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ANALYSIS OF SOME MASTER
NUCLEAR WASTE MANAGEMENT OPTIONS
VOLUME II: APPENDICES

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ABSTRACT

This report describes risk analyses performed on that portion of a nuclear fuel cycle which begins following solidification of high-level waste. Risks associated with handling, interim storage and transportation of the waste are assessed, as well as the long term implications of disposal in deep mined cavities. The risk is expressed in terms of expected dose to the general population and peak dose to individuals in the population. Volume I describes the analyses and discusses the results. Volume II consists of appendices which provide technical details of the work performed.

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APPENDIX A
PRE-EMPLACEMENT EXPECTED DOSE CALCULATIONS

A.1 OVERVIEW

This appendix discusses the methods, calculations and data used in computing expected doses for accidental radioactive releases. The accidents of interest are those which may occur during handling and interim storage of high-level solidified waste (HLSW) at the fuel reprocessing plant, its shipment to the repository site and its storage and handling at the repository. Section A.2 presents the general equations used for computing the expected dose to man from airborne and waterborne radioactivity. Section A.3 discusses the probabilistic factors in these equations that are uniquely specified by accident type, release mechanism and HLSW form. Section A.4 describes the radionuclide source terms, dose commitment factors and computational schemes used to generate such performance measures as whole-body, whole-body equivalent and critical-organ dose. Section A.5 discusses the atmospheric and hydrological models used to describe the spread of radionuclides through the biosphere. Section A.6 presents a summary of expected dose values by release mechanism, waste form and accident type.

A.2 GENERAL EXPECTED DOSE EQUATIONS

A.2.1 List of Indices and Symbols

The following indices are used in Eqs. A.2-1 to A.2-8 and throughout the remainder of Appendix A:

- i = index of pre-emplacment accident type;
see Table A.2-1
- j = index of airborne or waterborne release mechanism (or pathway); see Table A.2-2
- q = index of reference HLSW form; see Table A.2-3
- r = 1,...,R; index of radionuclide; see Table A.2-4
- s = index of waste age; see Tables A.2-5 and A.2-6
- u = index of affected organ; see Table A.2-7.

The following symbols are used in Eqs. A.2-1 to A.2-8:

- $A(x)$ = Area of the pie-shaped sector of radius x and angle $\pi/8$ that is bisected by the line drawn from the point of the accident in the direction of the prevailing wind. This is the area over which $\bar{X}$ for plumes is averaged and over which the plume release equation is integrated with population density to compute the airborne population dose. (Units are m^2 .)
- $A_p(x)$ = Cross-sectional area of a puff measured at ground level at a distance x meters downwind of an accident. It is the area over which $\bar{X}$ is averaged for puff releases. (Units are m^2 .)
- $D_{ijqsu}^D(x_f)$ = Fifty-year expected deposition dose to organ u (from continuous external exposure to ground gamma radiation and continuous internal exposure via ingestion of contaminated milk), integrated over a population out to x_f meters downwind of pre-emplacment accident i involving waste of form q and age s released to the air by mechanism j and re-deposited on the ground (man-rem/MWe-yr).
- $D_{ijqsu}^I(x_f)$ = Expected inhalation dose to organ u from a 50-year commitment of a single (acute) intake of radionuclides, integrated over

TABLE A.2-1
PRE-EMPLACEMENT ACCIDENT INDICES

T-1775

INDEX 1	PRE-EMPLACEMENT ACCIDENT
1	Handling at Reprocessing Plant, Crane Stall or Drop, Filtration <u>Works</u>
2	Handling at Reprocessing Plant, Crane Stall or Drop, Filtration <u>Fails</u>
3	Reprocessing Plant, Interim Water Basin Storage, Loss of Cooling Circulation, Filtration <u>Works</u>
4	Reprocessing Plant, Interim Water Basin Storage, Loss of Cooling Circulation, Filtration <u>Fails</u>
5	Reprocessing Plant, Interim Water Basin Storage, Drainage of Storage Pool
6	Truck Impact on Extremely Rigid Fixed Object (Urban)
7	Truck Impact on Extremely Rigid Fixed Object (Rural)
8	Railroad Crossing Accident, Impact of Train on Truck (Urban)
9	Railroad Crossing Accident, Impact of Train on Truck (Rural)
10	Truck Fire (Urban)
11	Truck Fire (Rural)
12	Truck Puncture (Urban)
13	Truck Puncture (Rural)
14	Train Impact on Extremely Rigid Fixed Object (Urban)
15	Train Impact on Extremely Rigid Fixed Object (Rural)
16	Train Fire (Urban)
17	Train Fire (Rural)
18	Train Puncture (Urban)
19	Train Puncture (Rural)
20	Handling at Repository Prior to Emplacement, Crane Drop, Filtration <u>Works</u>
21	Handling at Repository Prior to Emplacement, Crane Drop, Filtration <u>Fails</u>
22	Storage Outside Repository, High Impact of Airplane on Cask

TABLE A.2-2
PRE-EMPLACEMENT RELEASE MECHANISM INDICES

T-1776

INDEX 1	RELEASE MECHANISM
1	Particulate Dispersion (airborne)
2	Volatilization (airborne)
3	Dissolution (waterborne)

TABLE A.2-3
INDICES OF REFERENCE HLSW FORMS

T-1777

INDEX q	WASTE FORM
1	Spray Calcine
2	Borosilicate Glass
3	Fluidized Bed Calcine
4	Multibarrier Waste Form

TABLE A.2-4
INDICES OF RADIONUCLIDES IN HLSW

T-1778

INDEX r	RADIONUCLIDE	INDEX r	RADIONUCLIDE
1	⁸⁹ Sr	13	¹³⁴ Cs
2	⁹⁰ Sr	14	¹³⁷ Cs
3	⁹¹ Y	15	¹⁴⁴ Ce
4	⁹⁵ Zr	16	¹⁴⁷ Pm
5	⁹⁵ Nb	17	¹⁵⁴ Eu
6	¹⁰³ Ru	18	²³⁸ Pu
7	¹⁰⁶ Ru	19	²⁴⁰ Pu
8	¹²⁵ Sb	20	²⁴¹ Pu
9	^{127m} Te	21	²⁴¹ Am
10	¹²⁷ Te	22	²⁴³ Am
11	^{129m} Te	23	²⁴² Cm
12	¹²⁹ Te	24	²⁴⁴ Cm

TABLE A.2-5
WASTE AGE INDICES

T-1779

INDEX s	TIME SINCE REMOVAL FROM REACTOR, t_s (yr)
1	0.4
2	1.0
3	2.0
4	5.0
5	10.0

TABLE A.2-6
AGE OF EACH REFERENCE WASTE FORM BY
PRE-EMPLACEMENT ACCIDENT TYPE

T-1780

ACCIDENT \ HLSW FORM	WASTE AGE* (t_s) AND AGE INDEX* (s)			
	SPRAY CALCINE	BOROSILICATE GLASS	FLUIDIZED BED CALCINE	MULTIBARRIER WASTE FORM
Handling and Interim Storage at the Reprocessing Plant	s=4 t_s = 5.0 yr	s=2 t_s = 1.0 yr	s=4 t_s = 5.0 yr	s=1 t_s = 0.4 yr
Transportation; Storage and Handling at the Repository Site	s=5 t_s = 10.0 yr	s=5 t_s = 10.0 yr	s=5 t_s = 10.0 yr	s=5 t_s = 10.0 yr

- *Note:
- For all reprocessing plant accidents t_s is the waste age at solidification and is set on the basis of thermal criteria and federal regulations governing HLSW. It is assumed to be the age at which each waste form is first exposed to potential reprocessing plant handling accidents and the age at which each waste form enters interim storage.
 - For all transportation and repository accidents t_s is the age at which each waste form is exposed to potential transportation accidents in shipment or to potential handling and storage accidents at the repository site.

TABLE A.2-7
 INDICES OF ORGANS RECEIVING RADIATION DOSE COMMITMENTS
 T-1781

INDEX u	ORGAN AFFECTED
1	Whole Body (Internal)
2	Whole Body (External)
3	Whole-Body Equivalent (Internal)
4	Gastro-Intestinal Tract (Lower Large Intestine)
5	Thyroid
6	Bone
7	Liver
8	Lung
9	Kidney
10	Skin

a population out to x_f meters downwind of a pre-emplacment accident i involving waste of form q and age s released to the air by mechanism j (man-rem/MWe-yr).

$D_{ijqsu}^T(x_f)$ = Fifty-year total expected dose to organ u, integrated over a population out to x_f meters downwind of a pre-emplacment accident i involving waste of form q and age s released to the air and ground by mechanism j (man-rem/MWe-yr).

D_{ijqsu}^W = Fifty-year expected integrated population dose to organ u from a chronic intake (via ingestion of contaminated aquatic foods, drinking water, animals and plants) of soluble radionuclides released to water in a pre-emplacment accident of type i involving HLSW of form q and age s (man-rem/MWe-yr).

DF_{ru}^D = Deposition dose commitment factor accounting for radionuclide r's impact on organ u. A 50-year chronic external exposure to ground gamma radiation and chronic internal exposure through ingestion of milk contaminated via the forage-cow-milk pathway is assumed (rem- m^2 /Ci).

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- DF_{ru}^I = Inhalation dose commitment factor accounting for radionuclide r 's impact on organ u . A 50-year dose commitment of a single (acute) intake of radionuclides is assumed ($\text{rem-m}^3/\text{Ci-yr}$).
- FAC_{rsu}^W = A factor used to compute the 50-year integrated population dose to organ u from dissolution of radionuclide r . It incorporates the composite effects of a water pathway model, the inventory of soluble radionuclides in waste of age s , and the dose commitment factors for chronic exposure to these radionuclides (man-rem/MWe-yr).
- M_i = The total number of conditional probabilities associated with accident type i (dimensionless).
- P_{im} = The m^{th} conditional probability associated with an accident of type i (various dimensions).
- $Q_r(t)$ = Inventory of radionuclide r in HLSW after t years out of the reactor (Ci/MWe-yr).
- Q = Total activity of radionuclides emitted to the air in an instantaneous release (Ci).
- Q' = Rate of continuous-source radionuclide emission to the air (Ci/yr).
- RF_{ijqr} = The expected fraction of the inventory of radionuclide r released to the biosphere via pathway j from waste of form q , given exposure of canister(s) to failure in an accident of type i (dimensionless).
- $S_i(x_0, x_f)$ = Meteorology-demography pathway factor for accident type i used to compute population dose in an area between the distances x_0 and x_f downwind of the accident (man-yr/m^3).
- t_{iq}^F = Threshold age of failure of waste of form q in interim storage accident i ; that is, the age prior to which the probability of canister thermal failure given an accident is nonzero, and after which the probability of thermal failure is zero (yr).

- t_s = Waste age corresponding to age index s (yr). (See Table A.2-6.)
- $\bar{u}$ = Average wind speed (m/yr).
- v^D = Deposition velocity, which accounts for ground deposition of a portion of the volatiles and dispersed particulates in an airborne release (m/yr).
- $\rho_i(x)$ = Assumed population density at a distance x meters downwind of an accident of type i (man/m²).
- $\bar{X}(x)$ = Area-averaged surface air concentration on the puff or plume centerline x meters downwind of an accident (Ci/m³).

A.2.2 Airborne Release Equations

Equations A.2-1 and A.2-2 are used to compute the expected inhalation and deposition dose from airborne particulate dispersion and volatilization for all pre-emplacement accidents involving

- Handling at the reprocessing plant
- Transportation to the repository
- Storage and handling at the repository site.

$$D_{ijqsu}^I(x_f) = \left[\frac{M_i}{\pi} P_{im} \right] \left[\sum_{r=1}^R RF_{ijqr} Q_r(t_s) DF_{ru}^I \right] S_i(x_0, x_f)$$

($i=1,2,6,7,\dots,22$; $j=1,2$; all q,s,u)

(A.2-1)

$$D_{ijqsu}^D(x_f) = \left[\prod_{m=1}^{M_i} P_{im} \right] \left[\sum_{r=1}^R RF_{ijqr} Q_r(t_s) DF_{ru}^L \right] v^D S_i(x_0, x_f)$$

$$(i=1,2,6,7,\dots,22; j=1,2; \text{ all } q,s,u)$$

(A.2-2)

Equations A.2-3 and A.2-4 are used to compute the expected inhalation and deposition dose from all accidents occurring during interim storage at the reprocessing plant. These equations differ from Eqs. A.2-1 and A.2-2 in that an integral of source terms over waste age must be included to properly express risk as a function of each waste form's age of entering the storage pool, t_s , and threshold age of failure given an accident, t_{iq}^F . The reader should consult Section 2.2.2 of Chapter 2 for an explanation of the form of Eqs. A.2-3 and A.2-4.

$$D_{ijqsu}^I(x_f) = \begin{cases} \left[\prod_{m=1}^{M_i} P_{im} \right] \left[\sum_{r=1}^R RF_{ijqr} DF_{ru}^I \int_{t=t_s}^{t_{iq}^F} Q_r(t) dt \right] S_i(x_0, x_f) & \text{if } t_{iq}^F > t_s \\ 0 & \text{if } t_{iq}^F \leq t_s \text{ (} i=3,4,5; j=1,2; \text{ all } q,s,u \text{)} \end{cases}$$

(A.2-3)

$$D_{ijqsu}^D(x_f) = \begin{cases} \left[\prod_{m=1}^{M_i} P_{im} \right] \left[\sum_{r=1}^R RF_{ijqr} DF_{ru}^D \int_{t=t_s}^{t_{iq}^F} Q_r(t) dt \right] v^D S_i(x_0, x_f) & \text{if } t_{iq}^F > t_s \\ 0 & \text{if } t_{iq}^F \leq t_s \text{ (} i=3,4,5; j=1,2; \text{ all } q,s,u \text{)} \end{cases}$$

(A.2-4)

Note that when the failure threshold age of a given waste form exceeds the age at which the waste enters interim storage, there is a nonzero expected dose (e.g., for borosilicate glass and the multibarrier waste form). When t_{iq}^F is less than or equal to t_s , however, waste cannot fail in interim storage. Hence, the expected dose in this case is zero (e.g., for spray and fluidized bed calcine).

Equations A.2-5, A.2-6 and A.2-7 apply to all pre-
emplacement accidents. They are used to compute the total
expected airborne dose matrix and the meteorology-demography
pathway factors for both plume and puff releases:

$$D_{ijqsu}^T(x_f) = D_{ijqsu}^I(x_f) + D_{ijqsu}^D(x_f) \quad (j=1,2; \text{ all } i,q,s,u) \quad (\text{A.2-5})$$

$$S_i(x_0, x_f) = \begin{cases} \int_{x=x_0}^{x_f} \rho_i(x) \left[\frac{\bar{X}(x)}{Q} \right] dA(x) & (\text{A.2-6}) \\ \quad \text{(for plume releases;} \\ \quad \quad i=1,2,3,4,5,10,11,16,17,20,21,22) \\ \frac{1}{u} \int_{x=x_0}^{x_f} \rho_i(x) \left[\frac{\bar{X}(x)}{Q} A_p(x) \right] dx & (\text{A.2-7}) \\ \quad \text{(for puff releases;} \\ \quad \quad i=6,7,8,9,12,13,14,15,18,19) \end{cases}$$

The total expected airborne dose matrix (Eq. A.2-5) contains all the information needed to compute such performance measures as expected whole-body dose, whole-body equivalent dose and critical-organ dose by HLSW form, accident type and release mechanism. A detailed discussion of these computations is reserved for Section A.4.3. The

meteorology-demography pathway factor and the assumptions related to it are discussed in Section A.5.1.

A.2.3 Waterborne Release Equations

Waterborne escape of HLSW via dissolution is the third mechanism of importance in the dispersal of radioactivity from pre-emplacement accidents. Equation A.2-8 is used to compute the expected dissolution dose to man:

$$D_{ijqsu}^W = \left[\frac{M_i}{T} P_{im} \right] \left[\sum_{r=1}^R RF_{ijqr} FAC_{rsu}^W \right] \quad (j=3; u=1,6; \text{all } i,q,s) \quad (A.2-8)$$

This equation is simpler in format than the airborne dose equations due to use of the dose factor FAC_{rsu}^W , which is a composite measure of the water pathway release model assumed, the inventory of all soluble radionuclides, and dose commitment factors for chronic exposure to soluble radionuclides via ingestion. Section A.5.2 contains further references to the methods and data used to compute FAC_{rsu}^W .

The expected waterborne dose matrix, D_{ijqsu}^W , contains all the elements necessary for computing whole-body and critical-organ expected dose from releases via dissolution. Such computations are described in detail in Section A.4.3.

A.3 ACCIDENT AND PATHWAY-TO-BIOSPHERE PROBABILITIES AND EXPECTED RELEASE FRACTIONS: CALCULATIONS AND DATA

A.3.1 Introduction

In Section A.2 the general expected dose equations (Eqs. A.2-1 to A.2-8) were presented. The probabilistic

elements of these equations that vary from accident to accident will be described in detail in this section. These elements, as previously defined, include:

- P_{im} , the conditional probabilities of canister exposure to pre-emplacement accidents, e.g., crane accident probabilities, earthquake and loss of interim storage cooling circulation probabilities, transportation impact and fire accident probabilities and air crash probabilities at the repository site.
- RF_{ijqr} , the expected fraction of the inventory of each nuclide released to the biosphere from each waste form via each release mechanism, given exposure of canisters to failure in a pre-emplacement accident.

RF_{ijqr} can be expressed as the product of a pathway-to-biosphere factor and an expected release fraction characteristic of the HLSW form, accident type and release mechanism:

$$RF_{ijqr} = PP_{ij} E[F_{ijqr}] \quad (A.3-1)$$

where

PP_{ij} = probability of a pathway existing for the escape of radionuclides to the biosphere via release mechanism j , given that a canister or transportation cask is breached in an accident of type i (dimensionless). This can include factors such as the probability of failure of the building's filter following a reprocessing plant or repository accident, the probability of an energy source existing for dispersion of airborne particulates in a transportation accident or the probability of a water pathway existing for release via dissolution.

$E[F_{ijqr}]$ = Expected fraction of the inventory of radionuclide r that is available for release from waste of form q via mechanism j , given exposure of canisters to failure in an accident of type i (dimensionless).

F_{ijqr} , the "release function," may be a fixed quantity for all accident severities or may vary as a function of a random variable denoting some measure of accident severity -- e.g., velocity at impact or fire temperature in transportation accidents. In the first case, which includes all storage and handling accidents at the reprocessing plant and repository, $E[F_{ijqr}]$ is expressed as the product of canister failure probability, given exposure to failure in an accident, and the waste release fraction given canister failure. Both of the latter variables can be assigned constant nominal or worst-case values in these accidents. In the second case, the release function is denoted by $F_{ijqr}(s)$, where s is some measure of accident severity. $E[F_{ijqr}(s)]$ is then computed by multiplying $F_{ijqr}(s)$ by an appropriate accident severity probability density function $p_i(s)$ and integrating this product over all failure severities. The evaluation of transportation accident release fractions is described in detail in Section A.3.4.

Table A.3-1 gives an overview of the general expected dose equations that apply to each pre-emplacement accident type and release mechanism. Additionally, the tables and equations used to evaluate conditional probabilities P_{im} and expected biosphere release fractions RF_{ijqr} are summarized for each accident type. The details of these and other calculations are the subject of the remaining sections of this Appendix.

TABLE A.3-1
OVERVIEW OF EQUATIONS AND TABLES USED IN EVALUATING EXPECTED DOSE
FROM PRE-EMPLACEMENT ACCIDENTS

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ACCIDENTS	INDEX 1	GENERAL EXPECTED DOSE EQUATIONS THAT APPLY			SOURCES FOR EVALUATING			
		AIRBORNE PARTICULATE DISPERSION	VOLATILIZATION	DISSOLUTION	CONDITIONAL PROBABILITIES (P_{im})		EXPECTED BIOSPHERE RELEASE FRACTION (RF_{ijqr})	
					TABLES	EQUATIONS	TABLES	EQUATIONS
Reprocessing Plant - Handling	1,2	--	A.2-1 A.2-2 A.2-5 A.2-6	--	--	A.3-2	--	--
Reprocessing Plant - Interim Storage Loss of Cooling Circulation	3,4	--	A.2-3 A.2-4 A.2-5 A.2-6	--	--	A.3-6	--	A.3-8
Reprocessing Plant - Interim Storage Pool Drainage	5	--	A.2-3 A.2-4 A.2-5 A.2-6	--	--	A.3-9	--	A.3-11
Truck - Impact	6,7, 8,9	A.2-1 A.2-2 A.2-5 A.2-7	--	A.2-8	A.3-3	--	A.3-4 A.3-5 A.3-6	A.3-12 A.3-14 to A.3-20
Truck - Fire	10,11	A.2-1 A.2-2 A.2-5 A.2-6	A.2-1 A.2-2 A.2-5 A.2-6	A.2-8	A.3-3	--	A.3-7 A.3-8	A.3-13 A.3-21 to A.3-27
Train - Impact	14,15	A.2-1 A.2-2 A.2-5 A.2-7	--	A.2-8	A.3-3	--	A.3-4 A.3-5 A.3-6	A.3-12 A.3-14 to A.3-20
Train - Fire	16,17	A.2-1 A.2-2 A.2-5 A.2-6	A.2-1 A.2-2 A.2-5 A.2-6	A.2-8	A.3-3	--	A.3-7 A.3-8	A.3-13 A.3-21 to A.3-27
Repository - Handling	20,21	--	A.2-1 A.2-2 A.2-5 A.2-6	--	--	A.3-31	--	--
Repository - Storage	22	A.2-1 A.2-2 A.2-5 A.2-6	A.2-1 A.2-2 A.2-5 A.2-6	--	--	A.3-28	--	A.3-30

A.3.2 Fuel Reprocessing Plant Handling Accidents

The accidents analyzed at the fuel reprocessing plant involve a crane stall or drop during HLSW handling operations, coupled with the independent event of failure or non-failure of the building's air filtration system.

