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SUPPLEMENTARY ANALYSIS OF
NUCLEAR WASTE MANAGEMENT OPTIONS

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FOREWORD

This is a revised version of a report originally submitted on 17 March 1978. The work reported here was conducted between December 1977 and February 1978 as part of a continuing program of systematic analysis of nuclear waste management. The work was performed by the authors and Lawrence E. Berman, with computer programming assistance from Mark R. Schultz, Stephen P. Hodgin, and Gary P. Bogar.

ABSTRACT

This report describes studies pertaining to long-term risks from the disposal of high-level nuclear waste in deep mined cavities. The results presented supplement previously reported work. Previously studied scenarios are examined in greater depth, and the analysis is extended to deal with alternative fuel cycles.

TABLE OF CONTENTS

	<u>Page No.</u>
FOREWORD	ii
ABSTRACT	iii
List of Figures	v
List of Tables	vii
 1. INTRODUCTION	 1-1
2. MATHEMATICAL MODELS	2-1
2.1 An Approximate Method of Risk Calculation	2-1
2.2 Resaturation Time of Depository	2-4
2.3 Aggregation of Doses to Organs	2-7
2.3.1 Introduction	2-7
2.3.2 Equivalent Risk Model	2-7
3. WASTE CHARACTERISTICS	3-1
3.1 Radionuclide Inventories	3-1
3.2 Gas Content of Wastes	3-5
4. SENSITIVITY ANALYSIS	4-1
5. UNCERTAINTY ANALYSIS	5-1
5.1 Introduction	5-1
5.2 Refinements of Model Constraints	5-1
5.3 Monte Carlo Analysis	5-2
5.4 Conclusions	5-6
6. SUMMARY	6-1
 APPENDIX A RADIONUCLIDE INVENTORIES AND DOSES	 A-1
APPENDIX B GENERIC RANGE CONSTRAINTS USED IN UNCERTAINTY ANALYSIS	B-1
 REFERENCES	 R-1

LIST OF FIGURES

<u>Figure No.</u>		<u>Page No.</u>
2.1-1	The Whole-Body-Equivalent Population Dose Per MWe-yr of Waste Entering the Surface Water System Assuming Pu-Storage Fuel Cycle	2-3
2.1-2	The 50 Year Whole-Body-Equivalent Dose to an Individual Eating an Average Diet Per MWe-yr of Waste Entering the Surface Water System Per Year Assuming Pu-Storage Fuel Cycle	2-3
2.2-1	Features Appearing in Calculation of Resaturation Time	2-5
3.1-1	The Potential Hazard of HLW From the Pu-Storage Fuel Cycle Measured as a 50 Year Whole-Body-Equivalent Dose to an Individual Eating an Average Diet	3-2
3.1-2	The Potential Hazard of HLW From the Pu-Storage Fuel Cycle Measured as a Whole-Body-Equivalent Population Dose	3-2
3.1-3	The Potential Hazard of Spent Fuel Measured as a 50 Year Whole-Body-Equivalent Dose to an Individual Eating an Average Diet	3-3
3.1-4	The Potential Hazard of Spent Fuel Measured as a Whole-Body-Equivalent Population Dose	3-3
3.1-5	The Potential Hazard of HLW From the Pu-Throw-away Fuel Cycle Measured as a 50 Year Whole-Body-Equivalent Dose to an Individual Eating an Average Diet	3-4
3.1-6	The Potential Hazard of HLW From the Pu-Throw-away Fuel Cycle Measured as a Whole-Body-Equivalent Population Dose	3-4
4-1	Time of Arrival of Dose Peak at River (T_{peak}) as a Function of Time to Travel a Dispersion Length (T)	4-5
4-2	Peak Individual Dose as a Function of Time to Travel a Dispersion Length (T)	4-5

LIST OF FIGURES (Continued)

<u>Figure No.</u>		<u>Page No.</u>
4-3	Time of Arrival of Dose Peak at River (T_{peak}) as a Function of Dimensionless Aquifer Length ($\bar{Z}$)	4-6
4-4	Peak Individual Dose as a Function of Dimensionless Aquifer Length ($\bar{Z}$)	4-6
4-5	Individual Dose as a Function of Time for Time to Travel a Dispersion Length Equal to 3.2×10 Years	4-9
4-6	Individual Dose as a Function of Time for Time to Travel a Dispersion Length Equal to 320 Years	4-10
4-7	Individual Dose as a Function of Time for Time to Travel a Dispersion Length Equal to 32 Years	4-10
4-8	Individual Dose as a Function of Time for Time to Travel a Dispersion Length Equal to 3.2 Years	4-11
4-9	Individual Dose as a Function of Time for Time to Travel a Dispersion Length Equal to 0.32 Years	4-11
5.3-1	Normalized Histograms of Peak Individual Dose on a Logarithmic Scale for GI-LLI (rem/MWe-yr)	5-5
5.3-2	Normalized Histograms of Integrated Population Dose on a Logarithmic Scale for GI-LLI (man-rem/MWe-yr)	5-6

LIST OF TABLES

<u>Table No.</u>		<u>Page No.</u>
2.3-1	Cancer Risk Factors	2-8
2.3-2	Risk Coefficients for Latent Cancer Fatalities	2-9
3.2-1	Principal Gases in Spent Fuel at 10 Years	3-6
3.2-2	Gases in Spent Fuel as a Function of Time	3-6
5.3-1	Peak Aquifer Concentrations From Fifty Monte Carlo Trials (Ci/m^3)	5-3
5.3-2	Sample Dose Statistics From Fifty Monte Carlo Trials	5-5

1.

INTRODUCTION

The possible release of radioactivity from a deep mined repository is a major public concern relating to radioactive waste management. TASC is engaged in analyzing such possible releases for Lawrence Livermore Laboratory, as part of a program being conducted for the U.S. Nuclear Regulatory Commission.

As part of this work, TASC has developed models to calculate the consequences of such releases and has used these models to calculate potential doses to humans from repositories in a considerable number of scenarios. This work was conducted between October 1976 and November 1977 and is described in a previous report (Ref. 1), entitled "Analysis of Some Nuclear Waste Management Options" (UCRL-13917).

The present report describes additional work in the same area conducted between December 1977 and February 1978. This work involves model improvement and additional model exercise. The topics covered include:

- An approximate method of calculating the release of radioactivity from a repository
- Resaturation of the depository cavity
- Aggregation of doses to different organs into a single index of harm
- Radionuclide inventories in wastes from different fuel cycles

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- Additional sensitivity and uncertainty analysis of the previous results.

This report should be read as a supplement to Ref. 1.

2.

MATHEMATICAL MODELS

2.1 AN APPROXIMATE METHOD OF CALCULATING CONSEQUENCES OF
RELEASES FROM A REPOSITORY

An essential element in analyses of repository performance is the calculation of radionuclide transport to the biosphere. This transport will depend on the status of the geologic formations and engineered structures of the repository. Together with a model of biosphere transport and human dose mechanisms, a model of subsurface transport makes possible assessment of the doses to humans in any given scenario.

Complete analysis of a repository requires analysis of a large number of possible circumstances. In order to reduce the number of scenarios requiring detailed analysis, it is useful to have an approximate method of calculating nuclide transport and doses. Scenarios which clearly do not contribute to overall risk can be identified by approximate calculations and excluded from further calculations.

This section presents such an approximate method of consequence calculation. No derivation is given; however, the equations used follow directly from the results given in Appendix J of Ref. 1.

For each path segment and each class of nuclides, one may define a flow time, T_f , and a dispersion time, T_D , by

$$T_f = \frac{zB}{V} \quad (2.1-1)$$

and

$$T_D = \frac{2B}{V} \sqrt{\sigma z} \quad (2.1-2)$$

where z is the length of the path segment, V is the water velocity, B is the retardation factor for the nuclide class, and σ is the dispersion constant. If the Green's function for the shape of a pulse of waste is thought of as a probability density function for the location of a single particle, the dispersion time corresponds to the variance multiplied by $\sqrt{2}$.

