity of Sandstone (RH)	-0.001	-0.001	-0.001	-0.007	-0.002	-0.002	0.001	0.005
3	Permeability of Shale (RH)	-0.001	-0.001	0.002	-0.160	0.062	0.062	0.026	-0.112

*Table entries smaller than 0.001 but not zero are denoted by -0.001

¹D: Dissolution LH: Local Hydrology RH: Regional Hydrology

TABLE

CHANGES IN CURIES DUE TO 10% INCREASE IN SELECTED PARAMETERS, IN SCENARIO
WITH IMPERMEABLE SALT, UPSTREAM SHAFT AND OUTFLOW THROUGH LARGE BOREHOLE.

TABLE 5-3
BASELINE AND RANGE VALUES FOR SCENARIO
WITH UPSTREAM SHAFT AND FRACTURED ROCK

BARRIER	VARIED PARAMETER	BASELINE VALUE	RANGE VALUE
Dissolution	Fraction of Iodine Saturation Conc. of UO_2	1.0×10^{-1} 9.0×10^0	4.0×10^{-1} 9.0×10^2
Local Hydrology	Head of Lower Aquifer	3.6×10^0	6.0×10^1
	Permeability of Lower Salt	1.0×10^{-8}	1.0×10^{-6}
	Permeability of Upper Salt	1.0×10^{-8}	1.0×10^{-6}
	Porosity of Upper Salt	1.0×10^{-4}	1.0×10^{-5}
	Permeability of Fractured Shale	1.0×10^{-6}	1.0×10^{-4}
	Porosity of Fractured Shale	1.0×10^{-4}	1.0×10^{-5}
Regional Hydrology	Length of Upper Aquifer	5.5×10^1	1.5×10^1
	Gradient of Upper Aquifer	6.0×10^{-3}	1.5×10^{-2}
	Porosity of Sandstone	1.0×10^{-1}	1.0×10^{-2}
	Permeability of Unfractured Shale	6.3×10^{-5}	2.0×10^{-4}
	Fission Product Retardation	3.0×10^1	3.0×10^0
	Actinide Retardation	1.0×10^3	5.0×10^1

If the aquifer is likely to heavily retard the actinides, it is also likely to heavily retard the fission products. The reverse is also true. For this reason an additional run was made with the retardation factor to the worst credible value for both the group II and group III nuclides. The net result an increase in the integrated curies for all nuclide groups of 0.23 from the baseline value; the increase due to changing

TABLE 5-4
CHANGE IN CURIES DUE TO 10% INCREASE IN SELECTED PARAMETERS
IN SCENARIO WITH UPSTREAM SHAFT AND WITH FRACTURED ROCK

T-3936

RANK ON PEAK CURVES	VARIED PARAMETER AND BARRIER ¹	CHANGE IN CURIES							
		INTEGRATED CURIES				PEAK CURIES			
		ALL NOCLINES	CLASS 1	CLASS 2	CLASS 3	ALL NOCLINES	CLASS 1	CLASS 2	CLASS 3
1	Fraction of Indine (D)	0.001	0.096	<0.001	0	0.100	0.100	<0.001	0
3	Permeability of Lower Salt (LH)	0.032	0.017	0.020	0.200	0.076	0.076	0.200	0.200
12	Saturation Concentration of SO ₂ (S)	0.009	0.003	0.100	0.100	<0.001	0.001	0.072	0.100
2	Gradient of Upper Aquifer (RH)	0.008	0.006	0.010	1.246	0.008	0.008	0.041	1.040
5	Length of Upper Aquifer (RH)	-0.007	-0.006	-0.010	-0.696	-0.046	-0.046	-0.030	-0.651
6	Porosity of Sandstone (RH)	-0.002	-0.002	-0.004	-0.341	-0.023	-0.023	-0.012	-0.307
9	Permeability of Upper Salt (LH)	0.001	<0.001	0.008	0.008	0.004	0.004	0.008	0.008
13	Actinide Retardation (RH)	<-0.001	<-0.001	<-0.001	-0.575	0	0	<-0.001	-0.510
7	Porosity of Fractured Shale (LH)	<-0.001	<-0.001	<-0.001	0	-0.007	-0.007	-0.001	<-0.001
14	Fission Product Retardation (RH)	<-0.001	<-0.001	-0.011	0	0	0	-0.039	0
4	Permeability of Unfractured Shale (RH)	<-0.001	<-0.001	0.001	-0.181	0.055	0.055	0.013	-0.135
8	Porosity of Upper Salt (LH)	<-0.001	<-0.001	<-0.001	-0.001	-0.005	-0.005	<-0.001	<-0.001
10	Permeability of Fractured Shale (LH)	<-0.001	<-0.001	<-0.001	0.001	<-0.001	<-0.001	<-0.001	<-0.001
11	Head of Lower Aquifer (LH)	<-0.001	<-0.001	<-0.001	0.001	-0.001	<-0.001	<-0.001	<-0.001

¹Table entries smaller than 0.001 but not zero are denoted by <0.001

²D: Dissolution LH: Local Hydrology RH: Regional Hydrology

TABLE

CHANGE IN CURIES DUE TO 10% INCREASE IN SELECTED PARAMETERS
IN SCENARIO WITH UPSTREAM SHAFT AND WITH FRACTURED ROCK

TABLE 5-5
CHANGE IN CURIES DUE TO RANGE CHANGE IN SELECTED PARAMETERS
IN SCENARIO WITH UPSTREAM SHAFT AND FRACTURED ROCK

T-3843

RANK ON PEAK CURIES	VARIABLE PARAMETER AND BARRIER ¹	CHANGE IN CURIES							
		INTEGRATED CURIES				PEAK CURIES			
		ALL NUCLIDES	CLASS 1	CLASS 2	CLASS 3	ALL NUCLIDES	CLASS 1	CLASS 2	CLASS 3
10	Saturation Concentration of H_2O (D)	3.415	3.027	8.259	95.034	0.016	0.019	33.038	92.965
1	Fraction of Iodine (D)	2.724	2.804	0	0	2.999	2.999	-0.001	0
2	Permeability of Unfractured Shale (RH)	0.393	0.005	0.171	270.950	2.723	2.723	1.417	303.700
3	Gradient of Upper Aquifer (RH)	0.351	0.103	1.427	158.903	1.825	0	2.290	47.238
14	Actinide Retardation (RH)	0.221	0	0	197.210	0	0	-0.001	45.302
4	Length of Upper Aquifer (RH)	0.165	0.052	0.110	97.641	0.689	0.689	0.452	20.265
6	Permeability of Lower Salt (LH)	0.004	0.039	0.833	0.835	0.090	0.090	0.833	0.835
7	Permeability of Upper Salt (LH)	0.020	0.12	0.163	0.164	0.063	0.063	0.163	0.164
14	Fission Product Retardation (RH)	0.008	0	0.153	0	0	0	1.096	0
5	Porosity of Sandstone (RH)	-0.007	-0.005	-0.009	-0.964	0.168	0.168	0.011	-0.946
8	Porosity of Fractured Shale (RH)	0.006	0.006	-0.001	0.001	0.049	0.049	0.001	0.001
9	Porosity of Upper Salt (LH)	0.004	0.004	-0.001	0.001	0.035	0.035	0	0
11	Permeability of Fractured Shale (LH)	-0.001	-0.001	0.001	0.001	-0.001	-0.001	0.001	0.001
12	Head of Lower Aquifer (LH)	-0.001	-0.001	0.001	0.001	-0.001	-0.001	0.001	0.001

*Table entries smaller than 0.001 but not zero are denoted by -0.001

¹D: Dissolution LH: Local Hydrology RH: Regional Hydrology

TABLE
CHANGE IN CURIES DUE TO RANGE CHANGE IN SELECTED PARAMETERS, IN SCENARIO
WITH UPSTREAM SHAFT AND FRACTURED ROCK

TABLE 5-6
MODIFIED CHANGE IN CURIES DUE TO RANGE CHANGE IN
SELECTED PARAMETERS IN SCENARIO WITH UPSTREAM SHAFT AND FRACTURED ROCK

T-3846

RANK ON PEAK CURIES	VARIED PARAMETER AND BARRIER ¹	CHANGE IN CURIES							
		INTEGRATED CURIES				PEAK CURIES			
		ALL INCLIDES	CLASS 1	CLASS 2	CLASS 3	ALL INCLIDES	CLASS 1	CLASS 2	CLASS 3
3	Fraction of Iodine (D)	0.907	0.960	0	0	0.990	0.990	<-0.001	0
2	Gradient of Upper Aquifer (RH)	0.235	0.069	0.952	105.99	1.218	1.218	1.528	31.500
14	Actinide Retardation (RH)	-0.232	<-0.001	0	-207.07	0	0	<-0.001	-47.651
4	Length of Upper Aquifer (RH)	-0.226	-0.072	-0.152	-134.26	-0.947	-0.947	-0.621	-27.864
1	Permeability of Unfractured Shale (RH)	0.101	0.039	0.079	124.64	1.253	1.253	0.652	139.702
10	Saturation Concentration of I^{129} (D)	0.034	0.030	0.083	0.95	0.001	<-0.001	0.330	0.930
13	Fission Product Retardation (RH)	-0.009	<-0.001	-0.170	0	0	0	-1.216	0
5	Porosity of Sandstone (RH)	0.008	0.006	0.010	1.07	-0.106	-0.185	-0.012	1.050
6	Porosity of Upper Salt (LH)	-0.004	-0.005	-0.001	0	-0.039	-0.039	0	-0.001
7	Permeability of Lower Salt (LH)	-0.001	<-0.001	0.008	0.01	<-0.001	<-0.001	0.008	0.008
8	Permeability of Upper Salt (LH)	<-0.001	<-0.001	0.002	0	<-0.001	<-0.001	0.002	0.002
9	Porosity of Fractured Shale (LH)	<-0.001	<-0.001	0	0	<-0.001	<-0.001	0	0
11	Head of Lower Aquifer (LH)	<-0.001	<-0.001	-0.001	0	<-0.001	<-0.001	<-0.001	0
12	Permeability of Fractured Shale (LH)	0	<-0.001	0.001	0	<-0.001	<-0.001	0	0

*Table entries smaller than 0.001 but not zero are denoted by <0.001

¹D: Dissolution LH: Local Hydrology RH: Regional Hydrology

TABLE
MODIFIED CHANGE IN CURIES DUE TO RANGE CHANGE IN SELECTED PARAMETERS IN SCENARIO
WITH UPSTREAM SHAFT AND FRACTURED ROCK

only the retardation factor of the actinides was 0.22. That is, the total integrated curie output was not markedly changed when the retardation factor for the fission products was also changed. It would not even change the ranking of first four parameters. The peak curies remains unchanged from the baseline value in this run.

Scenario 4: The presence of boreholes in this scenario makes the sensitivity analysis more complex for the ten percent changes (Table 5-7). There are now nine parameters which alter the integrated curies for all nuclides by more than two percent. In the previous scenarios only one or two parameters had this great an effect. The permeability and cross-section of the borehole alter the integrated and peak curies by more than six percent. A change in the gradient of the aquifer has its usual large effect on the output of nuclide group III.

The range changes for this scenario (described in Table 5-8^{*}) do not show the fraction of iodine released as the parameter which causes the greatest amount of change in the outputs (Tables 5-9 and 5-10). The unmodified range changes place the permeability of the borehole as the highest ranking parameter, while the modified range changes show the porosity of the upper salt layer and the permeability of unfractured shale as sensitive parameters. The increase in the integrated curies of the actinides seen when either the retardation factor or the permeability of the unfractured shale is changed is striking. However, it should be noted that an increase of three orders of magnitude in the integrated curies for the actinides has only a one order of magnitude increase in the total integrated curies.

*Note that, in exception to the usual practice, the cross section of the borehole is changed to the least detrimental value.

TABLE 5-7
CHANGE IN CURIES DUE TO 10% INCREASE IN SELECTED PARAMETERS
IN SCENARIO WITH PERMEABLE SALT, UPSTREAM SHAFT,
AND LARGE BOREHOLE OUTFLOW

I-3837

RANK ON PEAK CURIES	VARIABLE PARAMETER AND UNIT ¹	CHANGE IN CURIES							
		INTEGRATED CURIES				PEAK CURIES			
		ALL INCLIDES	CLASS 1	CLASS 2	CLASS 3	ALL INCLIDES	CLASS 1	CLASS 2	CLASS 3
2	Fraction of Iodine (D)	0.092	0.096	0	0	0.100	0.100	<-0.001	0
4	Permeability of Borehole (LU)	0.062	0.064	0.010	0.035	0.090	0.090	0.002	0.029
3	Cross-Section of Borehole (LU)	0.062	0.064	0.010	0.035	0.090	0.090	0.002	0.029
8	Head of Lower Aquifer (LU)	0.060	0.058	0.107	0.147	<-0.001	<-0.001	0.005	0.053
14	Porosity of Upper Salt (LU)	-0.050	-0.056	-0.102	-0.136	<-0.001	0	-0.003	-0.143
1	Gradient of Upper Aquifer (RH)	0.037	0.035	0.041	1.712	0.106	0.106	0.066	1.537
10	Permeability of Lower Salt (LU)	-0.026	-0.025	-0.040	-0.061	<-0.001	-0.039	-0.001	-0.064
5	Permeability of Upper Salt (LU)	-0.025	-0.028	0.048	0.045	-0.009	-0.009	0.044	0.053
6	Permeability of Unfractured State (RH)	0.024	0.024	0.018	-0.167	0.069	0.069	0.038	-0.136
9	Saturation Concentration of UO_2 (D)	0.007	0.003	0.090	0.100	<-0.001	0	0.090	0.100
11	Permeability of Tunnel Backfill (RH)	0.003	0.003	0.006	0.008	<-0.001	<-0.001	0.005	0.001
7	Porosity of Sandstone (RH)	-0.002	-0.001	-0.004	-0.377	-0.029	-0.029	-0.004	-0.355
12	Actinide Retardation (RH)	<-0.001	0	0	-0.614	0	0	<-0.001	-0.593
13	Fission Product Retardation (RH)	<-0.001	0	-0.009	0	0	0	-0.004	0

* Table entries smaller than 0.001 but not zero are denoted by <-0.001

¹D: Dissolution LU: Local Hydrology RH: Regional Hydrology

TABLE 5-8
BASELINE AND RANGE VALUES FOR SCENARIO WITH PERMEABLE SALT,
UPSTREAM SHAFT AND LARGE BOREHOLE OUTFLOW

BARRIER	VARIED PARAMETER	BASELINE VALUE	RANGE VALUE
Dissolution	Fraction of Iodine Saturation Conc. of UO_2	1.0×10^{-1} 9.0×10^0	4.0×10^{-1} 9.0×10^2
Local Hydrology	Permeability of Tunnel Backfill	1.0×10^{-6}	1.0×10^{-4}
	Permeability of Borehole	1.0×10^{-4}	5.0×10^{-3}
	Cross-Section of Borehole	3.0×10^{-1}	1.0×10^{-1}
	Permeability of Upper Salt	1.0×10^{-10}	1.0×10^{-8}
	Porosity of Upper Salt	1.0×10^{-2}	5.0×10^{-3}
	Permeability of Lower Salt	1.0×10^{-10}	1.0×10^{-8}
	Head of Lower Aquifer	3.6×10^0	6.0×10^1
Regional Hydrology	Porosity of Sandstone	1.0×10^{-1}	1.0×10^{-2}
	Permeability of Shale	6.3×10^{-5}	2.0×10^{-4}
	Gradient of Upper Aquifer	6.0×10^{-3}	1.5×10^{-2}
	Fission Product Retardation	3.0×10^1	3.0×10^0
	Actinide Retardation	1.0×10^3	5.0×10^1

For reasons given above, an additional run was made with the retardation factors for the fission products and actinides set to worst possible values. As was seen in the previous scenario, there is a small increase in the integrated output for all nuclide groups (to 1.093) from the 1.086 due to changing only the retardation of the actinides. The increase would not change the rank of the first five parameters in Table 5-9. The peak curies for all nuclide groups is not affected by the dual changes made in this run.

TABLE 5-9

CHANGE IN CURIES DUE TO RANGE CHANGE IN SELECTED PARAMETERS
IN SCENARIO WITH PERMEABLE SALT, UPSTREAM SHAFT AND LARGE BOREHOLE OUTFLOW

T-3845

RANK ON PEAK CURIES	VARIED PARAMETER AND BARRIER ¹	CHANGE IN CURIES							
		INTEGRATED CURIES				PEAK CURIES			
		ALL INCLINES	CLASS 1	CLASS 2	CLASS 3	ALL INCLINES	CLASS 1	CLASS 2	CLASS 3
1	Permeability of Borehole (IR)	15.041	15.592	2.710	8.65	23.694	23.694	5.726	7.30
9	Head of Lower Aquifer (LI)	6.524	6.340	10.340	25.85	-0.001	-0.001	6.777	22.56
8	Saturation Concentration of H_2O_2 (H)	5.166	2.930	54.420	98.35	0.014	0.014	47.643	98.07
3	Fraction of Iodine (I)	2.764	2.806	0	0	3.000	3.000	0	0
2	Permeability of Unfractured Shale (RI)	2.106	0.462	0.468	1025.28	22.045	22.045	0.322	404.85
11	Actinide Retardation (RI)	1.086	0	0	1203.28	0	0	0	260.20
12	Porosity of Upper Salt (LI)	0.727	0.718	0.909	2.14	0	0	0.665	2.14
4	Gradient of Upper Aquifer (RI)	0.718	0.401	0.500	347.23	1.576	1.576	0.489	157.68
10	Permeability of Lower Salt (LI)	0.631	0.615	0.977	1.81	-0.001	-0.001	0.748	1.82
6	Cross-Section of Borehole (LI)	-0.438	-0.433	-0.070	-0.24	-0.662	-0.662	-0.014	-0.20
5	Permeability of Upper Salt (LI)	0.122	0.002	1.006	1.04	-0.991	-0.991	0.826	1.89
14	Permeability of Tunnel Backfill (LI)	0.065	0.063	0.117	0.16	0	0	0.093	0.17
13	Fission Product Retardation (RI)	0.008	0	0.181	0	0	0	0.147	0
7	Porosity of Sandstone (RI)	-0.004	-0.003	-0.006	-0.98	0.271	0.231	-0.018	-0.97

*Table entries smaller than 0.001 but not zero are denoted by -0.001

¹I: Dissolution LI: Local Hydrology RI: Regional Hydrology
CHANGE IN CURIES DUE TO RANGE CHANGING IN SELECTED PARAMETERS IN SCENARIO
WITH PERMEABLE SALT, UPSTREAM SHAFT AND LARGE BOREHOLE OUTFLOW

TABLE 5-10

MODIFIED CHANGE IN CURIES DUE TO RANGE CHANGE IN SELECTED PARAMETERS
IN SCENARIO WITH PERMEABLE SALT, UPSTREAM SHAFT AND LARGE BOREHOLE OUTFLOW

T-3844

RANK ON PEAK CURIES	VARIABLE PARAMETER AND BARRIER ¹	CHANGE IN CURIES							
		INTEGRATED CURIES				PEAK CURIES			
		ALL MIGRATES	CLASS 1	CLASS 2	CLASS 3	ALL MIGRATES	CLASS 1	CLASS 2	CLASS 3
12	Porosity of Upper Salt(LH)	-1.454	-1.436	-1.018	-4.3	0	0	-1.330	-4.28
10	Actinide Retardation(RH)	-1.140	0	0	-1263.4	0	0	0	-273.21
1	Permeability of Unfractured Shale(RH)	0.920	0.213	0.216	0.39.6	10.141	10.141	0.148	186.23
3	Fraction of Iodine(D)	0.920	0.961	0	0	0.993	0.999	0	0
4	Cross-Section of Borehole(LH)	0.627	0.650	0.105	0.4	0.993	0.993	0.021	0.30
2	Gradient of Upper Aquifer(RH)	0.479	0.267	0.333	231.6	1.051	1.051	0.326	105.17
14	Head of Lower Aquifer(RH)	0.418	0.405	0.662	1.2	0	0	0.433	1.44
5	Permeability of Borehole(LH)	0.301	0.312	0.054	0.2	0.474	0.473	0.115	0.15
8	Saturation Concentration of $\text{UO}_2(\text{D})$	0.052	0.029	0.544	1.0	-0.001	-0.001	0.476	0.98
11	Fission Product Retardation(RH)	-0.008	0	-0.201	0	0	0	-0.158	0
13	Permeability of Lower Salt(LH)	0.006	0.006	0.018	0	0	0	0.008	0.02
6	Porosity of Sandstone (RH)	0.004	0.008	0.007	1.1	-0.257	-0.256	0.020	1.08
7	Permeability of Upper Salt(LH)	0.001	-0.001	0.010	0	-0.010	-0.010	0.008	0.02
9	Permeability of Tunnel Backfill(LH)	-0.001	-0.001	0.001	0	0	0	-0.001	

*Table entries smaller than 0.001 but not zero are denoted by -0.001

¹D: Dissolution LH: Local Hydrology RH: Regional Hydrology

TABLE
MODIFIED CHANGE IN CURIES DUE TO RANGE CHANGE IN SELECTED PARAMETERS IN SCENARIO
WITH PERMEABLE SALT, UPSTREAM SHAFT AND LARGE BOREHOLE OUTFLOW

In summary, a few general points may be made:

- The total integrated curies is fairly insensitive to most parameter changes
- The total integrated curies and total peak curies are so dominated by the output of nuclide group I that large changes in the outputs of the other nuclide groups barely register
- The output of the actinides can be radically altered by changes in parameters which affect release rate, retardation or travel time in the aquifer. However, these changes are rarely important to the total outputs.