The conditional accident probabilities represent the probability per hour of a crane accident and the nominal number of hours each canister is handled:

$$\prod_{m=1}^2 P_{im} = \left(3.0 \times 10^{-6} \frac{\text{drops}^*}{\text{hr}} + 1.5 \times 10^{-6} \frac{\text{stalls}^{\dagger}}{\text{hr}} \right) \left(\frac{1}{3} \frac{\text{hr}}{\text{canister}} \right)$$

$$= 1.5 \times 10^{-6} \text{ (probability of exposure of canisters to handling accidents)}$$

(A.3-2)

The handling time per canister is an estimated value based on the water basin storage concept shown in Chapter 21 of Ref. A.3.

To compute the expected biosphere release fraction from handling accidents, both the pathway probabilities and the expected waste release fractions must be determined. The pathway probabilities for handling accidents at the reprocessing plant, PP_{ij} , are expressed as the product of three elements relating to the building's filter performance: the fraction of released volatiles reaching the filter; the probability that the filter works (or fails) for one week (the assumed time needed for cleanup of an accident); and the fraction of volatiles passed by a working (or failed) filter.

*Ref. A.2

†Conversations with Mr. Norman Smith, Materials Handling Institute.

Volatiles; Filter Works:

$$\begin{aligned}
 PP_{ij} &= \left(10^{-2} \frac{\text{volatiles reaching filter}}{\text{volatiles released in accident}}^* \right) (1.0^\dagger) \\
 &\quad \times \left(10^{-9} \frac{\text{volatiles passed by working filter}^\ddagger}{\text{volatiles reaching filter}} \right) \\
 &= 10^{-11}
 \end{aligned}
 \tag{A.3-3}$$

Volatiles; Filter Fails:

$$\begin{aligned}
 PP_{ij} &= \left(10^{-2} \times 1.92 \times 10^{-8}^\S \right) \\
 &= 1.92 \times 10^{-10}
 \end{aligned}
 \tag{A.3-4}$$

Releases Via Airborne Particulate Dispersion and Dissolution:

$$PP_{ij} = 0 \tag{A.3-5}$$

The pathway probabilities for radioactive release via airborne particulate dispersion and dissolution are zero due to an assumed lack of airborne dispersion energy sources and surface water pathways in reprocessing plant accidents.

However, the expected waste release fraction, $E[F_{ijqr}]$, is zero for all solid forms and radionuclides since HLSW has been shown not to fail in handling accidents.[¶] Thus, by Eq. A.3-1, the biosphere release fraction, RF_{ijqr} , is also

*Ref. A.1.

†This is the probability of filter success for one week, and is actually $(1 - 1.92 \times 10^{-8})$.

‡Ref. A.4 (a 3-stage silica-gel filter is assumed).

§Ref. A.2 (probability of filtration failure in a random 1-week interval).

¶Ref. A.1.

zero and there is no expected dose to man from handling accidents at the reprocessing plant.

A.3.3 Fuel Reprocessing Plant Interim Storage Accidents

The expected dose equations for interim storage accidents (Eqs. A.2-3 and A.2-4) must account for an age-varying risk since HLSW cools down and decays while in storage. For all other pre-emplacement accidents there is no age-varying risk since the expected dose calculations are performed at one specified waste age for each accident.

The factors which must be included in the integration of interim storage risk over waste age are:

- t_s , the lower limit of integration in Eqs. A.2-3 and A.2-4.
- t_{iq}^F , the upper limit of integration in Eqs. A.2-3 and A.2-4. Its value is a function of the degree of canister heatup in an accident, which depends on the HLSW age, the degree of separation of HLSW of different ages in the pool, and the inter-canister separation distance. The nominal values of t_{iq}^F are summarized in Table A.3-2.
- $Q_T(t)$, the radionuclide inventory function that is integrated over waste age (see Section A.4.1).

Loss-of-Cooling-Circulation Accident - In the loss-of-cooling-circulation accident, a mechanical failure is assumed to cause a loss of circulation and cooling of the water in the interim storage pool, followed by a loss of the makeup water supply and a boiloff of the pool's water. The independent event of failure or proper operation of the building's filtration system is also considered.

TABLE A.3-2
NOMINAL FAILURE THRESHOLD AGES OF WASTES
IN INTERIM STORAGE ACCIDENTS

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ACCIDENT TYPE	UNITS OF FAILURE THRESHOLD AGE, t_{iq}	WASTE FORM			
		SPRAY CALCINE (q=1)	BOROSILICATE GLASS (q=2)	FLUIDIZED BED CALCINE (q=3)	MULTIBARRIER WASTE FORM (q=4)
Interim Storage - Loss of Cooling Circulation (i=3,4)	yr	2.0*	2.0*	2.0*	2.0*
Interim Storage - Drainage of Pool (i=5)	yr	3.0†	3.0†	3.0†	3.0†

*Assumed values.

†Thermal calculations, per Appendix B, for a nominal inter-canister spacing of 1.5 ft and segregation by waste age in the pool.

The conditional accident probabilities are:

$$\begin{aligned}
 {}^2_{m=1} P_{im} &= \left(10^{-1} \frac{\text{cooling circulation failures}^\ddagger}{\text{year}} \right) \left(10^{-6}{}^\S \right) \\
 &= 10^{-7}/\text{yr} \qquad \qquad \qquad (\text{A.3-6})
 \end{aligned}$$

Note that the product has dimensions of yr^{-1} , which cancels the time units that arise when performing the integrations in Eqs. A.2-3 and A.2-4.

The pathway probabilities relating to filter performance in these accidents, PP_{ij} , are identical to those for handling accidents (Eqs. A.3-3 through A.3-5):

‡Ref. A.2.

§Ref. A.2 (probability of non-restoration of cooling resulting in boiloff).

$$PP_{ij} = \begin{cases} 1.0 \times 10^{-11} & \text{for volatilization when the filter works for one week after the accident} \\ 1.92 \times 10^{-10} & \text{for volatilization when the filter fails within one week after the accident} \\ 0 & \text{for airborne particulate dispersion and dissolution.} \end{cases}$$

(A.3-7)

The expected waste release fractions, $E[F_{ijqr}]$, are set to an assumed worst-case value of one for all volatile radionuclides[†] released in this accident and to zero for all other radionuclides. Substituting the pathway probabilities and expected waste release fractions into Eq. A.3-1, the expected biosphere release fractions for glass and multi-barrier waste exposed to interim storage loss-of-pool-cooling accidents are:

$$RF_{ijqr} = \begin{cases} 1.0 \times 10^{-11} & \text{for volatile radionuclides[†] released when the filter works for one week after the accident,} \\ 1.92 \times 10^{-10} & \text{for volatile radionuclides[†] released when the filter fails within one week after the accident,} \\ 0 & \text{for all other radionuclides.} \end{cases}$$

(A.3-8)

[†]Volatile radionuclides released in each of the three interim storage accident include ^{103}Ru , ^{106}Ru , ^{127m}Te , ^{127}Te , ^{129m}Te , ^{129}Te , ^{134}Cs and ^{137}Cs (from conversations with R. Van Konynenburg, Lawrence Livermore Laboratory).

As a consequence of these results and the remaining computations indicated in Eqs. A.2-3 and A.2-4, the expected dose to man from interim storage loss-of-cooling-circulation accidents is small compared to other components of total pre-emplacment dose. See Section A.6 for further detail.

Pool Drainage Accident - The pool drainage accident scenario involves a damaging earthquake of Mercalli intensity IX or greater and the resulting rupture and complete drainage of the pool.

The conditional accident probabilities governing this accident are:

$$\prod_{m=1}^2 P_{im} = \left(10^{-5} \frac{\text{severe earthquakes}^*}{\text{year}} \right) \times \left(10^{-1} \frac{\text{pool drainage events}}{\text{severe earthquake}} \right) \quad (\text{A.3-9})$$

The probability of pool drainage given a severe earthquake is an estimate based on best engineering judgment. Note that the product of the conditional probabilities has dimensions of yr^{-1} , which cancels the time units that arise when performing the integrations in Eqs. A.2-3 and A.2-4.

Since the event causing the pool drainage is also assumed to rupture the building containing the pool, the pathway probabilities are as follows:

$$PP_{ij} = \begin{cases} 1 & \text{for volatilization,} \\ 0 & \text{for airborne particulate dispersion} \\ & \text{and dissolution.} \end{cases} \quad (\text{A.3-10})$$

*Ref. A.2.

Again, a pathway probability of zero has been assigned to release via airborne particulate dispersion and dissolution due to an assumed lack of airborne dispersion energy sources and surface water pathways in reprocessing plant accidents.

Substituting these pathway probabilities and an expected waste release fraction of 1* for all volatile radionuclides into Eq. A.3-1 yields the following biosphere release fractions for glass and multibarrier waste exposed to interim storage pool drainage accidents:

$$RF_{ijqr} = \begin{cases} 1 & \text{for volatile radionuclides,} \\ 0 & \text{for all other radionuclides.} \end{cases} \quad (A.3-11)$$

All volatile radionuclides are thus presumed to be released to the biosphere given a pool drainage accident. This fact coupled with the relatively high accident probability of 10^{-6} /yr makes the pool drainage scenario one of the major contributors to total expected dose from all pre-emplacment accidents. See Section A.6 for further detail.

A.3.4 Transportation to Repository Site: Truck and Train Accidents

Accidents can occur during shipment of HLSW from the reprocessing plant to the repository via truck or train. The major accidents of concern during these shipments are impact accidents resulting in the potential release of HLSW via airborne particulate dispersion or dissolution, and fire accidents that can result in release via airborne particulate

*The probability of canister failure given exposure to a pool drainage accident is 1 for glass and multibarrier wastes younger than the failure threshold age, and the waste release fraction given canister failure is 1 (due to the assumed long period of elevated temperatures following a drainage accident -- Appendix B), yielding a nominal expected waste release fraction of 1.

dispersion, dissolution or volatilization. Puncture accidents have been shown to have an expected biosphere release fraction (RF_{ijqr}) of zero and thus always have an expected dose of zero (Ref. A.1).

The conditional accident probabilities are summarized in Table A.3-3. They represent the probability per mile of a train or truck accident of any kind, the nominal number of miles traveled per trip to the repository, the probability of an impact or fire accident given a truck or train accident of any kind and the estimated probability that an accident occurs in an urban or rural area. It is assumed that all canisters carried in a truck or rail car shipment are exposed to breach in impact and fire accidents.

The pathway probability is the assumed frequency at which "natural" pathways are available to assist in the release of radionuclides from impact and fire accidents. These include the availability of an energy source for airborne particulate dispersion or the presence of a water pathway (ditch, stream, river, etc.) for dissolution of HLSW, and are summarized in Table A.3-4. Note that the probability of the presence of an energy source for airborne dispersion is 0.1 for impact accidents, but rises to 1.0 for fire accidents. This is due to the assumption that a fire of sufficient size to breach the cask will contain sufficient energy to disperse the waste. Volatilization is assumed to proceed without the need of any additional energy source once the canisters in the cask are reached in a fire accident, so its pathway probability is 1.0.

The equation for computing the expected fraction of HLSW released to the biosphere in transportation accidents has one of two forms. For impact accidents, the waste release function is $F_{ijqr}(v)$, where v is a random variable denoting train or truck velocity at impact:

TABLE A.3-3
CONDITIONAL PROBABILITIES FOR TRUCK AND TRAIN ACCIDENTS

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ACCIDENT	LOCATION	ACCIDENT INDEX (i)	CONDITIONAL PROBABILITIES (P_{im})				
			(m=1)	(m=2)	(m=3)	(m=4)	
TRUCK			P (TRUCK ACCIDENT OF ANY KIND PER MILE)	NOMINAL NUMBER OF MILES PER SHIPMENT	P (ACCIDENT OF TYPE 1 GIVEN AN ACCIDENT)	P (URBAN ACCIDENT GIVEN AN ACCIDENT)	P (RURAL ACCIDENT GIVEN AN ACCIDENT)
Impact on an Extremely Rigid Fixed Object	Urban	6	$2.5 \text{ E}-6/\text{mi}^*$	$1.50 \text{ E}3 \text{ mi}^\dagger$	$5.1 \text{ E}-2^*$	$5.0 \text{ E}-1$	--
	Rural	7	↓	↓	--	--	$5.0 \text{ E}-1$
Impact by Train in a Crossing Accident	Urban	8	↓	↓	$3.1 \text{ E}-3^\ddagger$	$5.0 \text{ E}-1$	--
	Rural	9	↓	↓	--	--	$5.0 \text{ E}-1$
Fire	Urban	10	↓	↓	$1.0 \text{ E}-2^5$	$5.0 \text{ E}-1$	--
	Rural	11	↓	↓	--	--	$5.0 \text{ E}-1$
Puncture	Urban	12	↓	↓	$2.0 \text{ E}-1^*$	$5.0 \text{ E}-1$	--
	Rural	13	↓	↓	--	--	$5.0 \text{ E}-1$
TRAIN			P (RAILCAR ACCIDENT OF ANY KIND PER MILE)	NOMINAL NUMBER OF MILES PER SHIPMENT	P (ACCIDENT OF TYPE 1 GIVEN AN ACCIDENT)	P (URBAN ACCIDENT GIVEN AN ACCIDENT)	P (RURAL ACCIDENT GIVEN AN ACCIDENT)
Impact on an Extremely Rigid Fixed Object	Urban	14	$1.6 \text{ E}-6/\text{mi}^*$	$1.50 \text{ E}3 \text{ mi}^\dagger$	$5.1 \text{ E}-2^*$	$5.0 \text{ E}-1$	--
	Rural	15	↓	↓	--	--	$5.0 \text{ E}-1$
Fire	Urban	16	↓	↓	$3.7 \text{ E}-2^5$	$5.0 \text{ E}-1$	--
	Rural	17	↓	↓	--	--	$5.0 \text{ E}-1$
Puncture	Urban	18	↓	↓	$5.5 \text{ E}-1^*$	$5.0 \text{ E}-1$	--
	Rural	19	↓	↓	--	--	$5.0 \text{ E}-1$

*Ref. A.5.

†Ref. A.1.

‡Value is figure of 6.2×10^{-3} from Ref. A.5 multiplied by a derating factor of 0.5 to account for the fact that major energy is dissipated on the tank only when the locomotive frame impacts on it.

⁵Value is 1.6×10^{-2} from Ref. A.5 for truck fires, or 5.9×10^{-2} for railcar fires, multiplied by a derating factor of 0.625 (from conversations with A. Dennis, Sandia Laboratories) to account for the fact that no other cargo is carried.

TABLE A.3-4
 PATHWAY PROBABILITIES FOR TRUCK AND TRAIN ACCIDENTS
 T-1767

ACCIDENT	PATHWAY PROBABILITY (PP _{ij})		
	AIRBORNE PARTICULATE DISPERSION	VOLATILIZATION	DISSOLUTION
Truck and Train Impact and Puncture (i=6,7,8,9,12,13,14,15,18,19)	0.1	0.0	0.01
Truck and Train Fire (i=10,11,16,17)	1.0	1.0	0.01

$$RF_{ijqr} = PP_{ij} E[F_{ijqr}(v)] \quad (A.3-12)$$

For fire accidents, the release function is $F_{ijqr}(T)$, where T is a random variable denoting the fire temperature:

$$RF_{ijqr} = PP_{ij} E[F_{ijqr}(T)] \quad (A.3-13)$$

The remainder of this section will address the calculations used to evaluate $E[F_{ijqr}(v)]$ and $E[F_{ijqr}(T)]$.

Truck and Train Impact Accidents - The following impact accident scenarios are assumed:

- Urban and rural truck impact onto an extremely rigid fixed object

- Urban and rural train impact onto a truck cask in a crossing accident
- Rural train impact onto an extremely rigid fixed object.

A sixth scenario, that of urban train impact onto an extremely rigid fixed object, has an expected biosphere release fraction of zero due to the 40 mph speed restrictions assumed for urban trains and the fact that no release is expected for impact at velocities less than 40 mph.

For each of these accidents, the expected waste release fraction is

$$E[F_{ijqr}(v)] = \int_{v=0}^{v_{fi}} p_i(v) F_{ijqr}(v) dv; \quad (A.3-14)$$

where

$F_{ijqr}(v)$ is as described in Section A.3.1

$p_i(v)$ = the probability density function (pdf) of impact velocity v for accident type i (1/mph)

v_{fi} = an "upper-credible" impact velocity for accident type i (mph)

An upper-credible velocity was selected for each impact accident and used as an upper limit in the expected release fraction integration. This was done to eliminate as much of the uncertainty introduced by the pdf tail at high severity values as possible. The values chosen were:

$$v_{fi} = 120 \text{ mph for urban impact accidents,} \quad (A.3-15)$$

$$v_{fi} = 180 \text{ mph}^* \text{ for rural impact accidents.} \quad (A.3-16)$$

*Maximum attainable free-fall velocity into a gorge 1050 feet deep.

The following functional form was assumed for each of the three impact velocity probability density functions:

$$p_i(v) = (\alpha_{2i}/\alpha_{1i}) \exp\left[-(v/\alpha_{1i})^{\alpha_{2i}}\right] (v/\alpha_{1i})^{(\alpha_{2i}-1)} \quad (A.3-17)$$

where α_{2i} and α_{1i} are parameters estimated via a fit to empirical data. This is a two-parameter Weibull probability density function, which has been shown (Ref. A.5) to exhibit flexibility in fitting a wide variety of empirical distributions. The values of the estimated parameters α_{1i} and α_{2i} and sources of data used are summarized in Table A.3-5. A detailed discussion of the techniques used to estimate values for α_{1i} and α_{2i} can be found in Section C.3.2 of Appendix C.

TABLE A.3-5
SUMMARY OF ESTIMATED PARAMETER VALUES FOR TRANSPORTATION
IMPACT ACCIDENT PROBABILITY DENSITY FUNCTIONS

T-176R

ACCIDENT TYPE	INDEX 1	SOURCE IN REF. A.5	ASSUMPTIONS	ESTIMATED PARAMETER VALUES		RANGE OF CALIBRATION
				α_{1i}	α_{2i}	
<u>Truck</u>						
Impact on extremely rigid fixed object	6.7	Vol. III, Fig. 4 (Overturn curve)		46.41	3.03	40-75 (mph)
Impact of train on truck	8.9	Vol. IV, Table II		10.49	0.82	5-70 (mph)
<u>Train</u>						
Impact on extremely rigid fixed object - rural areas	15	Vol. IV, Table III	Half of all accidents in each 5-mph group under 40 mph occur in urban areas; the other half occur in rural areas. All accidents at speeds exceeding 40 mph occur in rural areas	30.49	1.703	40-70 (mph)

The release functions for impact accidents, $F_{ijqr}(v)$, assume one of the following functional forms (Ref. A.8):

- Step-ramp-step function - This function describes airborne particulate dispersion and dissolution releases from impact accidents involving borosilicate glass or multibarrier waste:

$$F_{ijqr}(v) = \begin{cases} 0, & v < v_0 \\ A + B(v - v_0), & v_0 \leq v \leq \frac{1-A}{B} + v_0 \\ 1, & v > \frac{1-A}{B} + v_0. \end{cases} \quad (A.3-18)$$

- Ramp-step function - This function describes airborne particulate dispersion releases from impact accidents involving spray or fluidized bed calcine waste:

$$F_{ijqr}(v) = \begin{cases} 0, & v \leq v_0 \\ \frac{B}{A}(v - v_0), & v_0 < v \leq v_0 + A \\ B, & v > v_0 + A. \end{cases} \quad (A.3-19)$$

- Step function - This function describes dissolution releases from impact accidents involving spray or fluidized bed calcine waste:

$$F_{ijqr}(v) = \begin{cases} 0, & v < v_0 \\ A, & v \geq v_0. \end{cases} \quad (A.3-20)$$

Table A.3-6 associates each release function $F_{ijqr}(v)$ with its proper functional format and the corresponding values of parameters v_0 , A and B . Note that the species of escaping

TABLE A.3-6
NOMINAL WASTE RELEASE FUNCTIONS FOR TRUCK AND TRAIN IMPACT ACCIDENTS

T-1772

RELEASE MECHANISM*	WASTE FORM	ESCAPING RADIO- NUCLIDES	EQUATION SHOWING FORM OF RELEASE FUNCTION	RELEASE FUNCTION PARAMETER VALUES†			RADIONUCLIDES HAVING ZERO RELEASE AT ALL ACCIDENT SEVERITIES
				v ₀ (mph)	A	B	
Airborne Particulate Dispersion	Spray Calcine	All	A.3-19	67	8.0	5.0 E -1	None
	Borosilicate Glass	All	A.3-18	67	1.0 E -4	7.69 E -6	None
	Fluidized Bed Calcine	All	A.3-19	67	8.0	1.0 E -1	None
	Multibarrier Waste Form	All	A.3-18	67	1.0 E -6	7.69 E -8	None
Volatilization	All	None	--	--	--	--	All
Dissolution	Spray Calcine	Sr and Cs	A.3-20	67	1.0	--	All <u>except</u> Sr and Cs
	Borosilicate Glass	All	A.3-18	67	1.0 E -4	3.08 E -5	None
	Fluidized Bed Calcine	Sr and Cs	A.3-20	67	4.0 E -1	--	All <u>except</u> Sr and Cs
	Multibarrier Waste Form	All	A.3-18	67	1.0 E -6	3.08 E -7	None

- *Note: ● For airborne particulate dispersion, the release function represents the fraction of escaping radionuclides released as particulates less than 10 μ in diameter.
- For dissolution, the release function represents the fraction of escaping radionuclides released to water in one day.