For a flow network consisting of flow paths in series, the total flow time and dispersion time will be given by

$$T_f^{\text{tot}} = T_{\text{fill}} + \sum_p T_f^p \quad (2.1-3)$$

$$T_D^{\text{tot}} = \sqrt{T_s^2 + \sum_p (T_D^p)^2} \quad (2.1-4)$$

where p is an index denoting flow paths, T_{fill} is the resaturation time of the depository cavity, and T_s is the dissolution time of the waste.

The population dose and dose to an average individual per unit of waste released can be calculated by the method described in Appendix G of Ref. 1 and are designated $P_j(t)$ and $I_j(t)$, respectively. The index j denotes the different classes of nuclides, as distinguished by their retardation factors. Figures 2.1-1 and 2.1-2 show these two functions measured as the whole-body-equivalent dose defined below in Section 2.3. The approximate values of integrated population dose and dose to an average individual are then

Figure 2.1-1 The Whole-Body-Equivalent Population Dose Per MWe-yr of Waste Entering the Surface Water System Assuming Pu-Storage Fuel Cycle

Figure 2.1-2 The 50 Year Whole-Body-Equivalent Dose to an Individual Eating an Average Diet per MWe-yr of Waste Entering the Surface Water System per Year Assuming Pu-Storage Fuel Cycle

$$IPD = \sum_j P_j (T_{fj}^{tot}) \quad (2.1-5)$$

$$AID = \frac{1}{\sqrt{\pi}} \sup \left[\frac{1}{T_{Dj}^{tot}} I_j (T_{fj}^{tot}) \right] \quad (2.1-6)$$

Figures 2.1-1 and 2.1-2 show whole-body-equivalent doses for high-level waste from the plutonium storage fuel cycle as a function of time since removal from reactor; similar curves are available for the whole body and individual organs and for wastes from other fuel cycles. A number of plots for other fuel cycles are given in Section 2.2.1.

When parallel paths exist, the P_j and I_j must be weighted by a_i , the proportion of water which flows through path i :

$$IPD = \sum_i \sum_j a_i P_j (T_{fij}^{tot}) \quad (2.1-7)$$

$$AID = \frac{1}{\sqrt{\pi}} \sup \left[\frac{a_i}{T_{Dij}^{tot}} I_j (T_{fij}^{tot}) \right] \quad (2.1-8)$$

When two or more values of T_{Dij}^{tot} are identical, the appropriate terms should be summed in the calculation of individual dose.

The resulting values are estimates of the doses to individuals and the population. They may be used for preliminary studies, to check the reliability of computer calculations, or perhaps as a part of the licensing procedure. This calculation will be quite accurate when the functions P_j and I_j are slowly varying. It will be least accurate when the fission products are released to the biosphere during the period from 100 yr to 700 yr during which ^{137}Cs and ^{90}Sr are decaying rapidly.

2.2 RESATURATION TIME OF DEPOSITORY

In the analysis to date, the value of the depository resaturation time has simply been assumed to take a baseline value of 100 yr. In conjunction with Golder Associates a method has been developed for relating resaturation time to the existence of permeable pathways between the depository and the adjacent aquifers. The physical situation envisaged in this calculation is shown in Fig. 2.2-1.

From Ref. 2, Section 3.2.1.6, the resaturation time is given by

$$T_{\text{fill}} = \frac{A}{Q_0} (\text{Len} + 2DS_g H) \quad (2.2-1)$$

Figure 2.2-1 Features Appearing in Calculation of Resaturation Time

where

Q_0 is the initial inflow to the mine

A is the area of the mine

L is the height of rooms

e is the extraction ratio, or ratio of the floor area of the storage rooms and corridors to the total area occupied by the depository

n is the porosity of backfill

D is the distance to the aquifer

S_s is the specific storage of the rock mass (change in water content of the rock per unit change in water pressure)

H is the difference in the water pressure in the mine before and after resaturation (head change).

Q_0 is the sum of the inflow from above, Q_a , and the inflow from below, Q_b . By Darcy's Law, these inflows can be related to the post-resaturation flow through the mine, Q_s , by

$$\frac{Q_s}{H_s} = \frac{Q_a}{H_a} \quad (2.2-2)$$

$$\frac{Q_s}{H_b - H_a - H_s} = \frac{Q_b}{H_b} \quad (2.2-3)$$

where

H_a is the height from the depository to the piezometric level of the overlying aquifer

H_b is the height from the depository to the piezometric level of the underlying aquifer

H_s is the head difference between the depository and the overlying aquifer in the post-resaturation steady state.

Substituting into Eq. 2.2-1, and using the relation $H = H_a + H_s$, we obtain

$$T_{fill} = \frac{A}{Q_s} \left[\frac{Len + 2DS_s(H_a + H_s)}{\frac{H_a}{H_s} + \frac{H_b}{H_b - H_a - H_s}} \right] \quad (2.2-4)$$

2.3 AGGREGATION OF DOSES TO ORGANS

2.3.1 Introduction

The ultimate consequences of a release of radioactivity involve potential doses to all the organs of the body. Organs differ in their susceptibility to cancer induction by radioactivity. In previous work (Ref. 1), the dose to each of the more significant organs was calculated individually. A single number representing the total hazard resulting from an exposure would be a more convenient measure of consequences.

The index presented here is a measure of the likelihood of cancer induction by any exposure. It is called a whole-body-equivalent dose because any exposure of the various organs resulting in a whole-body-equivalent dose of x has the same chance of inducing cancer as a uniform irradiation of the whole body with a dose of x . The whole-body-equivalent dose is calculated by summing the doses to each individual organ weighted by the cancer risk. The method follows from Ref. 3.*

*Use of the method was suggested by letter from Y. Ng, Lawrence Livermore Laboratory, to C.M. Koplik, 26 May 1977.

Whole-body-equivalent doses may be calculated for both pre- and post-emplacment releases. They are not, however, appropriate as a measure of the hazard of exposures which are large enough to cause radiation sickness or other non-stochastic damage. They also fail to reflect the hazard of mutations, which are due exclusively to doses to the gonads.

2.3.2 Equivalent Risk Model

The following equation is used to calculate net equivalent dose factors:

$$DF50(r,p,0) = \sum_{u=1}^8 DF50(r,p,u)R(u) \quad (2.3-1)$$

where

DF50(r,p,u) is the fifty-year dose factor for chronic exposure to organ u from nuclide r via pathway p

DF50(r,p,0) is the net fifth-year dose equivalent factor for chronic exposure from nuclide r via pathway p

R(u) is the cancer risk factor for organ u.

The four pathways which could be considered are ingestion, inhalation, immersion, and external exposure. The organs considered and the corresponding cancer risk factors are given in Table 2.3-1.

The risk factors are based on cancer risk coefficients given in Ref. 4 and reproduced in Table 2.3-2. The total risk to an adult is the sum over all cancers and amounts

TABLE 2.3-1
CANCER RISK FACTORS

T-1995

u	ORGAN	R(u)
1	WHOLE BODY	0.451
2	GI-LLI	0.158
3	THYROID	0.034
4	BONE	0.034
5	LIVER	0.014
6	LUNG	0.223
7	KIDNEY	0.086
8	SKIN	0.0

TABLE 2.3-2
RISK COEFFICIENTS FOR LATENT CANCER FATALITIES
(SOURCE: Ref. 4)

T-1996

TYPE OF CANCER	AGE AT TIME OF IRRADIATION	LATENT PERIOD (YEARS)	LATENT PERIOD (YEARS)	RISK COEFFICIENT $\times 10^{-6}$ (DEATHS/YR-REM)
Leukemia	<u>In utero</u>	0	10	25
	0-9.5	2	25	2
	10+	2	25	1
Lung	10+	15	30 ^(a)	1.3
Gastrointestinal tract, including stomach	10+	15	30 ^(a)	1.0
Breast	10+	15	30 ^(a)	1.5 ^(b)
Bone	10+	15	30 ^(a)	0.2
All other ^(c)	<u>In utero</u>	0	10	25 ^(d)
	0-9.9	15	30 ^(a)	2 ^(d)
	10+	15	30 ^(a)	1 ^(e)

(a) Remaining life expectancy stated as an alternative plateau period.