Factors which affect refill time of the repository (e.g., head of lower aquifer or permeability of lower salt) do not appear to cause great differences in the outputs of the scenarios studied. Factors concerning the dissolution of the waste (e.g., the fraction of iodine released or solubility of uranium) appear to be a more sensitive class of parameters. This is especially true for nuclide group I where the iodine output determines the overall peak and most of the integrated total. Factors which affect the regional hydrology (e.g., the aquifer) may have a marked effect on the output of nuclide group III but even these changes do not perturb the total outputs to any great extent. Local hydrology becomes a potentially important factor only when a low capacity pathway, such as a borehole, is present.

6.

UNCERTAINTY ANALYSIS

6.1 INTRODUCTION

The effect of parameter uncertainty on repository performance uncertainty is presented in this chapter. A potentially significant waste release scenario and a selection of parameters likely to have an effect on repository performance were chosen for analysis. Two "case studies" were developed to describe a poorly-characterized repository with wide uncertainty bounds and the same repository with the regional hydrology better known. A comparison of the results from the case studies can provide information on the effect that the state of knowledge of the regional hydrology barrier has on the uncertainty of repository performance.

The uncertainty of repository performance was assessed using Monte Carlo techniques which involve the generation of a set of "random" repository descriptions based on the distributions of the input parameters. Since this analysis is being performed on a generic repository the range seen in the outputs is illustrative only and not necessarily indicative of what may be seen with an actual site. A statistical analysis of the performance measures provides an estimate of the contribution of measurement uncertainty to overall performance uncertainty. Correlation analysis of measurement uncertainty to overall performances, on the other hand, identifies those inputs which most probably contribute to the overall uncertainty in repository performance. A further description of these techniques and their applicability towards assessing an actual repository site may be found in Ref. 21.

6.2 DESCRIPTION OF UNCERTAINTY ANALYSIS

6.2.1 Waste Release Scenario and Case Studies

The waste release scenario used in the uncertainty analysis is one where the repository is located in fractured salt and the shale above and below the salt layer is also fractured. Water also enters the repository via an upstream shaft. A further description of this scenario may be found in Section 3.2.2.

Not all parameters were varied; parameters with small uncertainties (e.g., distance to river) were set to their baseline values for all computer runs. Of the remaining parameters, a subset of seventeen was chosen to be varied because previous work, including that in Chapter 5, Scenario 3, indicated they were likely to have a significant effect on repository performance. These parameters and their distributions are described more fully in Section 6.2.2.

The "case studies" may be considered a variation on the state of knowledge concerning the model parameters, i.e.:

- Case 1: The entire system of barriers is not well-characterized and the uncertainty bands around each of the parameters is large. This case could reflect the situation where a waste disposal system has just come under investigation.
- Case 2: The uncertainties concerning the regional hydrology are much smaller than in Case 1, perhaps reflecting additional study of this barrier to nuclide transport. The uncertainties of the remaining barriers are unchanged.

6.2.2 Model Parameters and Their Uncertainties

The four barriers to waste release (refill time of the repository, waste form dissolution, local and regional

hydrology) are represented in the subset of parameters chosen to be varied in the Monte Carlo analysis.

Refill Time of the Repository: The time at which waste is first available for leaching and transport is usually the same as the time it takes the canister to corrode. This parameter is assumed to have a lognormal distribution with a median of 500 years and an uncertainty of 0.5. When the term uncertainty is used in conjunction with the parameters of a lognormal distribution, it refers to the standard deviation of the log-transformed data. This distribution was not changed in the second case study.

Waste Form Dissolution: Three parameters were included in this group: fraction of iodine in the outer zone of the waste, and the saturation concentrations of uranium and zirconium. Each of these is assumed to follow a lognormal distribution and the medians as well as the uncertainties are given in Table 6.2-1. These distributions were not changed in the second case study. The fraction of iodine was constrained to be less than or equal to 1.0 for obvious reasons.

TABLE 6.2-1
ASSUMED STATISTICS FOR LOGNORMAL DISTRIBUTIONS
DESCRIBING WASTE FORM DISSOLUTION

PARAMETER	MEDIAN	UNCERTAINTY
Fraction of Iodine *	0.1	0.3
Saturation Concentration of Uranium	9.0	1.0
Saturation Concentration of Zirconium	6.0×10^{-5}	1.0

* Constrained to be at most 1.0

Local Hydrology: All of the parameters given in Table 6.2-2 are assumed to have lognormal distributions. In addition, the permeability and porosity within the shale and salt layers are assumed to be correlated with a coefficient of $\rho = 0.8$. The permeability of the upper and lower salt layers are equally correlated while the permeabilities of the upper salt and upper shale layers are correlated with a coefficient of $\rho = 0.7$. The uncertainties for these parameters were not changed in any of the cases. These parameters determine the amount of water flowing through the repository, which, in turn, affects the dissolution rate of the waste (e.g., the amount of waste released is proportional to the total flow through the repository) and the refill time of the repository. In other words, these first three barriers are not independent of each other.

TABLE 6.2-2
ASSUMED STATISTICS FOR LOGNORMAL DISTRIBUTIONS
DESCRIBING LOCAL HYDROLOGY

T3507

PARAMETER	MEDIAN	UNCERTAINTY	CORRELATION COEFFICIENT	CORRELATED PARAMETER
Overall Head Drop	3.6	0.3	-	-
Lower Salt				
Permeability	1.0×10^{-8}	1.0	0.8	Permeability, Upper Salt
Upper Salt			0.8	Permeability, Lower Salt
Permeability	1.0×10^{-8}	1.0	0.8	Porosity, Upper Salt
Porosity	1.0×10^{-4}	0.5	0.8	Permeability, Upper Salt
Dispersion	50	0.4	-	-
Upper Shale				
Permeability	1.0×10^{-6}	0.75	0.7	Permeability, Upper Salt
Porosity	1.0×10^{-4}	0.375	0.8	Permeability, Upper Shale
Dispersion	50	0.4	-	-

Regional Hydrology Parameters: The permeability and retardation factors of the combined two-layer regional aquifer are also assumed to have lognormal distributions and the statistics and changes in uncertainty for them are given in Table 6.2-3. The retardation factors (B) for the various nuclide groups were generated to follow the inequality:

$$B \text{ (Fission Products)} < B \text{ (Radium)} < B \text{ (Actinides)}$$

A description of the generation process may be found in Appendix D. Group 1 nuclides are assumed not to be retarded in any medium.

TABLE 6.2-3
ASSUMED STATISTICS FOR LOGNORMAL DISTRIBUTIONS
DESCRIBING REGIONAL HYDROLOGY

PARAMETER	MEDIAN	UNCERTAINTIES	
		CASE 1	CASE 2
Permeability	4.4×10^{-4}	0.8	0.4
Retardation Factors			
Fission Products	30	0.7	0.4
Radium	200	0.85	0.45
Actinides	1000	1.0	0.5

The description of the distribution of the dispersion in the aquifer is not given in Table 6.2-3. The dispersion (α) for case 1 was then calculated by:

$$\log_{10} \alpha = \frac{10}{3}y + \log_{10} 1866 - (40/16.5) \quad (6.2-1)$$

while for case 2 it was calculated by:

$$\log_{10} \alpha = \left(\frac{5}{3}y\right) + \log_{10} 1866 - (40/16.5) + (4/3) \quad (6.2-2)$$

where 1866 is the baseline value for dispersion in the aquifer and parameter y was generated from a beta distribution with $a = 2$ and $b = 1/2$. The expected value of y is $a/(a+b)$ and the variance of y is $(ab/(a+b)^2)/(a+b+1)$ (Ref. 22). Adjusting the end points from Eq. 6.2-1 to Eq. 6.2-2 reduces by one-half the possible range of the values for the dispersion. Each case gives an expected value of $\log_{10} \alpha$ of 3.51. (The corresponding value of α is 3260 m.) The second case has the end points and the standard deviation reduced by one-half.

6.2.3 Repository Performance Measures

The NUTRAN computer code was used to generate eight measures of repository performance for each repository description:

- Peak 50-yr individual dose (rem)
- Time of peak 50-yr individual dose (yr)
- Peak population dose (man-rem/yr)
- Time of peak population dose (yr)
- Integrated population dose (man-rem)
- Peak flow rate of radioactivity (Ci/yr)
- Time of peak flow rate of radioactivity (yr)
- Integrated radioactivity release (Ci).

In this study, the environmental impact of the waste reaching the biosphere is calculated with the assumption that the aquifer

fer system flowed into a river resembling the Colorado River. "Output" for this investigation is defined as "released curies" as well as "dose".

6.2.4 Validation of Random Repository Descriptions

The first fifty random repository descriptions were checked to ascertain whether or not they were properly generated before the remaining descriptions were generated. The observed and theoretical distributions were compared using the Kolmogorov-Smirnov goodness-of-fit test (Ref. 23). No significant differences were found. The correlations between the parameters describing the local hydrology were calculated and checked to determine whether they fell within the 95% confidence interval for a sample of fifty (Ref. 24). All correlations passed this criteria. These procedures were repeated on the full sample size of two hundred runs for Case 1, and were taken to insure that the random variables used in the Monte Carlo analysis were, indeed, correctly generated from their probability distributions. The generated input distributions were also checked for Case 2.

6.3 MONTE CARLO ANALYSES

The summary statistics of the outputs for each case were calculated and are presented in Table 6.3-1. The "inter-quartile spread" is one-half the difference between the 75th and 25th percentile values. In all cases, the means are consistently higher than the medians, indicating skewed distributions with tails to the right. A full set of the histograms described in the text is presented in Appendix E.

For Case 1 the means for the output values are noticeably higher than the baseline values. (The baseline case is the

last scenario of Table 4.4-2.) In Case 2, where the regional hydrology is better known, the means and their standard deviations drop by approximately a factor of two for the peak individual and peak population doses. The means and standard deviations of the integrated population dose and the integrated flow are only very slightly reduced. The average times of peak individual dose and peak population dose increase slightly while the time of peak flow rate remains relatively unchanged. The medians and interquartile spreads for all the outputs either do not change or decrease slightly.

TABLE 6.3-1
SUMMARY STATISTICS OF MONTE CARLO ANALYSIS -
CASES 1 AND 2

T3508

VARIABLE	BASLINE VALUE	CASE	MEAN	STANDARD DEVIATION	MEDIAN	INTERQUARTILE SPREAD
Peak 50-yr Dose (rem)	5.9×10^{-2}	1	1.2×10^{-1}	4.6×10^{-1}	2.3×10^{-2}	2.6×10^{-2}
		2	6.6×10^{-2}	1.9×10^{-1}	3.0×10^{-2}	2.3×10^{-2}
Time of Peak 50-yr Dose (yr)	5.9×10^3	1	1.3×10^5	4.9×10^5	1.2×10^4	1.6×10^4
		2	2.4×10^5	7.0×10^5	9.4×10^3	6.0×10^3
Peak Population Dose (man-rem/yr)	2.3×10^4	1	4.6×10^4	1.9×10^5	9.5×10^3	1.0×10^4
		2	2.5×10^4	7.6×10^4	1.2×10^4	8.3×10^3
Time of Peak Population Dose (yr)	5.9×10^3	1	1.3×10^5	4.9×10^5	1.2×10^4	1.6×10^4
		2	2.5×10^5	7.8×10^5	1.0×10^4	6.4×10^3
Integrated Population Dose (man-rem)	2.1×10^8	1	1.3×10^{10}	4.2×10^{10}	2.6×10^8	1.3×10^9
		2	9.0×10^9	3.0×10^{10}	2.9×10^8	1.5×10^9
Peak Flow Rate (Ci/yr)	2.9×10^1	1	3.4×10^1	7.0×10^1	1.1×10^1	1.2×10^1
		2	2.7×10^1	4.5×10^1	1.3×10^1	1.1×10^1
Time of Peak Flow Rate (yr)	5.9×10^3	1	2.3×10^4	3.7×10^4	1.0×10^4	9.4×10^3
		2	1.2×10^4	1.2×10^4	8.4×10^3	4.9×10^3
Integrated Flow (Ci)	1.1×10^5	1	2.4×10^5	3.7×10^5	1.3×10^5	2.9×10^5
		2	2.2×10^5	2.6×10^5	1.4×10^5	6.9×10^4

It is interesting to note that means and standard deviations of the times of peak 50-yr individual and peak population dose increase when the regional hydrology is better known. The increased means are caused by a higher number of repository descriptions where the peak times occur after one million years in Case 2 (fifteen in Case 2 compared with seven in Case 1). The reason for increased uncertainty in the outputs when the ranges of the input parameters is decreased is that the contribution from each nuclide group is better defined. Having decreased the range seen in the dispersion of the aquifer, we have lost those cases where a large dispersion leads to a low broad peak from the actinides. In other words, when the rise from the actinide peak falls within the time frame used in this study, the rise is steeper for Case 2 than for Case 1. The better definition of the iodine and actinide peaks, however, reduces the interquartile spread for the time of peak dose since this measure of variability is less affected by outliers than the standard deviation.

The statistics for the log transformed data appear in Table 6.3-2. The values of the peak 50-yr individual and population doses and peak flow rate are higher for the baseline case than they are for the means and medians of the Monte Carlo samples. This occurs because the base case dispersion is lower than the median dispersion of the uncertainty analysis. This situation is reversed for the remaining variables. The means for these variables are also slightly larger than the medians, indicating that the distributions are still skewed even after transformation. The integrated population dose still shows little reduction in uncertainty from Case 1 to Case 2. The increase in the uncertainty in the times of peak outputs is still evident.

The reduction in the uncertainties of the regional hydrology lower the range of the peak outputs by about an order

of magnitude (Figure 6.3-1 and E-1). In Case 2, the peak from the actinides is well enough defined that repository descriptions where the actinides control the peak dose fall only in the right-hand side of the distribution. In Case 1 they occur throughout the distribution.

TABLE 6.3-2
SUMMARY STATISTICS FOR LOG-TRANSFORMED DATA OF
MONTE CARLO ANALYSIS - CASES 1 AND 2

T3509

VARIABLE	BASELINE VALUE	CASE	MEAN	STANDARD DEVIATION	MEDIAN	INTERQUARTILE SPREAD
Peak 50-yr Dose (rem)	-1.23	1	-1.62	0.76	-1.63	0.40
		2	-1.52	0.51	-1.52	0.29
Time of Peak 50-yr Dose (yr)	3.77	1	4.71	0.72	4.09	0.49
		2	4.11	0.78	3.98	0.26
Peak Population Dose (man-rem/yr)	4.36	1	3.99	0.74	3.98	0.40
		2	4.08	0.50	4.09	0.27
Time of Peak Population Dose (yr)	3.77	1	4.21	0.72	4.09	0.49
		2	4.18	0.81	4.00	0.26
Integrated Population Dose (man-rem)	8.32	1	8.76	1.02	8.41	0.70
		2	8.78	0.98	8.47	0.73
Peak Flow Rate (Ci/yr)	1.46	1	1.02	0.73	1.04	0.40
		2	1.14	0.53	1.10	0.29
Time of Peak Flow Rate (yr)	3.77	1	4.02	0.53	4.00	0.38
		2	3.91	0.36	3.93	0.24
Integrated Flow (Ci)	5.04	1	5.15	0.42	5.12	0.25
		2	5.16	0.37	5.14	0.20

The highest doses observed in the Monte Carlo analysis had a peak 50-yr individual dose 5.6 rem and an integrated population dose of 2.8×10^{11} man-rem. Taking reconcentration factors into account, this is equivalent to a release rate of 1510 picocuries of radium per m^3 . For comparison, the mean annual concentration of ^{226}Ra in the Colorado River at the U.S.

Mexican Border is approximately 0.17 picograms per liter or 170 pico curies per m^3 (Ref. 25). Such an increase in radium concentration of the river, however, occurs only once in 200 cases. A more reasonable comparison is the median case, where 6.5×10^{-6} curies of all actinides are released. If this release were entirely radium, it would result in a release rate of 2.4×10^{-3} picocuries/ m^3 , well below the average annual concentrations. (In the median case, the peak dose is due to Group 1 nuclides.)

It should be mentioned that one repository description (in Case 1) was generated such that the actinide pulse had not been spread enough for the usual approximation for the reconcentration factors to be used (Ref. 13). Consequently, the peak doses are upper estimates for this case while integrated outputs are unaffected. This particular case resulted in a peak 50-yr individual dose of 0.5 rem, a peak population dose of 2.2×10^5 man-rem/yr and an integrated population dose of 2.2×10^{11} man-rem. Referring to the histogram of the integrated population dose (Figs. 6.3-2 and E-4), it can be seen that this is a case which falls in the right-hand tail of the distribution.

The integrated outputs do not show the same reduction in range as the peak outputs (Figs. 6.3-2 and E-4 and Figs. 6.3-3 and E-5). Unlike the peak doses, which are controlled by Nuclide Group I about 90% of the time, the integrated outputs receive a substantial contribution from the actinides. As such, the integrated outputs reflect the behavior of both nuclide groups. Better definition of the behavior of the aquifer may result in a reduction in the uncertainty of the outputs from each individual nuclide group, but it may not necessarily reduce the overall uncertainty of repository performance due to the mixture of these groups.

a) Case 1

b) Case 2

KEY

- ▬ = PEAK DOSES CONTROLLED BY NUCLIDE CLASS I
- ▨ = PEAK DOSE CONTROLLED BY NUCLIDE CLASS III

Figure 6.3-1 Histograms of Peak 50-yr Individual Dose Cases 1 and 2

a) Case 1

b) Case 2

KEY

- = PEAK DOSES CONTROLLED BY NUCLIDE CLASS I
- ▨ = PEAK DOSE CONTROLLED BY NUCLIDE CLASS III

Figure 6.3-2 Histograms of Integrated Population Dose Cases 1 and 2

a) Case 1

b) Case 2

KEY

□ = PEAK DOSES CONTROLLED BY NUCLIDE CLASS I

▨ = PEAK DOSE CONTROLLED BY NUCLIDE CLASS III

Figure 6.3-3 Histograms of Integrated Flow Cases 1 and 2

The suggestion that overall repository performance is a mixed distribution may explain the difference in behavior between the parametric (mean and standard deviation) and the non-parametric (median and interquartile spread) statistics for the peak doses. The mean and standard deviation are sensitive to changes in the tails of the distribution, which are predominantly controlled by the actinides. Reducing the uncertainty of the aquifer parameters pulls in these tails, resulting in a similar reduction in the standard deviation and mean. The "non-tail" part of the distribution is determined by the peak, which in turn is governed more by the dissolution model than the regional hydrology. Since the dissolution parameters were not changed for Case 2, there is very little change seen in the median and interquartile spread of the peak doses from Case 1 to Case 2.

6.4 CORRELATION ANALYSIS

6.4.1 Description of Spearman's Rank Correlation Coefficient

The correlation measure used in this study is Spearman's rank correlation coefficient (r), a non-parametric measure with the following advantages:

- It requires no assumptions concerning the underlying distributions of the variables
- the test may be used with variables which may be ranked as well as with variables which can be measured more quantitatively
- the test identifies any monotonic relationship between variables, not just linear relationships.

In addition, the probability of an observed value of r occurring between independent variables strictly by chance for a given sample size may be calculated (called the "probability of independence"). There are two possible drawbacks to Spearman's rank correlation coefficient. First, it does not identify non-monotonic relationships between variables. However, there is no correlation coefficient at present which can identify unspecified non-monotonic relationships between variables. Second, the square of r does not represent the proportion of variation in one variable accounted for by its dependence on another, because the relationship between the variables is not explicitly defined. A further description of Spearman's r may be found in Reference 21.

6.4.2 Results of the Correlation Analysis

The results of the correlation analysis are presented in Tables E-1 through E-3. The first table lists the correlation coefficients and their probability of independence for the input parameters and the peak outputs. The second and third tables present the information the integrated outputs and times of peak outputs respectively. To be included in any of these tables, an input parameter had to be correlated with at least one output measure with a probability of independence of at most 0.05. The input parameters are listed according to the average rank on the correlation with the outputs from Case 1. These three tables will be discussed in turn.

Factors Affecting Peak Outputs (Table E-1): The permeability of the aquifer is the highest ranking parameter affecting peak output for both Case 1 and Case 2. This is understandable because this parameter, in part, determines the travel time of the various nuclide groups through the largest and most dispersive flow path.