†Source: Ref. A.8.

radionuclides vary from release function to release function depending on the release mechanism and HLSW form. For example, all radionuclides in the two calcine waste forms are assumed to be released through particulate dispersion, but only Cs and Sr are assumed to be released via dissolution.

Truck and Train Fire Accidents - Fire accidents, as described in Chapter 2, consist of long time, high temperature fires that completely surround the transportation cask. The primary failure mechanism is considered to be breaching of the cask lid seal, followed by thermally accelerated corrosion of the canisters by the waste* once the failure threshold temperature is reached. Appendix B contains a complete description of the thermal analysis upon which this discussion is based.

Since the severity of fire accidents is measured by two variables, fire time and temperature (Ref. A.5), the analysis becomes somewhat more complex than that for impact accidents. In previous fire accident analyses (Refs. A.5 and A.6), these variables were combined to form a composite measure of fire severity: the fire temperature-time product. Although this was a simplified and convenient measure of fire severity, it lacked the descriptiveness needed to correctly represent certain fire environments. For instance, a high temperature-short duration fire could have the same severity index as a low temperature-long duration fire, when in fact the former was a far more damaging fire. To circumvent this difficulty, the fire accident failure locus approach was conceived. Appendix B has a complete discussion.

The failure locus is a curve of fire temperature versus canister time-to-failure and is derived by:

*Or failure of the waste coating in the case of multibarrier waste.

- Obtaining curves of HLSW canister temperatures versus fire time for a discrete number of high-severity fires (in excess of 2100°F) for both the truck and rail car reference casks.
- Drawing a horizontal line representing the known failure temperature* corresponding to each waste form across these curves. The times at which the curves intersect this line are the failure times associated with each curve's fire temperature.
- Plotting failure time for each waste form versus fire temperature for truck and rail car, then fitting an analytic function to each set of locus points so obtained.

The analytic function selected for the failure locus, as discussed in Appendix B, is

$$t = 60 \left[\alpha - \beta \ln (T - T_c) \right] \quad (\text{A.3-21})$$

where

t = time interval from the beginning of the fire until failure (min)

T = fire temperature (°F)

T_c = temperature at which thermally accelerated failure of the canister wall (or failure of the coating of multibarrier waste) occurs for HLSW of a given form (°F)

α, β = parameters estimated via a least-squares fit to the data.

*This is the coating failure temperature in the case of multibarrier waste, since it is greater than the canister failure temperature (Ref. A.8).

Table A.3-7 contains the values of α , β and T_c used in the subsequent analyses of this section. Figures describing these loci can be found in Appendix B.

TABLE A.3-7
NOMINAL PARAMETER VALUES USED IN THE FAILURE LOCUS EQUATION
FOR TRUCK AND TRAIN FIRES*

T-1769

ACCIDENT	WASTE FORM	NOMINAL FAILURE TEMPERATURE (°C)	NOMINAL FAILURE TEM- PERATURE (T _c) (°F)	α	β
Truck Fire	Spray and Fluidized Bed Calcine	1300	2372	4.90	0.577
	Multibarrier Waste Form				
	Borosilicate Glass	1200	2192	5.21	0.627
Train Fire	Spray and Fluidized Bed Calcine	1300	2372	27.1	3.98
	Multibarrier Waste Form				
	Borosilicate Glass	1200	2192	17.7	2.35

*Source: Appendix B.

Once the failure locus has been established, one can perform the expected release function calculation by integrating the fire temperature and time probability distributions with the release function $F_{ijqr}(T)$ over the temperature-time "failure space" above the failure locus. This is expressed analytically as:

$$E[F_{ijqr}(T)] = \int_{T=T_c+\epsilon}^{\infty} F_{ijqr}(T) p_i(T) \left[\int_{t=60[\alpha-\beta \ln(T-T_c)]}^{\infty} p_i(t) dt \right] dT$$

(A.3-22)

where

$p_i(t)$ = the probability density function of
fire time t for accident type i
(min^{-1})

$p_i(T)$ = the probability density function of
fire temperature T for accident type
 i ($^{\circ}\text{F}^{-1}$)

ϵ = a small positive increment of tempera-
ture that is used to begin the numeri-
cal integration process at a temperature
just greater than T_c . T cannot equal T_c
because of the $\ln(T-T_c)$ term in the
locus equation (Eq. A.3-21).

The probability density functions for fire times,
obtained from Vols. III and IV of Ref. A.5, are:

- For truck fires;

$$p_i(t) = \begin{cases} 0.032t^{0.38} \exp\left[-\left(\frac{t}{15.3}\right)^{1.38}\right], & \\ 0 \leq t \leq 20 \text{ min} & \\ \frac{0.023}{(t-20)^{0.448}} \exp\left[-\left(\frac{t-20}{24.3}\right)^{0.552}\right], & \\ t > 20 \text{ min.} & \end{cases} \quad (\text{A.3-23})$$

- For train fires;

$$p_i(t) = \begin{cases} 0.0025t^{0.807} \exp\left[-\left(\frac{t}{38.2}\right)^{1.807}\right], & \\ 0 \leq t \leq 50 \text{ min} & \\ 0.0019 \exp\left[-\left(\frac{t-50}{104}\right)\right], & \\ t > 50 \text{ min.} & \end{cases} \quad (\text{A.3-24})$$

Ref. A.7 yields the following probability density functions for train and truck fire temperatures:

$$P_i(T) = \begin{cases} 0, & T \leq 1400 \text{ } ^\circ\text{F} \\ 1.5 \times 10^{-3} - 6.0 \times 10^{-9}(T-1900)^2, & 1400 \text{ } ^\circ\text{F} < T \leq 2400 \text{ } ^\circ\text{F} \\ 0, & T > 2400 \text{ } ^\circ\text{F}. \end{cases} \quad (\text{A.3-25})$$

The release functions for all truck and train fire accidents, $F_{ijqr}(T)$, assume one of the following functional forms (Ref. A.8):

- Arrhenius function (Refs. A.6 and A.8) - This function describes the rate of release via volatilization from all four waste forms for temperatures that exceed T_c , the failure temperature. To determine total release it is assumed that the canister temperature and therefore the release rate are roughly constant over a four hour period that corresponds to the thermal response time of a large shipping cask.

$$F_{ijqr}(T) = \begin{cases} 0, & T \leq T_c \\ Ae^{-B/T_K}, & T_c < T \leq \frac{9}{5} \left[\frac{B}{\ln A} - 273.16 \right] + 32 \\ 1, & T > \frac{9}{5} \left[\frac{B}{\ln A} - 273.16 \right] + 32. \end{cases} \quad (\text{A.3-26})$$

Here, T_K is in degrees Kelvin and T is in $^\circ\text{F}$.

- Step function - This function describes release via airborne particulate dispersion and dissolution from all four waste forms (except for glass dispersion, whose release function is zero):

$$F_{ijqr}(T) = \begin{cases} 0, & T < T_c \\ A, & T \geq T_c \end{cases} \quad (A.3-27)$$

Table A.3-8 associates each release function $F_{ijqr}(T)$ with its proper functional format and the corresponding values of parameters T_c , A and B .

This concludes the discussion of the derivation of transportation accident expected release fractions. Section A.6 summarizes the expected dose to man from pre-emplacement accidents involving high-level solidified waste.

A.3.5 Repository Site Storage Accidents

The assumed storage accident at the repository site involves a plane crashing into a shipping cask awaiting off-loading outside the repository building, causing release via airborne particulate dispersion and volatilization.

The conditional accident probabilities represent the probability per square mile per year of a plane crash, the average area a cask presents to a plane crash, and the nominal time spent by a cask outside the repository building awaiting off-loading:

$$\begin{aligned} \sum_{m=1}^3 P_{im} &= \left(1.27 \times 10^{-10} \frac{\text{crashes}^*}{\text{mi}^2\text{-yr}} \right) \left(3.22 \times 10^{-5} \text{mi}^2{}^\dagger \right) \\ &\quad \times \left(1.92 \times 10^{-2} \frac{\text{yr storage}}{\text{cask}} \right) \\ &= 7.85 \times 10^{-17} \text{ (probability of exposure of} \\ &\quad \text{canisters to storage accidents at the} \\ &\quad \text{repository site)} \end{aligned} \quad (A.3-28)$$

*Ref. 2.

†Nominal cask area presented to an air crash, using dimensions found in Appendix B. This value may not be an accurate estimate of the collision cross-section, but is sufficient as an order-of-magnitude estimate.

TABLE A.3-8
NOMINAL WASTE RELEASE FUNCTIONS FOR TRUCK AND TRAIN FIRE ACCIDENTS

T-1773

THE ANALYTIC SCIENCES CORPORATION

RELEASE MECHANISM*	WASTE FORM	ESCAPING RADIO-NUCLIDES	EQUATION SHOWING FORM OF RELEASE FUNCTION	RELEASE FUNCTION PARAMETER VALUES†			RADIONUCLIDES HAVING ZERO RELEASE AT ALL ACCIDENT SEVERITIES
				T _c (DEG F)	A	B	
Airborne Particulate Dispersion	Spray and Fluidized Bed Calcine	All	A.3-27	2372	1.0 E -2	--	None
	Borosilicate Glass	None	--	--	--	--	All
	Multibarrier Waste Form	All	A.3-27	2372	1.0 E -4	--	None
Volatilization	Spray and Fluidized Bed Calcine	Cs	A.3-26	2372	1.74	7.6 E 3	All <u>except</u> Cs
		Ru	A.3-26	2372	2.36 E 6	2.79 E 4	All <u>except</u> Ru
	Borosilicate Glass	Cs	A.3-26	2192	8.13 E 6	2.92 E 4	All <u>except</u> Cs
	Multibarrier Waste Form	Cs	A.3-26	2372	5.89 E 6	3.37 E 4	All <u>except</u> Cs
Dissolution	Spray and Fluidized Bed Calcine	Sr and Cs	A.3-27	2372	5.0 E -1	--	All <u>except</u> Sr and Cs
	Borosilicate Glass	All	A.3-27	2192	1.0 E -4	--	None
	Multibarrier Waste Form	All	A.3-27	2372	1.0 E -5	--	None

- *Note:
- For airborne particulate dispersion, the release function represents the fraction of escaping radionuclides released as particulates less than 10 μ in diameter.
 - For volatilization, the release function represents the fraction of escaping radionuclides released to the air in four hours.
 - For dissolution, the release function represents the fraction of escaping radionuclides released to water in one day.

†Source: Ref. A.8.

The time spent in storage outside the repository building by the transportation cask is estimated to be one week.

Since there is no building containing the accident, nor any need for an energy source for dispersion other than the post-crash fire, nor a credible chance of release via dissolution, the pathway probabilities for this accident are as follows:

$$PP_{ij} = \begin{cases} 1 & \text{for volatilization and airborne} \\ & \text{particulate dispersion} \\ 0 & \text{for dissolution} \end{cases} \quad (A.3-29)$$

A worst-case expected waste fraction $E[F_{ijqr}]$ of 1 is assumed for all dispersable radionuclides.* Thus, the biosphere release fractions (Eq. A.3-1) for storage accidents at the repository site involving HLSW of each of the four reference forms are:

$$RF_{ijqr} = \begin{cases} 1 & \text{for airborne particulate dispersion} \\ & \text{of all radionuclides in the HLSW} \\ 0 & \text{for volatilization and dissolution} \end{cases} \quad (A.3-30)$$

Although all radionuclides are released given exposure of canisters to an accident, the probability of their exposure to an accident (Eq. A.3-28) is so small as to render the expected dose from this scenario low in comparison to other major pre-emplacement accidents. See Section A.6 for further detail.

*Since all radionuclides in the HLSW are assumed to be ultimately released to the air, the biosphere release fraction for particulate dispersion (which involves all species of radionuclides) is set to 1 and that for volatilization (which involves only certain species of radionuclides) is set to 0 to avoid double-counting volatile radionuclides when computing expected dose.

A.3.6 Repository Site Handling Accidents

A single handling accident at the repository, coupled with the independent event of failure or non-failure of the building's air filtration system, is considered. This accident involves a crane dropping a canister of waste during the process of removing it from the cask and lowering it for final emplacement.

The conditional accident probabilities represent the probability per hour of a crane drop and the nominal number of hours each canister is handled:

$$\begin{aligned} \prod_{m=1}^2 P_{im} &= \left(1.5 \times 10^{-6} \frac{\text{drops}^*}{\text{hr}} \right) \left(\frac{1}{6} \frac{\text{hr}}{\text{canister}} \right) \\ &= 2.5 \times 10^{-7} \text{ (probability of exposure of canisters} \\ &\quad \text{to handling accidents)} \end{aligned} \tag{A.3-31}$$

The handling time per canister is an estimate based on a conceptualized view of the handling operation (Ref. A.3).

The pathway probability relates to the building's filter performance -- those shown in Eqs. A.3-3, A.3-4 and A.3-5 for interim storage are assumed to apply and will not be repeated here.

The expected waste release fraction $E[F_{ijqr}]$ is again assumed to be zero for all release mechanisms, solid forms and radionuclides for the reasons given in Section A.3.2. Thus, by Eq. A.3-1, the biosphere release fraction is zero and there is no expected dose to the general population from handling accidents at the repository site.

*Conversations with Mr. Norman Smith, Materials Handling Institute.

A.4 RADIONUCLIDE INVENTORIES, DOSE COMMITMENT FACTORS
AND DOSIMETRY CALCULATIONS

A.4.1 Inventory of Airborne Radionuclides

In order to compute the expected dose to man from pre-emplacement accidents involving HLSW, the inventory of biologically significant radionuclides capable of airborne release must be known. Table A.4-1 shows these values for each radionuclide of interest at five different waste ages since removal from the reactor. They depend on parameters governing the reactor irradiation rate, the chemical processes used in separating the actinides and fission products from plutonium and uranium, and other processes. All such parameters are fully discussed in Appendix A of Ref. A.6.

Most of the pre-emplacement risk analyses require knowing the value of the inventory, $Q_T(t)$, at only one of the discrete ages for which data are presented in Table A.4-1. For all interim storage risk calculations, however, $Q_T(t)$ must be expressed as a continuous function of waste age in order to perform the integrations indicated in Eqs. A.2-3 and A.2-4. To accomplish this, a separate piecewise-linear function was fit to the discrete data of Table A.4-1 for each radionuclide r .

Explicit inventories of waterborne radionuclides were not needed in the pre-emplacement calculations. Rather, as will be explained in Section A.5.2, the waterborne dosimetry calculations of Appendix G of this report were incorporated directly.

TABLE A.4-1
INVENTORY OF BIOLOGICALLY SIGNIFICANT RADIONUCLIDES IN HLSW

T-1774

RADIONUCLIDE	INDEX r	SOURCE TERM ^a , $Q_r(t)$ (Ci/MWe-yr)				
		t=0.4 yr	t=1.0 yr	t=2.0 yr	t=5.0 yr	t=10.0 yr
⁸⁹ Sr	1	3.0E3	1.7E2	1.4	8.7E-7	0
⁹⁰ Sr	2	2.4E3	2.4E3	2.3E3	2.1E3	1.9E3
⁹¹ Y	3	5.0E3	3.9E2	5.4	1.4E-5	0
⁹⁵ Zr	4	8.6E3	8.7E2	1.9E1	1.7E-4	0
⁹³ Nb	5	1.6E4	1.9E3	4.1E1	3.6E-4	0
¹⁰³ Ru	6	2.8E3	6.5E1	1.1E-1	0	0
¹⁰⁶ Ru	7	1.3E4	8.5E3	4.2E3	5.3E2	1.7E1
¹²⁵ Sb	8	2.5E2	2.2E2	1.7E2	7.9E1	2.2E1
^{127m} Te	9	1.9E2	4.9E1	4.8	4.5E-3	4.1E-8
¹²⁷ Te	10	1.9E2	4.9E1	4.8	4.5E-3	4.1E-8
^{129m} Te	11	2.1E2	2.6	1.6E-3	0	0
¹²⁹ Te	12	1.3E2	1.7	1.0E-3	0	0
¹³⁴ Cs	13	6.7E3	5.5E3	3.9E3	1.4E3	2.6E2
¹³⁷ Cs	14	3.3E3	3.3E3	3.2E3	3.0E3	2.7E3
¹⁴⁴ Ce	15	2.4E4	1.4E4	5.7E3	3.8E2	4.7
¹⁴⁷ Pm	16	3.1E3	2.7E3	2.1E3	9.3E2	2.5E2
¹⁵⁴ Eu	17	2.1E2	2.1E2	2.0E2	1.8E2	1.4E2
²³⁸ Pu	18	1.1	2.5	3.2	3.4	3.2
²⁴⁰ Pu	19	7.6E-2	8.1E-2	9.2E-2	1.2E-1	1.4E-1
²⁴¹ Pu	20	1.8E1	1.7E1	1.6E1	1.4E1	1.0E1
²⁴¹ Am	21	5.4	5.4	5.4	5.4	5.5
²⁴³ Am	22	5.4E-1	5.4E-1	5.4E-1	5.4E-1	5.4E-1
²⁴² Cm	23	4.7E2	1.9E2	4.5E1	4.2E-1	2.2E-1
²⁴⁴ Cm	24	7.8E1	7.6E1	7.3E1	6.5E1	5.4E1

^aSource: Ref. A.6 with errors corrected.

A.4.2 Dose Commitment Factors

Airborne dose to members of the exposed population is considered to result from three processes (Ref. A.6):

- Inhalation of radioactivity from the passing cloud
- Exposure to gamma radiation from radioactivity deposited from the cloud onto the ground
- Ingestion of radioactivity that enters the food chain via the forage-cow-milk-man pathway after having been deposited on the ground from the cloud.

Dose commitment factors have been developed for each of these processes to compute the long-term effects of radiation on man.

The dose commitment factor is a measure of the radiation damage done to specific body organs by specific radionuclides, given certain assumptions regarding:

- The concentration of radioactivity after release to the air or deposition on the ground
- The rate of decay for each radionuclide and the type of radiation each emits
- The time to which an "average" person is exposed to this radioactivity
- The degree to which each radionuclide tends to accumulate in key body organs and the energy imparted to the tissues of these organs by such radionuclides.

In accordance with the procedures outlined in Ref. A.9, dose commitment factors for the three processes described at the beginning of this section have been established. Tables A.4-2 and A.4-3 contain, respectively, the values used in the 50-year inhalation and deposition dose commitment matrices. References A.10 and A.11 have been used as data sources as well as Ref. A.6*. Explicit dose commitment factors for

*Based on suggestions made by Y. Ng of Lawrence Livermore Laboratory in Ref. A.12.