(b) Includes males and an assumed 50% cure rate.

(c) Includes thyroid and skin.

(d) "All other" denotes all cancers except leukemia.

(e) "All other" denotes all cancers except those specified in table.

to 5.83×10^{-6} deaths/yr-rem.* The risk factors in Table 2.3-1 were calculated by normalizing the risk coefficients to an adult given in Table 2.3-2 by the total risk.

A number of difficulties arose because risk coefficients are not available for all the organs for which TASC computes doses. Furthermore, several cancers for which risk coefficients are available, notably leukemia, do not have computed dose coefficients.† These problems were addressed in the following way. Risk coefficients for the thyroid and liver based upon data presented in Ref. 4 were found given in Refs. 5 and 6, respectively. The values given were 0.2×10^{-6} deaths/yr-rem for the thyroid assuming a 95% cure rate and 0.08×10^{-6} deaths/yr-rem for the liver. Since the cancer risk ascribed to the liver is included in Table 2.3-2 in the risk to the GI-LLI, the value given for the GI-LLI was reduced to 0.92×10^{-6} deaths/yr-rem. A cancer risk for the kidney of 0.5×10^{-6} deaths/yr-rem was based upon an estimate given in Ref. 3 and the cancer risk for the skin was assumed to be negligible based upon Ref. 5.

The risks in Table 2.3-2 ascribed to leukemia and breast cancer were then aggregated into the classification "all other". This represents the residual cancer risk to the whole body and amounts to 2.63×10^{-6} deaths/yr-rem. Since dose factors were not available for these cancers they were multiplied by the whole-body dose factor in the calculation of net dose equivalent. This is a conservative assumption for

*The cancer risk to an adult for leukemia was weighted by 5/6 to reflect its shorter plateau period.

†It should be mentioned that a study of health effects would include cancer incidence and genetic effects as well as cancer fatalities.

most dose calculations since for the ingestion and inhalation pathways there is little exposure to the breast.

The result of this procedure is to provide a reasonable and convenient measure of the hazard to an individual or to a population.

3. WASTE CHARACTERISTICS

3.1 RADIONUCLIDE INVENTORIES

The radionuclide content of high-level waste has been recalculated using the ORIGEN code in order to make possible greater accuracy and flexibility than can be obtained by the use of published tables like those used in the calculations of Ref. 1. The same reactor parameters were assumed as in Ref. 1. The nuclides ^{135}Cs , ^{59}Ni , and ^{225}Ra were incorporated into the calculations, and smaller time steps were used to reduce interpolation errors. The three nuclides had previously been excluded because consideration had been limited to a list of prescribed nuclides (Ref. 1, Appendix H). The potential hazard of high-level waste, in terms of the whole-body-equivalent population dose and dose to a single individual eating an average diet over fifty years, is illustrated in Figs. 3.1-1 and 3.1-2 as a function of time after removal from the reactor. These figures refer to waste from enriched uranium fuel from which uranium and plutonium have been removed by reprocessing, or the so-called plutonium-storage fuel cycle. The potential hazards for spent fuel from a once-through fuel cycle burning enriched uranium are presented in Figs. 3.1-3 and 3.1-4. Those from high-level waste from the plutonium-throwaway fuel cycle, in which fuel is reprocessed and uranium is removed but plutonium is left in the waste, are presented in Figs. 3.1-5 and 3.1-6. The radionuclide inventories in these wastes are listed in Appendix A, along with the doses per unit release of each nuclide as calculated by the BIDOSE code.

Figure 3.1-1 The Potential Hazard of HLW From the Pu-Storage Fuel Cycle Measured as a 50 Year Whole-Body-Equivalent Dose to an Individual Eating an Average Diet

Figure 3.1-2 The Potential Hazard of HLW From the Pu-Storage Fuel Cycle Measured as a Whole-Body-Equivalent Population Dose

Figure 3.1-3 The Potential Hazard of Spent Fuel Measured as a 50 Year Whole-Body-Equivalent Dose to an Individual Eating an Average Diet

Figure 3.1-4 The Potential Hazard of Spent Fuel Measured as a Whole-Body-Equivalent Population Dose

Figure 3.1-5 The Potential Hazard of HLW From the Pu-Throwaway Fuel Cycle Measured as a 50 Year Whole-Body-Equivalent Dose to an Individual Eating an Average Diet

Figure 3.1-6 The Potential Hazard of HLW From the Pu-Throwaway Fuel Cycle Measured as a Whole-Body-Equivalent Population Dose

The differences between the curves for the different wastes are due primarily to the removal of uranium, plutonium, and iodine in the reprocessing plant. In all three cases, the curve for actinides and their daughters has a peak at about 200,000 years due to ^{226}Ra formed by decay of ^{238}Pu . In the plutonium-storage fuel cycle, this ^{238}Pu is primarily formed by decay of ^{242}Cm which is not removed by reprocessing. If spent fuel were aged for a few years to allow the ^{242}Cm to decay (its half-life is $5\frac{1}{2}$ months) instead of being reprocessed after 150 days as assumed in these calculations, the radium peak for this fuel cycle would disappear. In the other two fuel cycles, all ^{238}Pu enters the waste stream, and the radium peak is considerably higher and insensitive to reprocessing time.

The iodine-technetium curve dies off rapidly with the decay of ^{99}Tc for both reprocessing wastes. Spent fuel, however, contains much more of the longer-lived ^{129}I , and the curve is therefore affected much less by the technetium decay.

3.2 GAS CONTENT OF WASTES

Gases in a repository might be of concern because of the potential for escape of radioactivity in gaseous form or for escape of contaminated water due to gas pressure. Tables 3.2-1 and 3.2-2 give the gas content of spent fuel. Both radioactive and non-radioactive isotopes are included. These results were calculated using the ORIGEN code.

If fuel is reprocessed, then carbon-14 becomes a new gaseous waste, largely in the form of carbon dioxide. About 4.4×10^{-3} gm/MWe-yr and 2.0×10^{-2} Ci/MWe-yr are produced (Ref. 7). Carbon-14 has a half-life of 5.7×10^3 years.

TABLE 3.2-1
PRINCIPAL GASES IN SPENT FUEL AT 10 YEARS

T-1993a

ELEMENT AND RADIOISOTOPES	HALF-LIFE (yr)	gm/MWe-yr	Ci/MWe-yr
Rn(220,222)	1.8×10^{-6} 0.01	5.94×10^{-13}	5.0×10^{-4}
Kr(85)	10.7	1.13×10^1	1.86×10^2
Xe(131m,133)	0.03 0.01	1.7×10^2	0
I(129,131)	1.7×10^7 0.02	8.43	1.17×10^{-3}
H(3)	12.3	1.3×10^{-3}	1.26×10^1
He	stable	2.82×10^{-2}	0

TABLE 3.2-2
GASES IN SPENT FUEL AS A FUNCTION OF TIME
(gm/MWe-yr)

ELEMENT	100 YR	500 YR	5×10^6 YR
^{222}Rn	3.83×10^{-12}	1.25×10^{-10}	6.38×10^{-8}
Kr	1.08×10^1	1.08×10^1	1.08×10^1
Xe	1.70×10^2	1.70×10^2	1.71×10^2
I	8.43	8.43	7.11
^3H	8.17×10^{-6}	1.33×10^{-15}	--
He	1.62×10^{-1}	5.11×10^{-1}	1.4×10^1

The principal volatiles in spent fuel and HLW are Cs, Te, Ru, and Rh.