The next highest ranking correlation is the fraction of iodine on the cladding. These quick-leaching nuclides determine the peak output in most cases. The permeabilities and porosities of the shale and salt layers are intercorrelated, so it is to be expected that they show similar correlations with the outputs. The importance of these parameters to repository performance lies in the fact that they determine the flow of water through the repository, which, in turn, determines the dissolution rate of the waste form and the local flow times. The saturation concentration of uranium is positively correlated with peak outputs.

The inclusion of the corrosion time of the canister in Table E-1 is intriguing since its only obvious effect ought to be to determine when the waste is available for transport. It has its highest effect on peak flow rate for Case 1, which is usually dominated by the extremely long-lived Class I nuclides. The starting time of transport should not radically affect this performance measure. In addition, it is not significantly correlated with peak population dose which is also governed by the Class I nuclides. This, and the fact that it is not as highly correlated for Case 2 imply that the inclusion of canister corrosion time in the table may be an artifact of the chosen significance level (0.05). The latter implies that one out of twenty "significant" correlations may occur strictly by chance and the table has sixty-six entries.

The first six parameters in Table E-1 did not substantially change in importance from Case 1 to Case 2. (In all cases the probability of independence is at most 0.001.) Three more parameters describing the local hydrology appear in the table for Case 2. In other words, as more is known about the regional hydrology, the uncertainty about the local hydrology becomes more important.

Factors Affecting Integrated Outputs (Table E-2):

There are five factors which affect the integrated population dose with a probability of independence of at most 0.0005 for both cases: permeability of the aquifer, fraction of iodine in the waste, saturation concentration of uranium and the retardation factors of radium and the actinides. The peak doses are predominantly governed by the behavior of iodine alone, while the integrated dose reflects a mixture of effects from iodine and the Class III nuclides. Since the retardation factors do not affect the Class I nuclides, their presence in Table E-2 and their absence from Table E-1 is another indication of the differences between these measures of repository performance.

A few factors describing local hydrology appear to drop in importance from Case 1 to Case 2 for the integrated population dose. The travel time of the actinides in these pipes is much shorter than in the aquifer, and so the regional hydrology is of greater importance. Dispersion in the aquifer appears to be more important for Case 2 than for Case 1. A possible explanation for this may be: having narrowed the range of uncertainty in the other factors describing the aquifer (permeability and retardation rates), the actinide peak becomes narrower and more defined. Whether or not part of this peak is seen before the three million year cutoff point may depend on the spreading of this peak by dispersion as it travels through the aquifer.

The integrated radioactive release (Ci) reacts somewhat differently than the integrated population dose. This is due, in part, to the differences between dose and curies as measurements of repository performance. The curie amount of nuclide group III is very small compared to that of group I, yet, the

relative biological impact of a curie of each of these different nuclide groups is not considered. Only the permeability of the aquifer, fraction of iodine in the waste and the saturation concentration of uranium affect the integrated flow with a probability of independence ≤ 0.0001 . The retardation factors do not have that high a level of effect, although they are still important. The local hydrology, however, appears to be more important for this measure than for the integrated population dose. In neither case does the dispersion of the aquifer appear to be of much importance. The most noticeable change from Case 1 to Case 2 is the increased correlation of integrated flow with the overall head drop, perhaps indicating that once the regional hydrology is better defined, the uncertainty concerning the local hydrology becomes more important.

Factors Affecting Time of Peak Outputs (Table E-3):

The permeability of the aquifer is the factor with the highest ranked correlation for all measures and for both cases. These measures are governed by the iodine peak in the large majority of cases. Factors affecting the travel time of this unretarded peak through the different pipes, therefore, should appear in this table and they do. Factors describing local hydrology show increased correlations for Case 2, where the regional hydrology is better defined. The corrosion time of the canister appears in the table because it determines the time at which the iodine peak begins to move through the repository system.

For those cases where the Class III nuclides govern the peak outputs, an additional set of parameters must be considered. The positive correlation between the saturation concentration of uranium oxide and the peak and integrated outputs is straightforward, but the correlation with time of peak outputs is less obvious. When the actinides control the peak

dose, the peak inevitably falls later than it would if it were controlled by the Class I nuclides because the former is always more heavily retarded than the latter. It is because of the importance of these parameters to repository performance for this subset of cases that the parameters rank as high as they do when all cases are considered in the analysis.

It should be noted that ten to twelve out of the seventeen varied parameters qualify under the general description for inclusion in Tables E-1 to E-3. This is due, in part, because the parameters were specifically selected because they might have an effect on repository performance. A very different situation occurred for the correlation analysis reported in Ref. 21, where only seven of twenty-six parameters met this qualification. This comparison indicates the results of a correlation analysis are scenario-specific and that the results of one analysis cannot be uncritically applied to a different scenario.

For this study, then, the uncertainty of the permeability of the aquifer appears to have the most significant effect on the uncertainty of repository performance, even when its range of uncertainty is more closely defined. Factors affecting the dissolution of the waste (either as intrinsic characteristics of the waste form or the amount of water flowing around the waste) appear to be the second most important body of parameters. These factors tend to increase in importance as the uncertainty concerning the regional hydrology is decreased.

6.5 SUMMARY

Several observations may be drawn from this study of the effect of parameter uncertainty on repository performance.

- Whether or not the uncertainty in peak outputs drops when the uncertainty in the regional hydrology is reduced depends, in part, on the statistic used to measure that uncertainty.

The mean and standard deviation are very sensitive to outliers in the tails of distributions. These estimates show a reduction comparable to the reduction in the uncertainty of the regional hydrology for Case 2 because the actinide peak is better defined. The median and interquartile spread are nonparametric measures of central location and uncertainty and they are not heavily influenced by the behavior in the tails of a distribution. These measures did not change as substantially from Case 1 to Case 2 as the previous measures. This is due, in part, because the peak outputs are predominantly governed by the iodine peak which, in turn, is affected somewhat more by the uncertainties in the dissolution barrier than in the regional hydrology. The uncertainties in the times of peak doses decrease for the nonparametric measure while it increases for the parametric measure from Case 1 to Case 2. The performance of both measures is more consistent when they are applied to the log-transformed data.

- The statistics for the integrated outputs did not change markedly when the uncertainty in the behavior of the aquifer was reduced.

As mentioned above, the peak outputs are predominately governed by the Nuclide Class I peak with some small effects due to the peak from Class III nuclides. The situation is quite different for the integrated outputs which reflect a significant contribution from the Class III nuclides. Because of this mixture of populations, it is possible to better define the peak contribution from each nuclide group without substantially reducing the uncertainty concerning the mixture of these distributions.

- The permeability of the aquifer was the parameter with the highest ranking correlation with all peak and time-of-peak outputs for both cases.

It is understandable that the parameter which helps to determine travel time in the longest pipe between the repository and biosphere shows this high a correlation with all the peak outputs. When the regional hydrology is better known, however, the uncertainty of the parameters describing local hydrology appear to become more important.

It must be kept in mind, however, that these observations were drawn from a study of a generic repository and may change when an actual site is studied.

7.

WELL WATER ANALYSIS

7.1 INTRODUCTION

In previous work on generic bedded-salt repository analysis the worst doses were obtained from cases in which wells were drilled into the aquifer. This result is not surprising 1) because the wells "short circuit" the aquifer, thereby reducing the amount of decay and dispersion experienced by the waste and 2) because dilution of the waste in the river does not occur. The effect of the wells was also large because the wells were placed in the worst possible positions for these analyses -- directly downstream of the repository. In the following, the hazard from wells is considered when they are placed arbitrarily in the vicinity of the repository.

The purpose of this section is to assess radiological hazards to man from the drilling of wells in the vicinity of a bedded-salt nuclear waste repository. (The repository chosen for this analysis is the one described in previous sections of this report.) Waste enters the aquifer above the formation containing the repository over a period of time as the spent fuel dissolves and is transported out of the repository by ground water. Water wells could be drilled into this aquifer if the water within it were potable and knowledge of the location of the repository were lost at some future date. No attempt is made in this analysis to assess the probability of this occurrence; however, the consequences of specific scenarios involving wells are calculated.

The analysis reported in this chapter evaluates the spatial patterns of dose from sink wells, which are wells having large withdrawal rates. Well withdrawal rates span a

range of values and wells may be located off the centerline of the repository. This work presents the requisite analytical techniques for addressing the continuum of hazard due to variation of these parameters.

7.2 METHODOLOGY

Sink wells are wells with large withdrawal rates (typically 200 gallon per minute or more). These wells are used primarily for irrigation or as sources of drinking water. Their large withdrawal rates can change both the magnitude and direction of the aquifer's water velocity and lower the piezometric heads in adjacent portions of the aquifer and repository. This results in a U-shaped "stagnation envelope" for the well (Ref. 13): all streamlines contained within this envelope flow to the well while those lying on or outside the envelope flow past the well. The width of this envelope is dependent on the thickness, effective porosity, and flow velocity of the aquifer as well as the well's withdrawal rate.

The technique for analyzing spatial dose and hazard profiles for a single sink well located arbitrarily in the repository region at any time is reviewed below. The assessment of hazards from multiple adjacent sink wells is a complex undertaking. An evaluation must be made of the effect of multiple wells on aquifer heads, interstitial water velocities, well radii of influence, and stagnation envelope dimensions. There were not sufficient resources to attack these problems in this study.

An important assumption made here is that waste is released from one or more point sources in the aquifer. This assumption allows losses due to lateral dispersion across the well's stagnation envelope to be neglected because of the small

cross-flow dimension of the point source relative to the stagnation envelope width. Reference 26 discusses cases where lateral dispersion may not be negligible, such as releases from repositories that are best characterized as large line or area sources.

The first step is the definition of the edge of the well dose profile. This is illustrated in Fig. 7.2-1 for a well drilled into an aquifer downstream from a point source of waste at the origin. Whenever the point source is contained within the stagnation envelope of the well, its entire output (neglecting dispersion across the envelope's edge) is intercepted by the well. Thus, the edge of the dose profile is the locus of well coordinates whose stagnation envelopes pass through (0,0) (for example, see wells labeled A and B in Fig. 7.2-1). Any well located at a greater distance from the flow axis will not intercept any waste from the point source and will thus yield no radiological dose. Note that the maximum width of the dose profile shown in Fig. 7.2-1 is a function of the well withdrawal rate (Q_w) and the aquifer's thickness (b), effective porosity (ϵ), and flow velocity (V).

Within this dose profile, isopleths of dose are approximated as straight lines perpendicular to the flow axis (for example, see line from point A to B in Fig. 7.2-1). This is because all wells located along a given perpendicular line within the dose profile (fixed distance downstream) intercept about the same amount of waste emanating from the point source. Here, the assumption is made that the average streamline velocity does not change substantially as the waste follows a more curved streamline to a well located off the x-axis. This is a conservative assumption which results in slightly underestimating particle travel times (hence, overestimating dose) for off-centerline wells.

Figure 7.2-1 Construction of Dose Profiles for a Single Sink Well and Point Source in the Repository Region

An area of hazard within the dose profile can now be defined. Typically, this is done by comparing the plotted dose values against a regulatory dose threshold. All well locations where dose values exceed this threshold are indicated as a shaded area on the dose profile.

7.3 WELL DOSE AND HAZARD PROFILES FOR TWO BEDDED-SALT REPOSITORIES

For the purpose of illustrating the use of dose and hazard profiles for sink wells, two flawed bedded-salt repositories were analyzed. These were characterized as having impermeable and permeable salt, respectively. In the first case, waste is released into the aquifer from a borehole drilled into the repository; the second case considers waste released through a similar borehole and, additionally, by means of porous flow through the strata overlying the repository. In both cases the shaft/tunnel fracture zones serve as an inflow pathway.

Dose values for the straight-line isopleths shown in Fig. 7.2-1 were computed using the NUTRAN nuclide transport codes (Chapter 2). For the sink well, a continuous withdrawal rate of $4 \times 10^5 \text{ m}^3/\text{yr}$ (200 gpm) and a radius of influence of 10^4 m were assumed in all analyses (Ref. 27). Computations were performed at locations ranging from $x=2,000 \text{ m}$ to $x=50,400 \text{ m}$ (end of the aquifer). A one-dimensional aquifer waste transport equation (Ref. 13) was solved at times of interest, assuming:

- 1) One or more point-source releases of waste into the aquifer
- 2) A constant, unidirectional flow velocity whose magnitude depends upon the aquifer characteristics, the pumping rate of the well, and the well's location on the x-axis relative to the point source
- 3) Simple convection, with negligible lateral dispersion (longitudinal dispersion is included).

Average individual doses, population doses, and rates of radionuclide flow were calculated assuming the consumption of contaminated well water at various times over the history of the repository. Models of ecosystems patterned after those adjacent to the Colorado and Columbia Rivers were employed in the calculation of potential hazard, using both the irrigation and drinking-water pathways (see Section 4.1). It is important to note that dose values are lower for the Columbia River ecosystem than for the Colorado River ecosystem. This is due to the shallower depth of irrigation assumed in the Columbia River system model compared to that used in the Colorado. Also, the rate of rainfall is assumed to equal the rate of evapotranspiration in the Columbia River system, which allows percolation of all contaminated irrigation water drawn from wells back to the river (hence, eventually out of the ecosystem). In the Colorado River system, however, the only loss of the irrigation water

occurs via crop intake, resulting in the retention of most of the contaminated water within the ecosystem. (Reference 20 should be consulted by those readers desiring a more thorough description of these ecosystems.)

For the impermeable and permeable bedded-salt repositories, results are presented for both a single-layer and double-layer aquifer. The double-layer aquifer, as described in Section 3.2, is a homogenization of the upper sandstone and shale layers (see Fig. 3.2-2). The single-layer aquifer models flow in the upper sandstone layer only. Hydrologic parameters for the upper sandstone layer are listed in Table 3.2-2. The principal difference between the two aquifer models is in the value of the longitudinal dispersion constant: 50 m for the single-layer model and 1,866 m for the double-layer model. Consequently, the two models give different results when used (e.g., peak aquifer concentrations in a single-layer aquifer are higher than those in a double-layer aquifer). The double-layer results are most correct when the distance the waste has travelled in the aquifer is long since, in that case, there will be considerable mixing between the sandstone and shale layers (Ref. 29). However, if the distance is short there will not be much mixing and the single-layer model will be more applicable. For the sake of completeness, each model was used at each distance studied in this well analysis.

Impermeable Salt - Figures 7.3-1 through 7.3-4 illustrate dose profiles for a single sink well drilled near an impermeable bedded-salt repository that is penetrated by a borehole. Results are presented separately for the single-layer and double-layer aquifers. The Colorado-like and Columbia-like River ecosystems are used as the basis for potential hazard calculations. Separate profiles are drawn at three points in time. These times span the interval during which the initial pulse of radionuclides leaves the borehole and travels

Figure 7.3-1 Dose from a Single Sink Well at (x,y) as a Percent of Peak Value -- Impermeable Salt Repository with Single-Layer Aquifer and "Colorado-Like" River Ecosystem

a) Dose Pattern When Peak of Borehole Pulse is at $x = 2,000$ m.

b) Dose Pattern When Peak of Borehole Pulse is at $x = 25,000$ m.

c) Dose Pattern When Peak of Borehole Pulse is at $x = 40,000$ m.

NOTE: SHADED AREAS DENOTE WELL LOCATIONS WHERE WHOLE-BODY-EQUIVALENT DOSE TO THE AVERAGE INDIVIDUAL EXCEEDS 0.17 REM/PERSON, ANNUAL AVERAGE.

Figure 7.3-2 Dose from a Single Sink Well at (x,y) as a Percent of Peak Value -- Impermeable Salt Repository with Double-Layer Aquifer and "Colorado-Like" River Ecosystem

Figure 7.3-3 Dose from a Single Sink Well at (x,y) as a Percent of Peak Value -- Impermeable Salt Repository with Single-Layer Aquifer and "Columbia-Like" River Ecosystem

a) Dose Pattern When Peak of Borehole Pulse is at $x = 2,000$ m.

b) Dose Pattern When Peak of Borehole Pulse is at $x = 25,000$ m

c) Dose Pattern When Peak of Borehole Pulse is at $x = 50,400$ m.

NOTE SHADED AREAS DENOTE WELL LOCATIONS WHERE WHOLE-BODY EQUIVALENT DOSE TO THE AVERAGE INDIVIDUAL EXCEEDS 0.17 REM PERSON, ANNUAL AVERAGE.

Figure 7.3-4 Dose from a Single Sink Well at (x,y) as a Percent of Peak Value -- Impermeable Salt Repository with Double-Layer Aquifer and "Columbia-Like" River Ecosystem

the length of the aquifer. Lines of constant dose are drawn and dose values are expressed as percentages of peak value on each profile. The actual values for dose and radionuclide flow rates corresponding to the 100% lines are given in Table 7.3-1 for the Colorado-like River ecosystem (Figs. 7.3-1 and 7.3-2) and in Table 7.3-2 for the Columbia-like River ecosystem (Figs. 7.3-3 and 7.3-4). (Note that the percentage lines are applicable for scaling individual dose, population dose, and radionuclide release rates.) The dose values shown at $x=2,000$ m for the single-layer aquifer (Figs. 7.3-1 and 7.3-3) should be viewed as upper limits, not exact values.

TABLE 7.3-1
PEAK VALUES OF DOSE FROM A SINK WELL --
IMPERMEABLE SALT REPOSITORY AND "COLORADO-LIKE" RIVER ECOSYSTEM

1-3456a

AQUIFER	LOCATION OF PEAK OF AQUIFER PULSE, $x(m)$	TIME, $t(yr)$	WHOLE-BODY-EQUIVALENT DOSE FROM A WELL AT x AT TIME $t^{\pm}$		RATE OF RADIONUCLIDE RELEASE FROM A WELL AT x AT TIME $t^{\pm}$ (Ci/yr)	APPROXIMATE "AREA OF HAZARD" (m^2)
			AVERAGE INDIVIDUAL (50 YR) DOSE (rem)	POPULATION DOSE $\frac{man-rem}{yr}$		
Single-Layer (Fig. 7.3-1)	2,000	5,300	7.5×10^3	1.7×10^5	2.3×10^2	1.1×10^7
	25,000	7,270	5.1×10^3	1.2×10^5	1.6×10^2	3.4×10^7
	50,400	9,450	3.1×10^3	7.3×10^4	1.0×10^2	1.4×10^7
Double-Layer (Fig. 7.3-2)	2,000	5,300	3.6×10^3	8.0×10^4	1.1×10^2	2.2×10^7
	25,000	7,270	1.4×10^3	3.3×10^4	4.6×10^1	6.5×10^7
	50,400	9,450	9.4×10^2	2.2×10^4	3.1×10^1	5.6×10^7

*These are the actual values corresponding to the 100% lines of constant dose in Figs. 7.3-1 and 7.3-2. These lines correctly scale individual dose, population dose, and radionuclide release rates for each ecosystem.

The initial pulse of radionuclides released to the aquifer from the borehole consists of ^{129}I , ^{99}Tc , and ^{14}C : this pulse yields the largest dose values experienced during the life of the repository. It reaches a well at $x=2,000$ m at approximately 5300 years and a well at the end of the aquifer ($x=50,400$ m) at about 9450 yrs. There is a later actinide

mode (not shown in Figs. 7.3-1 through 7.3-4) evident at times of 10^5 and beyond that yields average individual doses near the annual recommended limit throughout the length of the aquifer.

TABLE 7.3-2
PEAK VALUES OF DOSE FROM A SINK WELL --
IMPERMEABLE SALT REPOSITORY AND "COLUMBIA-LIKE" RIVER ECOSYSTEM

T-3457a

AQUIFER	LOCATION OF PEAK OF AQUIFER PULSE, x(m)	TIME, t(yr)	WHOLE-BODY-EQUIVALENT DOSE FROM A WELL AT x AT TIME t*		RATE OF RADIONUCLIDE RELEASE FROM A WELL AT x AT TIME t* (Ci/yr)	APPROXIMATE "AREA OF HAZARD" (m ²)
			AVERAGE INDIVIDUAL (50 YR) DOSE (rem)	POPULATION DOSE man-rem yr		
Single-Layer (Fig. 7.3-3)	2,000	5,300	2.5×10^2	2.2×10^3	2.3×10^2	1.0×10^7
	25,000	7,270	1.6×10^2	1.4×10^3	1.6×10^2	2.1×10^7
	50,400	9,450	8.8×10^1	8.1×10^2	1.0×10^2	4.7×10^6
Double-Layer (Fig. 7.3-4)	2,000	5,300	1.2×10^2	1.0×10^3	1.1×10^2	1.0×10^7
	25,000	7,270	4.4×10^1	3.9×10^2	4.6×10^1	4.6×10^7
	50,400	9,450	2.7×10^1	2.5×10^2	3.1×10^1	2.9×10^7

* These are the actual values corresponding to the 100% lines of constant dose in Figs. 7.3-3 and 7.3-4. These lines correctly scale individual dose, population dose, and the radionuclide release rates for each ecosystem.