TABLE A.4-2
DOSE COMMITMENT FACTORS FOR BIOLOGICALLY SIGNIFICANT
RADIONUCLIDES IN AIR: INHALATION

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RADIONUCLIDE	INDEX 7	INHALATION DOSE COMMITMENT FACTOR* $DF_{T_y}^1$ (rem-n ³ /Ci-yr)									
		WHOLE BODY (INTERNAL) (u=1)	WHOLE BODY (EXTERNAL) (u=2)	WHOLE BODY EQUIVALENT (INTERNAL) (u=3)	GASTRO- INTESTINAL (LOWER LARGE INTESTINE) (u=4)	THYROID (u=5)	BONE (u=6)	LIVER (u=7)	LUNG (u=8)	KIDNEY (u=9)	SKIN (u=10)
⁸⁸ Sr	1	7.8E6	0	6.3E6	3.2E6	0	2.6E6	0	1.3E9	0	0
⁹⁰ Sr	2	5.6E9		1.8E10	6.6E6		6.1E10	0	8.7E9	0	
⁹¹ Y	3	1.1E7		1.0E9	3.5E6		4.2E6	0	1.6E9	0	
⁹⁵ Zr	4	2.1E7		9.3E6	1.4E6		8.8E7	3.1E7	1.6E9	4.0E7	
⁹⁵ Zr	5	3.6E6		2.9E6	9.5E7		1.3E7	7.1E6	4.6E6	7.0E6	
¹⁰⁰ Ru	6	6.0E5		2.5E6	1.0E6		1.4E6	0	4.6E6	5.3E6	
¹⁰⁶ Ru	7	7.9E6		4.4E6	6.3E6		6.3E7	0	8.6E9	1.2E6	
¹²⁵ Se	8	1.2E7		6.9E6	9.2E7		4.9E7	5.7E5	1.6E9	0	
¹²⁷ Te	9	1.4E6		5.2E6	1.4E6		1.1E7	5.2E6	8.7E6	4.2E7	
¹²⁷ Te	10	2.8E2		2.4E7	5.2E7		1.2E3	5.6E2	8.9E6	4.6E3	
¹²⁹ Te	11	1.4E6		7.2E6	3.3E6		6.9E6	4.3E6	1.1E9	3.3E7	
¹³⁰ Te	12	1.1E7		6.9E6	1.4E6		4.8E1	2.2E1	1.6E6	1.7E2	
¹³⁴ Cs	13	6.6E6		9.4E6	9.5E6		3.4E6	7.7E6	6.9E7	2.8E6	
¹³⁷ Cs	14	3.9E6		6.2E6	7.7E6		4.4E6	5.7E6	6.9E7	3.0E6	
¹³⁷ Cs	15	1.7E6		4.6E9	7.4E6		5.1E9	1.3E9	7.1E9	7.7E6	
¹⁴⁷ Pr	16	2.3E7		3.7E6	4.0E7		6.1E6	5.7E7	4.6E6	1.1E6	
¹⁵⁴ Eu	17	4.7E6		4.0E9	3.5E6		5.4E9	6.6E6	4.3E9	3.2E9	
²⁰⁸ Pu	18	5.1E11		3.8E12	3.3E6		2.0E13	2.8E12	1.3E12	2.2E12	
²⁴⁰ Pu	19	5.7E11		4.2E12	3.1E6		2.3E13	3.2E12	1.3E12	2.4E12	
²⁴¹ Pu	20	9.4E9		6.1E10	6.3E6		4.7E11	2.4E10	1.1E9	4.3E10	
²⁴¹ Am	21	4.9E11		2.6E12	3.4E6		7.4E12	2.6E12	4.4E11	3.7E12	
²⁴² Am	22	4.6E11		2.5E12	3.9E6		7.4E12	2.5E12	4.2E11	3.6E12	
²⁴² Cf	23	7.2E9		2.0E11	5.6E6		1.1E11	1.1E11	2.9E11	3.3E10	
²⁴⁴ Cm	24	2.6E11		1.5E12	3.4E6		4.3E12	1.8E12	4.4E11	1.2E12	

*For internal dose delivered over a 50-year period following a single (acute) inhalation of air (Ref. A.6).

*Source: Ref. A.10.

*Source: Ref. A.11.

waterborne radionuclides were not needed for this analysis;
the dosimetry calculations of Appendix G of this report were
directly applied.

The use of these dose commitment factors in computing
the specific performance indices required for the pre-employment
analysis will now be described.

TABLE A.4-3

DOSE COMMITMENT FACTORS FOR BIOLOGICALLY SIGNIFICANT
RADIONUCLIDES RELEASED TO AIR AND DEPOSITED ON THE GROUND:
INTERNAL AND EXTERNAL EXPOSURE

1-1786

RADIONUCLIDE	INDEX	DEPOSITION DOSE COMMITMENT FACTOR*, DF_{TU}^D (rem-r ² /Ci)									
		WHOLE BODY (INTERNAL) (u=1)	WHOLE BODY (EXTERNAL) (u=2)	WHOLE BODY EQUIVALENT (INTERNAL) (u=3)	GASTRO- INTESTINAL (LOWER LARGE INTESTINE) (u=4)	THYROID (u=5)	BONE [†] (u=6)	LIVER [†] (u=7)	LUNG (u=8)	KIDNEY [†] (u=9)	SKIN (u=10)
⁸⁹ Str	1	4.07 E3	3.0	2.5 E4	2.26 E4	0	1.42 E5	0	0	0	0
⁹⁰ Str	2	1.16 E6	0	1.6 E6	6.49 E4	1	4.84 E6	0		0	
⁹¹ Y	3	2.74 E-2	1.5 E2	2.3 E2	5.65 E2		1.02	0		0	
⁹⁴ Tc	4	4.89 E-1	2.9 E4	9.0 E2	2.24 E3		2.25	7.22 E-1		1.14 E0	
⁹⁵ Ni	5	5.66 E-2	1.6 E4	5.4 E2	7.34 E3		3.07 E-1	5.31 E-1		2.16 E-1	
¹⁰³ Ru	6	1.61 E-2	0	1.8	4.36		3.74 E-2	0		1.42 E-1	
¹⁰⁶ Ru	7	2.26 E-2	0.8 E4	1.9 E1	4.74 E1		7.22 E-1	0		1.42	
¹²⁵ Sb	8	4.01	2.4 E5	1.1 E3	1.76 E2		2.00 E1	2.35 E-1		0	
¹²⁷ I	9	6.49 E1	7.2 E2	3.3 E2	1.77 E3		5.35 E2	1.86 E2		2.16 E2	
¹²⁷ Te	10	0	0	0	0		0	0		0	
¹²⁹ Te	11	1.11 E2	6.8 E3	2.2 E1	3.52 E2		7.00 E2	2.62 E2		2.92 E3	
¹²⁹ Xe	12	0	0	0	0		0	0		0	
¹³⁴ Cs	13	3.78 E5	6.3 E5	7.5 E5	5.06 E5		1.94 E5	4.62 E5		1.50 E5	
¹³⁷ Cs	14	2.30 E5	5.1 E6	7.7 E5	6.76 E5		2.47 E5	3.51 E5		1.19 E5	
¹⁴⁴ Ce	15	0.26 E-1	9.6 E3	7.7 E2	1.43 E3		4.22	1.35		1.05	
¹⁴⁷ Sm	16	2.57 E-2	0	1.2 E1	6.00 E1		6.78 E-1	6.36 E-2		1.20 E-1	
¹⁵⁴ Eu	17	4.88 E-1	1.0 E6	2.0 E2	4.97 E2		5.59	6.87 E-1		5.26	
²³⁸ Pl	18	7.54 E-1	2.9 E4	6.0 E0	3.31		3.06 E3	4.22		5.25	
²⁴⁰ Yb	19	8.54 E-1	8.5 E4	6.5 E0	3.08		3.49 E3	4.72		3.61	
²⁴¹ Pl	20	1.51 E-2	2.5 E5	1.2 E-1	6.34 E-2		7.07 E-1	3.84 E-2		6.92 E-2	
²⁴¹ Am	21	4.78 E2	5.1 E5	2.6 E3	6.75 E2		7.36 E3	1.53 E5		3.60 E3	
²⁴³ Am	22	4.78 E2	3.1 E6	2.6 E3	6.64 E2		7.36 E3	2.46 E3		5.59 E3	
²⁴² Cm	23	6.66	3.0 E4	3.2 E2	6.60 E2		1.30 E2	1.37 E2		4.06 E1	
²⁴⁴ Cm	24	0.61 E2	3.5 E4	1.5 E3	6.85 E2		4.40 E3	1.68 E3		1.22 E3	

*For internal dose delivered over a 50-year period of ingestion of cow's milk contaminated following a single deposition of radioactivity on forage, or for external dose delivered due to 50-year continuous exposure to ground gamma radiation following a single deposition of radioactivity on the ground.

[†]Source: Ref. A.10.

*Source: Ref. A.6.

[†]Source: Ref. A.11.

A.4.3 Dose Calculations

Airborne Releases - There are three major performance measures (Ref. A.6) that can be computed from the expected airborne dose matrices defined in Eqs. A.2-1 to A.2-5:

- Whole-Body Dose - This measure is computed by adding the whole-body inhalation dose, the whole-body internal dose from milk contaminated by radionuclides deposited on the ground and the whole-body external dose due to gamma radiation from radionuclides deposited on the ground:

$$D_{ijqs}^{WB(A)}(x_f) = D_{ijqsu}^I(x_f) \Big|_{u=1} + D_{ijqsu}^D(x_f) \Big|_{u=1} + D_{ijqsu}^D(x_f) \Big|_{u=2} \quad (A.4-1)$$

This equation holds for each waste form (q) and for all accidents (i) involving the release of radionuclides via airborne particulate dispersion or volatilization.

In Eq. A.4-1,

$D_{ijqsu}^I(x_f)$ = expected 50-year inhalation dose matrix, defined in Section A.2.1,

$D_{ijqsu}^D(x_f)$ = expected 50-year deposition dose matrix, defined in Section A.2.1,

$D_{ijqs}^{WB(A)}(x_f)$ = expected 50-year whole-body dose from radionuclides released via airborne mechanism j from a pre-emplacement accident of type i involving waste of form q and age s, integrated over a population out to x_f meters downwind of the accident (man-rem/MWe-yr).

- Whole-Body Equivalent Dose - This measure is "... the whole-body dose that is associated with the same biological risk as a given dose to a specified organ, which may be the 'critical' organ ..." (Ref. A.12). It is computed by adding the whole-body equivalent inhalation dose, the whole-body equivalent internal dose from milk contaminated by radionuclides deposited on the ground, and the whole-body external dose due to gamma radiation from radionuclides deposited on the ground:

$$D_{ijqs}^{EQ(A)}(x_f) = D_{ijqsu}^I(x_f) \Big|_{u=3} + D_{ijqsu}^D(x_f) \Big|_{u=3} + D_{ijqsu}^D(x_f) \Big|_{u=2} \quad (A.4-2)$$

This equation holds for each waste form (q) and for all accidents (i) involving the release of radionuclides via airborne particulate dispersion or volatilization.

In Eq. A.4-2,

$D_{ijqs}^{EQ(A)}(x_f)$ = expected 50-year whole-body equivalent dose from radionuclides released via airborne mechanism j from a pre-emplacement accident of type i involving waste of form q and age s, integrated over a population out to x_f meters downwind of the accident (man-rem/MWe-yr).

- Critical Organ Dose - This measure is computed by finding the maximum of total internal organ dose (inhalation plus deposition) over all organs and then adding the whole-body external dose due to gamma radiation from radionuclides deposited on the ground:

$$D_{ijqs}^{CO(A)}(x_f) = \max_{u=\{4,5,\dots,10\}} \left[D_{ijqsu}^T(x_j) \right] + D_{ijqsu}^D(x_j) \Big|_{u=2} \quad (A.4-3)$$

This equation holds for each waste form (q) and for all accidents (i) involving the release of radionuclides via airborne particulate dispersion or volatilization.

In Eq. A.4-3,

$D_{ijqsu}^T(x_f)$ = expected 50-year total airborne dose matrix, defined in Section A.2.1,

$D_{ijqs}^{CO(A)}(x_f)$ = expected 50-year critical-organ dose from radionuclides released via airborne mechanism j from a pre-emplacement accident of type

i involving waste of form q and age s, integrated over a population out to x_f meters downwind of the accident (man-rem/MWe-yr).

Numerical values of these three dose measures for each pre-emplacement accident are displayed in Section A.6.

Waterborne Releases - Whole-body and critical-organ expected doses are also computed for waterborne releases of radioactivity from pre-emplacement accidents. The computational procedure makes direct use of critical organ results obtained in Appendix G and so is simpler than the airborne dose analysis:

$$D_{ijqs}^{WB(W)} = D_{ijqsu}^W \Big|_{u=1} \quad (j=3) \quad (A.4-4)$$

$$D_{ijqs}^{CO(W)} = D_{ijqsu}^W \Big|_{u=6} \quad (j=3) \quad (A.4-5)$$

where

D_{ijqsu}^W = expected 50-year integrated waterborne dose matrix, defined in Section A.2.1,

$D_{ijqs}^{WB(W)}$ = expected 50-year integrated whole-body dose from waterborne radioactivity released in a pre-emplacement accident of type i involving waste of form q and age s (man-rem/MWe-yr),

$D_{ijqs}^{CO(W)}$ = expected 50-year integrated critical organ (i.e., bone) dose from waterborne radioactivity released in a pre-emplacement accident of type i involving waste of form q and age s (man-rem/MWe-yr).

Equations A.4-4 and A.4-5 apply for each waste form and all accidents involving dissolution of radionuclides from HLSW.

A.5 BIOSPHERE PATHWAY MODELS

A.5.1 Airborne Releases

The meteorology-demography pathway factor $S_1(x_0, x_f)$, defined in Eqs. A.2-6 and A.2-7, is an integral of the product of two functions: a Gaussian diffusion equation governing radioactive cloud concentration and the population density downwind of the accident site.

Meteorology Models - Two basic Gaussian diffusion models are used to describe the airborne spread of radio-nuclides from pre-emplacement accidents.

- A plume model, which describes a continuous emission of airborne radio-activity from the accident site. The plume model is used to describe:
 - Release of volatiles from handling and interim storage accidents at the reprocessing plant
 - Release of volatiles and dispersion of airborne particulates in train and truck fire accidents
 - Release of volatiles from handling accidents at the repository site
 - Dispersion of airborne particulates and volatiles from storage accidents occurring outside the repository building.

The plume model used in Eq. A.2-6 is given by (Ref. A.13):

$$\left[\frac{\bar{X}(x)}{Q} \right] dA(x) = \left(5.6 \times 10^{-8} x^{-1.7} \right) \left(\frac{\pi}{8} x dx \right) \\ = \left(2.2 \times 10^{-8} x^{-0.7} \right) dx \quad (A.5-1)$$

where x is in meters and all other terms are as defined in Section A.2.1.

- A puff model, which describes an instantaneous emission of airborne radio-activity from the accident site. The puff model is used to describe the dispersion of airborne particulates released in train and truck impact and puncture accidents. Ref. A.13 contains a complete description of the puff model and analytic techniques used in computing $S_i(x_0, x_f)$ for instantaneous releases.

Additional factors, defined in Section A.2.1, are assigned the following values for use in Eqs. A.2-1 to A.2-8:

$$v^D = 3.16 \times 10^5 \text{ m/yr}^* \text{ (used to compute the rate of cloud depletion onto the ground)} \quad (\text{A.5-2})$$

$$\bar{u} = 1.58 \times 10^8 \text{ m/yr}^* \text{ (windspeed for D-stability)} \quad (\text{A.5-3})$$

$$x_0 = 1.0 \times 10^2 \text{ m}^* \text{ (inner limit of Gaussian diffusion model calibration)} \quad (\text{A.5-4})$$

$$x_f = 1.0 \times 10^6 \text{ m}^\dagger \text{ (outer limit of population dose integration)} \quad (\text{A.5-5})$$

Demography Models - A generic Gaussian distribution was fit to population profiles surrounding the reprocessing plant (Barnwell, SC), urban (Dallas-Fort Worth, TX) and rural transportation accident locations and the repository site (Nevada Test Site) (Ref. A.13):

*Ref. A.13.

†Ref. A.13 suggests a value of $1.0 \times 10^5 \text{ m}$, but $1.0 \times 10^6 \text{ m}$ was selected to capture as much of the population dose as possible.

$$\rho_i(x) = \begin{cases} (\rho_{ci} - \rho_{si}) \exp[-b_{1i}(kx - x_{ci})^2] + \rho_{si} & (0 \leq kx \leq x_{ci}) \\ (\rho_{ci} - \rho_{ri}) \exp[-b_{2i}(kx - x_{ci})^2] + \rho_{ri} & (kx > x_{ci}) \end{cases}$$

(A.5-6)

where

$\rho_i(x)$ = population density x meters
downwind of an accident of type
 i (man/m²)

$\rho_{ci}, \rho_{si}, \rho_{ri},$
 $k, b_{1i}, b_{2i}, x_{ci}$ = parameters determining the shape
of the Gaussian population density
curve. See Table A.5-1 for the
values used.

TABLE A.5-1
VALUES FOR DEMOGRAPHY EQUATION PARAMETERS

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ACCIDENTS	ACCIDENT INDICES (i)	DEMOGRAPHY EQUATION PARAMETERS*						
		ρ_{ci} (man/m ²)	ρ_{si} (man/m ²)	ρ_{ri} (man/m ²)	b_{1i} (km ⁻²)	b_{2i} (km ⁻²)	x_{ci} (km)	k (km/m)
Reprocessing Plant-Handling and Interim Storage	1,2,3,4,5	1.0E-4	5.0E-6	2.2E-5	8.0E-2	5.0E-2	12	1.0E-3
Truck and Train - Urban Transportation	6,8,10,12, 14,16,18	1.28E-3	1.28E-3	2.2E-5	1.0E-3	1.0E-3	0	1.0E-3
Truck and Train - Rural Transportation	7,9,11,13, 15,17,19	2.2E-5	2.2E-5	2.2E-5	1.0E-3	1.0E-3	0	1.0E-3
Repository Site-Handling and Storage	20,21,22	3.8E-7	0	2.0E-7†	4.0E-3	4.0E-4	45	1.0E-3

*Source: Ref. A.13, except as noted.

†Value chosen by author.

Table A.5-2 summarizes the computed values of the meteorology-demography pathway factors used in overall dose Eqs. A.2-1 to A.2-4.

TABLE A.5-2
VALUES FOR METEOROLOGY-DEMOGRAPHY FACTORS USED IN COMPUTING
EXPECTED AIRBORNE DOSE FROM PRE-EMPLACEMENT ACCIDENTS

T-1783

ACCIDENTS	ACCIDENT INDICES (i)	METEOROLOGY-DEMOGRAPHY PATHWAY FACTOR [*] , $S_2(x_0, x_f)$ (man-yr/m ³)	
		PLUME RELEASES	PUFF RELEASES
Reprocessing Plant-Handling and Interim Storage	1,2,3,4,5	9.84E-11	--
Truck and Train - Urban Impact and Puncture	6,8,12,14,18	--	2.15E-9
Truck and Train - Rural Impact and Puncture	7,9,13,15,19	--	1.28E-10
Truck and Train - Urban Fire	10,16	1.65E-9	--
Truck and Train - Rural Fire	11,17	9.53E-11	--
Repository Site - Handling and Storage	20,21,22	7.10E-13	--

*See Eqs. A.2-6 and A.2-7 for the analytic basis of calculating $S_2(x_0, x_f)$.

A.5.2 Waterborne Releases

The waterborne dose pathway factor, FAC_{rsu}^W , was presented in Eq. A.2-8 as a composite measure of the water pathway release model, the source terms of all soluble radionuclides, and the dose commitment factors for chronic exposure to soluble radionuclides via ingestion. The reader should refer to Appendix G for a full discussion of each of these three measures. Table A.5-3 presents the values of FAC_{rsu}^W used in the analysis of expected pre-emplacement dissolution dose.

TABLE A.5-3
VALUES USED FOR THE WATERBORNE DOSE PATHWAY FACTOR

T-1787a

RADIONUCLIDE	WATERBORNE DOSE PATHWAY FACTOR, $FAC_{rsu}^W * \left(\frac{\text{man-rem}}{\text{MWe-yr}} \right)$		
	WHOLE-BODY (INTERNAL) (u = 1)	BONE (CRITICAL ORGAN) (u = 6)	ALL OTHERS
Sr	5.0 E5	2.1 E6	0
Cs	4.1 E4	4.5 E4	0
All Others	0	0	0

*Source: BIDOSE model described in Appendix G.
The values of FAC_{rsu}^W shown are for ten-year old waste only (s = 5).

A.6 TABLES AND GRAPHS OF EXPECTED DOSE TO MAN

A.6.1 Tables of Expected Dose

A computer code (PREDOSE) has been developed to calculate expected whole-body, whole-body equivalent and critical-organ doses for all pre-emplacement accidents, based on Eqs. A.2-1 to A.2-8 and Eqs. A.4-1 to A.4-5. These doses are displayed on an accident-by accident basis by release mechanism and waste form in Tables A.6-1 to A.6-4. In addition to displaying dose summaries from these individual accidents, these tables present several aggregated dose measures. Aggregated dissolution doses, it should be noted, do not include post-emplacement dose.

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To assist the reader, the following explanation of the titles and abbreviations used in these tables is given:

- "ACCIDENT TYPE" - The full accident name corresponding to each abbreviated name shown in this category appears in Table A.2-1. In most cases the abbreviated names used are sufficiently mnemonic to be recognizable.
- "ORGAN NAME" - "LI" refers to liver and "BO", to bone.
- "TRUCK TOTAL" - Total expected dose from all of the eight truck accidents by release mechanism and dose type.
- "TRAIN TOTAL" - Total expected dose from all of the six train accidents by release mechanism and dose type.
- "OV TOTAL WITH TRUCK" - Total expected dose from the five reprocessing plant accidents, eight truck accidents and three pre-emplacment accidents at the repository by release mechanism and dose type.
- "OV TOTAL WITH TRAIN" - Total expected dose from the five reprocessing plant accidents, six train accidents and three pre-emplacment accidents at the repository by release mechanism and dose type.
- "TOTAL OF VOL, DISP AND DISSOL. DOSES." - Overall whole-body expected dose, obtained by summing the whole-body doses of "OV TOTAL WITH TRUCK" and "OV TOTAL WITH TRAIN," respectively, over each of the three release mechanisms.