The quantity of ^{222}Rn gas peaks at about 200,000 years. The peak content is 3.57×10^{-2} Ci/MWe-yr for spent fuel and 8.28×10^{-4} Ci/MWe-yr for high-level waste from the Pu-storage fuel cycle.

4.

SENSITIVITY ANALYSIS

In assessing the variability of doses and concentrations as a function of the various geohydrologic parameters, sensitivity studies to date have concentrated on changing specific physical parameters, such as permeabilities, retardation factors, etc. In many instances, scaling one parameter is entirely equivalent to scaling a different parameter (e.g., head change and retardation factor in the aquifer) and therefore sensitivity analysis could be considerably consolidated if the full set of such "lumped scaling parameters" was elucidated.

Since doses are linearly related to the concentrations, it is only necessary to study the latter quantities. Within the context of the stream tube models used in Ref. 1, the concentrations as a function of position and time are completely determined by leaching behavior of the canisters, the time constants for geologic and deterioration events, and the Green's functions $G(z,t)$ for each pipe and nuclide (or, equivalently, for the discrete time approximation, the time integral of the Green's function $g(z,t)$). Explicitly we have (Ref. 1, Eqs. F.2-7 and F.2-11):

$$G(z,t) = \frac{V}{B} \frac{1}{\sqrt{4\pi\alpha V/Bt}} \exp \left\{ - \frac{\left(z - \frac{V}{B}t \right)^2}{4\alpha \frac{V}{B}} \right\} \quad (4-1)$$

$$g(z,t) = \int_0^t G(z,t') dt' = \operatorname{erfc} \left\{ \frac{z - \frac{V}{B} t}{\sqrt{\frac{4\alpha V t}{B}}} \right\} - \operatorname{erfc} \left\{ \frac{z + \frac{V}{B} t}{\sqrt{\frac{4\alpha V t}{B}}} \right\} e^{z/\alpha} \quad (4-2)$$

where

z is the length of the pipe

t is the time difference between the time of entry into the pipe and the time of emergence

V is the interstitial water velocity

B is the retardation factor

α is the dispersion constant.

Multiplying and dividing the argument inside the brackets of Eq. 4-1 by α^2 (or by α for Eq. 4-2) and defining the two quantities:

$$\bar{z} = z/\alpha \quad (4-3)$$

$$T = \frac{\alpha B}{V} \quad (4-4)$$

allows $G(z,t)$ to be written as

$$G(z,t) = \frac{1}{\sqrt{4\pi t/T}} \exp \left\{ - \frac{(\bar{z} - t/T)^2}{4t/T} \right\} \quad (4-5)$$

A similar reduction occurs in $g(z,t)$. It should be noted that each $\bar{z}$ and T actually carries suppressed subscripts identifying the particular pipe and nuclide being considered.

Physically, T may be interpreted as the mean time required for the nuclide to travel the length given by the dispersion constant, and $\bar{z}$ as the length of the pipe divided by that dispersion length. The mean travel time of the nuclide through the pipe is

$$T_f = zT \quad (4-6)$$

Thus each pipe is characterized by a set of $2j_{\max}$ parameters, where $j_{\max}$ is the total number of retardation factors considered in the problem. These parameters are not usually independent since the velocities occurring in the definition of T are not in general independent. For certain regimes of geohydrology parameter values, a particular pipe may dominate the head drop and its T consequently scale in accordance with Darcy's Law and a simplified resistance network.

For the baseline repository (Ref. 1), such scaling regimes have been characterized but will not be presented here. Instead, a systematic study of the aquifer is undertaken since its flow velocity (and associated T) is considered independent of the geohydrology properties of the lower layers. For simplicity, a pipe configuration corresponding to fracture flow along a shaft and tunnel and interstitial flow through the depository and barrier layers is used for the lower layers.

The aquifer values for $\bar{z}$ and T are then scaled through two orders of magnitude on either side of their baseline values (320 and 32 B_j yr, respectively). The values for B_j are the normal ones of 1 (^{129}I and ^{99}Tc), 10^2 (fission products), and 10^4 (actinides). This was done for three different sets of values for the underlying pipe network parameters when varying T (two when varying $\bar{z}$). The three cases for T correspond to a

baseline case, a fast fracture zone case, and a fast interstitial flow case. The latter was dropped when varying $\bar{z}$ since it was largely predictable given the T case.

The geohydrology parameter values for the baseline case are given in Table H-1 of Ref. 1. The values for the other two cases were obtained from the baseline by increasing the permeability of the fracture zone by one order of magnitude, or the interstitial flow by two orders of magnitude, respectively.

The values of the time when the first peak reached the river and its associated whole-body dose were plotted as a function of $\bar{z}$ or T on a logarithmic scale. Figures 4-1, 4-2, 4-3, and 4-4 reproduce these curves. Only the doses and arrival times for the first peak were plotted because overlap among subsequent peaks due to different flow paths and retardation factors complicate the interpretation of results and would make plots unnecessarily complex.

The first peak corresponds in the baseline and fast fracture zone cases to the fracture flow peak for ^{129}I and ^{99}Tc . In the fast interstitial flow case it corresponds to the sum of the doses for both the fracture and interstitial flows (for ^{129}I and ^{99}Tc), since they arrive at the aquifer simultaneously. However, the magnitude of the flow is three orders of magnitude higher for the interstitial contribution than for the fracture zone contribution. Thus the dose may be said to reflect the interstitial transport of ^{129}I and ^{99}Tc .

To understand the shapes of and differences between these curves, it is first necessary to pinpoint the cause of the decrease in dose for large $\bar{z}$ or T. This could be due to either dispersion in the aquifer or the decay of the nuclides.

Figure 4-1 Time of Arrival of Dose Peak at River (T_{peak}) as a Function of Time to Travel a Dispersion Length (T)

Figure 4-2 Peak Individual Dose as a Function of Time to Travel a Dispersion Length (T)

Figure 4-3 Time of Arrival of Dose Peak at River (T_{peak}) as a Function of Dimensionless Aquifer Length ($\bar{Z}$)

Figure 4-4 Peak Individual Dose as a Function of Dimensionless Aquifer Length ($\bar{Z}$)

The latter can be ruled out since the decay constants for ^{129}I and ^{99}Tc are not reflected in the curves. Thus dispersion is the cause of the decrease in dose. If dispersion were not present, a pulse entering the aquifer from below would travel unchanged in shape with the velocity of the water.

Dispersion can change the time of the maximum dose as well as the shape of the curve. However, assuming that the input pulse has approximately a Gaussian shape, it can be shown that the peak travels with the water velocity. Thus dispersion does not affect the location of the peak (to within the Gaussian approximation); therefore varying $\bar{z}$ or T should produce identical curves for the peak T . As can be seen from the curves, this is actually the case.

On the other hand, the Gaussian model does predict a difference in dose due to dispersion. From Ref. 1, Appendix J,

$$\log \frac{c_{\text{in}}^{\text{max}}}{c_{\text{out}}^{\text{max}}} = \log \sqrt{\frac{T_s^2 + T_D^2}{T_s^2}} = \log \sqrt{1 + \left(\frac{T_D}{T_s}\right)^2} \quad (4-7)$$

Here $c_{\text{in}}^{\text{max}}$ and $c_{\text{out}}^{\text{max}}$ are the maximum values of the concentrations at the beginning and the end of the aquifer respectively, T_s is the half-width of the input Gaussian pulse, and $T_D = \sqrt{4\alpha z} \frac{s_B}{v} = 2\sqrt{zT}$. T_D is a measure of the amount of dispersion (pulse widening for a Gaussian input) that takes place over the length of the aquifer.