The shaded areas of Figs. 7.3-1 through 7.3-4 ("areas of hazard") indicate the portion of each profile where annual whole-body-equivalent dose to the average individual exceeds the recommended annual limit of 0.17 rem/person* (Ref. 28). Note from Figs. 7.3-1 through 7.3-4 that although the cross-flow dimension of the area of hazard for the single-layer aquifer is greater than that for the double-layer aquifer

* 0.17x50, or 8.5 rem in 50 years to a member of the general populace is the limit used for comparative purposes in the profiles.

(about 1,890 m vs. 1,350 m), the total area of hazard (Tables 7.3-1 and 7.3-2) is less. This is due to the fact that the aquifer concentration's pulse width in the direction of flow is much narrower for the single-layer aquifer than for the double-layer aquifer. This factor offsets the greater cross-flow dimension of the single-layer aquifer's profile, resulting in a smaller area of hazard.

Since the single-layer aquifer is felt to yield the best results for wells close to the borehole and the double-layer aquifer to yield the best results for wells further downstream, a composite picture of well hazard profiles for impermeable repositories can be constructed in the following way:

- To obtain a hazard profile for an impermeable repository and the "Colorado-like" River ecosystem, combine Figs. 7.3-1a, 7.3-2b, and 7.3-2c.
- To obtain a hazard profile for an impermeable repository and the "Columbia-like" River ecosystem, combine Figs. 7.3-3a, 7.3-4b, and 7.3-4c.

Permeable Salt - The second scenario analyzed involves a single sink well drilled near a permeable bedded-salt repository that is penetrated by a borehole. In this case, a second pathway of escape is present in the form of interstitial flow of waste, which is assumed to enter the single- or double-layer upper aquifer as a point source 6,000 m downstream from the borehole. Because of this additional pathway of escape into the aquifer, the dose profiles (Figs. 7.3-5 through 7.3-8) are drawn at times both during and after the passage of the initial radionuclide pulse from the borehole. The actual dose values corresponding to the 100% lines in these profiles are given in Table 7.3-3 for the Colorado-like River ecosystem (Figs. 7.3-5 and 7.3-6) and in Table 7.3-4 for the Columbia-like River eco-

NOTE: SHADED AREAS DENOTE WELL LOCATIONS WHERE WHOLE-BODY-EQUIVALENT DOSE TO THE AVERAGE INDIVIDUAL EXCEEDS 0.17 REM/PERSON ANNUAL AVERAGE

Figure 7.3-5 Dose From a Single Sink Well at (x,y) as a Percent of Peak Value -- Permeable Salt Repository with Single-Layer Aquifer and "Colorado-Like" River Ecosystem

a) Dose Pattern When Peak of Borehole Pulse is at $x = 25,000$ m.

b) Dose Pattern When Interstitial Pulse Reaches Aquifer.

c) Dose Pattern at End of Simulated Time

NOTE SHADED AREAS DENOTE WELL LOCATIONS WHERE WHOLE-BODY EQUIVALENT DOSE TO THE AVERAGE INDIVIDUAL EXCEEDS 0.17 REM/PERSON, ANNUAL AVERAGE

Figure 7.3-6 Dose from a Single Sink Well at (x,y) as a Percent of Peak Value -- Permeable Salt Repository with Double-Layer Aquifer and "Colorado-Like" River Ecosystem

Figure 7.3-7 Dose from a Single Sink Well at (x,y) as a Percent of Peak Value -- Permeable Salt Repository with Single-Layer Aquifer and "Columbia-Like" River Ecosystem

a) Dose Pattern When Peak of Borehole Pulse is at $x = 25,000$ m.

b) Dose Pattern When Interstitial Pulse Reaches Aquifer.

c) Dose Pattern at End of Simulated Time

Figure 7.3-8 Dose from a Single Sink Well at (x,y) as a Percent of Peak Value -- Permeable Salt Repository with Double-Layer Aquifer and "Columbia-Like River Ecosystem"

TABLE 7.3-3

PEAK VALUES OF DOSE FROM A SINK WELL -- PERMEABLE SALT
REPOSITORY AND "COLORADO-LIKE" RIVER ECOSYSTEM

T-6558

AQUIFER	LOCATION OF PEAK OF AQUIFER PULSE, x(m)	TIME, t(yr)	WHOLE-BODY-EQUIVALENT DOSE FROM A WELL AT x AT TIME t*		RATE OF RADIONUCLIDE RELEASE FROM A WELL AT x AT TIME t (Ci/yr)	APPROXIMATE "AREA OF HAZARD" (m ²)
			AVERAGE INDIVIDUAL (50 YR) DOSE (rem)	POPULATION DOSE ($\frac{\text{man-rem}}{\text{yr}}$)		
Single-Layer (Fig. 7.3-5)	25,000	2,520	1.8×10^{-2}	3.8×10^3	5.6	1.9×10^7
	8,000	7.81×10^5	2.6	6.5×10^1	2.8×10^{-3}	None
	8,000	3×10^6	1.5×10^1	3.7×10^2	3.4×10^{-3}	2.9×10^7
Double-Layer (Fig. 7.3-6)	25,000	2,520	3.6×10^1	7.1×10^2	1.1	4.1×10^7
	2,000	7.81×10^5	1.5	3.9×10^1	1.6×10^{-3}	None
	8,000	3×10^6	1.1×10^1	2.8×10^2	2.7×10^{-3}	9.1×10^6

* These are the actual values corresponding to the 100% lines of constant dose in Figs. 7.3-5 and 7.3-6. These lines correctly scale the average individual and population dose measures for each ecosystem.

† These are the actual radionuclide release rates at the indicated distances and times only. The do not scale according to the percentage lines in Figs. 7.3-5 and 7.3-6.

TABLE 7.3-4

PEAK VALUES OF DOSE FROM A SINK WELL -- PERMEABLE SALT
REPOSITORY AND "COLUMBIA-LIKE" RIVER ECOSYSTEM

T-6559

AQUIFER	LOCATION OF PEAK OF AQUIFER PULSE, x(m)	TIME, t(yr)	WHOLE-BODY-EQUIVALENT DOSE FROM A WELL AT x AT TIME t*		RATE OF RADIONUCLIDE RELEASE FROM A WELL AT x AT TIME t (Ci/yr)	APPROXIMATE "AREA OF HAZARD" (m ²)
			AVERAGE INDIVIDUAL (50 YR) DOSE (rem)	POPULATION DOSE ($\frac{\text{man-rem}}{\text{yr}}$)		
Single-Layer (Fig. 7.3-7)	25,000	2,520	7.2	5.9×10^1	5.6	None
	8,000	7.81×10^5	1.5	2.2×10^1	2.8×10^{-3}	None
	8,000	3×10^6	9.1	1.3×10^2	3.4×10^{-3}	1.3×10^7
Double-Layer (Fig. 7.3-8)	25,000	2,520	1.4	1.1×10^1	1.1	None
	2,000	7.81×10^5	9.8×10^{-1}	1.4×10^1	1.6×10^{-3}	None
	8,000	3×10^6	7.1	9.9×10^1	2.7×10^{-3}	None

* These are the actual values corresponding to the 100% lines of constant dose in Figs. 7.3-7 and 7.3-8. These lines correctly scale the average individual and population dose measures for each ecosystem.

† These are the actual radionuclide release rates at the indicated distances and times only. The do not scale according to the percentage lines in Figs. 7.3-7 and 7.3-8.

system (Figs. 7.3-7 and 7.3-8). (The percentage lines in Figs. 7.3-5 through 7.3-8 are applicable for scaling the two dose measures only). The dose values shown at $x=2,000$ and $x=8,000$ m for the single-layer aquifer (Figs. 7.3-5 and 7.3-7) should be viewed as upper limits, not exact values.

Figures 7.3-5 through 7.3-8 show separate dose profiles at three points in time using the Colorado and Columbia-like River ecosystems, respectively, as the basis for potential hazard calculations. Results are presented separately for the single-layer and double-layer aquifer. The first profile in each of these figures illustrates the dose pattern when the initial radionuclide pulse from the borehole peaks at $x=25,000$ m (middle of the aquifer). Comparison of Figs. 7.3-5a, 7.3-6a, 7.3-7a, and 7.3-8a to Figs. 7.3-1b, 7.3-2b, 7.3-3b, and 7.3-4b, respectively, shows that the shaded "area of hazard" due to this initial radionuclide pulse is smaller for the permeable repository than for the impermeable repository. This is due to the fact that a large portion of the radionuclides are undergoing interstitial flow from the permeable repository, leaving less waste available for escape through the borehole. Figures 7.3-5b, 7.3-6b, 7.3-7b, and 7.3-8b illustrate dose profiles at the time when the interstitial flow pulse rate first reaches the aquifer (about 7.8×10^5 yrs). Note that there is no "area of hazard" at this time. Figures 7.3-5c, 7.3-6c, 7.3-7c, and 7.3-8c show profiles of dose at the end of simulated time (3×10^6 yrs), where the actinide mode is the primary contributor to dose.

Since the single-layer aquifer is felt to yield the best results for wells close to either the borehole or the porous flow point source and the double-layer aquifer to yield the best results for wells further downstream, a composite picture of well hazard profiles for permeable repositories can be constructed in the following way:

- To obtain a hazard profile for a permeable repository and the "Colorado-like" River ecosystem, combine Figs. 7.3-6a, 7.3-5b (or -6b), and 7.3-5c.
- To obtain a hazard profile for a permeable repository and the "Columbia-like" River ecosystem, combine Figs. 7.3-7a (or -8a), 7.3-7b (or -8b), and 7.3-7c.

7.4. RESULTS AND CONCLUSIONS

For both the impermeable and permeable bedded-salt repositories modeled, a portion of the aquifer becomes contaminated as the initial pulse of radionuclides enters it. The size of the "area of hazard" varies depending on the type of repository, aquifer, and surface ecosystem chosen. The largest such area is $6.5 \times 10^7 \text{ m}^2$ for an impermeable salt repository with a double-layer aquifer and a "Colorado-like" River ecosystem. The peak 50-yr individual dose in this period is 7.5×10^3 rem for an impermeable salt repository with a single-layer aquifer and a "Colorado-like" River ecosystem. The aquifer concentrations then become low until the actinide mode appears at times beyond 10^5 years. Thereafter, the entire length of the aquifer becomes contaminated at relatively low levels, resulting in well doses near or below the recommended annual limit. The peak 50-yr individual dose in this period is 15 rem for a permeable salt repository with a single-layer aquifer and a "Colorado-like" River ecosystem.

Aquifer salinity would not appear to be a factor in mitigating well risk. Little salt enters the aquifer above an impermeable salt repository. Thus, the likelihood that the aquifer will be used as a source of drinking or irrigation water is not lessened. Salt concentrations are likely to be higher in aquifers overlying a permeable salt repository, thus

making its use as a water source less likely. However, this simply mitigates an already small risk.

8. SUMMARY OF PRINCIPAL RESULTS

TASC's functions in LLL's technical evaluation of bedded salt as a nuclear waste repository medium were to analyze the waste release scenarios chosen by LLL and to determine the implications of the results for the overall evaluation. The scenario analysis was performed using the NUTRAN computer codes and some qualitative calculations.

The scenarios analyzed were all based on a generic salt basin model provided by LLL. This model was not chosen to be representative of a particular group of basins. Rather, it is an attempt to model the more obvious characteristics of bedded salt basins. As a consequence some of the conclusions based on the study may be greatly influenced by the nature of the modeling assumptions, while others are generically indicative of the nature of waste transport in bedded salt. In the next section, the effects of certain key modeling assumptions are summarized. Our overall conclusions and recommendations are summarized in Section 8.2

8.1 THE EFFECT OF KEY MODELING ASSUMPTIONS

The waste dissolution model and the large dispersion constant for the aquifer (1866 m; other studies have typically used dispersion constants on the order of 100 m) profoundly affect the scenario analysis results. The waste dissolution model is used in all of the bedded salt analyses performed for this study. The large dispersion constant is used in the scenario and sensitivity analyses and was the median value of

the dispersion constant for the uncertainty analysis. In the well analysis, the assumption of mixing between the upper shale and sandstone layers, which is the basis for the large dispersion constant, is addressed. The well analyses are performed both with the large dispersion constant, and with a much smaller one (50 m). As a consequence the dissolution and dispersion assumptions influence almost every result in this study.

These two assumptions will not necessarily hold at every bedded salt repository. The waste dissolution model requires that the canister niche geometry remains unchanged for three million years. The large dispersion constant requires significant mixing of the groundwater in two adjacent strata. Because these assumptions affect all of our results, but represent events which may or may not occur at every bedded salt repository, it was thought prudent to delineate their effects on the results. We have attempted to carefully discriminate between results which are profoundly affected by these and other modeling assumptions, and generic conclusions which reflect the generic behavior of bedded salt repositories.

In the waste dissolution model, the quick-leaching group I nuclides on the cladding initially enter solution about one million times faster than the nuclides in the waste matrix. As a result, the quick leaching nuclides define the peak dose in every waste migration scenario analyzed. The integrated dose is principally determined by the very small dissolution rate of the waste matrix. This dissolution rate, and hence, the integrated dose, is insensitive to the flow rate of water through the repository unless that flow rate becomes quite large. Thus, with this dissolution model, the source term of the waste always consists of a quick pulse of unretarded nuclides followed by a very small constant output from the waste matrix. The quick pulse determines the peak dose; the small constant

output determines the integrated dose. In the vast majority of cases this outflow is insensitive to the local geology which determines the flow rate of water through the repository.

The large dispersion constant has two effects. First, it severely reduces the height of the quick-leaching nuclide pulse which determines the peak dose. This attenuation is strong enough to reduce the effect of the local geology unless the local geology flow times are extremely long or extremely short. Second, the spreading of the actinides by dispersion allows them to reach the biosphere in less than three million years even though their flow time across the aquifer is about 4.5×10^6 years.

These two assumptions therefore tend to mask the effect of the local geology in two ways: first, by making the source term essentially independent of the local geology; second, by extensively dispersing the waste reaching the aquifer.

8.2 SUMMARY OF PRINCIPAL CONCLUSIONS

The NUTRAN computer codes were used to analyze the outflow from a large number of waste release scenarios. Scenarios with impermeable salt were limited to waste migration through the shaft/tunnel fracture zone and one additional flaw. Permeable salt scenarios with more complicated flow geometries were also modeled. The results of the NUTRAN analysis were augmented with a qualitative analysis to form a unified explanation of waste transport in the bedded salt. The principal generic conclusions based on the explanation are:

- If molecular diffusion is the only waste transport mechanism the resulting doses are negligible

- The highest peak doses occur for impermeable salt scenarios with a single outflow path that provides a high flow rate
- The presence of a permeable salt outflow path reduces the amount of waste in other outflow paths, and consequently tends to reduce peak and integrated doses.

The following scenario study conclusions relating only to differences between scenarios are so dependent on modeling assumptions that they may not be generic.

- Peak doses are primarily influenced by the amount of dispersion in the local and regional barriers. These doses are at worst about one percent of background
- Integrated doses are primarily influenced by the flow rate of water through the repository, and are essentially the same unless there is a low resistance pathway between aquifers which also intercepts the repository. In that case integrated doses can be greatly increased.

Sensitivity analysis was performed on selected scenarios. The principal generic conclusion drawn from this analysis is:

- Entry of actinides to the biosphere is very sensitive to the regional hydrology and the dissolution properties of the waste.

The following conclusions may not be generic:

- The integrated radioactive release is fairly insensitive to most parameter changes
- The peak and integrated radioactive releases are so dominated by nuclide group 1 that large changes in the outputs of the other nuclide groups barely register.

Two case studies were performed in the uncertainty analysis of a selected waste release scenario. The first case involved a repository scenario with large uncertainties; the second case was similar to the first except for a reduction in the uncertainties in the regional hydrology. The principal generic conclusion drawn from these analyses is:

- The reduction in uncertainty did not affect the integrated outputs but did produce a reduction in the range and uncertainty of the peak outputs.

The difference in behavior between the peak and integrated outputs indicates that they measure different aspects of repository performance. This point should be borne in mind when a measure is chosen by the regulatory agency to assess repository performance.

A well water analysis was also undertaken to develop a methodology for evaluating the hazard from an irrigation or drinking-water well drilled near the repository. In earlier studies, such wells were located directly downstream from the center of the repository and were assigned worst-case (from a dose standpoint) withdrawal rates. The new methodology that was developed allows for well withdrawal rates to span a range of values and for wells to be located arbitrarily in the basin region. Results from an illustrative example indicate a time-varying area of hazard for wells whose size depends on the permeability of the salt, the regional hydrology, and the surface ecosystem employed in the potential hazard calculation.

The principal conclusion is that:

- Methodology exists for evaluation of well hazards on a regional basis.

The following recommendations are offered for future studies. We feel that these suggestions would significantly increase our understanding of waste transport in bedded salt:

- A more detailed model of waste motion within the repository should be developed
- Lateral dispersion should be explicitly included in the well analysis
- The concepts used for qualitative analysis should be further developed for use in prescreening possible scenarios for more detailed analysis
- The sensitivity of results to the dissolution model and the large aquifer dispersion should be more carefully studied.

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APPENDIX A
THE APPROXIMATE WASTE DISSOLUTION RATE

The dissolution model used in these studies is documented in Ref. A-1, and was developed at LLL by A.M. Kaufman.

The fractional dissolution rate, R_D , is calculated from the following equation derived in Ref. A-1:

$$R_D = \frac{\frac{QC_s f_c}{PN}}{1 - \exp \left(\frac{-q_1 \ell_1}{D_1} - \frac{q_2 \ell_2}{D_2} \right)} \quad (A-1)$$

where

- Q is the steady-state flow rate of water through the repository (m^3/yr)
- C_s is the saturation concentration of uranium in water ($9gm/m^3$)
- P is the amount of uranium in a single canister (413kg)
- N is the number of canisters in the repository (1.5×10^5)
- ℓ_1 is the distance between the top of a canister and the bottom of its plug (0.76m)
- ℓ_2 is the distance between the bottom of the plug and the floor of the repository (3.05m)
- α is the longitudinal dispersivity of the overpack (0.1m)

- α_m is the molecular diffusion constant of uranium
($0.03\text{m}^2/\text{yr}$)
- a is the emplacement hole radius (0.254m)
- w is the pathway width around the concrete plug
(.0381m)
- f_c is the fraction of the water entering storage
rooms from the rock formation which passes near
waste canisters (0.1)

and the q and D are given by:

$$q_1 = \frac{Qf_c}{N\pi a^2}$$

$$q_2 = \frac{Qf_c}{N\pi w(2a-w)}$$

$$D_1 = \alpha q_1 + \alpha_m$$

$$D_2 = \alpha q_2 + \alpha_m$$

The value of Q is scenario dependent. The following analysis is designed to approximate R_D as a function of Q .

Substitution of the values of the parameters into Eq. A-1 leads to

$$R_D = 1.45 \times 10^{-11} Q \cdot \frac{1}{1 - \exp \left(\frac{-4.1 \times 10^{-8} Q}{0.03 + 5.4 \times 10^{-8} Q} - \frac{3.6 \times 10^{-5} Q}{0.03 + 1.2 \times 10^{-7} Q} \right)}$$

Consider the exponential. For all positive values of Q the second term dominates the first, so to a reasonable approximation.

$$R_D \approx \frac{1.45 \times 10^{-11} Q}{1 - \exp\left(\frac{-3.6 \times 10^{-5} Q}{0.03 + 1.2 \times 10^{-7} Q}\right)} \quad (\text{A-2})$$

If $Q < 5000$, then the denominator of the exponential in Eq. (A-2) is about 0.03, so

$$R_D \approx \frac{1.45 \times 10^{-11} Q}{1 - \exp(-1.2 \times 10^{-3} Q)} \quad (\text{A-3})$$

Further, for small x ,

$$1 - e^{-x} \approx x$$

Hence, if $Q < 40$,

$$R_D \approx \frac{1.45 \times 10^{-11} Q}{1.2 \times 10^{-3} Q} = 1.2 \times 10^{-8} \quad (\text{A-4})$$

Thus, for very small flow rates ($Q < 40 \text{ m}^3/\text{yr}$) the dissolution rate is almost independent of flow rate. However, for $40 \leq Q < 5000$, Eq. A-3 holds and the dissolution rate increases with flow rate.