TABLE A.6-1
NOMINAL VALUES OF EXPECTED DOSE -- SPRAY CALCINE

EXPECTED DOSE -- MAN-REM/MWE-YR

INDEX	ACCIDENT TYPE	VOLATILIZATION				DISPERSION				DISSOLUTION			
		WHOLE BODY	WHOLE BODY EQ	CRIT. ORGAN	ORGAN NAME	WHOLE BODY	WHOLE BODY EQ	CRIT. ORGAN	ORGAN NAME	WHOLE BODY	CRIT. ORGAN	ORGAN NAME	AGE
1	REPRO-HNDL-ACC.F WK	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		5Y
2	REPRO-HNDL-ACC.F FL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		5Y
3	REPRO-STOR-LOC.F WK	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		5Y
4	REPRO-STOR-LOC.F FL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		5Y
5	REPRO-STOR-DRAINAGE	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		5Y
6	TRUCK-IMPCT.ERFO-UR	0.0	0.0	0.0		1.1E+00	1.2E+00	1.8E+00	BO	2.7E-02	1.0E-01	BO	10Y
7	TRUCK-IMPCT.ERFO-RU	0.0	0.0	0.0		6.4E-02	7.2E-02	1.1E-01	BO	2.7E-02	1.0E-01	BO	10Y
8	TRUCK-CROSSNG AC-UR	0.0	0.0	0.0		1.8E-02	2.9E-02	3.1E-02	BO	3.3E-04	1.3E-03	BO	10Y
9	TRUCK-CROSSNG AC-RU	0.0	0.0	0.0		1.1E-03	1.2E-03	1.8E-03	BO	3.3E-04	1.3E-03	BO	10Y
10	TRUCK-FIRE-URBAN	2.8E-05	2.9E-05	2.9E-05	LI	2.5E-05	2.9E-05	4.3E-05	BO	1.2E-06	4.6E-06	BO	10Y
11	TRUCK-FIRE-RURAL	1.6E-06	1.7E-06	1.7E-06	LI	1.6E-06	1.6E-06	2.3E-06	BO	1.2E-06	4.6E-06	BO	10Y
12	TRUCK-PUNCTUR-URBAN	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
13	TRUCK-PUNCTUR-RURAL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
	TRUCK TOTAL	3.0E-05	3.1E-05	3.1E-05	LI	1.2E+00	1.3E+00	2.0E+00	BO	5.4E-02	2.1E-01	BO	
14	TRAIN-IMPCT.ERFO-UR	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
15	TRAIN-IMPCT.ERFO-RU	0.0	0.0	0.0		2.1E-02	2.4E-02	3.6E-02	BO	7.4E-03	2.9E-02	BO	10Y
16	TRAIN-FIRE-URBAN	1.0E-07	1.1E-07	1.1E-07	LI	9.2E-08	1.0E-07	1.6E-07	BO	4.4E-09	1.7E-08	BO	10Y
17	TRAIN-FIRE-RURAL	6.0E-09	6.2E-09	6.2E-09	LI	5.3E-09	6.0E-09	9.1E-09	BO	4.4E-09	1.7E-08	BO	10Y
18	TRAIN-PUNCTUR-URBAN	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
19	TRAIN-PUNCTUR-RURAL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
	TRAIN TOTAL	1.1E-07	1.1E-07	1.1E-07	LI	2.1E-02	2.4E-02	3.6E-02	BO	7.4E-03	2.9E-02	BO	
20	REPOS-HNDL-ACC.F WK	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
21	REPOS-HNDL-ACC.F FL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
22	REPOS-STOR-INT IMPCT	1.6E-13	1.7E-13	1.7E-13	LI	2.1E-13	2.4E-13	3.6E-13	BO	0.0	0.0		10Y
	OV TOTAL WITH TRUCK	3.0E-05	3.1E-05	3.1E-05	LI	1.2E+00	1.3E+00	2.0E+00	BO	5.4E-02			
	OV TOTAL WITH TRAIN	1.1E-07	1.1E-07	1.1E-07	LI	2.1E-02	2.4E-02	3.6E-02	BO	7.4E-03			
	TOTAL OF VOL. DISP AND DISSOL. DOSES:												
	WITH TRUCK:	1.2E+00											
	WITH TRAIN:	2.8E-02											

TABLE A.6-2
NOMINAL VALUES OF EXPECTED DOSE -- BOROSILICATE GLASS

INDEX	ACCIDENT TYPE	VOLATILIZATION				DISPERSION				DISSOLUTION			AGE
		WHOLE BODY	WHOLE BODY EQ	CRIT. ORGAN	ORGAN NAME	WHOLE BODY	WHOLE BODY EQ	CRIT. ORGAN	ORGAN NAME	WHOLE BODY	CRIT. ORGAN	ORGAN NAME	
1	REPRO-HNDL-ACC.F WK	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		1Y
2	REPRO-HNDL-ACC.F FL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		1Y
3	REPRO-STOR-LOC.F WK	5.3E-13	5.7E-13	5.5E-13	LI	0.0	0.0	0.0		0.0	0.0		1Y
4	REPRO-STOR-LOC.F FL	1.0E-11	1.1E-11	1.1E-11	LI	0.0	0.0	0.0		0.0	0.0		1Y
5	REPRO-STOR-DRAINAGE	9.9E-01	1.1E+00	1.0E+00	LI	0.0	0.0	0.0		0.0	0.0		1Y
6	TRUCK-IMPCT.ERFO-UR	0.0	0.0	0.0		5.4E-04	6.1E-04	9.3E-04	BO	7.7E-06	3.0E-05	BO	10Y
7	TRUCK-IMPCT.ERFO-RU	0.0	0.0	0.0		3.2E-05	3.6E-05	5.5E-05	BO	7.7E-06	3.0E-05	BO	10Y
8	TRUCK-CROSSNG AC-UR	0.0	0.0	0.0		9.7E-06	1.1E-05	1.7E-05	BO	1.9E-07	7.2E-07	BO	10Y
9	TRUCK-CROSSNG AC-RU	0.0	0.0	0.0		5.8E-07	6.6E-07	1.0E-06	BO	1.9E-07	7.2E-07	BO	10Y
10	TRUCK-FIRE-URBAN	7.3E-03	7.6E-03	7.5E-03	LI	0.0	0.0	0.0		2.2E-08	8.4E-08	BO	10Y
11	TRUCK-FIRE-RURAL	4.2E-04	4.4E-04	4.3E-04	LI	0.0	0.0	0.0		2.2E-08	8.4E-08	BO	10Y
12	TRUCK-PUNCTUR-URBAN	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
13	TRUCK-PUNCTUR-RURAL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
	TRUCK TOTAL	7.7E-03	8.0E-03	8.0E-03	LI	5.8E-04	6.6E-04	1.0E-03	BO	1.6E-05	6.1E-05	BO	
14	TRAIN-IMPCT.ERFO-UR	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
15	TRAIN-IMPCT.ERFO-RU	0.0	0.0	0.0		1.0E-05	1.2E-05	1.8E-05	BO	2.9E-06	1.1E-05	BO	10Y
16	TRAIN-FIRE-URBAN	4.6E-03	4.8E-03	4.8E-03	LI	0.0	0.0	0.0		1.2E-08	4.5E-08	BO	10Y
17	TRAIN-FIRE-RURAL	2.7E-04	2.8E-04	2.8E-04	LI	0.0	0.0	0.0		1.2E-08	4.5E-08	BO	10Y
18	TRAIN-PUNCTUR-URBAN	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
19	TRAIN-PUNCTUR-RURAL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
	TRAIN TOTAL	4.9E-03	5.1E-03	5.1E-03	LI	1.0E-05	1.2E-05	1.8E-05	BO	2.9E-06	1.1E-05	BO	
20	REPOS-HNDL-ACC.F WK	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
21	REPOS-HNDL-ACC.F FL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
22	REPOS-STOR-HI IMPCT	1.6E-13	1.7E-13	1.7E-13	LI	2.1E-13	2.4E-13	3.6E-13	BO	0.0	0.0		10Y
	OV TOTAL WITH TRUCK	1.0E+00	1.1E+00	1.0E+00	LI	5.8E-04	6.6E-04	1.0E-03	BO	1.6E-05			
	OV TOTAL WITH TRAIN	1.0E+00	1.1E+00	1.0E+00	LI	1.0E-05	1.2E-05	1.8E-05	BO	2.9E-06			
	TOTAL OF VOL. DISP AND DISSOL. DOSES:												
	WITH TRUCK:	1.0E+00											
	WITH TRAIN:	1.0E+00											

TABLE A.6-3
NOMINAL VALUES OF EXPECTED DOSE -- FLUIDIZED BED CALCINE

INDEX	ACCIDENT TYPE	VOLATILIZATION				DISPERSION				DISSOLUTION			AGE
		WHOLE BODY	WHOLE BODY EQ	CRIT. ORGAN	ORGAN NAME	WHOLE BODY	WHOLE BODY EQ	CRIT. ORGAN	ORGAN NAME	WHOLE BODY	CRIT. ORGAN	ORGAN NAME	
1	REPRO-HNDL-ACC.F WK	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		5Y
2	REPRO-HNDL-ACC.F FL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		5Y
3	REPRO-STOR-LOC.F WK	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		5Y
4	REPRO-STOR-LOC.F FL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		5Y
5	REPRO-STOR-DRAINAGE	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		5Y
6	TRUCK-IMPCT.ERFO-UR	0.0	0.0	0.0		2.1E-01	2.4E-01	3.7E-01	BO	1.1E-02	4.1E-02	BO	10Y
7	TRUCK-IMPCT.ERFO-RU	0.0	0.0	0.0		1.3E-02	1.4E-02	2.2E-02	BO	1.1E-02	4.1E-02	BO	10Y
8	TRUCK-CROSSNG AC-UR	0.0	0.0	0.0		3.6E-03	4.1E-03	6.2E-03	BO	1.3E-04	5.1E-04	BO	10Y
9	TRUCK-CROSSNG AC-RU	0.0	0.0	0.0		2.1E-04	2.4E-04	3.7E-04	BO	1.3E-04	5.1E-04	BO	10Y
10	TRUCK-FIRE-URBAN	2.8E-05	2.9E-05	2.9E-05	LI	2.8E-05	2.9E-05	4.3E-05	BO	1.2E-06	4.6E-06	BO	10Y
11	TRUCK-FIRE-RURAL	1.6E-06	1.7E-06	1.7E-06	LI	1.6E-06	1.6E-06	2.5E-06	BO	1.2E-06	4.6E-06	BO	10Y
12	TRUCK-PUNCTUR-URBAN	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
13	TRUCK-PUNCTUR-RURAL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
	TRUCK TOTAL	3.0E-05	3.1E-05	3.1E-05	LI	2.3E-01	2.6E-01	4.0E-01	BO	2.2E-02	8.4E-02	BO	
14	TRAIN-IMPCT.ERFO-UR	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
15	TRAIN-IMPCT.ERFO-RU	0.0	0.0	0.0		4.2E-03	4.7E-03	7.2E-03	BO	2.9E-03	1.1E-02	BO	10Y
16	TRAIN-FIRE-URBAN	1.0E-07	1.1E-07	1.1E-07	LI	1.0E-07	1.0E-07	1.6E-07	BO	4.4E-09	1.7E-09	BO	10Y
17	TRAIN-FIRE-RURAL	6.0E-09	6.2E-09	6.2E-09	LI	5.9E-09	6.0E-09	9.1E-09	BO	4.4E-09	1.7E-09	BO	10Y
18	TRAIN-PUNCTUR-URBAN	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
19	TRAIN-PUNCTUR-RURAL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
	TRAIN TOTAL	1.1E-07	1.1E-07	1.1E-07	LI	4.2E-03	4.7E-03	7.2E-03	BO	2.9E-03	1.1E-02	BO	
20	REPOS-HNDL-ACC.F WK	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
21	REPOS-HNDL-ACC.F FL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
22	REPOS-STOR-HI IMPCT	1.6E-13	1.7E-13	1.7E-13	LI	2.1E-13	2.4E-13	3.6E-13	BO	0.0	0.0		10Y
	OV TOTAL WITH TRUCK	3.0E-05	3.1E-05	3.1E-05	LI	2.3E-01	2.6E-01	4.0E-01	BO	2.2E-02			
	OV TOTAL WITH TRAIN	1.1E-07	1.1E-07	1.1E-07	LI	4.2E-03	4.7E-03	7.2E-03	BO	2.9E-03			
	TOTAL OF VOL. DISP AND DISSOL. DOSES:												
	WITH TRUCKS:	2.9E-01											
	WITH TRAINS:	7.1E-03											

TABLE A.6-4
NOMINAL VALUES OF EXPECTED DOSE -- MULTIBARRIER WASTE FORM

EXPECTED DOSE -- MAN-REM/HWE-YR															
INDEX	I	ACCIDENT TYPE	VOLATILIZATION				DISPERSION				DISSOLUTION				AGE
			WHOLE BODY	WHOLE BODY EO	CRIT. ORGAN	ORGAN NAME	WHOLE BODY	WHOLE BODY EO	CRIT. ORGAN	ORGAN NAME	WHOLE BODY	CRIT. ORGAN	ORGAN NAME		
1		REPRO-HNDL-ACC.F WK	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		150	
2		REPRO-HNDL-ACC.F FL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		150	
3		REPRO-STOR-LOC.F WK	8.9E-13	9.6E-13	9.2E-13	LI	0.0	0.0	0.0		0.0	0.0		150	
4		REPRO-STOR-LOC.F FL	1.8E-11	1.8E-11	1.8E-11	LI	0.0	0.0	0.0		0.0	0.0		150	
5		REPRO-STOR-DRAINAGE	1.3E+00	1.5E+00	1.4E+00	LI	0.0	0.0	0.0		0.0	0.0		150	
6		TRUCK-IMPCT.ERFO-UR	0.0	0.0	0.0		5.4E-06	6.1E-06	9.3E-06	BO	7.7E-08	3.0E-07	BO	10Y	
7		TRUCK-IMPCT.ERFO-RU	0.0	0.0	0.0		3.2E-07	3.6E-07	5.5E-07	BO	7.7E-08	3.0E-07	BO	10Y	
8		TRUCK-CROSSNG AC-UR	0.0	0.0	0.0		9.7E-08	1.1E-07	1.7E-07	BO	1.9E-09	7.2E-09	BO	10Y	
9		TRUCK-CROSSNG AC-RU	0.0	0.0	0.0		5.8E-09	6.6E-09	1.0E-08	BO	1.9E-09	7.2E-09	BO	10Y	
10		TRUCK-FIRE-URBAN	6.3E-06	6.6E-06	6.6E-06	LI	2.5E-07	2.9E-07	4.3E-07	BO	2.4E-11	9.2E-11	BO	10Y	
11		TRUCK-FIRE-RURAL	3.6E-07	3.8E-07	3.8E-07	LI	1.5E-08	1.6E-08	2.5E-08	BO	2.4E-11	9.2E-11	BO	10Y	
12		TRUCK-PUNCTUR-URBAN	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y	
13		TRUCK-PUNCTUR-RURAL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y	
		TRUCK TOTAL	6.7E-06	7.0E-06	6.9E-06	LI	6.1E-06	6.9E-06	1.0E-05	BO	1.6E-07	6.1E-07	BO		
14		TRAIN-IMPCT.ERFO-UR	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y	
15		TRAIN-IMPCT.ERFO-RU	0.0	0.0	0.0		1.0E-07	1.2E-07	1.8E-07	BO	2.9E-08	1.1E-07	BO	10Y	
16		TRAIN-FIRE-URBAN	2.4E-08	2.5E-08	2.5E-08	LI	9.2E-10	1.0E-09	1.6E-09	BO	8.7E-14	3.4E-13	BO	10Y	
17		TRAIN-FIRE-RURAL	1.4E-09	1.5E-09	1.4E-09	LI	5.9E-11	6.0E-11	9.1E-11	BO	8.7E-14	3.4E-13	BO	10Y	
18		TRAIN-PUNCTUR-URBAN	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y	
19		TRAIN-PUNCTUR-RURAL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y	
		TRAIN TOTAL	2.6E-08	2.7E-08	2.7E-08	LI	1.0E-07	1.2E-07	1.8E-07	BO	2.9E-08	1.1E-07	BO		
20		REPOS-HNDL-ACC.F WK	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y	
21		REPOS-HNDL-ACC.F FL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y	
22		REPOS-STOR-HI IMPCT	1.6E-13	1.7E-13	1.7E-13	LI	2.1E-13	2.4E-13	3.6E-13	BO	0.0	0.0		10Y	
		OV TOTAL WITH TRUCK	1.3E+00	1.5E+00	1.4E+00	LI	6.1E-06	6.9E-06	1.0E-05	BO	1.6E-07				
		OV TOTAL WITH TRAIN	1.3E+00	1.5E+00	1.4E+00	LI	1.0E-07	1.2E-07	1.8E-07	BO	2.9E-08				
		TOTAL OF VOL. DISP AND DISSOL. DOSES:													
		WITH TRUCK:	1.3E+00												
		WITH TRAIN:	1.3E+00												

A.6.2 Plots of Airborne Dose Versus Distance
From Accident

In addition to observing the various airborne dose measures that are computed by integrating out to a single specified distance downwind of each accident, it is instructive to observe dose as a function of distance. Insights can thereby be gained into the adequacy of existing meteorology and demography models. This is accomplished by varying the distance downwind of the accident (x_f) in the meteorology-demography pathway factor appearing in Eqs. A.2-6 and A.2-7, then plotting expected dose vs. x_f .

Figures A.6-1 to A.6-4 contain plots of expected airborne dose summed over all truck and train accidents that have been generated by the computer code. A separate figure is used for each of the four reference waste forms, with expected dose broken down into dispersion and volatilization components in each case. The dose curves are monotonic increasing functions because the expected release is integrated over a larger population as distance downwind of the accident increases. However, most curves appear to level off asymptotically. Note that the expected dose from dispersion is greater than expected dose from volatilization for the calcines, but that the reverse is true for borosilicate glass.

These tables and figures are presented as a summary of important dose measures. The reader is referred to Section 2.5 of the main report for an interpretation of these analyses.

Figure A.6-1 Nominal Values of Expected Whole-Body Airborne Dose from Truck and Train Accidents -- Spray Calcine

Figure A.6-2 Nominal Values of Expected Whole-Body Airborne Dose from Truck and Train Accidents -- Borosilicate Glass

Figure A.6-3 Nominal Values of Expected Whole-Body Airborne Dose from Truck and Train Accidents -- Fluidized Bed Calcine

Figure A.6-4 Nominal Values of Expected Whole-Body Airborne Dose from Truck and Train Accidents -- Multibarrier Waste Form

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APPENDIX B
THERMAL ANALYSIS

B.1 RAIL CASK THERMAL ANALYSIS

B.1.1 Objectives

This work was concerned with:

- Validating the design and normal performance characteristics of a baseline LLL-designed rail shipping cask
- Determining the thermal response to various hypothesized non-fire accidents
- Determining cask and canister failure thresholds for a series of fire conditions from moderate to severe.

B.1.2 Shipping Cask Description

The baseline rail shipping cask is an LLL modification of the GE IF-300 spent fuel cask described in Ref. B.1. The salient features of this cask, depicted in Fig. B.1-1, are the following:

- A 37.5-in. diameter, 10-ft long cavity containing four 12-in. diameter HSLW canisters
- A dry stainless steel insert surrounding the canisters and acting as a heat transfer medium
- A depleted uranium gamma-ray shield 4 in. thick
- A 5-in. thick water neutron shield on the outside of the cask enclosed by a corrugated stainless steel sleeve

Figure B.1-1 Baseline Rail Shipping Cask

- Finned ends to act as impact limiters and also to augment heat transfer to the ambient air
- A stainless steel GrayLoc seal ring to prevent release of contents
- Mechanical cooling (fans) during transportation.

B.1.3 Heat Conduction Computer Code

The HEATING5 computer code, obtained from ONRL, was the chief computational tool for performing thermal analysis on the rail shipping cask. The code is described in detail in Ref.B.2. HEATING5 is a generalized heat conduction code designed to solve steady-state and/or transient heat conduction problems in one-, two- or three-dimensional Cartesian

or cylindrical coordinates or one-dimensional spherical coordinates. The thermal conductivity, density and specific heat may have both spatial and temperature dependence. The thermal conductivity may be anisotropic. Materials may undergo a change of phase for steady-state calculations. Heat generation rates may be dependent on time, temperature and position, and boundary temperatures may be time-dependent. The boundary conditions, which may be surface-to-boundary or surface-to-surface, may be fixed temperatures or any combination of prescribed heat flux, forced convection, natural convection and radiation. The boundary condition parameters may be time- and/or temperature-dependent. The mesh spacing can be variable along each axis. The code is designed to allow a maximum of 100 regions, 50 materials and 50 boundary conditions. The maximum number of lattice points can be easily adjusted to fit the problem and the computer storage requirements.

The point successive overrelaxation iterative method and a modification of the "Aitken δ^2 extrapolation process" are used to solve the finite difference equations, which approximate the partial differential equations for a steady-state problem.

The transient problem may be solved using any one of several finite difference schemes. These include an implicit technique which can range from Crank-Nicolson to the Classical Implicit Procedure, an explicit method which is stable for a time step of any size, and the Classical Explicit Procedure which involves the first forward time difference. The solution of the system of equations arising from the implicit technique is accomplished by point successive overrelaxation iteration and includes procedures to estimate the optimum acceleration parameter. The time step size for implicit transient calculations may be varied as a function of the maximum temperature change at a node.

B.1.4 Waste Forms

The baseline waste form with which the bulk of the current work was carried out is 10-yr old waste mixed with borosilicate glass. This has a heat output of 3.3 kW per canister. With the exception of the temperature distribution in the waste canister itself, the results are applicable as well to suitably diluted calcine -- i.e., dilution to the 3.3 kW level -- for which some steady-state calculations were done. Wastes with ages down to two years were examined as part of preliminary studies. These early studies were intended primarily to test the adequacy of various cask/canister concepts for normal, non-accident operation. Design conservatism dictated the use of 10-yr waste material in conjunction with the cask described previously; all calculations presented in subsequent sections will assume the use of 10-yr waste (3.3 kW for a 0.222 m^3 canister).