The output concentration is approximately equal to the input concentration in the limit where $T_D \ll T_s$. In the opposite limit ($T_D \gg T_s$), the left hand side of Eq. 4-7 becomes $\log \frac{T_D}{T_s}$. On a logarithmic plot of dose against $\bar{z}$ or T , the first limit should correspond to a horizontal straight

line, whereas the other limit corresponds to a straight line with slope -1 or -1/2 when varying z or T respectively.

This behavior is reflected in Figs. 4-2 and 4-4. We see that the curves are horizontal for values of $z \lesssim 200$ or $T \lesssim 300$ corresponding to values of $T_D = 1000$ yr. For values of $T \gtrsim 1000$ or $\bar{z} \gtrsim 10,000$ the curves are straight lines, with slopes which vary somewhat with the type of repository flow considered. For the baseline case, the slopes are approximately 1 and 2/3 for the T and $\bar{z}$ graphs respectively. The fast fracture flow case has slopes of about 2 and 3/2 respectively. These are very approximate values since only 3 non-trivial points were available to draw the curves.

A more detailed study of the variation would yield a more definitive curve. But even with this preliminary analysis, the slopes for $\bar{z}$ are qualitatively less than those for T and both are in the range one would expect for a Gaussian pulse. Deviations from the model would presumably be due to the non-Gaussian structure of the input pulse.

It is evident that the dispersion of the aquifer is not a limiting barrier for $T_D < 1000$ yrs. For T_D larger than this value it gradually becomes a significant source of dose reduction until $T_D \approx 10,000$ yrs, when it is the dominant barrier. In the intermediate region, both the structure of flow previous to arrival in the aquifer and the aquifer dispersion are significant sources of dose variation. These plots give an intuitive idea of the extent to which the aquifer characteristics must change to compensate (in the sense of maintaining the same dose) for variations from the baseline repository configuration.

Up to this point, only characteristics of the first peak have been analyzed. The qualitative changes in absolute and relative locations of the various peaks as a function of T or $\bar{z}$ are best investigated by looking at the plots directly. Plots of whole-body doses to an average individual for the fast fracture repository have been reproduced in Figs. 4-5 through 4-9. These five plots represent five different values for T . All other dose plots for the fast fracture repository are virtually identical in form, differing only in the dose scale. The plots for the other two repository configurations have certain differences in form (e.g., broader peaks, steeper slopes) but no substantive differences.

Starting with the baseline aquifer case (Fig. 4-7), three distinct peaks can be discerned. The peaks, in increasing order of time, are due to ^{129}I and ^{99}Tc , fracture zone; ^{129}I and ^{99}Tc , interstitial flow; and other fission products, fracture zone. All other peaks occur after the three million

Figure 4-5 Individual Dose as a Function of Time for Time to Travel a Dispersion Length Equal to 3.2×10^6 Years

Figure 4-6 Individual Dose as a Function of Time for Time to Travel a Dispersion Length Equal to 320 Years

Figure 4-7 Individual Dose as a Function of Time for Time to Travel a Dispersion Length Equal to 32 Years

Figure 4-8 Individual Dose as a Function of Time for Time to Travel a Dispersion Length Equal to 3.2 Years

Figure 4-9 Individual Dose as a Function of Time for Time to Travel a Dispersion Length Equal to 0.32 Years

year period under study. When T is increased by a factor of 10 (Fig. 4-6), the peaks are all delayed so that the third peak is off the plot. The minimum between the second and last peaks has decreased significantly (in fact, off the plot) due to the increased dispersion at these long times. Increasing T another order of magnitude (Fig. 4-5) causes both the second peak and the minimum to be moved off scale.

Decreasing T by powers of 10 inverts this phenomenon. In Fig. 4-8 the second and third peaks have coalesced. The interstitial peak has not moved appreciably (its peak is determined primarily by the time to reach the aquifer), whereas the third peak has arrived several hundred thousand years earlier. The third peak's time of arrival is primarily determined by its aquifer travel time; it travels 100 times slower than ^{129}I and ^{99}Tc . Decreasing T by another factor of 10 (Fig. 4-9) reverses the order of the last two peaks, and the latter appears as a plateau.

Varying $\bar{z}$ instead of T does not change this qualitative picture, although the heights and slopes of the various peaks are altered.

5.

UNCERTAINTY ANALYSIS

5.1 INTRODUCTION

TASC is using monte carlo techniques to perform parametric uncertainty analysis on the subsurface waste migration model. A description of this approach and the results of an earlier study for a shale repository are reported in Ref. 1. The study presented herein is a refinement of the earlier study and does not differ substantially in approach. The primary modification consists in the addition of some model constraints, which are discussed in the next section.

5.2 REFINEMENTS OF MODEL CONSTRAINTS

The model constraints used in the uncertainty analysis (Ref. 1) have been refined to more closely reflect empirical knowledge. In the earlier study (Ref. 1) certain combinations of randomly generated model parameters were found to exceed physical limitations. In particular, unreasonably high rates of vertical flow from the lower to upper aquifer were observed. In the current uncertainty analysis, this effect has been eliminated through two refinements. The first, specified by Golder Associates (Ref. 2), is a mass balance constraint on the vertical head difference and interstitial permeabilities to eliminate cases in which the amount of water leaking up through the repository layer into the aquifer exceeds the amount being carried away in the aquifer. The second refinement consists of a correction factor applied to the random data to account for the depressurization of the lower aquifer due to the

excavation of the shaft and tunnel. The latter correction factor was calculated by treating the regional hydrology as a resistor network. This approach ignores the two-dimensional geometry of the aquifers and therefore gives only an order-of-magnitude upper limit on the size of the effect; however, the correction is generally quite small.

An additional set of constraints has been imposed on the random data, referred to herein as generic range constraints. The purpose of these constraints is to reject random input data which exceed their generic limits. These constraints were specified by Golder Associates (Ref. 8) and Lawrence Livermore Laboratory (Ref. 9), and a detailed listing is provided in Appendix B.

5.3 MONTE CARLO ANALYSIS

This section contains the results of a statistical analysis of the results of a monte carlo analysis incorporating the constraints described above. The quantities analyzed include peak nuclide concentrations in the aquifer, population dose, and peak individual dose for fifty trials. Since the statistical characteristics of the input data were quite similar to that used in the earlier analysis (Ref. 1), several comparisons between the outputs will be drawn. The same radio-nuclide inventories were assumed so as to facilitate comparison; the inventory revisions described in Section 3.1 were not incorporated.

Concentrations - Table 5.3-1 lists the sample statistics for the maximum concentrations of technetium and tin in the aquifer for fifty monte carlo trials. The results of the previous analysis presented in Ref. 1 are repeated in parentheses

TABLE 5.3-1
PEAK AQUIFER CONCENTRATIONS FROM FIFTY
MONTE CARLO TRIALS (Ci/m³)

T-3515

NUCLIDE	MPC _w	BASELINE	SAMPLE MEDIAN	LOGARITHMIC STANDARD DEVIATION	SAMPLE MAXIMUM
⁹⁹ Tc	3×10 ⁻⁴	1.2×10 ⁻⁴	1.3×10 ⁻⁴ (1.9×10 ⁻⁴)	11 (37)	3.6×10 ⁻² (1.7×10 ⁻¹)
¹²⁶ Sn	2×10 ⁻⁵	7.8×10 ⁻⁸	3.9×10 ⁻⁹ (1.6×10 ⁻⁸)	4.0×10 ⁻⁴ (7.6×10 ⁻⁴)	1.3×10 ⁻³ (4.0×10 ⁻⁴)

below the new values. The repository is assumed, conservatively, to contain 6×10^6 MWe-yr of waste, which is an estimate of the total nuclear waste generation in the United States through the year 2005.