For $Q \geq 5000 \text{ m}^3/\text{yr}$, the denominator of Eq. A-3 is approximately unity so

$$R_D \approx 1.45 \times 10^{-11} Q$$

In summary, the dissolution rate of the waste is given by Eq. A-1. This rather forbidding equation may be simplified to give approximate values of R_D as a function of Q . The function R_D is approximately constant for small flow rates ($Q < 40$),

goes through a transition for moderate flow rates ($40 \leq Q < 5000$) and is linear for large flow rates ($Q \geq 5000$). This behavior is summarized in Table A.1

TABLE A.1
DISSOLUTION RATE AS A FUNCTION OF FLOW RATE

FLOW RATE, Q (m^3/yr)	DISSOLUTION RATE (fraction of waste per year)
$0 < Q < 40$	1.2×10^{-8}
$40 \leq Q < 5000$	$\frac{1.45 \times 10^{-11} Q}{1 - \exp(-1.21 \times 10^{-3} Q)}$
$Q \geq 5000$	$1.45 \times 10^{-11} Q$

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APPENDIX B
THE UNFLAWED REPOSITORY TRANSPORT MODEL

B.1 INTRODUCTION

The original version of the WASTE computer code did not model nuclear waste transport along repository or geologic formation pathways where molecular diffusion is the sole mechanism for movement of waste. Such a situation arises, for example, when the permeability of the geologic formation is sufficiently low that water velocities in the repository are negligible. Bedded salt in an unflawed condition is presently thought to have a permeability of this magnitude.

This limitation of the WASTE code has been circumvented. The flow of waste moving through the repository and a shaft is determined analytically and is used as a time-dependent source term for the aquifer. The WASTE code predicts transport along the aquifer, given the source, and the customary risk assessments are thus able to be performed.

In this appendix the source of waste to an aquifer is derived. Soluble waste is assumed to be generated according to a quasi-steady-state dissolution model. The diffusion equation is solved for a series of pipes representing various repository tunnel and shaft segments. Laplace transform techniques are employed. The result of the analysis is the fraction of waste in the repository discharged per year; a sample calculation of this time-dependent function is presented for a typical repository geometry.

B.2 FORMULATION OF PROBLEM

Figure B.2-1 is a typical representation of repository flow paths connecting the geologic formation and aquifer. Each flow path terminates in a node. We assume the repository is a 1-D pipe between nodes 1 and 2 with length L . Flow in the repository is by the process of molecular diffusion only. At every point $0 \leq x \leq L$ the repository pipe is fed soluble waste from a canister region below it according to a source term per unit volume $S(x,t)$. The nature of the source term is presented in Section B.3. Along the flowpath 2-3-4 the waste is transported by diffusion, but there are no external source terms. The required result is the time-dependent current at node 4, which acts as the source for the aquifer, i.e., the pipe between nodes 4 and 5.

Figure B.2-1 Repository and Formation Flow Network

Consider first the repository pipe between nodes 1 and 2. This pipe contains a backfill material. Define:

ε = Porosity of backfill

$C(x,t)$ = Concentration of waste (g/m^3)

$J(x,t)$ = Flow rate of waste (g/yr)

D = Diffusion coefficient (m^2/yr)

L = Pipe length (m)

A = Pipe cross-sectional area (m^2)

For a pure diffusion process, the concentration, flow rate, and source term are related by

$$J(x,t) = -D\epsilon A \frac{\partial C(x,t)}{\partial x} \quad (B.2-1)$$

A mass balance at any section of the pipe between $0 \leq x \leq L$ gives

$$\epsilon A \frac{\partial C(x,t)}{\partial t} = \frac{-\partial J(x,t)}{\partial x} + S(x,t) \quad (B.2-2)$$

Combining Eq. B.2-1 and Eq. B.2-2 results in

$$\epsilon A \frac{\partial C(x,t)}{\partial t} = D\epsilon A \frac{\partial^2 C(x,t)}{\partial x^2} + S(x,t) \quad (B.2-3)$$

B.3 THE SOURCE TERM

The source term in Eq. B.2-3, $S(x,t)$, is related to the rate at which waste moves into the backfilled repository from the region below the repository floor where the waste canisters are buried. Figure B.3-1 illustrates a waste canister with overpack material between it and the repository floor. The length of the overpack is L_o ; its cross-sectional area is A_o . The overpack is taken to have the same porosity ϵ and diffusion coefficient D as the repository backfill material.

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Figure B.3-1 Schematic of Canister Niche

We assume that the concentration of waste is C_s at the canister top, where C_s is the saturation concentration of waste in water. At the top of the overpack the waste concentration is that at the repository floor, $C(x, t)$. Note that this boundary condition differs from that of Ref. B-1, which sets that concentration to zero.

We also assume a quasi-steady-state in the canister niche where the concentration is linear with vertical position between the canister top and the repository floor. The quasi-steady-state assumption is based on the small volume of the canister niches compared to the entire repository volume. Ignoring rapid transients in the overpack region, the flow rate of waste into the repository from a single canister located at position x is given by:

$$J_s(x, t) = \frac{\varepsilon A_0 D}{L_0} [C_s - C(x, t)] \quad (\text{B.3-1})$$

The source term in Eq. B.2-3 is related to the waste flow rate by

$$S(x,t) = \frac{NJ_s(x,t)}{V} \quad (B.3-2)$$

where

N = Number of canisters in the repository

V = Total volume of the repository.

Thus, the governing equation for concentration in the repository is

$$\frac{D\partial^2 C(x,t)}{\partial x^2} + \frac{NA_o D}{L_o V} [C_s - C(x,t)] = \frac{\partial C(x,t)}{\partial t} \quad (B.3-3)$$

Note that the porosity ϵ does not enter into Eq. B.3-3.

Equation B.3-1 can be made more general if the canister niche consists of a number of subregions, each with length L_i and area A_i ; the procedure is to sum the flow resistances of the various subregions, which is equivalent to setting

$$\frac{A_o}{L_o} = \left[\sum_i \frac{L_i}{A_i} \right]^{-1} \quad (B.3-4)$$

B.4 PROBLEM SOLUTION

To solve Eq. B.3-3, it is necessary to determine first an initial condition and two boundary conditions.

For the initial condition we assume that the concentration of waste at $t = 0$ is zero, that is

$$C(x,0) = 0 \quad (B.4-1)$$

For the boundary condition at node 1 ($x = 0$) we assume that the flow of waste is zero, so that

$$J(0,t) = 0 \quad (B.4-2)$$

The solution is greatly simplified if for purposes of setting boundary conditions at $x = L$ we assume that the pipes in the region $x > L$ are infinite in extent and have properties identical to the pipe in the region $0 \leq x \leq L$, with the exceptions that no sources are present for $x > L$ and the pipe dimensions may be different. The boundary condition at $x = L$ then involves matching both concentration and flow rate in the two regions.

Equation B.3-3 can be solved by means of Laplace transforms. Let $\tilde{C}$ be the transform of C such that

$$\tilde{C}(x) = \int_0^{\infty} e^{-st} C(x,t) dt \quad (B.4-3)$$

with s as the transform variable. The transformed equation, using Eq. B.4-1, is

$$s\tilde{C} = D \frac{d^2\tilde{C}}{dx^2} + v\left(\frac{C_s}{s} - \tilde{C}\right) \quad (B.4-4)$$

with

$$v = \frac{NA_o D}{L_o \bar{V}}$$

The general solution to Eq. B.4-4 is

$$\tilde{C} = \lambda_1 \sinh \left(\sqrt{\frac{s+v}{D}} x \right) + \lambda_2 \cosh \left(\sqrt{\frac{s+v}{D}} x \right) + \frac{vC_s}{s(s+v)} \quad (B.4-5)$$

where λ_1 and λ_2 are arbitrary constants. By Eq. B.4-2 and Eq. B.2-1 it is seen that $\lambda_1 = 0$.

Consider now the region $x > L$ external to the repository. Assume it has a porosity ϵ , a diffusion coefficient D , a flow area A_{ext} , and a length L_{ext} . The transformed equation

$$s\tilde{C} = \frac{Dd^2\tilde{C}}{dx^2} \quad (B.4-6)$$

then applies, with the boundary condition

$$\tilde{C}(\infty) = 0 \quad (B.4-7)$$

The general solution for $x > L$ is

$$\tilde{C}(x) = \lambda_3 \exp \left[-\sqrt{\frac{s}{D}}(x-L) \right] \quad (B.4-8)$$

Equating $\tilde{C}$ for the two regions at $x=L$ yields

$$\lambda_2 \cosh \sqrt{\frac{s+v}{D}} L + \frac{vC_s}{s(s+v)} = \lambda_3 \quad (B.4-9)$$

Similarly, equating flow rate at $x = L$ gives

$$-\varepsilon AD \sqrt{\frac{s+v}{D}} \lambda_2 \sinh \sqrt{\frac{s+v}{D}} L = + \varepsilon A_{\text{ext}} D \sqrt{\frac{s}{D}} \lambda_3 \quad (\text{B.4-10})$$

Equations B.4-9 and B.4-10 can be simultaneously solved for λ_2 and λ_3 . Substitution of these results into Eq. B.4-5 and use of the definition of the flow rate, Eq. 2-1, allows us to determine the transform of the flow rate at $x=L$, i.e.,

$$\tilde{J}(L) = \frac{\frac{\varepsilon A_{\text{ext}} v C_s \sqrt{D}}{\sqrt{s(s+v)}} \sinh \sqrt{\frac{s+v}{D}} L}{\frac{A_{\text{ext}}}{A} \sqrt{s} \cosh \sqrt{\frac{s+v}{D}} L + \sqrt{s+v} \sinh \sqrt{\frac{s+v}{D}} L} \quad (\text{B.4-11})$$

Inversion of Eq. B.4-11 is a complicated procedure; however, it is noted that for most repository configurations the flow area of the external pipes is considerably less than that of the repository itself. The ratio A_{ext}/A in Eq. B.4-11 can reasonable be set to zero, leaving

$$\tilde{J}(L) = \frac{\varepsilon A_{\text{ext}} v C_s \sqrt{D}}{\sqrt{s(s+v)}} \quad (\text{B.4-12})$$

The flow rate at the end of the external pipe $x = L + L_{\text{ext}}$ is obtained from Eqs. B.4-8 and B.4-12

$$\tilde{J}_{\text{ext}} = \frac{\varepsilon A_{\text{ext}} v C_s \sqrt{D}}{\sqrt{s} (s+v)} \exp \left[-\sqrt{\frac{s}{D}} L_{\text{ext}} \right] \quad (\text{B.4-13})$$

Inversion of Eq. B.4-13 is carried out without much difficulty from standard tables as a convolution integral.

The result is

$$J_{\text{ext}}(t) = \frac{\varepsilon A_{\text{ext}} v C_s \sqrt{D}}{\sqrt{\pi}} \int_0^t \frac{d\tau}{\sqrt{\tau}} \exp \left[v(\tau - t) - \frac{L_{\text{ext}}^2}{4D\tau} \right] \quad (\text{B.4-14})$$

The quantity $J_{\text{ext}}(t)$ has units of grams of waste per year. Dividing Eq. B.4-14 by the total mass of waste (M_u) in the repository gives the fraction per year discharged to the repository.

Equation B.4-14 strictly applies to the case where there is a single external pipe between the repository. If, as in Fig. B.2-1, there are two or more pipes in the region $x > L$, then Eq. B.4-14 should be approximately correct if L_{ext} represents the sum of the lengths of the external pipes.

B.5 NUMERICAL RESULTS

A calculation was performed to determine the source term $J_{\text{ext}}(t)$ using Eq. B.4-14 for some typical repository parameters:

$$N = 150,000 \text{ canisters}$$

$$A_o/L_o = 0.0175 \text{ m for canister region}$$

$$D = 0.03 \text{ m}^2/\text{yr}$$

$$V = 8.27 \times 10^6 \text{ m}^3$$

These parameters yield a value of $v = 9.5 \times 10^{-6} \text{ yr}^{-1}$. Other parameters are:

$$\begin{aligned}\epsilon &= 0.01 \\ A_{\text{ext}} &= 64 \text{ m}^2 \\ L_{\text{ext}} &= 560 \text{ m} \\ C_s &= 9 \text{ g/m}^3 \\ M_u &= 6.2 \times 10^{10} \text{ g U in repository.}\end{aligned}$$

Based upon these data $J_{\text{ext}}(t)$ was calculated and is presented in Fig. B.5-1 for times up to 10^7 years, which is roughly the transit time of a diffusion pulse through the external pipe network. As is evident, the amount of waste leaking into the aquifer is extremely low. At the computed rates, the waste in the repository would require of the order of 10^{15} years to be exhausted.

Figure B.5-1 Aquifer Source Term for Diffusion Dominated Waste Transport

The derivation of Eq. B.4-13 has interesting implications. By neglecting the flow area of the external pipe network, a bottleneck to waste flow at the outlet end of the repository is created. The waste concentration in the repository builds up to an asymptotic value of C_s with a time constant v ; the waste concentration is essentially constant spatially. The flow into the exterior network from the repository first increases, then decreases with time, with a maximum at about $1/v$ years.

B.6 SUMMARY

An approximate model has been developed to describe the extreme case of transport of waste through a repository located in an impermeable geologic medium such that there is no flow of water and diffusion is the dominant transport mechanism. The model begins with the dissolution of waste canisters as a source of saturated, waste-bearing water, traces the diffusion process through various 1-D or pipe representations of waste pathways, and finally determines the fraction per year of the initial waste content of the repository entering an aquifer. The result is a simple analytical expression, which has been evaluated for typical repository parameters. Calculations show that water in the repository becomes saturated with waste at about 10^5 years. Diffusion through tunnels and shafts external to the repository requires about 10^7 years. Because of the large diffusion transit time, the relatively small area available to waste flow in external pipes, and the rapid attainment of saturation, the flow rates of waste to an aquifer are extremely low.

REFERENCE

- B-1 Kaufman, A.M.. "Waste Form Dissolution in Bedded Salt,"
Lawrence Livermore Laboratory Draft Report, WM-79-758-D,
June 19, 1979.

APPENDIX C
QUALITATIVE BEHAVIOR OF WASTE TRANSPORT
IN A BEDDED SALT REPOSITORY

The purpose of this appendix is to present qualitative arguments supporting the contentions stated in the analysis of the flawed repository scenario results. The arguments are qualitative in that, where appropriate, approximate parameter values are used, simplifying assumptions are made, and limiting cases are considered. Consequently, the equality signs used in the following mathematical development are often only approximately true. However, the purpose of this appendix - to help the reader better understand the nature of waste transport near a repository - is usefully served by the license taken with usual mathematical terminology.

Strictly speaking, this appendix deals with the hydrology in the repository region. Knowledge of the water flow rates in the waste transport pathways allows for approximate calculation of both the time required for waste flow and the reduction in waste pulse height caused by dispersion (Ref. C-1). Neither of these calculations is strictly correct, however they provide useful estimates which allow for qualitative understanding of the waste flow. This understanding is useful both to predict which scenarios are interesting enough to be analyzed with NUTRAN and to serve as a check on the accuracy of NUTRAN results.

The principal tool used in the hydrological calculations is the analogy between Darcy's law and Ohm's law. This analogy is discussed in the next section. The following two

sections contain qualitative discussions of the impermeable and permeable salt scenarios, respectively. The last section summarizes the results of the appendix.

C.1 RESISTOR NETWORK CALCULATIONS

Ohm's law relates the flow of electricity, or current, I , in a length of conductor, to the resistance, R , of the conductor and to the potential difference E between the ends of the conductor:

$$I = E/R$$

Darcy's law relates Q , the volumetric flow rate of water in a path, to the permeability, k , the length, z , and the cross-sectional area, W , of the path and to the hydraulic head difference, ΔH , between the ends of the path:

$$Q = \left(\frac{kW}{z} \right) \Delta H$$

The natural analogy between these two laws suggests identifying flows (Q with I), potential differences (E with ΔH) and "resistances" (R with z/kW). It is then natural to use resistor networks to analyze hydrologic flow problems. This approach will be used throughout the following analyses.

In order to illustrate the construction of the resistance network associated with a scenario consider the case of a new fault located three kilometers upstream from the repository with a connection via an interbed. The repository is assumed to lie in impermeable salt and to have a lateral shaft. This configuration is illustrated in the upper portion of Fig. C.1-1 where the various pipes are labeled according to their designations in Table 3.1-4.

Figure C-1-1 Representation of a Scenario as a Resistor Network

Ground water flows up from the lower aquifer through the fault passing through the shale layer (L2) and salt layer (L1), and then through the interbed (R3) to the repository. The contaminated ground water leaves the repository through

the tunnel (C1 and C2) and up the shaft (D1 and D2) to reach the upper aquifer (U), and finally the river.

In order to construct the equivalent resistor network to this configuration one must assign values to the resistance of each path and also assign "boundary values" for the hydraulic potentials. The assignment of resistances is accomplished using the analogy defined in the previous section. The resistance of each path segment is its length divided by the product of its permeability and cross section. To assign heads to appropriate boundaries, we assume that the water flow rate through the repository is negligible compared to the flow rates in the aquifers. Thus, potentials in the aquifers are determined by the 3.6 m vertical head difference between the aquifers throughout the basin and the 0.006 horizontal gradient in the aquifers.

The central portion of Fig. C.1-1 shows the assignment of resistances and hydraulic heads for the problem under study. The head at the intersection of the shaft and upper aquifer was arbitrarily set at 0.0m. The head of the lower aquifer directly below the repository is 3.6m. The head at the intersection of the fault and the lower aquifer is 21.6m because the 3km length of the interbed adds 18m of head due to the assumed hydraulic gradient. The head of the river is -312m because of the horizontal gradient and the aquifer length (52km). The resistances are given in units of yr/m^2 and are obtained using the values in Table 3.1-4.

The resistance of the upper aquifer was not computed for two reasons. First, the hydraulic heads at the ends of the aquifer are known so it is easy to compute the flow in the aquifer without explicitly computing the resistance. Second,

because the flow through the repository is ignored at the aquifers there is not an explicit flow balance at points in the aquifer. Hence, there is no need to compute resistances in the aquifer.

Because all of the resistances in this scenario are in series the total resistance of the path between the aquifers is the sum of the individual resistances which is 21.16 yr/m^2 . The total flow rate between the aquifers is given by the potential difference (21.6m) divided by the resistance (21.16 yr/m^2). The flow rate is $1.02 \text{ m}^3/\text{yr}$.

If desired, the heads at the intermediate nodes could be calculated by equating the inflow to the outflow. These calculations are easy in this case since there are only one inflow and one outflow path at each node. More complicated situations will be encountered in the permeable scenarios.

The bottom portion of figure C.1-1 shows an equivalent circuit for computing the head of the repository in this case. The series resistances have been "lumped" to give a two equivalent resistances: one between the lower aquifer and the repository and one between the repository and the upper aquifer. Let H denote the head of the repository. Then inflow equals outflow produces the equation

$$\frac{21.6 - H}{2.5} = \frac{H - 0.0}{18.66}$$

Thus $H = 19.05\text{m}$

These computations are quite easy for this scenario (and the other impermeable salt scenarios) because all flow paths are in series. For permeable salt scenarios the situation is more complex because of branching in the resistor

networks, however the same principles employed to construct networks for impermeable salt scenarios are applicable.

C.2 ANALYSIS OF IMPERMEABLE SALT SCENARIOS

The impermeable salt scenarios all contain a single flaw plus the tunnel/shaft fracture zone. Either an upstream shaft serves as the inflow path for groundwater to the repository, and waste leaves the repository via the flaw, or a lateral shaft serves as an exit path for waste, and inflow is provided by the flaw. Figures 3.2-4 and 3.2-5 are schematic representations of the impermeable salt flow paths. The shaft is upstream in Fig. 3.2-4 and exit via a flaw and an interbed/flaw system is depicted. The shaft is lateral in Fig. 3.2-5 and the various flaw combinations are depicted.

Because of the simplicity of these scenarios, each may be represented by a simplified resistor network such as in Fig. C.1-1. Each scenario will have a flaw system, possibly including an interbed, as one path, and the shaft/tunnel (S/T) fracture zone as another path from the repository to an aquifer. In the following R_f denotes the total resistance in the flaw pathway, and R_s denotes the total resistance in the S/T pathway. H_f and H_s denote the heads at the intersection of the flaw with an aquifer, and of the shaft with an aquifer, respectively. Then the simplified resistor network in Fig. C.2-1 represents all of the impermeable salt scenarios under the convention that water can flow in either direction in the figure.

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Figure C.2-1 Resistor Network for Impermeable Salt Scenarios

For the network of Fig. C.2-1 it is easy to see that the flow rate of water, Q , through the repository is given by

$$Q = \Delta H / (R_f + R_s) \quad (C.2-1)$$

where ΔH is the positive head difference between the shaft and flau, i.e. $\Delta H = H_s - H_f$. This equation is the basis of the qualitative scenario analysis.

The flow of nuclear waste to the river is impeded by four barriers: the refill barrier, the dissolution barrier, the local flow barrier, and the regional flow barrier. The results of the waste migration scenarios can be understood by consideration of these barriers.

The quality of the refill barrier is measured by the amount of time which passes before waste flow is initiated. Two independent events must occur before waste flow begins: a canister must corrode and the repository must refill. In this study the canister corrosion time is set at 500 yr for all scenarios. The repository refill time, t_{ref} , is approximately given by

$$t_{ref} = 420 R_f R_s / (R_f + R_s)$$

A detailed discussion of the refill model may be found in Ref. C-2. This expression for t_{ref} is based on the specific storage of the repository being zero and the void volume of the repository being $2.1 \times 10^5 \text{ m}^3$.