B.1.5 Accident Descriptions

Thermal analyses were performed for three classes of environments:

- Normal steady-state rail transportation with cooling fans operating
- Non-fire accidents. These encompassed:
 - Loss of neutron shielding water due to a faulty valve or puncture of the corrugated sleeve. This type of accident leaves a wide air gap in place of the water-filled region, offering a high thermal resistance which prevents the escape of waste heat.
 - Loss of mechanical cooling. A shutdown of the fans considerably decreases the convective cooling from the sides of the cask and leads to an increase in internal temperature.
 - Both of the above occurring simultaneously.

- Fires. These generally fall into two categories:
 - Moderate temperature fires (such as the 1475°F fire defined under Type B specifications) that damage only the shipping cask.
 - Severe, long duration, high temperature fires in excess of 2000°F that may induce waste canister damage.

Treatment of these two fire types is different in that the corrugated sleeve is presumed to remain intact during a moderate fire. Severe fires, on the other hand, assume complete removal of the corrugated sleeve, greatly reducing the thermal resistance of the system.

B.1.6 Materials and Properties

Table B.1-1 gives the thermal properties for all materials used in shipping cask/canister thermal response calculations.

B.1.7 Geometry

As can be seen in Fig. B.1-1 the actual rail shipping cask is a complex three-dimensional configuration. The cask contains four waste canisters of 12-in. diameter and 18-in. center-to-center spacing; the canisters are of 3/8-in. thick stainless steel construction. The canisters are located in a stainless steel insert whose outside diameter is 37 in. Outside the cavity is a 4-in. thick depleted uranium gamma-ray shield that is enclosed by two stainless steel liners, a 1/2 in.-thick inner liner and a 1.56-in. thick outer liner. The water neutron shield is 5.13-in. thick and is enclosed by a 1/8-in. stainless steel corrugated sleeve forming the outer boundary

TABLE B.1-1
THERMAL PROPERTIES OF RAIL SHIPPING CASK MATERIALS

T-1400

PROPERTY	STAINLESS STEEL (TYPE 317, 403)	AIR (NARROW GAP)	AIR (WIDE ANNULUS)	WATER (WITH CONVECTION)	DEPLETED URANIUM	GLASS INSUL	CALCULATED LOSS
Density (lb/in. ³)	0.285	0°F 5.00 × 10 ⁻⁵ 500°F 2.39 × 10 ⁻⁵ 1000°F 1.57 × 10 ⁻⁵ 1500°F 1.17 × 10 ⁻⁵	0°F 5.00 × 10 ⁻⁵ 500°F 2.39 × 10 ⁻⁵ 1000°F 1.57 × 10 ⁻⁵ 1200°F 1.17 × 10 ⁻⁵	0.361	0.683	0.126	0.4722
Specific Heat (Btu/lb.-°F)	0.12	0.237	0.237	1.00	0.228	0.179	0.155
Thermal Conductivity (Btu/hr.-in.-°F)	1600°F 0.63 3000°F 0.71 5000°F 0.79 8000°F 0.90 12000°F 1.05	0°F 0.0109 500°F 0.0205 1000°F 0.0281 1500°F 0.0345	0.0142	1500°F 1.23 2000°F 1.44 2500°F 1.59 3000°F 1.74 4000°F 1.95	1000°F 1.19 3000°F 1.33 5000°F 1.49 8000°F 1.63 12000°F 1.88	77°F 0.4309 1112°F 0.4675 1346°F 0.1200	32°F 8.405 1052°F 10.8

of the cask. It was necessary to simplify the geometric description of the cask and canister so that HEATING5 could perform thermal analyses with a minimum of computer time. It was decided that the most convenient way of proceeding was to encode the cask geometry with two separate views in cylindrical coordinates:

- An R-Z representation -- i.e., treating the cask as a figure of revolution about the centerline and looking at temperature distributions axially and radially from a side view.
- An R- θ representation -- i.e., treating the cask as though it were infinitely long, thereby ignoring end effects, and examining the radial and angular temperature variations from a top view.

The R-Z geometry gives a good overall picture of cask temperature profiles, although it precludes a detailed picture of the distributions around the individual canisters for the steady-state case. The R- θ geometry is a better description of the canister temperatures, especially away from the cask ends, i.e., near the mid-plane. A combination of the separate two representations gives a complete steady-state thermal analysis.

R-Z Representation - Figure B.1-2 shows an end view, roughly to scale, of the cask interior including key dimensions. The HEATING5 code is restricted to region boundaries that are parallel to coordinate axes; in the present case, a cylindrical geometry with the origin along the cask centerline was expedient. For an R-Z view regions must be bounded by lines of constant radius (circles centered on the axis) and planes perpendicular to the axis. It is seen from Fig. B.1-2 that the waste canisters themselves do not obey this restriction; they are cylinders, but are not centered on the cask axis.

Figure B.1-2 Rail Shipping Cask - End View

The solution was to convert the canister region into an "equivalent" annular region able to be handled by the code. Thus, those portions of Fig. B.1-2 labeled "insert" and "waste" were mapped into three new regions:

- An inner annulus consisting of insert material (stainless steel)
- A center annulus of waste material surrounded by thin annuli representing canisters and air gaps
- An outer annulus of insert material.

Requirements on the dimensions of the waste material annulus were the following:

- The volume of the equivalent annulus had to equal the total volume of the four waste canisters
- The first moment of the mass distribution of the waste annulus (or center-of-mass) had to equal that of the actual waste cylinders.

These constraints enabled the inner and outer radii of the waste region to be uniquely obtained. Figure B.1-3 shows the R-Z geometry used by HEATING5, with dimensions indicated. Note from Fig. B.1-2 that outside the insert the R-Z geometry does not require approximations to acquire cylindrical symmetry. Figure B.1-3 depicts one quadrant of the entire cask cross-section.

R- θ Representation - To utilize R- θ coordinates, the waste canisters in Fig. B.1-2 must be described in terms of lines of constant radius (circles centered about the axis) and constant angle lines emanating from the axis in a spoke-like fashion. The intersections of those two types of possible region boundaries form wedges. Hence, the mapping converts the actual waste cylinders into equivalent wedges with three dimensions to be determined: inner radius, outer radius and wedge angle. The unknowns were uniquely obtained from the following conditions:

- The wedge areas were forced to equal the waste cylinder areas
- The maximum distance between wedge boundary and the waste cylinder boundary was minimized.

Figure B.1-3 Cross Section of Modified GE IF-300 Rail Shipping Cask for R-Z Thermal Analyses

Figure B.1-4 gives the R- θ geometry encoded into HEATING5. The smallest repeated unit, 1/8 of a circle or 45 deg, is shown; this symmetry cell includes half of one of the four waste canisters.

Figure B.1-4 HEATING5 Code R-θ Geometry

To recapitulate the use of these two representations, the R-Z geometry was principally employed to give steady-state temperatures outside the waste canister region. In order to keep the model two-dimensional it was necessary to approximate the waste canisters by annular regions -- a rather crude model. The representation of the sides and ends of the cask are, in contrast, much more nearly exact. Hence, for steady-state calculations HEATING5 was more accurate in regions away from the canisters.

The R-θ geometry provides a better model for the waste cylinders -- discrete wedges -- that can account for heat flow around canisters. The R-θ view, however, cannot account for temperature variations in the Z-direction or end boundary conditions. Therefore, the R-θ model is better suited

to describe thermal response in steady state in the vicinity of the waste canisters and away from the ends, i.e., near the cask mid-plane.

For severe transient fire environments where the main heat source is external, the R-Z geometry is clearly superior and was used exclusively.

B.1.8 Boundary Conditions

Boundary condition numbers (B1, B2, etc.) are indicated on Fig. B.1-3.

Boundary B1 - The boundary condition along the side of cask includes heat flow by radiation and forced convection to 130°F ambient from a corrugated sleeve. A 1 BTU/hr-in.² time-invariant incident solar flux is assumed.* Convective losses are computed using an effective area increased due to corrugations. The view factor for radiation includes heat losses to cask support structures as well as to ambient air. During a loss of mechanical cooling accident, the forced convection heat transfer coefficient is replaced by a natural convection coefficient.

Boundaries B2 Through B5 - These represent boundaries with fins. Heat transfer coefficients for radiation and natural convection are adjusted for fin efficiencies and effective areas. Fin dimensions and numbers vary with position; hence B2 through B5 have different heat transfer coefficients. Solar heating and forced convection are not heat exchange mechanisms at these boundaries. The differences among these boundaries are:

*This is equivalent to a 24-hour average solar heat flux at a latitude of 42° during the summer solstice.

- B2 - 6-in. fins
- B3 - 6-in. and 9.5-in. fins
- B4 - 9.5-in. fins
- B5 - bare stainless steel; no fins.

Boundaries B6 and B7 - These are internal boundary conditions which allow for radiation (in addition to conduction) across the air gaps. The emissivity of the canister is assumed to be 0.6; that of the insert is taken to be 0.3. During a loss of neutron shield water accident, radiation is also allowed to pass across the neutron shield annulus according to the B7 internal surface-to-surface boundary condition.

During fires, the external boundary conditions change. The only heat transfer mechanism allowed is radiation from the flame at the flame temperature, with an effective flame emissivity of 0.8. Forced and natural convection and solar heating are eliminated. In the case of moderate temperature fires (below 2000°F) the corrugated outer sleeve remains intact except for loss of the water; the fire acts on the sleeve and heat is transferred across the air-filled annulus formerly occupied by the water. In the case of severe fires (above 2000°F) the presumption is that the sleeve is destroyed and the external boundary is placed on the outer gamma shield liner. The neutron shield annulus is completely removed.

B.1.9 Cases Run

Normal steady-state operation - Both 10-yr glass and 10-yr calcine HLSW (including mechanical cooling) cases were run.

Non-fire accidents - 10-yr glass and calcine HLSW

- Loss of neutron shielding water
- Loss of mechanical cooling
- Both of the above

Fire accidents - 10-yr glass HLSW

- 1475[°], 30-min fire (Type B fire)
- 3-hr cooldown after Type B fire
- 1890[°]F, 1-hr fire
- 2100[°]F, 12-hr fire
- 2400[°]F, 12-hr fire
- 2700[°]F, 6-hr fire

B.1.10 Results

Table B.1-2 summarizes the results of the HEATING5 normal, steady-state computer runs; the non-fire accidents; and the Type B 1475[°]F, 30-min fire. Results are also included for a 3-hr cooldown period following the Type B fire. The last column, post-fire steady state, gives the temperatures at critical cask locations after infinite time cooldown: this is equivalent to a steady-state condition simulation with both loss of shielding water and loss of mechanical cooling.

No potential damage modes are apparent for any of the conditions reported in Table B.1-2 save for an approach to the calcination temperature of the calcine waste during a loss of shielding water accident.

TABLE B.1-2
SUMMARY OF BASELINE RAIL CASK TEMPERATURES
FOR NON-FIRE ACCIDENTS AND TYPE B FIRE

T-1416

LOCATION	NORMAL STEADY- STATE	LOSS OF SHIELDING WATER	LOSS OF MECHANICAL COOLING	1475°F, 30 MIN FIRE TRANSIENT	3 HR. COOLDOWN TRANSIENT	POST-FIRE STEADY- STATE
CALCINE } WASTE	1340	1510	1380	1340	1340	1520
GLASS }	708	883	751	708	709	904
CANISTER MIDPOINT	619	803	661	619	623	824
CAVITY SURFACE	447	571	495	448	464	590
CORRUGATED SLEEVE	172	165	257	1196	203	224
SEAL	199	271	243	286	334	281
CASK TOP AT AXIS	218	256	240	664	328	261
ALL TEMPERATURES IN DEG F DRY INSERT CASK DESIGN 10-YR OLD WASTE						

Figures B.1-5, B.1-6 and B.1-7 give temperature-time histories computed from the R-Z geometry for rail casks under severe fire conditions at locations that are most likely going to allow release pathways for radioactive materials. These locations are, respectively:

- Canister end (R = 13.73 in., Z = 60 in.)
- Canister midpoint (R = 13.73 in., Z = 0 in.)
- Seal (R = 18.75 in., Z = 60 in.)

Figure B.1-5 shows canister end profiles for fire temperatures of 2100°F, 2400°F and 2700°F. The 2100°F and 2400°F fire transients were followed for 12 hr; the 2700°F fire was followed for 6 hr. Depicted as well are canister failure temperatures due to rapid corrosion within a time of several hours by glass (1200°C or 2192°F) and by calcine (1300°C or 2372°F).

Figure B.1-5 Rail Cask Canister End Temperature Profiles for Severe Fires

Figure B.1-6 Rail Cask Canister Midpoint Temperature Profiles for Severe Fires

Figure B.1-7 Rail Cask Seal Temperature Profiles for Severe Fires

Figure B.1-6 presents the same data for the canister midpoint. It can be seen, for the cases examined, that critical temperatures are exceeded first at the canister end.

Figure B.1-7 shows GrayLoc seal temperatures as a function of time for each of the three severe fire conditions plus the 1-hr, 1890°F fire. Studies of the seal have indicated that a 1000°F failure temperature is reasonable. Assuming this value, failure occurs in the range of 0.5 to 0.7 hr for the severe conditions. Seal failure does not take place within the first hour during the 1890°F fire; a rough extrapolation yields a failure time in the vicinity of 1.25 to 1.5 hr at that temperature.

B.1.11 Failure Loci and Sensitivity Analyses

Temperature-time histories at the canister end position can be qualitatively characterized by:

- An initial time delay before the temperature begins to rise from the initial steady-state value
- A rapid temperature excursion toward the fire temperature
- A leveling off at or near the fire temperature.

It was found that this behavior could be very adequately described by a functional form:

$$T = a - be^{-\lambda t} \quad (B.1-1)$$

where

T = canister temperature

t = time after initiation of the fire

a = fit constant related to the initial canister temperature

b = fit constant related to the initial time delay

λ = fit constant related to the thermal time constant of the shipping cask

A least squares procedure was used to compute a, b and λ from the HEATING5 results; that procedure follows the exponential approximation method detailed in Ref. B.3.

LLL has defined error limits on glass and calcine corrosion failure temperatures as $\pm 50^{\circ}\text{C}$ (Refs. B.4 and B.5); failure loci were thus computed over the range 1150°C to 1350°C

in increments of 50°C. After having determined the constants for each fire condition, Eq. B 1-1 was solved for the times at which failure occurred for the various assumed canister failure temperatures: 1150°C, 1200°C, 1200°C, 1300°C and 1350°C. Table B.1-3 summarizes the failure time results for rail fires. A dash indicates that no failures were obtained for a given fire temperature and failure temperature.

TABLE B.1-3
SUMMARY OF RAIL TRANSPORTATION CANISTER
FAILURE TIMES IN SEVERE FIRES
(FAILURE TIMES IN HOURS)

FAILURE TEMPERATURE	RAIL FIRE TEMPERATURES (°F)		
	2100	2400	2700
1150°C (2102°F)	--	4.15	2.76
1200°C (2192°F)	--	5.19	3.09
1250°C (2282°F)	--	6.92	3.50
1300°C (2372°F)	--	13.85	4.05
1350°C (2462°F)	--	--	4.88

In the initial phase of this study, failure time was correlated with fire temperature by an analytic fit of the form

$$t = \frac{A}{T-B} \quad (B.1-2)$$

where

t = failure time

T = fire temperature

A,B = constants determined by a fit to the temperature-time data

The above expression has been termed a failure locus. By definition, all time and temperature points that lie above the locus will lead to canister failure in an intense fire.

Eq. B.1-2 had a deficiency in that finite failure times were predicted for 2100°F fires, in contradiction to the results shown in Table B.1-3. Hence, it was decided to change the functional form of Eq. B.1-2 to reflect the fact that failures in general did not occur for 2100°F fires. It should be noted that the deficiency in the previous locus equation was not critical to prediction of canister failure conditional probabilities. The major contribution to the failure probabilities according to the Sandia rail and truck accident probability distribution functions (Ref. B.6) was at fire temperatures in excess of 2400°F. Errors in the 2100°F range contributed little to the overall failure probabilities.

The new failure locus was derived from Eq. B.1-1. To a good approximation the constant "a" can be associated with the fire temperature, T_F , since it is reasonably expected that after very long fire times the canister temperature should approach the fire temperature. When the canister temperature reaches the corrosion failure temperature, T_C , the failure time is t_c ; these variables are related by:

$$T_C = T_F - be^{-\lambda t_c} \quad (B.1-3)$$

Solving for t_c gives:

$$t_c = \alpha - \beta \ln(T_F - T_C) \quad (B.1-4)$$

where α and β are unknown constants related to b and λ . Equation B.1-4 is the new failure locus form, with α and β determined from failure times, t_c , and fire temperatures, T_F ;

a different failure locus is required for each assumed value of the failure temperature, T_c .

Using the failure time results of Table B.1-3, the constants α and β were computed for each value of T_c . These failure locus constants are presented in Table B.1-4 with units consistent with T_F expressed in deg F and t_c in hours.

TABLE B.1-4
RAIL FIRE CANISTER FAILURE LOCUS CONSTANTS

FAILURE TEMPERATURE	CONSTANTS	
	α	β
1150°C (2102°F)	15.52	1.996
1200°C (2192°F)	17.74	2.352
1250°C (2282°F)	19.82	2.704
1300°C (2372°F)	27.12	3.982
1350°C (2462°F)	--	--

Figure B.1-8 gives plots of the failure loci for rail fires, with failure temperatures ranging from 1150°C to 1300°C.

B.1.12 Conclusions

- For the baseline design rail cask, corrosion failures of the canister can take place with both calcine and glass wastes; fire temperatures must exceed 2100°F
- The corrosion failure locus can be described very well by an expression in the form of Eq. B.1-4. This formulation is superior to using the time-temperature product to describe failure results

Figure B.1-8 Rail Fire Accident Failure Loci for Various Canister Failure Criteria

- The baseline rail cask design is an adequate one for normal steady-state operation (with mechanical cooling needed) for the following reasons:
 - Calcine centerline temperature does not exceed the calcination temperature
 - Canister maximum temperature is well below that required for rapid corrosion
 - Stainless steel outer tank wall temperatures are quite moderate, approximately 1700F
- Failure of the GrayLoc seal takes place rapidly under severe fire temperatures, but not under 1475°F, 30-min duration conditions (Type B specification)
- A loss of shielding water accident is worse than a loss of mechanical cooling accident
- No obvious damage mechanisms occur during cooldown after a fire transient
- There is no release of waste material possible due to thermal effects under the Type B fire conditions.

B.2 TRUCK CASK THERMAL ANALYSIS

B.2.1 Objectives

Analysis of the truck cask was concerned with validating the design and performance characteristics of a baseline, LLL-recommended truck shipping cask for high level solid waste transportation and determining cask and canister failure thresholds during severe fire conditions for both glass and calcine HLSW forms.

B.2.2 Shipping Cask Description

The shipping cask studied was primarily based on a Nuclear Fuel Services spent fuel cask, the NFS-4. The important characteristics are:

- 178-in. long by 13.5-in. diameter internal cavity
- Lead γ -shielding, 6.65 in. thick
- Ethylene glycol/water neutron shield 4.5 in. thick
- A single 12-in. diameter fuel or waste canister
- 8-in. thick steel end caps to which are attached 12-in. balsa wood impact limiters and an asbestos sheet.

This cask was rated for a maximum internal decay heat load of 12.4 kW from spent fuel. A sketch of the NFS-4 cask is given in Fig. B.2-1; it was adapted from Ref. B.7. The only major modification made to the NFS-4 design was to reduce the cavity length to 10 ft to coincide with present HLSW canister designs.

Figure B.2-1 NFS-4 Spent Fuel Shipping Cask

B.2.3 Waste Forms

The high level solid waste assumed for thermal calculations was spray calcine diluted to a 3.3-kW per canister heat generation rate. Except for canister internal temperatures, the results are applicable as well to 3.3-kW glass HLSW.

B.2.4 Accident Description

The NFS-4 cask with a single HLSW canister was subjected to intense fire temperatures from 2100°F to 2700°F. For these accidents, the following were assumed:

- Very rapid disappearance of the balsa wood impact limiters

- Very rapid removal of the neutron shielding water plus disintegration of the outer neutron shield tank wall.

B.2.5 Materials and Properties

The materials employed in the truck cask/canister package are:

- Stainless steel - shells, tank wall and canister
- Spray calcine HLSW
- Lead γ -shield
- Water neutron shield
- Asbestos.

Values of the thermal conductivity, density and specific heat are given in Table B.2-1 for spray calcine, solid lead, liquid lead and asbestos. The properties of air, water and stainless steel are detailed in Section B.1.6. The following notes are of interest:

- An equivalent thermal conductivity for water, considerably higher than the normal value, has been used in order to account for convection currents in the neutron shield annulus
- The thermal properties of solid lead were used for a normal, steady-state calculation of the temperature distribution of the truck cask. For the fire environments, thermal properties for liquid lead were assumed, since lead very quickly reaches the melting point in an intense fire. Some error is introduced by ignoring the heat of fusion of lead, but this omission is compensated by the higher specific heat of liquid lead compared to the solid. Overall, the thermal capacity of the cask is underestimated by about 6 percent.