Although there are some differences between the results of the current analysis and the older values taken from Ref. 1, these differences are not always statistically significant. The generic range constraints may have resulted in the smaller scale factor variations observed in the current data analysis, since these constraints tend to reduce the variation of the input data.

The percentage of observations exceeding the Maximum Permissible Concentration in Water (MPC_w) dropped for both technetium and tin - from 50% for ⁹⁹Tc and 20% for ¹²⁶Sn (Ref. 1) to 28% for ⁹⁹Tc and 8% for ¹²⁶Sn in the current analysis. These drops may also be due to the generic range constraints (particularly on permeability) although there may be insufficient data to infer a causal relationship.

An inspection of the peak concentrations of ^{239}Pu , ^{226}Ra , and ^{90}Sr showed a small number of samples (2% to 4%) above their respective MPC_w values. No instances of this were observed in the preceding study. These occurrences, however, may not be statistically significant. An examination of the input data suggests a physical interpretation of the high concentration cases as follows: due to a combination of low sorption retardation and high permeability in the shaft and tunnel, the nuclides flow rapidly through the fracture zone and then encounter a relatively slow-moving aquifer. This results in a buildup of radionuclides in the aquifer. The phenomenon of high vertical flow rates through the fracture zone coupled with low horizontal flow velocity in the aquifer can occur within the current generic limits and can result in simultaneously high concentrations of a number of different nuclides.

Peak Dose and Population Dose - The sample statistics for whole-body population dose integrated over the three million year study period (IPD) and peak individual dose are displayed in Table 5.3-2. The results of the previous analysis are again given in parentheses. A comparison of the dose statistics from the two studies reveals only one apparently significant difference. The sample maximum for whole body IPD is nearly two orders of magnitude lower than the value reported in Ref. 1. This is because none of the input parameters for the current analysis resulted in "fast" ($\leq 4 \times 10^6$ yr) passage times for the actinides across the aquifer. An analysis of 1000 random input data sets generated with the currently used constraints showed that approximately 3% of the input data sets had "fast" actinides. This is about the same percentage as reported in Ref. 1. Thus no statistical significance is attached to the lack of appearance of such a case in the fifty trials analyzed here, and the resulting low maximum value of

TABLE 5.3-2
SAMPLE DOSE STATISTICS FROM FIFTY MONTE CARLO TRIALS

T-3516

DOSE TYPE	BASILINE	SAMPLE MEDIAN	LOGARITHMIC STANDARD DEVIATION	SAMPLE MAXIMUM
Whole-Body Integrated Population Dose (man-rem/HWe-yr)	1.3×10^{-3}	1.3×10^{-3} (1.0×10^{-3})	3.5 (3.7)	1.6×10^{-2} (1.12)
Whole-Body Peak Dose (rem/HWe-yr)	6.2×10^{-14}	6.3×10^{-14} (6.3×10^{-14})	9.7 (6.3)	1.9×10^{-11} (2.3×10^{-11})

IPD. The probability of fifty data sets not containing a "fast" actinide case is approximately 0.20.

For further comparison of the Ref. 1 uncertainty analysis with the current analysis, histograms of peak individual dose and integrated population dose for the gastrointestinal tract and lower large intestine (GI-LLI) are displayed in Figs. 5.3-1 and 5.3-2. The GI-LLI was the critical organ for most of the uncertainty runs.

A visual comparison of the results of the previous uncertainty analysis with those of the current analysis for the GI-LLI shows little difference. Figure 5.3-2 indicates that the distributions of integrated population dose for both analyses are similarly skewed towards the high end of the scale. The high values are due to the escape of both ^{126}Sn and ^{99}Tc into the biosphere. The low observations are due to the decay of technetium prior to reaching the biosphere, resulting in a dose due mainly to tin.

Figure 5.3-1 Normalized Histograms of Peak Individual Dose on a Logarithmic Scale for GI-LLI (rem/MWe-yr)

Figure 5.3-2 Normalized Histograms of Integrated Population Dose on a Logarithmic Scale for GI-LLI (man-rem/MWe-yr)

5.4 CONCLUSIONS

This section contains the most recent results from uncertainty analysis of a shale waste repository. A number of refinements were incorporated into this study which were not in the analysis given in Ref. 1. An analysis of the current monte carlo results has not shown any substantial impact from these refinements. This could be attributed to either or both of two factors:

- Insufficient number of monte carlo trials to display differences
- Insensitivity of the first- and second-order statistics of the repository performance measures to small variations in the low-order statistics of the input data.

The refinements have primarily served the purpose of eliminating physically unreasonable models from the uncertainty analysis, and thereby serve to increase confidence in the validity of the results.

6.

SUMMARY

This report contains the results of continuing studies relating to management of high-level nuclear waste. The work described augments the models presented in Ref. 1 in the following areas:

- A simple approximate method of calculating doses to individuals and the population
- Calculation of the depository resaturation time in a way consistent with assumptions regarding flow paths
- Aggregation of doses to the various organs into an overall measure of risk
- Calculation of the potential hazard of wastes from different fuel cycles.

These improvements will make possible more complete and accurate analysis of repository performance in the future.

The following aspects of the repositories analyzed in Ref. 1 were also studied further:

- The sensitivity of doses to lumped parameters describing the overlying aquifer
- Uncertainties due to parameter measurement error.

This work confirmed the conclusion of Ref. 1 that in most cases repository performance is determined by the most effective barrier (the "limiting barrier") alone.

APPENDIX A
RADIONUCLIDE INVENTORIES AND DOSES

Tables A-1 through A-3 list the radionuclide inventories in wastes from the various fuel cycles discussed in Chapter 3. The inventories are given as a function of time after removal of the spent fuel from the reactor.

The doses resulting from a unit release of waste into the reference surface water system are presented in Tables A-4 through A-6. These factors were calculated from the BIDOSE model (Ref. 1, Appendix G) for release more than 1000 years after removal of the wastes from the reactor. This calculation assumes radionuclide buildup in topsoil for a period of 100 years. When releases occur before 1000 years, the BIDOSE model assumes a shorter buildup period and will therefore calculate a smaller dose per curie released; however, the difference is insignificant for all nuclides except ^{126}Sn .

Tables A-4 and A-5 give the 50-year dose to an individual from a continuous release of one curie per year of any nuclide into the water system. Both tables refer to an individual who derives all his food, water, and water-related recreation from the contaminated river system; they differ in how much the individual eats, drinks, etc. Table A-4 refers to an individual with average usage rates and Table A-5 to one with maximum usage rates.

Table A-6 gives the population dose over all time resulting from a one-time release of one curie of any nuclide.

Equivalently, this may be interpreted as the steady-state dose or dose commitment to the population per year resulting from a continuous release of one curie per year.