In the previous section R_s was found to be 18.66 yr/m^2 , so, to a fair approximation,

$$t_{\text{ref}} = 8000 R_f / (19 + R_f) \quad (\text{C.2-2})$$

Thus, t_{ref} is small for a low resistance flow, so waste flow will begin in 500 yr. However, when R_f exceeds 1.3 yr/m^2 the waste will begin to flow at time t_{ref} .

The dissolution barrier is measured by the dissolution rate of the waste form which, in turn, depends on the flow rate of water through the repository. Table 3.2-1 gives the dissolution rate as a function of the flow rate of water based on the detailed calculations in Appendix B.

The maximum head difference between the shaft and the flow in the impermeable salt scenarios is 21.6 m, and, as was noted earlier, the resistance of the S/T fracture zone is 18.66 yr/m^2 . Substituting these values into Eq. C.2-1 shows that the maximum water flow rates in these scenarios is less than $1.13 \text{ m}^3/\text{yr}$. Using Table 3.2-1 we see that the dissolution rate of the waste will be approximately $1.2 \times 10^{-8} \text{ yr}^{-1}$ for all impermeable salt scenarios. Based on the preceding calculation, the 10% of the unretarded nuclides on the cladding will have a leach rate of about 85 years.

The local flow barrier is measured by the time for waste to flow from the repository to the aquifer, the local flow time is denoted t_{loc} .

The flow time of waste in the path from the repository to the aquifer can be found by dividing the void volume or capacity of the path by the flow rate of water in the path. In the following the capacity will be denoted by C so that

$$t_{loc} = C/Q \quad (C.2-3)$$

Note that when the outflow path consists of several segments in series, the total capacity is the sum of the individual segment capacities.

The capacity of a single segment is the product of its volume and porosity, i.e. the product of its length, cross section, and porosity. For the case considered in Section C.1 and illustrated in Fig. C.1-1 the outflow path consists of four segments. The segments and their capacities are given in Table C.2-1.

TABLE C.2-1
CAPACITIES OF TUNNEL AND SHAFT SEGMENTS

SEGMENT	PIPE TYPE	CAPACITY (m ³)
Tunnel Fracture Zone within Repository	C1	3960
Outer Tunnel Fracture Zone	C2	87
Shaft Fracture Zone in Salt	D1	11
Shaft Fracture Zone in Shale	D2	1

The capacity of the entire shaft/tunnel fracture zone is 4059 m³. Thus the local flow time for this scenario is approximately 3,980 yr given the flow rate of 1.02 m³/yr.

The resistances and capacities of various flaws, interbeds, and the (S/T) fracture zone are given in Table C.2-2.

TABLE C.2-2
RESISTANCES AND CAPACITIES OF FLOW PATHS

FLAW	RESISTANCE (yr/m ²)	CAPACITY (m ³)
Shaft/Tunnel Fracture Zone	18.7	4.06×10^3
Joint System	1.1×10^{-2}	1.77×10^5
New Fault	6.2×10^{-5}	3.54×10^4
Old Fault	5.6	3.54×10^4
Large Borehole	37.4	1.06
Breccia Pipe	1.12×10^{-6}	1.06×10^7
Interbed (3km long)	2.5	1.14×10^7

The regional flow barrier is measured by the flow time of the unretarded nuclide in the aquifer. In these scenarios, the length of the aquifer flow path depends on the entry point of the waste: it is either 49km or 52km. The water velocity in the aquifer is 11.1 m/yr. Thus to a reasonable approximation, the regional flow time, t_{reg} , is about 4500 yr.

The regional flow time for a retarded nuclide is the product of the retardation factor of the nuclide and t_{reg} . For example, fission products require about 1.35×10^5 yr and actinides 4.5×10^6 yr to traverse the aquifer.

In sum, the regional flow barrier and dissolution barrier function in about the same way for each of the impermeable salt scenarios. The differences in waste transport among scenarios are produced by the refill barrier and the local flow barrier.

Both of the barriers which affect results may be thought of as time delays: the more effective the barrier the longer it takes for waste to reach the river. However, the local flow barrier also reduces the peak amount of waste by dispersion. The amount of dispersion produced in the local flow path varies directly with t_{loc} . Thus scenarios with large local flow times produce both large time delays and large dispersions.

The effectiveness of dispersion in the local flow path is particularly important for these scenarios. The peak doses are produced by the 10% of unretarded nuclide which quickly leaches from the cladding. At the time that waste initially leaves the canister, these quick leaching unretarded nuclides enter the ground water at a rate of 2500 MWe-yr/yr while the rate of outflow of all other nuclides from the bulk waste from is only about 0.024MWe-yr/yr.

The time delays provided by the refill and local flow barrier do not produce significant radioactive decay in the quick-leaching nuclides because the principal constituent is ^{129}I with a 16 million year half-life. As a consequence, the principal reduction in peak dose from case-to-case is caused by dispersion in the local pathway, and, hence, t_{loc} is the primary predictive measure of scenario performance.

Substitution of Eq. C.2-1 into Eq. C.2-3 gives

$$t_{loc} = \frac{C(R_f + R_s)}{\Delta H} \quad (C.2-4)$$

From this equation we see that the highest peak doses should arise from scenarios where the outflow path capacity and flaw resistances are small and the head difference is large.

However, it should be noted that the effective of a low flow resistance is mitigated by the relatively large shaft resistance, and that the value of ΔH in these scenarios varies by at most a factor of 6. However, the capacity of possible outflow paths varies over several orders of magnitude and should be the determining factor for peak doses.

This conclusion was indeed borne out in the analysis where outflow through the low capacity borehole gave the highest results, while outflow through the large capacity breccia pipe did not allow waste to reach the river within three million years.

Note also that scenarios with outflow through the S/T fracture zone produced relatively large doses due to the fairly small capacity of these fractures.

C.3 PERMEABLE SALT SCENARIOS

The permeable salt scenarios analyzed in this report are more complicated than the impermeable scenarios both because of the additional flow paths through the salt and shale strata and because of the more complicated flaw geometries which were modeled. Figure C.3-1 shows the most complicated equivalent resistor network needed to analyze the impermeable cases. In this network the individual series resistances defining flaws, S/T fracture zones, or permeable flow paths have been lumped together into single resistors. In the figure, and the remainder of this section, R_p will be the resistance of the porous flow path through a salt and a shale stratum. The resistance is assumed to be the same for the layer between the repository and each aquifer. R_1 denotes the resistance of

Figure C.3-1 Resistor Network for Permeable Salt Scenarios

the flaw between the repository and the upper aquifer; R_2 fulfills the same definition for the lower aquifer. R_S is the S/T resistance.

In the scenarios it is mathematically convenient to set the hydraulic heads at the intersection of the permeable rock flow path and the lower aquifer at H_P , and at the intersection of the permeable rock flow path and the upper aquifer at $-H_P$. In these scenarios, $H_P = 1.8$ m. H_S denotes the hydraulic head at the top of the shaft while H_1 and H_2 denote the heads at the intersection of the flaws with the upper, and lower aquifer respectively.

It should be noted that Fig. C.3-1 is not meant to represent the actual physical location of the flaws and shaft with respect to each other or to the repository.

The head, H , at the repository can be obtained by equating inflow and outflow at the repository. The result is

$$H = \frac{H_s}{1 + \frac{R_s}{R_1} + \frac{R_s}{R_2} + \frac{2R_s}{R_p}} + \frac{H_1}{1 + \frac{R_1}{R_2} + \frac{R_1}{R_s} + \frac{2R_1}{R_p}} + \frac{H_2}{1 + \frac{R_2}{R_1} + \frac{R_2}{R_s} + \frac{2R_2}{R_p}} \quad (C.3-1)$$

The four barriers to flow perform differently when the salt strata are permeable. The refill barrier no longer varies with scenario. Waste flow always begins at the canister penetration time, 500 years, because inflow through the permeable pathways alone is sufficient to refill the repository in less than 200 years.

The dissolution barrier is no longer independent of scenario as it was for impermeable salt. With permeable pathways present, flow rates through the repository may become large enough to substantially increase the dissolution rate.

The local flow barrier must be analyzed on a case-by-case basis.

The regional flow barrier is essentially unaffected by the presence of a permeable salt strata and thus will function exactly as in the impermeable scenarios.

The lumped resistances and capacities of the features modeled in these scenarios are presented in Table C.3-1 for reference. These values are different from those used in the impermeable scenarios because of the difference between repository depths in the two cases. (See Table 3.2-4.)

TABLE C.3-1
RESISTANCES AND CAPACITIES OF FLOW PATHS
FOR THE PERMEABLE SALT SCENARIOS

FLOW	RESISTANCE (yr/m ²)	CAPACITY (m ³)
Shaft/Tunnel Fracture Zone	14.8	4.05×10^3
Failed Shaft/Tunnel Backfill	0.244	4.04×10^4
Porous Flow	0.66	5.2×10^6
Fractured Rock	6.7×10^{-3}	1.41×10^5
New Fault	3.9×10^{-5}	2.81×10^4
Old Fault	3.3	2.81×10^4
Large Borehole	29.7	0.843
Breccia Pipe Above Repository	8.9×10^{-7}	8.4×10^6
Breccia Pipe Below Repository	3.3×10^{-6}	-

The entry for porous flow in Table C.3-1 is based on the salt layer only. Motion through the shale layer is controlled by the horizontal gradient. Waste will flow horizontally with only a small vertical motion until it reaches the boundary of the local region. As described in Section 3.1, the waste is assumed to enter the aquifer at this boundary.

The time spent in the shale stratum is very small compared to the time spent in the salt stratum and hence will be ignored in the following qualitative analysis.

In the remainder of this section the permeable salt scenarios are discussed in four groups. In each group the porous flow pathway through the permeable salt and the S/T pathway are present. In subsection C.3.1 scenarios with no other flaws present are considered. Scenarios with one additional and two additional flaws are considered in the next two sections. Scenarios with a fractured salt and shale layer are then discussed. Finally a summary of the findings of this section is presented.

C.3.1 Scenarios With No Additional Flaws

These scenarios contain only the S/T pathway and the porous flow pathways. The repository head can be found from Eq. C.3-1 by letting the resistances R_1 and R_2 become very large. This is equivalent to "closing" the flaws. Thus,

$$H = \frac{H_s}{1 + 2R_s/R_p} \quad (C.3-2)$$

The flow rate out of the shaft from the repository, Q_s , is given by

$$Q_s = (H - H_s)/R_s \sim -H_s/R_s \quad (C.3-3)$$

because, for the baseline case, H is small.

The value of Q_s depends on the shaft location: it is about $-0.5 \text{ m}^3/\text{yr}$ for downstream, $0.1 \text{ m}^3/\text{yr}$ for lateral, and

0.8 m³/yr for upstream. The negative flow rate for the upstream case points out that the S/T fracture system is an inflow path for an upstream shaft.

Comparison of Eqs. C.3-3 and C.2-1 shows that the flow rate out of the shaft is essentially the same in these cases as in the impermeable cases with a very low resistance flaw.

The flow rate from the repository to the aquifer, Q_{up} , is given by

$$Q_{up} = (H + H_p)/R_p \sim H_p/R_p = 2.7\text{m}^3/\text{yr}.$$

The resulting flow time through the permeable strata is about two million years. During this time dispersion will significantly reduce the height of the nuclide puls, so flow through this pathway will not produce large doses.

The percentage of waste entering the tunnel is the same as the percentage of water entering the tunnel. Hence, only about 8% of the waste enters a lateral tunnel, and 22% of the waste enters a downstream tunnel. However, the tunnel is "leaky" and most of the water and waste which enter the tunnel flow up into the permeable rock before reaching the shaft. Consequently, the percentage of waste entering the aquifer from the shaft is significantly lower than the percentage of waste entering the tunnel (Ref. C-3).

Given the capacity of the S/T fracture zone, the flow time through a lateral shaft is at least 40,000 years and through a downstream shaft is at least 5000 years.

In sum, the shaft carries less waste and carries it more slowly than in the impermeable scenarios. Most of the waste travels through the very slow, highly dispersive permeable rock. As a consequence, these unflawed scenarios do not produce large doses.

If the backfill in the shaft and tunnel fails, this failed backfill will provide the principal S/T pathway because its resistance is much lower than the fracture zone. In this case,

$$H \approx H_s/1.75$$

Consequently,

$$Q_s = (H - H_s)/R_s = -3H_s/7R_s$$

and,

$$Q_{up} = (H + H_p)/R_p = (4H_s + 7H_p)/7R_p$$

From the signs of Q_s and Q_{up} , we see that there is inflow from the upstream shaft and outflow from the lateral and downstream shaft, and that in the downstream case, the permeable flow path above the repository provides inflow to the repository. The largest flow rate through the shaft backfill occurs in the downstream case: $Q_s = 20 \text{ m}^3/\text{yr}$. In this case all of the waste is committed to the S/T failed backfill, and flow time to the aquifer is about 2,000 years. This case provides doses comparable to the worst of the impermeable salt cases.

Note that in these cases the flow rate of water through the repository is fairly small so that the dissolution barrier remains as before.

C.3.2 Scenarios with One Flaw

Consider scenarios with a single flaw below the repository. The head of the repository is obtained from Eq. C.3-1 by letting R_1 become very large. Then,

$$H = \frac{H_s}{1 + \frac{R_s}{R_2} + \frac{2R_s}{R_p}} + \frac{H_2}{1 + \frac{R_2}{R_s} + \frac{2R_2}{R_p}} \quad (C.3-4)$$

If R_2 is large this equation reduces to Eq. C.3-2. The situation is roughly like that where no flaw is present.

If the flaw has a low resistance then

$$H \sim H_2 / (1 + 2R_2/R_p) \sim H_2 \quad (C.3-5)$$

Therefore,

$$Q_s \sim (H_2 - H_s)/R_s \sim -H_s/R_s$$

$$\text{and, } Q_{up} \sim (H_2 + H_p)/R_p$$

Hence, the flow through the shaft is not significantly increased by the presence of the flaw. However flow through the permeable stratum will be greatly increased. For the scenarios analyzed in this study, $H_2 \sim H_p$, so the porous flow rate is doubled. Consequently, the shaft pathway has only a slightly higher flow rate, and carries significantly less waste.

Even if the shaft backfill fails, the flow through the shaft will not be greatly increased from the failed backfill scenario with no flaw.

In these cases the dissolution barrier continues to function as in the previous scenarios.

For a single flaw above the repository, the important question is whether this flaw will become an important outflow path. The head of the repository can be obtained from Eq.

C.3-1 by letting R_2 become very large. Then,

$$H = \frac{H_s}{1 + \frac{R_s}{R_1} + \frac{2R_s}{R_p}} + \frac{H_1}{1 + \frac{R_1}{R_s} + \frac{2R_1}{R_p}}$$

If the flaw resistance is large, the results are essentially like the no-flaw case. However, when the flaw resistance is small,

$$H \approx H_1 / (1 + 2R_1/R_p) \approx H_1 \quad (C.3-6)$$

Therefore,

$$Q_s \approx -H_s/R_s$$

and

$$Q_{up} \approx (H_1 + H_p)/R_p$$

The shaft flow is about the same as when no flaw is present, but the porous flow is greatly reduced because for low resistance flaws $H_1 \approx -H_p$.

The flow rate through the flaw, Q_1 , is given by

$$Q_1 \approx (H - H_1)/R_1 \approx \left(\frac{H_1}{1 + 2R_1/R_p} - H_1 \right) / R_1$$

$$\approx - H_1/R_p$$

provided $R_p \gg R_1$

Because $H_1 \approx - H_p$ for a low resistance flaw, the flow rate through the flaw pathway is about the same as the flow rate through the porous rock in the absence of the flaw. However, low resistance flaws such as new faults may have significantly smaller capacities than the porous rock and, therefore, produce significantly larger doses than expected in the absence of the flaw.

The effect of failed backfill on these results is to increase the flow rate through the flaw by about 50%.

To summarize, the effect of the addition of a single flaw to the "unflawed" scenario is negligible unless the flaw has a low resistance. Low resistance flaws providing inflow to the repository do produce larger flow rates to the repository, but most of the excess water leaves the repository through the permeable pathway. As a result, the percentage of waste leaving the repository via the relatively fast shaft is decreased, while the percentage leaving via the relatively slow permeable pathway is increased. The net effect of these changes on output is difficult to predict, but, in any event, it should not be large.

Low resistance outflow paths can produce substantial increases in dose since they will become the flow path for water which would otherwise flow through the high capacity porous rock.

C.3.3 Scenarios with Two Flaws

Consider scenarios with flaws both above and below the repository. The head of the repository is given by Eq. C.3-1

$$H = \frac{H_s}{1 + \frac{R_s}{R_1} + \frac{R_s}{R_2} + \frac{2R_s}{R_p}} + \frac{H_1}{1 + \frac{R_1}{R_2} + \frac{R_1}{R_s} + \frac{2R_1}{R_p}} + \frac{H_2}{1 + \frac{R_2}{R_1} + \frac{R_2}{R_s} + \frac{2R_2}{R_p}}$$

If either R_1 or R_2 are large, the scenario will be like one of those discussed earlier in this appendix. So, let us consider the case where R_1 and R_2 are both very small. Physically, this means that there is a low resistance pathway passing through the repository, and connecting the two aquifers.

For R_1 and R_2 both small,

$$H \approx \frac{1}{2} (H_1 + H_2)$$

Because of the high resistance of the interbeds, it is reasonable to assume that the two low resistance flaws lie directly above and below the repository so that $H \approx 0$.

Therefore, the flow rates out of the repository are

$$\begin{aligned} Q_s &= -H_s/R_s \\ Q_{up} &= H_p/R_p = 2.7 \text{ m}^3/\text{yr.} \\ Q_1 &= -H_1/R_1 = 1.8/R_1 \end{aligned}$$

The shaft flow is inconsequential for the three shaft locations considered. The porous flow is about the same as in the absence of flaws. However, the flaw provides a pathway with a potentially very large flow.

The large outflow through the flaw has two consequences. First, as in the other cases, the local flow time, t_{loc} , will be short. For a flaw with capacity C ,

$$t_{loc} = C/Q_1 = R_1 C / 1.8$$

So the local flow time for outflow through a new fault or a breccia pipe is less than 1 yr, and virtually all of the waste leaves the repository through this pathway.

The second effect is on the dissolution barrier. The flow rate from the repository through a new fault is about 30,000 m³/yr. Hence, from Table 3.2-1, the dissolution rate is about 4.4×10^{-7} . The unretarded nuclides on the cladding have a leach time of about 2 years.

Peak doses in these cases will be about the same as for the worst of the impermeable salt scenarios. The peak dose is determined principally by the effect of the highly dispersive aquifer on the nuclide leaching from the cladding. Consequently, there is not much difference between the peak pulse height in these cases because all pulses flow through the same aquifer.

Integrated population doses are greatly increased in the two-flaw scenarios. The amount of waste leaving the repository per year is increased by a factor of 40 in the worst cases. Much of this waste will eventually reach the biosphere and produce higher chronic doses than in the other scenarios.

C.3.4 Scenarios with Fractured Salt

In these scenarios, the salt and shale layers are assumed to have fractured because of some unspecified cause. Consider first an "unflawed" scenario with fracture above the repository only and an upstream shaft. Denoting by R_f , the resistance of the fractured rock, the head of the repository is

$$H = \frac{H_s}{1 + \frac{R_s}{R_p} + \frac{R_s}{R_f}} + \frac{H_p}{1 + \frac{R_p}{R_s} + \frac{R_p}{R_f}} + \frac{-H_p}{1 + \frac{R_f}{R_s} + \frac{R_f}{R_p}}$$

From Table C.3-1, the fractured rock resistance is much smaller than either the porous rock or S/T resistance, so

$$H \approx -H_p / (1 + R_f/R_p) \approx -H_p$$

The flow rate through the fractured rock is approximately

$$Q_{up} = H_p/R_p$$

Thus, fracturing only the strata above the repository does not produce large increases in dose.

If there are fractures both above and below the repository, the head of the repository is

$$H = \frac{H_s}{1 + 2R_s/R_f} \approx 0$$

Thus the flow rate to the upper aquifer will be

$$Q_{up} \approx H_p/R_f \approx 270 \text{ m}^3/\text{yr.}$$

As a consequence, the local flow time is about 500 years, and the waste dissolution rate will increase over that found in the unflawed scenarios. Hence, this scenario is expected to produce large doses.

C.4 SUMMARY

The purposes of the foregoing qualitative analysis were to support the contentions stated in the scenario analysis (Ch. 4) and to provide the reader with some insight into the nature of waste transport in a nuclear waste repository. The method employed involved approximating the flow rates of water in the various pathways using equivalent resistor networks. These flow rates were used to calculate the effectiveness of the four barrier waste migration in various situations. The following summary of the results is structured to discuss the change in the effectiveness of the four barriers caused by various combinations of flaws.