TABLE B.2-1
THERMAL PROPERTIES OF TRUCK SHIPPING CASK MATERIALS

T-1461

PROPERTY	SPRAY CALCINE HLSW	LEAD (SOLID)	LEAD (LIQUID)	ASBESTOS
Density (lb/in. ³)	0.045	0.40	0.38	0.0208
Specific Heat (BTU/lb-°F)	150°F 0.147 968°F 0.160	0.0325	0.0380	0.025
Thermal Conductivity (BTU/hr-in.-°F)	32°F 4.38 1652°F 10.2	1.55	0.78	32°F 7.25 212°F 9.25 392°F 10.0 752°F 10.8

B.2.6 Geometry

Figure B.2-2 is a simplified representation in R-Z coordinates of the crossection of the NFS-4 used as the input to the HEATING5 code. Dimensions are in inches. Boundary condition designation numbers are also indicated. The waste is enclosed by a 3/8-in. stainless steel canister, with a 3/8-in. gap between the canister and the stainless steel inner shell 5/16 in. thick. A lead gamma-ray shield, 5-5/8 in. thick, is enclosed by the two stainless steel shields, the outer one being 1-1/4 in. thick. The last two regions include the 4-1/2 in. water neutron shield and an 0.165-in. tank wall.

The case end consists of 8 in. of stainless steel topped by a 1/8-in. asbestos layer. The balsa impact limiter is not included, as explained below.

Figure B.2-2 Cross Section of Modified NIS-4 Shipping Cask (Truck) Used for Thermal Analysis

B.2.7 Boundary Conditions

Heat is generated by the waste at the rate of about 3.3 kW per canister. For normal, steady-state operation heat travels radially and is removed at the outer wall by radiation and natural convection to 130°F air (boundary condition B4). The cask end, enclosed by balsa wood, a very poor conductor, is reasonably taken to be perfectly insulated (boundary conditions B1, B2, and B3). The internal boundary condition B5

allows for radiation and conduction across the canister inner shell air gap. In the normal state, solar heating at the rate of 1 BTU/hr-in.² is uniformly distributed around the cylinder.

For fire conditions, it is assumed that all external boundaries are subjected to a flame at temperatures from 2100°F to 2700°F with a flame emissivity of 0.8. Furthermore, it is assumed that with temperatures in this extreme range the outer wall will lose its mechanical integrity. Hence, during a fire the entire neutron shield region is removed and the fire environment impinges on the stainless steel outer shell (boundary condition B6).

B.2.8 Cases Run

The following HEATING5 cases were run in R-Z geometry to determine the thermal response of the truck cask:

- Normal steady state with solar heating, spray calcine waste and neutron shield in place
- 2100°F fire with neutron shield and tank wall removed, 8-hr duration
- 2400°F fire, 6-hr duration
- 2700°F fire, 4-hr duration.

B.2.9 Results

Normal steady-state temperatures are found as underlined numbers in the cask diagram, Fig. B.2-2. The steady-state tank wall temperature was found to be about 265°F. The initial temperature of the waste canister ranged from 471°F at the midpoint to 288°F at the canister end. On the axis of the cask the temperature of the calcine was a maximum at the

midpoint, 1440°F. The calcine initial temperature was 299°F at the canister end. The bottom of the cask has a maximum temperature of 280°F.

Figures B.2-3, B.2-4 and B.2-5 are temperature-time histories during the 2100°F, 2400°F and 2700°F fires at three locations within the cask/canister system.

- Figure B.2-3 - canister midpoint (Z=0, R=6 in.)
- Figure B.2-4 - canister end (Z=60 in., R=6 in.)
- Figure B.2-5 - waste midpoint (Z=0, R=0 in.)

For the three fires, the initial temperature distribution was obtained from the steady state with the neutron water shield in place and with solar heating.

Figure B.2-3 Truck Cask Canister Midpoint Temperature Histories for Severe Fires

Figure B.2-4 Truck Cask Canister End Temperature Histories for Severe Fires

Figure B.2-5 Truck Cask Canister Waste Centerline Temperature Histories for Severe Fires

It is to be emphasized that canister temperatures are virtually independent of waste form, i.e., calcine and glass at 3.3 kW give nearly identical canister temperatures; only waste centerline temperatures would be substantially different. Hence, from the canister temperature data obtained it is possible to infer the failure times for either glass or calcine HLSW forms.

In Fig. B.2-3 and Fig. B.2-4 failure criteria for the two waste forms of interest are shown. They are:

- 1200°C (2192°F), which corresponds to rapid corrosion of the canister within a time of several hours for borosilicate glass waste
- 1300°C (2372°F), which corresponds to corrosion of the canister with calcine waste.

As can be seen from these figures, canister failure occurs first at the midpoint rather than at the ends. Table B.2-2 summarizes the times at which canister failure first occur for various assumed failure temperatures in the range of 1150°C to 1350°C. The failure times were obtained by fitting the temperature histories in Fig. B.2-3 to Eq. B.1-1 and interpolating analytically.

TABLE B.2-2
SUMMARY OF TRUCK TRANSPORTATION
CANISTER FAILURE TIMES IN SEVERE FIRES
(FAILURE TIMES IN HOURS)

FAILURE TEMPERATURE	TRUCK FIRE TEMPERATURES (°F)		
	2100	2400	2700
1150°C (2102°F)	4.79	1.65	1.21
1200°C (2192°F)	--	1.86	1.30
1250°C (2282°F)	--	2.19	1.42
1300°C (2372°F)	--	2.98	1.56
1350°C (2462°F)	--	--	1.75

Figure B.2-5 gives waste (calcine) centerline midpoint temperatures versus time. For all three fires, the calcination temperature is exceeded; times range from 2.6 to 3.2 hours.

Using the failure time data from Table B.2-2, canister failure loci were derived for truck accident fires in the form of Eq. B.1-4, i.e.,

$$t_c = \alpha - \beta \ln(T_F - T_C)$$

that relates the failure time, t_c , and the fire temperature, T_F , for a given corrosion failure temperature, T_C . The results of the least squares fitting process, the constants α and β , are given in Table B.2-3.

Figure B.2-6 is a plot of failure loci for truck fires using the constants presented in Table B.2-3.

TABLE B.2-3
TRUCK FIRE CANISTER FAILURE LOCUS CONSTANTS

FAILURE TEMPERATURE	TRUCK	
	α	β
1150°C (2102°F)	7.32	0.966
1200°C (2192°F)	5.21	0.627
1250°C (2282°F)	5.09	0.609
1300°C (2372°F)	4.90	0.577
1350°C (2462°F)	--	--

Failure of the shipping cask TFE O-ring seal will take place very quickly, within a few minutes of the start of the fire. It is expected that this would hold for fire temperatures down to the hydrocarbon fueled fire minimum, 1400°F.

Figure B.2-6 Truck Fire Accident Failure Loci for Various Canister Failure Criteria

B.2.10 Conclusions

- For the baseline design truck cask corrosion failures of the canister can take place with calcine and glass wastes for fire temperatures in excess of 2100°F
- Corrosion failure can be correlated reasonably well by an expression in the form of Eq. B.1-4. The threshold fire temperature for corrosion failure is virtually the same as for the rail cask
- The baseline truck cask design is adequate for normal steady-state operation, with no mechanical cooling needed, for the following reasons:
 - Calcine centerline temperature does not exceed the calcination temperature
 - Canister maximum temperature is well below that required for rapid corrosion
 - The lead shielding remains in the solid state
 - Stainless steel outer tank wall temperatures are moderate, approximately 270°F

- Calcination temperatures are exceeded in the HLSW by severe fires in the 2100°F to 2700°F range with durations in the vicinity of 3 hr.

B.3 INTERIM STORAGE THERMAL ANALYSIS

B.3.1 Objectives

The objectives of the interim storage thermal analysis were;

- To establish a computer model with which to predict the temperature-time history of HLSW canisters subjected to an interim storage loss of water coolant (LOC) accident.
- To apply this model for representative solid waste forms, with emphasis on canister failure conditions.
- To determine the sensitivity of canister failure probabilities on important model parameters.

B.3.2 Description of Problem

During the interim storage at a surface storage facility, high level wastes are contained in stainless steel canisters. Large numbers of canisters are grouped in regular arrays and are located in a concrete basin filled with water to remove heat generated by the waste itself. A seismic event or other catastrophic accident could cause rupture of the basin and loss of the coolant water. As a consequence, without the prime heat removal medium, failures of the canisters could well occur due to corrosion or melting of the canister wall; both are thermally induced effects. The rapidity of failure depends upon the heating rate of the wastes and on the geometry of the canister array.

Modeling of the thermal response of single and multiple waste canisters was performed by ARHCO (Ref. B.8). Of particular interest were their analyses of transient temperatures following an instantaneous loss of cooling water from a surface storage facility. This facility was assumed to consist of 506 waste canisters, each producing 5 kW of heat, and set into a rectangular concrete basin. The ARHCO approach was to use a lumped parameter model that represented the system by a small number of nodes interconnected by a network of thermal transmittances. TASC has developed a similar, but expanded, capability that differs from ARHCO's work in the following ways:

- The HEATING5 code was utilized to solve the finite difference heat flow equations. Although a 1-D lumped parameter approach was used by TASC for initial results, a full 2-D treatment of heat transfer through the waste-canister array is possible for more accurate computations in the future
- Interim storage results were obtained over a variety of waste forms and ages (hence, heat generation rates)
- Heat transfer between the waste canisters and naturally circulating air was modeled by TASC in a manner to reflect more accurately the actual air flow rates and convective transfer coefficients.

The baseline configuration used by TASC was very nearly that treated by ARHCO:

- A 36.5-ft x 18.5-ft x 36-ft high basin with an open top
- 1-ft diameter, 10-ft long canisters at 18-in. center-to-center spacing
- 506 upright canisters in two layers, one directly above the other, with a 1-ft spacing between

- Instantaneous loss of cooling water to initiate the temperature excursion
- Cooling of the canisters by the mechanisms of natural convection to air, radiation to space, radiation to the concrete basin walls and conduction through the concrete walls.

B.3.3 Waste Forms

Spray calcine and borosilicate glass waste forms were considered, with ages ranging from 1 to 10 years after reprocessing. The wastes were taken to be diluted to the extent that 10-yr old wastes produced 3.5 kW of heat per canister. For other ages, the heat generation rates per canister for the same dilution were:

- 5-yr: 7.4 kW
- 2-yr: 18.1 kW
- 1-yr: 32.8 kW.

B.3.4 Geometry

The waste canister region was modeled as a single block with homogenized HLSW and stainless steel properties and a volume of 12,680 ft³. Instead of the actual rectangular solid shape, a cylinder of equivalent top area and height was used for computational convenience to represent the waste region. This approximation allowed the advantage of a 2-dimensional geometry with axial symmetry. The cylinder dimensions were:

- Radius: 13.9 ft
- Height: 21 ft.

Surrounding the waste block and separated from it by an air gap was an annular ring of concrete. Its thickness was 4 ft, but the thermal resistance input was equivalent to an 8-ft thickness (8 ft was found by ARHCO to be essentially an infinite thickness). The height of the concrete ring was 36 ft.

A mass of air was located on top of the waste block. The boundary condition between the air and the waste block simulated natural convective heat flow between canister surfaces and air. The heat transfer process simulation is described in more detail below. Figure B.3-1 is a sketch of the geometry input to HEATING5 with boundary conditions shown.

B.3.5 Heat Transfer Mechanisms and Boundary Conditions

After removal of cooling water, air flow by natural circulation around the canisters is a prime method by which heat is lost to the surroundings. The flow patterns are quite complex, with cooler air moving rapidly down the sides of the basin and air circulating more slowly back up, while being heated by the waste canisters. Figure B.3-2 is a sketch of the natural convection process indicating air entering the bottom of the basin at an initial ambient temperature, T_0 , of 120°F and leaving the top of the canister array at temperature T_A after exchanging heat isothermally with canisters at temperature T_c . Using the notation:

q = heat exchange rate between canisters and air (BTU/hr)

W_A = mass flow of air (lb/hr-ft²)

C_A = heat capacity of air (BTU/lb-°F)

A_f = flow area between canisters (ft²)

Figure B.3-1 Geometry for Baseline Interim Storage Problem

Figure B.3-2 Natural Convection in Interim Storage Canister Array

h = heat transfer coefficient between air
and vertical cylinders (BTU/hr-ft²-°F)

A_c = surface area of canisters (ft²)

a heat balance on the air gives *

$$q = C_A W_A A_f (T_A - T_O) = h A_c (T_c - T_A) \quad (B.3-1)$$

Equation B.3-1 is a valid representation of the actual heat transfer process if either of the following assumptions is approximately true:

- The heat flow per unit length of canister is a constant along the length of the canister array (axially) and equal to the difference between the canister and air temperatures at the top of array.
- The air may be considered well mixed, i.e., no appreciable temperature gradients exist axially.

Heat transfer across the gap between the air and waste block in Fig. B.3-1 (Boundary condition B1) across an area πR^2 approximates the right hand side of Eq. B.3-1, using a heat transfer coefficient

$$h' = h A_c / \pi R^2 \quad (B.3-2)$$

Heat transfer from air to ambient in Fig. B.3-1 (boundary condition B4), also across an area πR^2 , approximates the left-hand side of the Eq. B.3-1 with a heat transfer coefficient

*Solution of Eq. B.3-1 for T_A gives $T_A = C_1 T_O + C_2 T_c$, a formulation similar to that used by ARHCO. The TASC "constants," however, are temperature-dependent.

$$h'' = \frac{C_A W_A A_f}{\pi R^2} \quad (\text{B.3-3})$$

The unknown in Eq. B.3-1 is the natural circulation flow rate, W_A . This quantity was estimated by setting the h determined from natural convection heat transfer with an h determined from forced convection (turbulent flow); the latter depends on W_A and a solution for the mass flow can be obtained.

Both h' and h'' , the convective heat transfer coefficients for naturally circulating air, are temperature-dependent.

Boundary condition B5 from the waste block into the gap represents radiation from can tops to space at 75°F. A view factor of 0.5 and an emissivity of 0.45 have been assumed. These values were adopted from Ref. B.8. The view factor was chosen to account for about half the radiation being intercepted by the concrete structure. The emissivity is that of non-oxidized metal; it is a conservatively low value and tends to lead to somewhat higher canister temperatures.

Boundary condition B2 accounts for both radiation and convective losses from the waste block across a gap to the concrete basins. Heat transfer from canister top, bottom and sides is included here.

Boundary condition B3 appears to be a convective loss term at the outer side of the concrete wall to a 120°F ambient. However, the heat transfer coefficient has been selected to match the thermal conduction resistance of 4 additional feet of concrete. Therefore, the concrete temperatures are those of the inner 4 ft of an 8-ft thick basin.

B.3.6 Material Properties

Table B.3-1 gives the material properties, all assumed temperature-independent, used in the interim storage thermal calculations. Note that:

- Air and waste thermal conductivities were input as very high values (greater than 10^3 BTU/hr-ft- $^{\circ}$ F) to give essentially uniform spatial temperatures. Hence, derived temperatures are actually spatial averages and radial and axial gradients are neglected
- Glass and calcine densities are averaged over the waste block and reduced from their normal values because of the large air volume
- Glass and calcine heat capacities were adjusted to include a contribution from the stainless steel canisters.

TABLE B.3-1
MATERIAL PROPERTIES

Material Name	Conductivity (BTU/hr-ft- $^{\circ}$ F)	Density (lb/ft 3)	Specific Heat (BTU/lb- $^{\circ}$ F)
Glass	$> 10^3$	83.8	0.1700
Calcine	$> 10^3$	43.5	0.156
Air	$> 10^3$	0.06	0.237
Concrete	0.792	131.0	0.210

B.3.7 Cases Run for Baseline Configuration

Loss of coolant accidents were simulated by HEATING5 for times up to 40 hours after start of the thermal transient. In addition, a steady-state run was performed for each transient to determine the temperature distributions at a very long

time after the accident. The various cases run differed in the type and age (i.e., heat generation per unit volume) of waste:

- 1-yr glass
- 2-yr glass
- 5-yr calcine
- 10-yr glass

B.3.8 Results of Baseline Studies

Figures B.3-3 through B.3-6 show the temperature-time profiles up to 40 hours plus the steady-state temperatures for the above four waste ages. Illustrated are the average canister temperatures and the average air temperature.

For the purpose of evaluating the onset of canister failure it is desirable to have an estimate of the peak canister temperature rather than the average. An exact computation of the radiation transfer from canister to canister in a large array is difficult. However, a rough determination of the temperature difference, ΔT , between the peak central canister and the average canister temperature was carried out using an approximation that modeled the radiation transfer as though the canister array were a series of concentric rings, each with an emissivity equal to that of the canister surface. The results are:

<u>AGE OF WASTE (yr)</u>	<u>$\Delta T(^{\circ}\text{F})$</u>
1	11
2	17
5	36
10	72

As can be seen, the temperature difference is small.

Figure B.3-3 Interim Storage Loss-of-Coolant Temperature Profiles: 1-Year Glass

Figure B.3-4 Interim Storage Loss-of-Coolant Temperature Profiles: 2-Year Glass

Figure B.3-5 Interim Storage Loss-of-Coolant Temperature Profiles: 5-Year Calcine

Figure B.3-6 Interim Storage Loss-of-Coolant Temperature Profiles: 10 Year Glass

The difference between calcine and glass temperatures (at the same age -- i.e., same heat generation rate) lies only in the transient temperature profile. The calcine is of lower density; because of the lower mass per canister its temperature will approach steady-state more rapidly. The steady-state or long-term temperatures will be precisely the same for calcine as for glass.

B.3.9 Interim Storage Sensitivity Studies

Canister Spacing - The purpose of this study was to determine the sensitivity of the probability of canister rupture on canister spacing for an interim storage loss of coolant accident.

The work reported here extends the calculations to canister spacings of 2 ft and 3 ft, focusing in particular on 1-yr and 2-yr glass waste forms where temperatures high enough to cause failures were attained previously at 1.5-ft spacing. One year waste is rated at 32.7 kW/canister; two year waste is rated at 16.8 kW/canister. The canister array geometry described in Section B.3.4 was maintained for the new calculations. Only steady-state equilibrium temperatures were computed for loss-of-coolant accidents.

From the models employed for forced and natural convective cooling it was found that the various thermal parameters in Eq. B.3-1 could be scaled in a relatively simple way with the effective canister separation distance, δ . The quantity δ is defined to be the equivalent radius of a circular channel with an area equal to the actual flow area. That is:

$$A_F = \pi \delta^2 = L^2 - \pi r^2 \quad (\text{B.3-4})$$

where L is the actual inter-canister spacing and r is the canister radius. The following scaling laws were adopted to modify the thermal parameters in Eq. B.3-1:

$$h \propto \delta^{1/9} \quad (\text{B.3-5})$$

$$W_A \propto \delta^{7/18} \quad (\text{B.3-6})$$

Equations B.3-4, B.3-5 and B.3-6 were the basis for modifying code inputs to account for changes in canister spacing.

Table B.3-2 gives the chief results for 1-yr glass waste at 1.5-ft, 2-ft and 3-ft spacings. The table indicates:

- T , the spatially averaged steady-state canister temperature
- T_a , the spatially averaged steady-state air temperature
- q_{rad} , the heat loss rate via radiation to space
- q_{conv} , the heat loss rate by natural convection to air
- q_{conc} , the heat loss rate to the concrete basin
- q_{tot} , the sum of q_{rad} , q_{conv} and q_{conc} .

Table B.3-3 gives comparable results for glass waste aged 2 years.

From Table B.3-2 it can be seen that the average canister temperature is not very sensitive to canister spacing; doubling the spacing decreases the canister temperature by only 9 percent. The primary reason for the lack of

TABLE B.3-2
INTERIM STORAGE LOSS-OF-COOLANT CANISTER SPACING
SENSITIVITY RESULTS FOR 1-YR GLASS HLSW

T-2572

QUANTITY CALCULATED	CANISTER SPACING (ft)		
	1.5	2	3
T (deg F)	3940	3750	3580
T _a (deg F)	820	500	300
q _{rad} (BTU/hr) x 10 ⁻⁷	2.9	2.4	2.1
q _{conv} (BTU/hr) x 10 ⁻⁷	2.6	2.9	3.2
q _{conc} (BTU/hr) x 10 ⁻⁷	0.1	0.2	0.3
q _{tot} (BTU/hr) x 10 ⁻⁷	5.6	5.5	5.6

TABLE B.3-3
INTERIM STORAGE LOSS-OF-COOLANT CANISTER SPACING
SENSITIVITY RESULTS FOR 2-YR GLASS HLSW

T-2573

QUANTITY CALCULATED	CANISTER SPACING (ft)		
	1.5	2	3
T (deg F)	2960	2720	2470
T _a (deg F)	560	350	220
q _{rad} (BTU/hr)x10 ⁻⁷	1.1	0.8	0.6
q _{conv} (BTU/hr)x10 ⁻⁷	1.9	2.1	2.2
q _{conc} (BTU/hr)x10 ⁻⁷	0.1	0.1	0.2
q _{tot} (BTU/hr)x10 ⁻⁷	3.1	3.0	3.0

sensitivity is the strong influence of radiation to space as a heat loss mechanism. The T^4 dependence of radiative losses on temperature allows for large changes in heat flow by radiation with small changes in temperature. Air temperatures, on the other hand, do markedly decrease as spacing increases due to the greater air mass present.