TABLE A-1
RADIONUCLIDE INVENTORY OF HLW FROM THE
PLUTONIUM-STORAGE FUEL CYCLE
(Ci/MWe-yr)

RADIONUCLIDE	TIME (YR)				
	1.0E2	1.0E3	1.0E4	1.0E5	1.0E6
CM244	1.66E+00	2.05E-15	2.45E-15	2.25E-14	1.08E-13
CM242	1.49E-01	2.46E-03	3.73E-21	0.0	0.0
AM243	5.64E-01	5.20E-01	2.30E-01	6.62E-05	7.60E-06
AM241	4.71E+00	1.12E+00	4.85E-03	2.45E-06	4.36E-39
PU241	1.53E-01	9.26E-03	4.64E-03	2.45E-06	4.13E-39
PU240	2.70E-01	2.50E-01	9.93E-02	9.77E-06	8.29E-11
PU237	5.21E-02	6.44E-02	1.25E-01	1.81E-02	7.60E-09
PU236	1.54E+00	7.00E-03	9.00E-21	0.0	0.0
NP237	1.08E-02	1.15E-02	1.17E-02	1.14E-02	6.23E-03
U233	4.61E-06	4.78E-05	4.85E-04	4.03E-03	9.05E-03
PA231	7.75E-07	8.11E-07	1.22E-06	7.55E-06	1.05E-05
TH230	1.04E-06	1.09E-05	1.12E-04	6.89E-04	1.68E-04
TH229	2.30E-08	2.18E-06	1.74E-04	3.66E-03	9.18E-03
FA229	3.43E-08	1.97E-06	8.73E-05	6.92E-04	1.69E-04
FA228	2.30E-09	2.18E-06	1.74E-04	3.68E-03	9.18E-03
PC210	2.33E-08	1.97E-06	8.73E-05	6.98E-04	1.69E-04
PR210	2.33E-08	1.97E-06	8.73E-05	6.98E-04	1.69E-04
EU124	2.89E+00	3.39E-17	0.0	0.0	0.0
PM147	1.12E-08	0.0	0.0	0.0	0.0
CE144	6.84E-35	0.0	0.0	0.0	0.0
CE137	3.35E+02	3.13E-07	0.0	0.0	0.0
CE136	8.94E-03	8.94E-03	8.92E-03	8.74E-03	7.10E-03
CE134	1.65E-11	0.0	0.0	0.0	0.0
I129	1.55E-06	1.55E-06	1.55E-06	1.54E-06	1.49E-06
SN129	1.71E-02	1.70E-02	1.55E-02	8.54E-03	1.67E-05
RU106	1.94E-26	0.0	0.0	0.0	0.0
TC99	4.48E-01	4.47E-01	4.34E-01	3.23E-01	1.71E-02
NBS5	0.0	0.0	0.0	0.0	0.0
NBS34	5.87E-02	5.90E-02	5.87E-02	5.63E-02	3.72E-02
ZR95	0.0	0.0	0.0	0.0	0.0
ZR93	5.90E-02	5.90E-02	5.87E-02	5.63E-02	3.72E-02
Y91	0.0	0.0	0.0	0.0	0.0
YSO	2.06E+02	4.74E-08	0.0	0.0	0.0
SF90	2.06E+02	4.74E-08	0.0	0.0	0.0
SE95	0.0	0.0	0.0	0.0	0.0

TABLE A-2
RADIONUCLIDE INVENTORY OF SPENT
ENRICHED-URANIUM FUEL
(Ci/MWe-yr)

RADIONUCLIDE	TIME (YR)				
	1.0E2	1.0E3	1.0E4	1.0E5	1.0E6
C238	1.46E+00	2.05E-15	2.46E-15	2.2E-14	1.00E-13
C235	1.49E-01	2.46E-03	3.73E-21	0.0	0.0
AM241	5.64E-01	5.20E-01	2.33E-01	6.52E-05	7.60E-09
AM243	5.50E+01	2.37E+01	4.87E-03	2.45E-06	4.36E-39
PU241	2.25E+01	5.86E-03	4.68E-03	2.45E-06	4.13E-39
PU240	1.50E+01	1.37E+01	5.43E+00	5.34E-04	2.29E-11
PU239	1.01E+01	5.23E+00	7.65E+00	6.05E-01	7.60E-09
PU238	4.20E+01	4.36E-02	5.00E-21	0.0	0.0
NP237	1.34E-02	2.88E-02	3.35E-02	3.26E-02	2.43E-02
U233	6.22E-05	5.44E-05	1.35E-03	1.15E-02	2.58E-02
PA231	1.53E-06	1.24E-05	1.12E-04	7.18E-04	8.66E-04
TH230	2.55E-05	4.81E-04	4.60E-03	2.08E-02	1.40E-02
TH229	3.79E-06	3.63E-06	4.65E-04	1.05E-02	2.62E-02
PA226	5.89E-07	8.05E-05	3.59E-03	2.92E-02	1.45E-02
PA228	3.79E-08	3.63E-06	4.65E-04	1.05E-02	2.62E-02
PO213	3.30E-07	8.05E-05	3.59E-03	2.92E-02	1.40E-02
PR211	3.30E-07	8.05E-05	3.59E-03	2.92E-02	1.40E-02
EU154	2.69E+00	3.36E-17	0.0	0.0	0.0
PM147	1.11E-02	0.0	0.0	0.0	0.0
CE144	6.84E-35	0.0	0.0	0.0	0.0
CE137	3.35E+02	3.13E-07	0.0	0.0	0.0
CE125	8.54E-03	8.94E-03	6.52E-03	8.74E-03	7.10E-03
CE134	1.58E-11	0.0	0.0	0.0	0.0
1125	1.17E-03	1.17E-03	1.17E-03	1.17E-03	1.12E-03
SN125	1.71E-02	1.70E-02	1.55E-02	8.54E-03	1.67E-05
FU125	1.55E-26	0.0	0.0	0.0	0.0
TC99	4.48E-31	4.47E-01	4.34E-01	3.23E-01	1.71E-02
NB99	0.0	0.0	0.0	0.0	0.0
NB93M	5.27E-02	5.90E-02	5.87E-02	5.63E-02	3.72E-02
ZR95	0.0	0.0	0.0	0.0	0.0
ZR93	5.50E-02	5.90E-02	5.87E-02	5.63E-02	3.72E-02
Y61	0.0	0.0	0.0	0.0	0.0
Y90	2.06E+02	8.74E-08	0.0	0.0	0.0
EF90	2.06E+02	8.74E-08	0.0	0.0	0.0
ES95	0.0	0.0	0.0	0.0	0.0
MI99	1.20E-01	1.19E-01	1.12E-01	5.06E-02	2.68E-05

TABLE A-3
RADIOISOTOPE INVENTORY OF HLW FROM THE
PLUTONIUM-THROWAWAY FUEL CYCLE
(Ci/MWe-yr)

RADIO- NUCLIDE	TIME (YR)				
	1.0E2	1.0E3	1.0E4	1.0E5	1.0E6
CM244	1.66E+00	2.05E-15	2.85E-15	2.25E-14	1.05E-13
CM242	1.45E-01	2.46E-23	3.73E-21	0.0	0.0
AM243	5.64E-01	5.20E-21	2.30E-01	6.62E-05	7.10E-09
AM241	9.50E+01	2.37E+01	4.87E-03	2.45E-02	4.36E-39
PU241	2.85E+01	9.86E-03	4.64E-03	2.45E-06	4.13E-36
PU240	1.50E+01	1.37E+01	5.43E+00	5.34E-04	8.29E-11
PU239	1.01E+01	5.83E+00	7.69E+00	6.05E-01	7.60E-06
PU238	4.20E+01	4.36E-02	5.00E-21	0.0	0.0
NP237	1.34E-02	2.88E-02	3.35E-02	3.26E-02	2.43E-02
U233	5.09E-06	5.30E-05	1.34E-03	1.15E-02	2.58E-02
PA231	7.76E-07	9.14E-27	1.01E-05	2.09E-04	3.55E-04
TH230	5.35E-06	2.45E-04	2.67E-03	1.64E-02	3.00E-03
TH229	2.43E-08	3.70E-06	4.64E-04	1.05E-02	2.62E-02
FA226	1.63E-07	4.24E-05	2.09E-03	1.66E-02	3.01E-03
RA226	2.43E-09	3.70E-06	4.64E-04	1.05E-02	2.62E-02
PC210	8.48E-08	4.24E-05	2.09E-03	1.66E-02	3.01E-03
PB210	8.48E-08	4.24E-05	2.09E-03	1.66E-02	3.01E-03
EU154	2.98E+00	3.39E-17	0.0	0.0	0.0
PM147	1.12E-08	0.0	0.0	0.0	0.0
CE144	6.84E-35	0.0	0.0	0.0	0.0
CS137	3.35E+02	3.13E-07	0.0	0.0	0.0
CS135	8.94E-03	8.94E-03	8.92E-03	8.94E-03	7.10E-03
CE134	1.65E-11	0.0	0.0	0.0	0.0
I125	1.55E-06	1.55E-06	1.55E-06	1.54E-06	1.49E-06
SN125	1.71E-02	1.70E-02	1.55E-02	8.54E-03	1.67E-05
RU106	1.94E-26	0.0	0.0	0.0	0.0
TC99	4.48E-01	4.47E-01	4.34E-01	3.23E-01	1.71E-02
NBS5	0.0	0.0	0.0	0.0	0.0
NBS34	5.87E-02	5.90E-02	5.87E-02	5.63E-02	3.72E-02
ZR55	0.0	0.0	0.0	0.0	0.0
ZR53	5.90E-02	5.90E-02	5.87E-02	5.63E-02	3.72E-02
YS1	0.0	0.0	0.0	0.0	0.0
YS9	2.06E+02	4.74E-08	0.0	0.0	0.0
SP53	2.06E+02	4.74E-08	0.0	0.0	0.0
SFR9	0.0	0.0	0.0	0.0	0.0