The refill barrier does not exert a large influence on either peak or integrated dose. Peak doses are determined by the long-lived unretarded nuclides present in the cladding. A long refill time will not produce sufficient decay to affect either these quick-leaching nuclides or the unretarded nuclides in the waste form. The fission products and actinides do decay during the refill time, however this time is only a small percentage of the time spent by these retarded nuclides in traversing the aquifer. Hence, the barrier has little effect on either peak or integrated dose.

The dissolution barrier controls the percentage of the waste form dissolved per year. This barrier depends on the flow rate of water through the repository. In most scenarios this flow rate is small enough that only about 1.2×10^{-8} of the waste form dissolves per year. However, if a low resistance pathway exists between the two aquifers the flow rate of water will increase substantially and the dissolution rate can increase dramatically (a factor of 40 increase was observed in this study). The integrated dose depends on the dissolution rate, and thus is substantially affected by this barrier. The peak dose is much less affected by this barrier. The effect of an increased flow rate is to reduce the leach time of the nuclides in the cladding. However, this leach time is only 85 years in the slowest case. The extreme dispersivity of the aquifer masks any reduction in leach time to the extent that the difference in leach behavior cannot be discerned in the peak release rate to the biosphere.

The local flow barrier functions differently for the impermeable and the permeable scenarios. The principal cause of this difference is that in the impermeable scenarios there is only one flow path for waste to the aquifer. The capacity of this flow path determines the flow time of the waste to the aquifer. As was also true with the refill barrier, this time delay does significantly affect the peak or integrated dose. However, significant dispersion can occur during a long local flow time, and hence, can significantly reduce peak dose. Thus low capacity flaws tend to produce large peak doses.

In the permeable salt scenarios, the permeable pathway has a very large capacity, so waste traversing the porous rock has a long flow time with a large dispersion. Hence, this pathway does not contribute large peak doses. The permeable pathway will carry most of the waste unless there is a

connection between the aquifers with a lower resistance than the porous rock. In that case, the very large flow through the repository will move through the flaws which, in general, have a much smaller capacity than the permeable rock.

The regional flow barrier was not varied in these scenarios. However, it should be noted that the large dispersion constant (1866m) for this flow path has a large effect on the peak doses obtained, and masks many of the differences among the scenarios.

REFERENCES

- C-1 O'Connell, W.J., "Generic Bedded Salt Repository: Hand Calculation of Scenarios for Waste Migration," Lawrence Livermore NRC Waste Management Memo WM 79-919, August, 1979.

- C-2 Ross, B., Koplik, C.M., Giuffre, M.S., Hodgins, S.P., Duffy, J.J., "Nutran: A Computer Model of Long-Term Hazards from Waste Repositories," The Analytic Sciences Corporation, Report No. TR-1797-7, UCRL-15150, December 1979.

- C-3 Ostons, S.G., "A Preliminary Analytical Repository Flow Model," The Analytic Sciences Corporation, Report No. TIM-1797-5, UCRL-15184, July 1979.

APPENDIX D
CALCULATION OF RETARDATION FACTORS

This appendix concerns the generation (Ref. D-1) of the retardation factors for the fission products (B_F), radium (B_R) and the actinides (B_A). The method of generation must satisfy the following conditions:

- The retardation factors must be greater than or equal to 1.0
- The distributions must be approximately lognormal (logarithm to the base 10)
- $B_F < B_R < B_A$ with 99.9% probability. (D.1)

The parameters for the lognormal distribution are given in Table D-1.

The first two conditions are met by calculating the retardation factors as:

$$B_i = 1.0 + C_i$$

where $i = F, R$ or A , and

C_i is generated according to a lognormal distribution with the median one less than the median for B_i , but with the same uncertainty.

The third condition is more difficult to meet because it is quite possible to generate sets of retardation factors

where the inequality Eq. D.1 does not hold, given the parameters in Table D.1. An approach to eliminate this possibility is to create a factor (J_1) to obtain C_R from C_F . For example, if

$$\log C_R = J_1 + \log C_F \quad (D.2)$$

then given the distributions of C_F and C_R , J_1 is a random variable which is normally distributed, and

$$J_1 = \log C_R - \log C_F$$

This random variable, however, has too large a variance. If the uncertainty of J_1 is not reduced, it is possible for J_1 to go below 0, and the inequality Eq. D.1 will no longer hold. To compensate for this, the statistics of J_1 are adjusted. In particular we solve the following equations:

$$\mu_R = a_R \mu_F + M_R \quad (D.3)$$

$$\sigma_R = \sqrt{a_R^2 \sigma_F^2 + S_R^2} \quad (D.4)$$

where

μ_R = mean of $\log C_R$

a_R = constant

μ_F = mean of $\log C_F$

M_R = adjusted mean of J_1

σ_R = standard deviation of $\log C_R$

σ_F = standard deviation of $\log C_F$

S_R = adjusted standard deviation of J_1

TABLE D-1
ASSUMED STATISTICS FOR GENERATION
OF RETARDATION FACTORS

VARIABLE	MEDIAN	UNCERTAINTY	
		CASE 1	CASE 2
B_F	30	0.7	0.4
B_R	200	0.85	0.45
B_A	1000	1.0	0.5

The values of a_R , M_R and S_R are chosen so both equations D.3 and D.4 hold. If these equations hold then J_1 satisfied equation D.2. There are many values of a_R , M_R , and S_R which will satisfy the system of equations, and the choice of the set of values used has been made arbitrarily.

This procedure is repeated for calculating the retardation factor of the actinides as a function of the retardation factor of radium. For this situation, equations analogous to Eqs. D.3 and D.4 are written to obtain the constants for determining C_A from C_R using the same procedure as described above. Let J_2 denote the factor obtained analogously to J_1 . The value for the constants, means and standard deviations for the adjusted distributions J_1 and J_2 are given in Table D-2.

In summary, three distributions are used to generate B_F , B_R and B_A :

- C_F (lognormally distributed with median and uncertainty given in Table D-1)

- J_1 (normally distributed with median and standard deviation given in Table D-2)
- J_2 (normally distributed with median and standard deviation given in Table D-2).

From C_F , J_1 and J_2 randomly choose c_F , j_1 and j_2 respectively. Then let:

$$\log c_R = a_R \log c_F + j_1$$

$$\log c_A = a_A \log c_R + j_2$$

and let

$$B_F = 1.0 + c_F$$

$$B_R = 1.0 + c_R$$

$$B_A = 1.0 + c_A$$

By calculating the retardation factors by this method, all three conditions are met.

TABLE D-2
PARAMETERS FOR GENERATING ADJUSTED DISTRIBUTIONS

VARIABLE	CASE	a	J	
			M	S
C_R	Case 1	1.18	0.5732	0.2006
	Case 2	1.1	0.6903	0.0943
C_A	Case 1	1.165	0.3213	0.0987
	Case 2	1.0	0.7007	0.2179

REFERENCES

- D-1 O'Connell, W.J., "Uncertainty Analysis Inputs for Scenario VI-9, Fractured Salt and Shale Above and Below Repository," Lawrence Livermore Laboratory Memo WM 79-1240-D, November, 1979.

APPENDIX E
HISTOGRAMS AND CORRELATION TABLES FOR UNCERTAINTY ANALYSIS

Chapter 6 of this report concerns the analysis of the effect of parameter uncertainty on repository performance. Figures E-1 through E-5 are the histograms of the results of the Monte Carlo computer runs for Cases 1 and 2 for the following variables:

- Peak 50-yr Individual Dose (rem)
- Peak Population Dose (man-rem/yr)
- Peak Flow (Ci/yr)
- Integrated Population Dose (man-rem)
- Integrated Flow (Ci)

Tables E-1 through E-3 list the correlations of the input parameters with the following repository performance measures

- Peak Outputs
- Integrated Outputs
- Times of Peak Output.

a) Case 1

b) Case 2

KEY

□ = PEAK DOSES CONTROLLED BY NUCLIDE CLASS I

■ = PEAK DOSE CONTROLLED BY NUCLIDE CLASS III

Figure E-1 Histograms of Peak 50-yr Individual Dose
Cases 1 and 2

a) Case 1

b) Case 2

KEY

▬ = PEAK DOSES CONTROLLED BY NUCLIDE CLASS I

▨ = PEAK DOSE CONTROLLED BY NUCLIDE CLASS III

Figure E-2 Histograms of Peak Population Dose Cases 1 and 2

a) Case 1

b) Case 2

KEY

- = PEAK DOSES CONTROLLED BY NUCLIDE CLASS I
- = PEAK DOSE CONTROLLED BY NUCLIDE CLASS III

Figure E-3 Histograms of Peak Flow Cases 1 and 2

KEY

- = PEAK DOSES CONTROLLED BY NUCLIDE CLASS I
- ▨ = PEAK DOSE CONTROLLED BY NUCLIDE CLASS III

Figure E-4 Histograms of Integrated Population Dose
Cases 1 and 2

a) Case 1

b) Case 2

KEY

- = PEAK DOSES CONTROLLED BY NUCLIDE CLASS I
- = PEAK DOSE CONTROLLED BY NUCLIDE CLASS III

Figure E-5 Histograms of Integrated Flow
Cases 1 and 2

TABLE E-1
CORRELATION OF PARAMETERS WITH PEAK OUTPUTS - CASES 1 AND 2

PARAMETER	AVERAGE RANK		MEASURE	PEAK 50-YR DOSE		PEAK POPULATION DOSE		PEAK FLOW	
	CASE 1	CASE 2		CASE 1	CASE 2	CASE 1	CASE 2	CASE 1	CASE 2
Permeability of the Aquifer	1	1	r_{AA} p	0.71 0.0001	0.62 0.0001	0.69 0.0001	0.68 0.0001	0.71 0.0001	0.60 0.0001
Fraction of Iodine	2	2	r p	0.37 0.0001	0.48 0.0001	0.39 0.0001	0.50 0.0001	0.37 0.0001	0.48 0.0001
Permeability of Upper Salt Layer	3	6.5	r p	0.32 0.0001	0.30 0.0001	0.31 0.0001	0.28 0.0001	0.33 0.0001	0.35 0.0001
Permeability of Lower Salt Layer	6	6.3	r p	0.30 0.0001	0.30 0.0001	0.30 0.0001	0.29 0.0001	0.32 0.0001	0.35 0.0001
Permeability of Upper Shale Layer	5	7.3	r p	0.26 0.0001	0.20 0.006	0.26 0.0007	0.19 0.007	0.26 0.0002	0.26 0.0006
Porosity of Upper Salt Layer	6	3	r p	0.20 0.005	0.30 0.0001	0.20 0.006	0.29 0.0001	0.22 0.001	0.36 0.0001
Saturation Conc. of Uranium	7.7	10	r p	0.18 0.01	0.20 0.005	0.19 0.008	0.20 0.004	0.11 0.10	0.13 0.07
Corrosion Time of the Canister	8.3	12.3	r p	0.13 0.07	-0.004 0.96	0.14 0.06	0.01 0.91	0.16 0.02	-0.03 0.67
Porosity in the Upper Shale Layer	9.3	12.3	r p	0.10 0.17	0.11 0.13	0.09 0.18	0.10 0.15	0.11 0.11	0.16 0.05
Dispersion in the Upper Salt Layer	12.3	9.7	r p	-0.01 0.93	-0.13 0.06	-0.006 0.93	-0.13 0.06	0.01 0.86	-0.16 0.02
Overall Head Drop	15.7	6.3	r p	-0.02 0.75	0.23 0.0001	-0.02 0.75	0.23 0.0008	0.004 0.96	0.24 0.0008

* Spearman's rank correlation coefficient

** Probability of Independents

TABLE E-2
CORRELATION OF PARAMETERS WITH INTEGRATED OUTPUTS - CASES 1 AND 2

PARAMETER	AVERAGE RANK		MEASURE	INTEGRATED POPULATION NOISE		INTEGRATED FLOW	
	CASE 1	CASE 2		CASE 1	CASE 2	CASE 1	CASE 2
Saturation Conc. of Uranium	1.5	1.5	r^{**} p^{**}	0.52 0.0001	0.60 0.0001	0.50 0.0001	0.55 0.0001
Permeability of the Aquifer	3.5	2.5	r p	0.47 0.0001	0.53 0.0001	0.27 0.0001	0.30 0.0001
Ejection of Iodine	4	3.5	r p	0.22 0.001	0.29 0.0001	0.52 0.0001	0.66 0.0001
Retardation Factor of Radium	5	5	r p	-0.47 0.0001	-0.69 0.0001	-0.14 0.05	-0.17 0.02
Retardation Factor of the Actinides	5.5	5.5	r p	-0.48 0.0001	-0.68 0.0005	-0.14 0.05	-0.17 0.02
Permeability of Upper Salt Layer	6	10	r p	0.18 0.013	0.06 0.66	0.23 0.001	0.16 0.02
Permeability of Lower Salt Layer	7	11	r p	0.14 0.05	0.05 0.66	0.21 0.003	0.16 0.02
Retardation Factor of Fission Products	7.5	6.5	r p	-0.46 0.0001	-0.68 0.0001	-0.14 0.06	-0.18 0.01
Porosity of Upper Salt Layer	8	2.5	r p	0.13 0.07	0.11 0.17	0.16 0.03	0.19 0.01
Permeability of Upper Shale Layer	10	10.5	r p	0.10 0.15	0.06 0.66	0.14 0.05	0.12 0.10
Overall Head Drop	13.5	8	r p	-0.06 0.61	0.13 0.07	0.07 0.10	0.17 0.02
Dispersion in the Aquifer	16.5	8.5	r p	0.10 0.18	0.17 0.01	0.03 0.71	0.09 0.22

r^{**} Spearman's rank correlation coefficient

p^{**} Probability of Independence

TABLE E-3
CORRELATION OF PARAMETERS WITH TIME OF PEAK OUTPUT
CASES 1 AND 2

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PARAMETER	AVERAGE RANK CASE 1	AVERAGE RANK CASE 2	MEASURE	TIME OF PEAK 50-YR DOSE CASE 1	TIME OF PEAK 50-YR DOSE CASE 2	TIME OF PEAK POPULATION DOSE CASE 1	TIME OF PEAK POPULATION DOSE CASE 2	TIME OF PEAK FLOW CASE 1	TIME OF PEAK FLOW CASE 2
Permeability of the Aquifer	1	1	r_{50} p	-0.10 0.0001	-0.59 0.0001	-0.70 0.0001	-0.55 0.0001	-0.91 0.0001	-0.80 0.0001
Permeability of the Upper Shale Layer	3.3	5.3	r p	-0.16 0.02	-0.23 0.0009	-0.36 0.02	-0.23 0.001	-0.16 0.21	-0.22 0.002
Saturation Conc. of Radium	3.3	9	r p	0.19 0.007	0.16 0.065	0.19 0.007	0.16 0.02	-0.10 0.17	-0.10 0.18
Permeability of the Upper Salt Layer	5	2.7	r p	-0.16 0.065	-0.33 0.0001	-0.16 0.06	-0.31 0.0007	-0.26 0.0002	-0.39 0.0001
Permeability of the Lower Salt Layer	6	3.3	r p	-0.16 0.066	-0.32 0.0001	-0.16 0.06	-0.31 0.0001	-0.27 0.001	-0.62 0.0001
Dispersion in the Aquifer	7.7	16.3	r p	-0.13 0.09	-0.01 0.86	-0.12 0.10	0.02 0.77	-0.16 0.02	0.11 0.16
Retardation Factor of the Fission Products	8.3	13.3	r p	-0.16 0.03	-0.05 0.51	-0.15 0.03	-0.07 0.30	-0.002 0.98	0.05 0.56
Retardation Factor of Radium	8.7	12.7	r p	-0.15 0.03	-0.07 0.42	-0.15 0.06	-0.10 0.15	0.01 0.91	0.01 0.71
Porosity of the Upper Salt Layer	9.3	3	r p	-0.10 0.15	-0.33 0.0001	-0.10 0.15	-0.33 0.0001	-0.15 0.03	-0.37 0.0001
Retardation Factor of the Actinides	9.7	16	r p	-0.16 0.06	-0.05 0.68	-0.16 0.06	-0.07 0.32	0.01 0.87	0.05 0.65
Coagulation Time of the Coagulant	10.3	5.7	r p	-0.12 0.10	0.21 0.001	-0.12 0.10	0.21 0.001	0.01 0.61	0.25 0.0003
Overall Head Drop	12.3	9.3	r p	0.02 0.80	-0.12 0.09	0.02 0.80	-0.09 0.19	0.06 0.55	-0.18 0.009
Dispersion in the Upper Salt Layer	16.7	8	r p	0.02 0.82	0.17 0.02	0.02 0.81	0.15 0.01	0.03 0.09	0.16 0.08

^{*} Spearman's rank correlation coefficient

^{**} Probability of Independence

APPENDIX F
ALTERNATE FORMS OF OUTPUTS FOR
SENSITIVITY AND UNCERTAINTY ANALYSES

This appendix contains information generated by TASC at the request of LLL. This information was not used in the body of the report. However, it is reported here in order to provide a computer record of TASC's contribution to the bedded salt analysis effort.

F.1 ALTERNATE FORM OF SENSITIVITY STUDY RESULTS

An alternate method of computing the change in curies due to 10%, range and modified range changes was suggested by LLL for the third and fourth scenarios. The "fractional" changes were computed as follows:

$$\text{Change in Output} = \frac{A - A_0}{\text{Minimum } (A, A_0)}$$

where

A = output for sensitivity case

A₀ = output for baseline case.

These changes in peak curies and integrated curies were also completed with a modification factor to take into account the wide variation in the amount of range changes. These "ratioed" changes were computed as:

$$\text{"Ratioed" Change in Outputs} = \frac{A - A_0}{\text{Minimum } (A, A_0)} \bigg/ \frac{I - I_0}{\text{Minimum } (I, I_0)}$$

where

A = output for sensitivity case

A_0 = output for baseline case

I = value for input parameter sensitivity case

I_0 = value for input parameter, baseline case

The alternate forms of Tables 5-4 through 5-7, 5-9 and 5-10 are given in Tables F-1 through F-6. The parameters have been listed in order of rank on absolute change in peak curies. This differs from the tables given in Chapter 5 which are given in the order of absolute change in integrated curies. There are only minor changes in rankings for Scenario 3. In Scenario 4 the permeability of the upper salt now ranks 3rd, 1st, and 2nd in its effect on peak curies in the three tables. (In Tables 5-7 to 5-10 it was 5th, 5th, and 7th respectively.) This is a case where an increase in the parameter causes decrease in the peak dose, here because it draws more water and waste away from the fast borehole pathway.

The points made in the concluding page of Chapter 5 are not altered by the different method of calculating the changes. The insensitivity of the integrated outputs is even more evident from Table F-5 where the peak output changes by a factor of 10^2 while the integrated output changes by a factor of 10^{-1} . The effect of the local hydrology upon the height of the nuclide pulse is discussed in Section 4.1.

TABLE F-1
FRACTIONAL CHANGES IN CURIES DUE TO 10% INCREASE IN
SELECTED PARAMETERS IN SCENARIO WITH UPSTREAM SHAFT
AND FRACTURED ROCK

RANK ON INTEGRATED CURIES	KEY ¹	VARIED PARAMETER	CHANGE IN CURIES							
			PEAK CURIES				INTEGRATED CURIES			
			ALL NOCLIDES	CLASS 1	CLASS 2	CLASS 3	ALL NOCLIDES	CLASS 1	CLASS 2	CLASS 3
1	D	Fraction of Iodine	0.100	0.100	<-0.001	0.0	0.091	0.096	<-0.001	0.0
	RU	Gradient of the Upper Aquifer	0.008	0.008	0.061	1.060	0.008	0.006	0.010	1.266
2	LI	Permeability of Lower Salt	0.076	0.076	0.280	0.281	0.072	0.077	0.280	0.280
11	RU	Permeability of Unfractured Shale	0.055	0.055	0.011	-0.155	<-0.001	<-0.001	0.001	-0.721
5	RU	Length of Upper Aquifer	-0.068	-0.068	-0.010	-1.062	-0.002	-0.006	-0.010	-2.286
6	RU	Porosity of Sandstone	-0.024	-0.024	-0.012	-0.566	-0.003	-0.003	-0.006	-0.520
9	LI	Porosity of Fractured Shale	0.002	<-0.001	<-0.001	<-0.001	<-0.001	<-0.001	<-0.001	<-0.001
12	LI	Porosity of Upper Salt	-0.005	0.005	<-0.001	<-0.001	<-0.001	<-0.001	<-0.001	<-0.001
7	LI	Permeability of Upper Salt	0.004	0.004	0.008	0.008	0.001	0.001	0.008	0.008
13	LI	Permeability of Fractured Shale	<-0.001	<-0.001	<-0.001	<-0.001	<-0.001	<-0.001	<-0.001	<-0.001
15	LI	Head of Lower Aquifer	<-0.001	<-0.001	<-0.001	<-0.001	<-0.001	<-0.001	<-0.001	<-0.001
3	D	Saturation Concentration of Uranium	<-0.001	<-0.001	0.072	0.100	0.009	0.003	0.100	0.100
10	RU	Fission Product Retardation	0.0	0.0	-0.053	0.0	<-0.001	<-0.001	-0.013	0.0
8	RU	Actinide Retardation	0.0	0.0	<-0.001	-1.171	<-0.001	<-0.001	<-0.001	-1.056

¹D = Discontinuity, LI = Local Bedrock, RU = Regional Bedrock

²Table entries less than 0.001 but greater than zero are listed as < 0.001

TABLE F-2

FRACTIONAL CHANGES IN CURIES DUE TO RANGE CHANGE IN SELECTED
PARAMETERS IN SCENARIO WITH UPSTREAM SHAFT
AND FRACTURED ROCK

F-1552

RANK OF INTEGRATED CURIES	KEY ¹	VARIED PARAMETER	CHANGE IN CURIES							
			PEAK CURIES				INTEGRATED CURIES			
			ALL SLOPES	CLASS 1	CLASS 2	CLASS 3	ALL SLOPES	CLASS 1	CLASS 2	CLASS 3
2	B	Fraction of Incline	1.000	1.000	<0.001	0.0	2.726	2.884	0.0	0.0
3	RR	Permeability of Fractured Shale	2.723	2.723	1.517	303.700	0.193	0.085	0.172	270.950
4	RR	Gradient of Upper Aquifer	1.825	1.825	2.290	57.238	0.151	0.103	1.427	158.903
6	RR	Length of Upper Aquifer	0.689	0.689	0.652	20.765	0.164	0.625	0.110	97.641
10	RR	Porosity of Sandstone	0.168	0.168	0.011	-12.467	-0.007	-0.006	-0.009	-26.896
7	LI	Permeability of Lower Salt	0.091	0.091	0.833	0.835	0.086	0.039	0.833	0.835
8	LI	Permeability of Upper Salt	0.063	0.063	0.163	0.164	0.020	0.012	0.163	0.164
11	LI	Porosity of Fractured Shale	0.059	0.059	<0.001	0.001	0.006	0.006	<0.001	0.001
12	LI	Porosity of Upper Salt	0.035	0.035	0.0	0.0	0.006	0.005	<0.001	0.001
1	B	Saturation Concen- tration of Uranium	0.038	0.038	33.038	92.965	3.615	3.027	8.259	95.085
13	LI	Permeability of Fractured Shale	<0.001	<0.001	0.001	0.001	<0.001	<0.001	0.001	0.001
14	LI	Head of Lower Aquifer	<0.001	<0.001	<0.001	0.001	<0.001	<0.001	0.001	0.001
5	RR	Attitude Retarda- tion	0.0	0.0	<0.001	55.382	0.221	0.0	0.0	197.210
9	RR	Fission Product Retardation	0.0	0.0	1.096	0.0	0.008	0.0	0.153	0.0

¹ B: Dissolution LI: Local Hydrology RR: Regional Hydrology

² Table entries less than 0.001 but greater than zero are listed as <0.001

TABLE F-3
RATIOED CHANGES IN CURIES DUE TO RANGE CHANGE IN SELECTED
PARAMETERS IN SCENARIO WITH UPSTREAM SHAFT
AND FRACTURED ROCK

RANK ON INTEGRATED CURIES	KEY*	VARIED PARAMETER	CHANGE IN CURIES							
			PEAK CURIES				INTEGRATED CURIES			
			ALL NUCLIDES	CLASS 1	CLASS 2	CLASS 3	ALL NUCLIDES	CLASS 1	CLASS 2	CLASS 3
1	RI	Permeability of Fractured Shale	1.255	1.255	0.653	199.956	0.381	0.079	0.079	124.862
2	RI	Gradient of Upper Aquifer	1.217	1.217	1.527	11.492	0.236	0.069	0.951	105.935
3	D	Fraction of Tailine	1.000	1.000	<0.001	0.0	0.908	0.961	0.0	0.0
4	RI	Length of Upper Aquifer	-0.258	-0.258	-0.169	-7.590	-0.062	-0.020	-0.051	-36.520
5	RI	Porosity of Sandstone	-0.019	-0.019	0.001	1.930	<0.001	<0.001	<0.001	1.000
10	RI	Porosity of Upper Salt	-0.004	-0.004	0.0	0.0	<0.001	<0.001	<0.001	0.0
8	LI	Permeability of Lower Salt	<0.001	<0.001	0.008	0.008	<0.001	<0.001	0.008	0.008
11	LI	Permeability of Upper Salt	<0.001	<0.001	0.002	0.002	<0.001	<0.001	0.002	0.002
12	LI	Porosity of Fractured Shale	<0.001	<0.001	0.0	0.0	<0.001	<0.001	<0.001	0.0
5	D	Saturation Concen- tration of Uranium	<0.001	<0.001	0.135	0.939	0.015	0.011	0.081	0.960
13	LI	Head of Lower Aquifer	<0.001	<0.001	<0.001	0.0	<0.001	<0.001	<0.001	0.0
14	LI	Permeability of Fractured Shale	<0.001	<0.001	<0.001	0.0	<0.001	<0.001	<0.001	0.0
7	RI	Fission Product Retardation	0.0	0.0	-0.122	0.0	<0.001	0.0	<0.122	0.0
6	RI	Actinide Retarda- tion	0.0	0.0	<0.001	-2.189	-0.012	0.0	<0.001	-10.129

*D: Dissolution LI: Local Hydrology RI: Regional Hydrology

*Table entries less than 0.001 but greater than zero are listed as <0.001

TABLE F-4
FRACTIONAL CHANGES IN CURIES DUE TO 10% INCREASE IN
SELECTED PARAMETERS IN SCENARIO WITH PERMEABLE SALT,
UPSTREAM SHAFT AND LARGE BOREHOLE OUTFLOW

1-1554

RANK ON INTEGRATED CURIES	KEY ^a	VARIABLE PARAMETER	CHANGE IN CURIES							
			PEAK CURIES				INTEGRATED CURIES			
			ALL BOREHOLES	CLASS 1	CLASS 2	CLASS 3	ALL BOREHOLES	CLASS 1	CLASS 2	CLASS 3
6	RR	Gradient of the Upper Aquifer	0.106	0.106	0.066	1.532	0.037	0.035	0.061	1.712
1	D	Fraction of Iodine	0.100	0.100	-0.001	0.0	0.032	0.036	0.0	0.0
8	LR	Permeability of Upper Salt	-0.098	-0.098	0.066	0.051	-0.026	-0.029	0.068	0.065
1	LR	Cross-Section of Borehole	0.098	0.098	0.002	0.029	0.062	0.066	0.010	0.015
2	LR	Permeability of Borehole	0.098	0.098	0.002	0.029	0.062	0.066	0.010	0.015
9	RR	Permeability of Shale	0.069	0.069	0.038	-0.158	0.026	0.026	0.018	-0.200
10	RR	Porosity of Sandstone	-0.030	-0.030	-0.003	-0.550	-0.002	-0.002	-0.004	-0.605
5	LR	Head of Lower Aquifer	<-0.001	<-0.001	0.085	0.153	0.060	0.058	0.107	0.167
11	D	Saturation Concen- tration of Uranium	<-0.001	<-0.001	0.020	0.100	0.007	0.007	0.090	0.100
7	LR	Permeability of Lower Salt	<-0.001	<-0.001	-0.061	-0.069	-0.022	-0.025	-0.051	-0.065
12	LR	Permeability of Tunnel Backfill	<-0.001	<-0.001	0.005	0.008	0.003	0.003	0.006	0.008
16	RR	Fission Product Retardation	0.0	0.0	-0.006	0.0	<-0.001	0.0	-0.010	0.0
13	RR	Actinide Retarda- tion	0.0	0.0	<-0.001	-1.656	<-0.001	0.0	0.0	-1.589
4	LR	Porosity of Upper Salt	0.0	0.0	-0.020	-0.167	-0.061	-0.059	-0.111	-0.158

^a D: Dissolution; LR: Local Hydrology; RR: Regional Hydrology

Table entries less than 0.001 but greater than zero are listed as <0.001

TABLE F-5

FRACTIONAL CHANGE IN CURIES DUE TO RANGE CHANGE IN SELECTED
PARAMETERS IN SCENARIO WITH PERMEABLE SALT,
UPSTREAM SHAFT AND LARGE BOREHOLE OUTFLOW

RANK ON INTEGRATED CURIES	KEY ¹	VARIABLE PARAMETER	CHANGE IN CURIES							
			PEAK CURIES				INTEGRATED CURIES			
			ALL BOREHOLES	CLASS 1	CLASS 2	CLASS 3	ALL BOREHOLES	CLASS 1	CLASS 2	CLASS 3
11	LH	Permeability of Upper Salt	-105.68	-105.67	0.876	1.087	0.172	0.082	1.086	1.86
4	LH	Permeability of Borehole	21.69	21.69	5.716	1.301	15.061	15.581	2.710	8.65
5	RH	Permeability of Shale	22.06	22.06	0.122	606.858	2.109	0.662	0.660	1825.28
5	D	Fraction of Iodine	1.00	1.00	0.0	0.0	2.266	2.086	0.0	0.0
9	LH	Cross-Section of Borehole	-1.96	1.96	-0.016	-0.267	-0.718	-0.166	-0.025	-0.11
8	RH	Gradient of the Upper Aquifer	1.58	1.58	0.689	157.679	0.718	0.501	0.500	367.24
15	RH	Porosity of Sandstone	0.23	0.23	-0.018	-31.015	-0.005	-0.003	-0.002	-61.92
1	D	Saturated Conduc- tivity of Uranium	0.01	0.01	67.664	98.073	5.166	2.918	56.620	98.35
6	RH	Attitude Retarda- tion	0.0	0.0	0.0	260.197	1.086	0.0	0.0	1203.28
7	LH	Porosity of Upper Salt	0.0	0.0	0.665	2.140	0.727	0.718	0.909	2.16
13	RH	Erosion Product Retardation	0.0	0.0	0.162	0.0	0.008	0.0	0.18	0.0
12	LH	Permeability of Dune Backfill	0.0	0.0	0.094	0.167	0.065	0.064	0.117	0.16
2	LH	Head of Lower Aquifer	0.0	0.0	6.772	22.561	6.526	6.360	10.360	25.85
10	LH	Permeability of Lower Salt	0.0	0.0	0.768	1.816	0.631	0.615	0.922	1.81

¹LH - Local Hydrology; RH - Regional Hydrology

²Table entries less than 0.001 but greater than zero are listed as 0.001

TABLE F-6
RATIOED CHANGE IN CURIES DUE TO RANGE CHANGE IN
SELECTED PARAMETERS IN SCENARIO WITH PERMEABLE
SALT, UPSTREAM SHAFT, AND LARGE BOREHOLE OUTFLOW

1-3556

RANK ON INTEGRATED CURIES	KEY ¹	VARIABLE PARAMETER	CHANGE IN CURIES							
			PEAK CURIES				INTEGRATED CURIES			
			ALL NUCLIDES	CLASS 1	CLASS 2	CLASS 3	ALL NUCLIDES	CLASS 1	CLASS 2	CLASS 3
1	RR	Permeability of Shale	10,159	10,159	0.149	186,566	0.922	0.211	0.216	841,141
11	LR	Permeability of Upper Salt	-1.067	-1.067	0.008	0.019	0.001	0.001	0.010	0.019
6	RR	Gradient of the Upper Aquifer	1,050	1,050	0.126	185,119	0.479	0.268	0.311	231,689
2	D	Fraction of Iodine	1,000	1,000	0.0	0.0	0.921	0.962	0.0	0.0
6	LR	Concentration of Borehole	0.980	0.980	0.007	0.126	0.159	0.182	0.018	-0.155
7	LR	Permeability of Borehole	0.486	0.486	0.117	0.149	0.307	0.318	0.055	0.177
14	RR	Porosity of Sandstone	-0.026	-0.016	0.002	3.466	<0.001	<0.001	<0.001	4.658
9	D	Saturation Concentration of Bismuth	<0.001	<0.001	0.431	0.991	0.052	0.030	0.550	0.993
8	RR	Actinide Retardation	0.0	0.0	0.0	-13,695	-0.057	0.0	0.0	-61,111
12	RR	Fission Product Retardation	0.0	0.0	-0.016	0.0	<0.001	0.0	-0.02	0.0
13	LR	Permeability of Tunnel Backfill	0.0	0.0	<0.001	0.002	<0.001	<0.001	<0.001	0.002
3	LR	Porosity of Upper Salt	0.0	0.0	-0.665	-2,160	-0.227	-0.218	-0.909	-2,166
10	LR	Permeability of Lower Salt	0.0	0.0	0.008	0.018	0.006	0.006	0.010	0.018
5	LR	Head of Lower Aquifer	0.0	0.0	0.631	1.437	1.616	0.406	0.659	1.667

¹D: Dissolution LR: Local Hydrology RR: Regional Hydrology

²Table entries less than 0.001 but greater than zero are listed as <0.001

F.2 SUBPOPULATIONS FROM UNCERTAINTY ANALYSIS

The outputs from Case 1 in the uncertainty analysis were divided into two sets according to whether or not the Class III nuclides controlled the peak 50-yr individual dose. This was ascertained by whether or not the time of peak total curies coincided with the time of peak 50-yr individual dose. The statistics and correlation analyses for each subset of computer use were generated and included in this appendix as Tables F-7 through F-10 at the request of LLL.

Repository performance, however, reflects the dose or curie output from all nuclide groups, i.e., it is a mixed distribution. As such, the spread seen in the various measures of repository performance are taken by TASC to be an accurate reflection of the uncertainty in that performance given the specified waste migration scenario, the methods used to model this scenario and the uncertainties of the input parameters.

In addition, there are several possible methods of stratification and there is no overwhelming reason to choose one method over another. Another possible method would have been to separate the sets according to whether the time of peak curies coincided with peak population dose. For Case 1, this subset is the same as the one selected. This method would create different subsets for Case 2. Neither method, however, identifies those computer runs where the actinides contribute substantially to the integrated doses, but where the actinide peak does not surpass the Class I peak. The method of stratification will strongly affect what is seen in the correlation analysis. For these reasons, no discussion of the subsets is included in the text of the uncertainty analysis.

TABLE F-7
SUMMARY STATISTICS OF SUBSETS OF
UNCERTAINTY ANALYSIS - CASE 1

T-3557

VARIABLE	BASELINE VALUE	SUBSET	MEAN	STANDARD DEVIATION	MEDIAN	INTERQUARTILE SPREAD
Peak 50-yr Dose (rem)	5.9×10^{-2}	ACT.	7.0×10^{-1}	1.4×10^1	9.7×10^{-2}	3.0×10^{-1}
		NON-ACT.	6.2×10^{-2}	1.1×10^{-1}	2.2×10^{-2}	2.4×10^{-2}
Time of Peak 50-yr Dose (yr)	5.9×10^3	ACT.	1.2×10^6	1.2×10^6	6.2×10^5	8.4×10^6
		NON-ACT.	2.3×10^4	3.5×10^4	1.1×10^4	9.8×10^3
Peak Population Dose (man-rem/yr)	2.3×10^4	ACT.	2.9×10^5	5.7×10^5	3.9×10^4	1.0×10^5
		NON-ACT.	2.3×10^4	4.1×10^4	8.6×10^3	8.8×10^3
Time of Peak Population Dose (yr)	5.9×10^3	ACT.	1.2×10^6	1.2×10^6	6.2×10^5	7.8×10^5
		NON-ACT.	2.3×10^4	3.5×10^4	1.1×10^4	9.8×10^4
Integrated Population Dose (man-rem)	2.1×10^8	ACT.	1.1×10^{11}	9.6×10^{10}	6.8×10^{10}	8.8×10^{10}
		NON-ACT.	3.8×10^9	1.3×10^9	2.2×10^8	4.0×10^8
Peak Flow Rate (Ci/yr)	2.9×10^1	ACT.	4.6×10^1	1.0×10^2	1.9×10^1	1.7×10^1
		NON-ACT.	3.4×10^1	6.6×10^1	1.1×10^1	1.2×10^1
Time of Peak Flow Rate (yr)	5.9×10^3	ACT.	2.7×10^4	6.0×10^4	4.2×10^3	4.2×10^3
		NON-ACT.	2.3×10^4	3.4×10^4	1.1×10^4	9.9×10^3
Integrated Flow (Ci)	1.1×10^5	ACT.	1.0×10^6	8.4×10^5	5.7×10^5	6.0×10^5
		NON-ACT.	1.7×10^5	1.5×10^5	1.8×10^5	7.6×10^4

TABLE F-8
CORRELATION OF PARAMETERS WITH PEAK OUTPUTS -
ACTINIDE AND NON-ACTINIDE CONTROLLED
SUBSETS OF CASE 1

7-3558

SUBSET	PARAMETER	MEASURE	PEAK 50-YR DOSE	PEAK POPULATION DOSE	PEAK CURIES
Actinide Controlled	Saturation Conc. of Uranium	r_{**} p	0.92 0.0001	0.92 0.0001	0.69 0.0001
	Permeability of the Aquifer	r p	0.90 0.0001	0.90 0.0001	0.64 0.004
Non-Actinide Controlled	Permeability of the Aquifer	r p	0.69 0.0001	0.68 0.0001	0.71 0.0001
	Fraction of Iodine	r p	0.44 0.0001	0.46 0.0001	0.42 0.0001
	Permeability of the Lower Salt Layer	r p	0.31 0.0001	0.30 0.0001	0.31 0.0001
	Permeability of the Upper Salt Layer	r p	0.30 0.0001	0.30 0.0001	0.30 0.0001
	Permeability of the Upper Shale Layer	r p	0.29 0.0001	0.29 0.0001	0.28 0.0002
	Corrosion Time of the Canister	r p	0.23 0.002	0.23 0.001	0.21 0.004
	Porosity of the Upper Salt Layer	r p	0.20 0.006	0.20 0.007	0.20 0.006

* Spearman's rank correlation coefficient

** Probability of independence

TABLE F-9

CORRELATION OF PARAMETERS WITH TIME OF PEAK OUTPUTS -
ACTINIDE AND NON-ACTINIDE CONTROLLED SUBSETS OF CASE 1

T-3559

SUBSET	PARAMETER	MEASURE	TIME OF PEAK 50-YR DOSE	TIME OF PEAK POPULATION DOSE	TIME OF PEAK CURIES
Actinide Controlled	Corrosion Time of Canister	r*	-0.51	-0.51	0.40
		p	0.03	0.03	0.10
	Permeability of the Aquifer	r	-0.25	-0.25	-0.72
		p	0.32	0.31	0.0008
	Saturation Conc. of Uranium	r	-0.14	-0.14	-0.64
		p	0.57	0.58	0.004
Non-Actinide	Permeability of the Aquifer	r	-0.92	-0.92	-0.93
		p	0.0001	0.0001	0.0001
	Permeability of the Upper Salt Layer	r	-0.23	-0.23	-0.23
		p	0.002	0.002	0.002
	Permeability of the Lower Salt Layer	r	-0.21	-0.21	-0.21
		p	0.005	0.004	0.005
	Permeability of the Upper Shale Layer	r	-0.17	-0.18	-0.17
		p	0.02	0.02	0.02
	Dispersion in the Aquifer	r	-0.17	-0.17	-0.18
		p	0.02	0.02	0.02

*Spearman's rank correlation coefficient

**probability of independence

TABLE F-10
CORRELATION OF PARAMETERS WITH INTEGRATED OUTPUTS -
ACTINIDE AND NON-ACTINIDE CONTROLLED SUBSETS
OF CASE 1

T-3560

SUBSET	PARAMETER	MEASURE	INTEGRATED POPULATION DOSE	INTEGRATED PEAK CURIES
Actinide Controlled	Saturation Conc. of Uranium	[*] ^{**} p	0.85 0.0001	0.83 0.0001
	Permeability of the Aquifer	r p	0.87 0.0001	0.79 0.0001
Non-Actinide	Permeability of the Aquifer	r p	0.44 0.0001	0.20 0.007
	Retardation Factor of the Actinides	r p	-0.42 0.0001	-0.01 0.84
	Saturation Conc. of Uranium	r p	0.42 0.0001	0.40 0.0001
	Retardation Factor of Radium	r p	-0.41 0.0001	-0.02 0.82
	Retardation Factor of the Fission Products	r p	-0.40 0.0001	-0.02 0.76
	Fraction of the Iodine	r p	0.24 0.0002	0.78 0.0001
	Permeability of the Lower Salt Layer	r p	0.11 0.15	-0.19 0.01
	Permeability of the Upper Salt Layer	r p	0.12 0.10	0.18 0.01
	Permeability of the Upper Shale Layer	r p	0.12 0.11	0.17 0.03
	Porosity of the Upper Salt Layer	r p	0.12 0.10	0.15 0.04

* Spearman's rank correlation coefficient

** probability of independence