TABLE A-4

[illegible]

TABLE A-5

FASE - HOUR:MIN	WHOLE BODY EQUIV	WHOLE BODY	SI - LLI	THYROID	BONE	LIVER	LUNG	KIDNEY	SKIN
CNP42	5.00E-03	1.47E-04	1.84E-04	5.00E-08	4.00E-04	3.10E-04	1.00E-05	1.75E-04	1.00E-07
CNP43	1.00E-03	2.77E-04	1.85E-04	1.00E-07	3.00E-04	3.10E-04	1.00E-05	1.75E-04	1.00E-07
CNP44	1.00E-03	2.77E-04	1.85E-04	1.00E-07	3.00E-04	3.10E-04	1.00E-05	1.75E-04	1.00E-07
AI42	1.00E-03	3.00E-04	1.89E-04	1.00E-07	3.00E-04	3.10E-04	1.00E-05	1.75E-04	1.00E-07
U2241	2.65E-03	1.38E-04	1.15E-07	1.32E-07	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
U2243	3.00E-03	1.81E-04	1.77E-07	2.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PU232	3.75E-03	3.06E-04	1.44E-05	2.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
NP232	6.13E-03	3.06E-04	1.44E-05	2.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
U233	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA231	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI230	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
TI226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07	1.67E-07	1.37E-07	1.00E-07	1.00E-07
PA226	1.50E-04	1.31E-04	1.22E-04	4.00E-08	1.00E-07				

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APPENDIX B
GENERIC RANGE CONSTRAINTS USED IN UNCERTAINTY ANALYSIS

This appendix lists the generic range constraints currently used in the uncertainty analysis. They have been applied in addition to the constraints already listed in Appendix K of Ref. 1. The generic ranges are specified in terms of minimum and maximum achievable values for the monte carlo input parameters.

B.1 DISPERSION CONSTANTS

Table B.1-1 lists the minimum and maximum values for the dispersion constants along with the assumed median value used in the random number generator.

TABLE B.1-1
GENERIC RANGE FOR DISPERSION CONSTANTS

PATHWAY	MINIMUM VALUE (m)	MEDIAN (m)	MAXIMUM VALUE (m)
All Layers	10	50	100

B.2 STREAM TUBE CROSSSECTIONS

Table B.2-1 lists the median value and generic ranges for the cross-sections of the shaft and tunnel fracture zones. These values are from Ref. 8.

TABLE B.2-1
GENERIC RANGES FOR PIPE CROSS-SECTIONS

PATHWAY	MINIMUM VALUE (m ²)	MEDIAN (m ²)	MAXIMUM VALUE (m ²)
First Segment of Tunnel Fracture Zone	0	316	785
Second Segment of Tunnel Fracture Zone	0	18.96	47.1
Shaft Fracture Zone in Depository Layer	0	10.0	100.0
Shaft Fracture Zone in Barrier Layer	0	5.0	100.0

B.3 NUCLIDE RETARDATION FACTORS

Table B.3-1 lists the generic ranges for the nuclide retardation factors. As in Ref. 1, the statistics are listed according to pathway and nuclide group, where the groups are numbered as follows:

1. ^{129}I , ^{99}Tc
2. Other Fission Products
3. Actinides and Daughters.

The generic ranges for the retardation factors were obtained from Ref. 9.

TABLE B.3-1
GENERIC RANGES FOR RETARDATION FACTORS

PATHWAY	NUCLIDE GROUP	MINIMUM VALUE	MEDIAN	MAXIMUM VALUE
Aquifer	1	1.0	1.0	1.0
	2	1.0	1.0×10^2	1.0×10^3
	3	10.0	1.0×10^4	1.0×10^5
Fracture Zone (Shaft and Tunnel)	1	1.0	1.0	10.0*
	2	1.0	1.0×10^2	1.0×10^3 *
	3	1.0	1.0×10^4	1.0×10^5 *
Shale (Depository and Barrier)	1	1.0	1.0	10.0
	2	1.0	1.0×10^2	1.0×10^3
	3	10.0	1.0×10^4	1.0×10^5

*Although the generic ranges for the retardation in fractured rock were not supplied, these upper limits are implied by the inequality constraints listed in Ref. 1 (Appendix K).

B.4 PERMEABILITIES AND EFFECTIVE POROSITIES

B.4.1 Fracture Zones

No generic ranges were used for the permeability of fractured shale. The values were constrained simply to be positive. Similarly, the porosity of the fractured rock was constrained to lie between 0.0 and 1.0.

B.4.2 Undisturbed Rock

Table B.4-1 lists the generic ranges for the permeability of the undisturbed rock. These were obtained from Ref. 8.

TABLE B.4-1
GENERIC RANGES FOR PERMEABILITY IN
THE UNDISTURBED ROCK

LAYER	MINIMUM VALUE (cm/sec)	MEDIAN (cm/sec)	MAXIMUM VALUE (cm/sec)
Depository Layer	1.0×10^{-11}	1.0×10^{-9}	1.0×10^{-7}
Shale Barrier Layer Above Depository	1.0×10^{-9}	1.0×10^{-7}	1.0×10^{-5}
Aquifer	1.0×10^{-8}	1.0×10^{-4}	1.0×10^{-2}
Barrier Layer Below Depository *	1.0×10^{-7}	1.0×10^{-5}	1.0×10^{-3}

Table B.4-2 lists the generic ranges for the porosity of the undisturbed rock.

TABLE B.4-2
GENERIC RANGES FOR POROSITY IN
THE UNDISTURBED ROCK

LAYER	MINIMUM VALUE	MEDIAN	MAXIMUM VALUE
Depository Layer	0.01	0.05	0.10
Shale Barrier Layer Above Depository	0.01	0.05	0.10
Aquifer	0.02	0.10	0.20
Barrier Layer Below Depository *	0.02	0.10	0.20

*These values are based on an erroneous reading of Ref. 8; however, the error is in the direction of excess conservatism and has little impact on the results. The error was discovered during the writing of this report; it was not felt to be a worthwhile use of resources to redo the monte carlo calculations for such a small correction.

B.5 ADDITIONAL VARIATES

Generic ranges were not used for the following three variates:

- Horizontal head gradient in the aquifer
- Vertical head difference of the upper and lower aquifers
- Dissolution rate of the waste.

The assumed generic range of the time required to resaturate the depository void space (T_{fill}) is from 20 to 1000 years (Ref. 8). The model presented in Section 2.2 was not used to calculate resaturation times.

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