For all three spacings shown the canister temperature lies well above the 1200°C (2192°F) presumed canister failure temperature for glass waste by corrosion. Heat losses are predominantly through radiation and air convection; losses to concrete are minor. The total heat losses, q_{tot} , should be compared to the actual heat generation rate of the storage facility, 5.65×10^7 BTU/hr; agreement is very good indicating that a heat balance was obtained within the numerical accuracy of the code.

Two yr old wastes demonstrate lower steady-state temperatures because the heat generation rate has decayed to 3.12×10^7 BTU/hr. As was found for 1-yr wastes, the 2-yr waste steady-state temperature is above the threshold for corrosion at all spacings considered.

The results indicate that for 1-yr and 2-yr glass HLSW, increasing the canister spacing from 1.5 ft to 3 ft does not change the probability of release given an LOC accident -- it remains 1.0. Calculations have not been performed for 3-yr or older wastes at the new spacings, but extrapolation of the present results with confidence leads to the following conclusions:

- Increasing the spacing to 2 ft for 3-yr waste will reduce the steady state LOC temperature from 2400°F to a temperature below failure.

- 4-yr and older wastes would not fail in LOC accidents. Hence, the release probability for these wastes is 0 at all spacings 1.5 ft or greater.

Alternate Loading and Grouping Schemes - In the work presented to this point, the interim storage thermal analyses have assumed the HLSW to be segregated into groups of a single age, e.g., that the basin contains only 1-yr waste, 2-yr waste and so on up to 10-yr waste. Alternative storage schemes may aggregate the waste so that the basin consists of equal numbers of canisters containing wastes of all possible ages mixed in a reasonably homogeneous manner. The purpose of this study was to determine whether storage by aggregation offered any risk advantages over the method of segregation by age.

The approach taken was to determine the canister temperatures for the waste canisters in the aggregated basins and to compare these temperatures both with the segregated waste temperatures and with the failure criteria of particular waste forms. This procedure was followed for both the nominal 1.5-ft canister spacing and again for 2-ft spacing. Two different waste forms were considered here: glass and multibarrier. Furthermore, there were two types of aggregation methods that were examined; these are described below.

The first aggregation method was applied to the glass form only and assumed yearly batch inputs of fresh 1-yr old waste into the basin and simultaneous removal of 10-yr old waste. Just after this operation, 1/9 the basin contains 1-yr waste, 1/9 contains 2-yr waste and so on for all other waste ages up to and including 9-yr old waste. It is assumed that the LOC accident occurs precisely here. This scenario is a pessimistic one in that the basin contains waste material that is on the average younger than might be expected if the LOC had occurred at times between reload points.

The second aggregation method assumed continuous loading of fresh fuel for both glass and multibarrier waste forms and continuous removal of 10-yr old waste. In the case of glass the waste age distribution was uniform between 1 yr and 10 yr; for multibarrier waste, the distribution ranged between 150 days and 10 yr.

To compute the LOC steady-state temperatures for the batch-loaded glass waste it was necessary first to find the average heat output, $\bar{Q}$, for the aggregated waste in the basin; $\bar{Q}$ was found from:

$$\bar{Q} = 1/9 \sum_{i=1}^9 Q_i \quad (\text{B.3-7})$$

where Q_i = heat output (W/MWe-yr) for waste aged i years. The quantity $\bar{Q}$ was found to be 108.5 W/MWe-yr, roughly equivalent to that of a 3.5-yr old waste. By interpolation from previous HEATING5 run results for 1, 2, 5, and 10-yr wastes, it was determined that the average canister and air temperatures for the 1.5-ft spacing were, respectively:

- $\bar{T} = 2280^\circ\text{F}$
- $\bar{T}_a = 532^\circ\text{F}.$

The question remained whether the temperatures of the individual canisters varied significantly from the ensemble average. That is, was a 1-yr waste canister appreciably hotter than the average canister in the array? To determine the answer the following approach was used. A heat balance was taken on each individual canister:

$$Q_i = h_c A_s (T_i - \bar{T}_a) + h_r A_{\text{top}} (T_i^4 - T_o^4) + h_r' A_s (T_i^4 - \bar{T}^4) \quad (\text{B.3-8})$$

The first term represents convective losses to air with a coefficient h_c that is evaluated at temperature $1/2(\bar{T} + \bar{T}_a)$. A_s is the surface area of the canister (31.4 ft²). The quantity T_i is the temperature of a canister containing waste of age i years.

The second term represents external radiation losses from the canister top to space. The coefficient h_r was computed using a view factor of 0.5 and an emissivity of 0.45. The area of a canister top, A_{top} , is 0.785 ft². T_o was assumed to be 75°F.

The third term approximates internal radiative losses (or gains) from a canister of temperature T_i to a ring of surrounding canisters all at the average array temperature $\bar{T}$. The coefficient h_r' accounts for reradiation between two gray-bodies.

All heat losses on the right-hand side of the above equation were equated to Q_i , the total radionuclide decay heating rate. For each waste age i , a solution was found for T_i . Because of the high temperatures involved, it was discovered that the internal radiation heat fluxes were high enough to preclude large temperature differences among the canisters with different waste ages. That is, all tended to cluster near the average; the minimum and maximum temperatures were

$$T_{10} = 2267^{\circ}\text{F}$$

$$T_1 = 2331^{\circ}\text{F}$$

compared to the average temperature

$$\bar{T} = 2280^{\circ}\text{F}$$

The results are summarized in Fig. B.3-7 for 1.5-ft spacing. The histogram shows the average canister temperatures for segregated wastes of ages 1 yr to 9 yr, assuming isolation of each age group. The horizontal bar gives the temperature range of canisters in an aggregated facility, with all ages uniformly mixed together. Shown, as well, is a shaded horizontal bar that indicates the failure temperature range ($1200^{\circ}\text{C} \pm 50^{\circ}\text{C}$) of canisters by corrosion.

It is evident from Fig. B.3-7 that 1/3 of the canisters in segregated facilities would fail due to an LOC accident, i.e., those canisters containing 1-yr, 2-yr and 3-yr wastes.

The canisters in an otherwise similar batch-loaded, age-aggregated facility would all fail if the nominal 1200°C failure criterion is employed. In explanation, the high heat output of the young wastes raises the average temperature high enough to exceed the failure threshold. The scheme of integrating all waste ages thus appears to raise the probability that release of radioactivity for an LOC accident would take place. However, when the uncertainty band in the glass failure criterion ($\pm 90^{\circ}\text{F}$) and the potential errors in the simple thermal model used (perhaps of the order of a few hundred degrees F) are taken into account, no firm conclusions can be drawn regarding the fraction of failed glass waste canisters.

These calculations were repeated for a segregated facility with a 2-ft spacing. The following principal results were obtained:

$$T_{10} = 2000^{\circ}\text{F}$$

$$T_1 = 2080^{\circ}\text{F}$$

$$\bar{T} = 2020^{\circ}\text{F}$$

Figure B.3-7 Interim Storage Loss-of-Coolant-Accident Temperatures for Segregated and Aggregated Wastes

Again, the temperature variation between 1-yr and 10-yr canisters is small. It is of special note that all canisters are below the nominal 1200°C failure threshold temperature, although, as before, the uncertainties present are larger than the difference between computed canister temperatures and the corrosion failure temperature. In the segregated waste case for 2-ft spacing 1-yr and 2-yr wastes clearly fail in an LOC accident (see Tables B.3-2 and B.3-3) and 3-yr wastes are marginal.

Canister temperatures were also calculated for continuous waste input/output to and from the storage basin. In

order to find the average heat output, $\bar{Q}$, for the continuous distribution of waste ages in the facility, use was made of the analytical expression for the total heat decay rate taken from Ref. B.9:

$$Q(t) = 10^{f(t)},$$

with

$$f(t) = C_1 - C_2 \log_{10} t - C_3 (\log_{10} t)^2,$$

where

$$C_1 = 2.50786$$

$$C_2 = 0.804713$$

$$C_3 = 0.166584$$

$Q(t)$ is in units of W/MWe-yr when t is in years.

Performing the requisite integrals over 1 yr to 10 yr for glass and 150 d to 10 yr for multibarrier yields the following values of $\bar{Q}$:

$$\bar{Q}_{\text{glass}} = 93 \text{ W/MWe-yr}$$

$$\bar{Q}_{\text{mb}} = 112 \text{ W/MWe-yr}$$

Table B.3-4 summarizes the resultant average canister steady-state temperatures following a LOC accident for continuous waste movement for glass and multibarrier waste forms at both 1.5-ft and 2-ft canister spacing. The failure criteria for each form are listed for comparison. A number of interesting conclusions can be drawn from Table B.3-4 and previously presented results:

TABLE B.3-4
INTERIM STORAGE CANISTER TEMPERATURES FOR
CONTINUOUS WASTE LOADING

WASTE FORM	CANISTER SPACING		FAILURE CRITERION
	1.5 ft	2.0 ft	
Glass	2070°F	1800°F	2192 ± 90°F
Multibarrier	2330°F	2060°F	2372 ± 180°F

- LOC temperatures for glass under continuous loading are lower by about 200°F than under batch (worst case) loading.
- Canisters containing glass are not predicted to fail with the continuous loading scheme. If we somewhat arbitrarily assign (engineering judgement) a ± 200°F error band to the predicted canister temperatures, then the "no fail" conclusion is not firm for 1.5-ft spacing, but is probably realistic for 2-ft spacing.
- Multibarrier waste temperatures are higher than glass waste during an LOC accident by 260°F at both spacings owing to the additional presence of 150-day to 1-yr waste.
- No hard conclusions should be set forth with regard to multibarrier waste failures due to the large uncertainties in both predicted temperatures and the failure criterion. Nominally, failure will not take place for continuous loading, but presumably might for worst case batch loading.

B.3.10 Conclusions

For the baseline calculations involving glass HLSW in an array with 1.5-ft spacing and segregated according to age, failure or survival in an interim storage LOC accident depends upon:

- The specific heat rate of the waste, or for a given dilution, the waste age
- The failure temperature for rapid corrosion of the stainless steel canisters.

The baseline case results indicate that glass wastes with ages 1 yr to 3 yr will fail; older wastes will survive, given a 1200°C failure temperature. These results are probably somewhat insensitive to inaccuracies in the thermal model employed and to the failure criterion selected.

Sensitivity analyses performed on variations about the baseline case demonstrate the following:

- Canister temperatures are relatively insensitive to changes in canister spacing for separation distances in the range of 1 ft to 3 ft. For segregated wastes, the fraction of canister failures occurring in an LOC accident is likewise insensitive to spacing.
- The use of alternate storage schemes such as batch and continuous loading of the basin with fresh wastes and mixing or aggregating the wastes of various ages does not give clear-cut failure results. That is, predicted canister temperatures for an LOC accident are not statistically distinguishable from assumed corrosion failure temperatures, due principally to the large uncertainties in the thermal model employed, and to a lesser extent to the uncertainties in the glass and multibarrier failure criteria.
- Multibarrier materials have a higher chance of canister failure than does glass for aggregated storage owing to the inclusion of material between 150 days and 1 yr. Whether or not the difference is significant is masked by the large uncertainties involved.

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APPENDIX C
PRE-EMPLACEMENT SENSITIVITY ANALYSIS

This appendix describes the methods and results of the pre-emplacement accident sensitivity analysis. The objective was to show the variation of expected dose with respect to changes in important model parameters. In Section C.1 the general scope and methods of the analysis are presented, along with a brief overview of the major sets of accidents studied. Sections C.2 and C.3 describe the detailed sensitivity studies used in analyzing each set of accidents and present tabular summaries of expected dose.

C.1 METHODOLOGY

Among the pre-emplacement accidents involving high-level solidified waste (HLSW), as described in Chapter 2 and Appendix A, two sets of accidents were seen to dominate total expected dose:

- Interim storage pool drainage accidents that result in the release of volatiles from borosilicate glass and multibarrier waste.
- Truck and train impact and fire accidents occurring during shipment of waste that result in the release of airborne particulates and/or volatiles from all waste forms.

These two sets of accidents are the focal points for the sensitivity analysis; determining the potential ranges of the expected doses that may result is especially critical,

due to their high nominal expected dose values. All other pre-emplacement accidents have nominal expected dose values many orders of magnitude below those of the two major sets of accidents, so that even gross variation in their parameters would not bring their expected dose up to the same order of magnitude as that of the dominant components.

For the sets of major accidents, the general expected dose equations presented in Appendix A (Eqs. A.2-1 to A.2-4) were broken down into their components:

- Accident and pathway probabilities - Each accident's overall probability of occurrence is a product of several conditional probabilities. One can use a simple ratio formula to express the sensitivity of total expected dose from all accidents to perturbation of a conditional probability for any single accident. A similar line of reasoning applies to pathway probabilities. See Sections C.2.1 and C.3.1 for further detail.
- Expected biosphere release fraction given an accident - The biosphere release fraction is a simple product of parameters in the expected dose equation for interim storage pool drainage accidents. In transportation accidents, its evaluation requires integrating the product of the accident's probability density function and release function over all credible severities. Each of these two functions can vary within an ensemble bounded by "best-case" or "worst-case" functions or by more statistically rigorous limits such as 95% confidence intervals about the nominal function. Sensitivity of overall expected dose with respect to the parameters of transportation accident release fractions is inherently nonlinear and so becomes a major facet of the sensitivity analyses.

- Radionuclide inventories - The actual number of Ci/MWe-yr present in HLSW at each age, $Q_r(t)$, is a deterministic quantity. All accidents involving waste of a single age (e.g., transportation accidents) therefore need not undergo sensitivity analysis with respect to this variable. However, in interim storage accidents it is necessary to compute a mean inventory over the several waste ages exposed to potential release in an accident. This requires the integration of $Q_r(t)$ over these waste ages. It is necessary to evaluate the nonlinear sensitivity of expected dose to the value of the upper integration limit used (i.e., age beyond which the waste cannot fail given an accident). This parameter's value depends on the age aggregation and spacing designs used in the storage pool.
- Dose commitment factors - Dose factors are deterministic parameters, so no sensitivity analyses are performed with respect to them.
- Biosphere pathway models - Sensitivity of expected airborne dose with respect to meteorology and demography model parameters has not been treated in this study. Such analysis would require a knowledge of upper and lower bounds on model parameter values -- information not available at the time this analysis was performed.

Whenever possible, the sensitivity analysis made use of statistical confidence limits when choosing upper and lower bounds on functions or parameters. However, this type of rigorous analysis was possible for only a small subset of the functions analyzed -- i.e., for some of the probability density functions of transportation accident severity. In all other cases the data available were categorized with simple ordinal designations such as "maximum" or "minimum" parameter values or functions or else no data on extreme bounds were available. Hence, the most desirable objective, creation of a multivariate distribution among all function parameters and computation of

joint confidence intervals for expected dose, was not attainable.

In view of these limitations, the following approach was adopted for the sensitivity analysis:

- Simple relationships were developed showing the sensitivity of total expected pre-employment dose from all accidents studied to changes in the multiplicative (linear) parameters of a single accident. Upper and lower bounds for these "linear" parameters were not established, however.
- For each of the major pre-employment accidents, all parameters to which the accident's expected dose displayed a nonlinear sensitivity were simultaneously perturbed to establish "high" and "low" risks based on the perturbation of these parameters alone.

Such an analysis generates insights into how the parameters affect the risk. Knowing this, decisions can be made concerning whether one or more parameters need to be more precisely defined.

C.2 INTERIM STORAGE POOL DRAINAGE ACCIDENTS

In Appendix A it was shown that rupture and drainage of the interim storage pool was the major contributor to total expected dose from pre-employment accidents involving borosilicate glass and multibarrier waste. The sensitivity of total expected pre-employment dose to changes in the various parameters of this accident scenario are analyzed in this section.

C.2.1 Sensitivity of Expected Dose to Accident
and Pathway Probabilities

The total expected whole-body and critical-organ dose from pre-emplacment accidents is computed by summing the expected dose from each kind of accident separately by release mechanism and waste form. A simplified equation can be written to show the relationship between the accident or pathway probabilities of a pool drainage accident and expected dose from that accident:

$$D_p = [\pi P] k \quad (C.2-1)$$

where:

D_p = expected dose due to radionuclides released via volatilization from a pool drainage accident (man-rem/MWe-yr)

P = a conditional accident or pathway probability of the pool drainage accident

k = the remaining terms of the expected dose equation.

Total expected pre-emplacment dose is computed by summing expected releases from all pre-emplacment accidents, including the pool drainage scenario. Therefore, the total expected dose's sensitivity to changes in conditional pool drainage accident or pathway probabilities is

$$D' = D + D_p \left(\frac{P'}{P} - 1 \right) \quad (C.2-2)$$

where:

D, D' = total baseline and perturbed values, respectively, of expected pre-emplacment

dose due to radionuclides released from a given waste form. This measure is computed by summing expected dose over all non-transportation accidents and then separately over either truck or train accidents. Units are man-rem/MWe-yr.

P' = the perturbed value of the conditional pool drainage accident or pathway probability.

Thus, a linear sensitivity of total expected pre-emplacment dose to these parameters exists.* Knowledge of the baseline values of total and pool drainage expected doses and the new and old values of the parameter in question[†] are sufficient to evaluate the perturbed expected dose.

Substituting the nominal dose values calculated in Appendix A into Eq. C.2-2, the general sensitivity relationships of Table C.2-1 are found. These can be used to vary the probability of a severe earthquake or the probability of pool drainage given an earthquake to any desired feasible value.

C.2.2 Sensitivity of Expected Dose to Thermal Failure Parameters

The expected activity of radionuclides released is a function of the failure threshold age for each waste form --

*There are no expected dissolution or airborne particulate releases from pool drainage accidents due to an assumed lack of pathways to the biosphere for these mechanisms. The sensitivity of total pre-emplacment dose from these mechanisms to this accident's parameter values is therefore zero.

†The required data are available in Appendix A.

TABLE C.2-1

SENSITIVITY OF EXPECTED WHOLE-BODY DOSE
FROM ALL PRE-EMPLACEMENT ACCIDENTS AND PATHWAYS TO INTERIM
STORAGE POOL DRAINAGE ACCIDENT PROBABILITIES

TRANSPORTATION MODE	PERTURBED VALUE OF DOSE, D' (man-rem/MWe-yr)	
	BOROSILICATE GLASS	MULTIBARRIER WASTE FORM
Truck	$8.0 \times 10^{-3} + 0.99 \frac{P'}{P}$	$1.3 \times 10^{-5} + 1.3 \frac{P'}{P}$
Train	$4.9 \times 10^{-3} + 0.99 \frac{P'}{P}$	$1.6 \times 10^{-7} + 1.3 \frac{P'}{P}$

P = baseline value of an accident or pathway probability

P' = perturbed value of an accident or pathway probability

i.e., the age beyond which canister failure due to thermally accelerated corrosion does not occur. The threshold age is used as the upper limit of integration of radionuclide source terms over waste age in Eqs. A.2-3 and A.2-4. This age can assume a value between zero (indicating no waste failure at any age) and ten years (indicating failure of wastes of all anticipated ages at which they may be stored).

The failure threshold age, in turn, depends on the values of two design parameters, which were introduced in Appendix B:

- The inter-canister spacing in the storage pool, which affects canister-to-canister heat transfer. The separation distances assumed in this study were 1.5 ft, 2.0 ft and 3.0 ft between canister centerlines.
- The degree of physical disaggregation of the different ages of waste present in the pool. This affects the steady-state temperature achieved by each of the waste

ages present. One option is physical segregation of wastes by age category. In this case each age category of waste will achieve its own steady-state temperature given a pool drainage accident. The second option is uniform physical aggregation of all waste ages using a waste rotation management scheme. Fresh waste can be loaded into the pool either on a discrete basis, e.g., annually, (batch mode) or on a continuous basis as waste is removed for shipment to the repository. For aggregated storage, one mean steady-state temperature is computed for the entire ensemble following a pool drainage accident.

Definition of Nominal Scenario - The baseline configuration assumed for canister storage in the pool (Appendix B) is the age segregation option using a 1.5-ft inter-canister spacing. Figure B.3-7 shows the steady-state canister temperature achieved in each of the nine segregated age groups following a pool drainage accident. These temperatures apply for glass, calcine and multibarrier wastes, since the assumed heat generation rate at each age is the same for all waste forms and differences in waste forms' thermal conductivities do not affect steady-state canister temperatures. The assumed failure temperature for glass waste with its associated uncertainty band is also shown on the graph. The abscissa of the point of intersection of this failure temperature band with the waste temperature function is the failure threshold age for glass (about 3 yr). Although not shown in Fig. B.3-7, the failure temperature bands for calcine ($2372 \pm 90^{\circ}\text{F}$) and multibarrier waste ($2372 \pm 180^{\circ}\text{F}$)* (Ref. C.1) would also intersect at about 3 yr.

*This is actually the range of coating failure temperature for multibarrier waste, which is higher than the canister failure range of $1832 \pm 360^{\circ}\text{F}$ (Ref. C.1).

Thus, the probability of failure for all waste forms in this nominal configuration, given a pool drainage accident, is:

$$P(\text{fail}) = \begin{cases} 1.0 & \text{for waste } \leq 3 \text{ yr old} \\ 0 & \text{for waste } > 3 \text{ yr old.} \end{cases} \quad (\text{C.2-3})$$

The corresponding failure threshold age, τ_{iq}^F , to use in dose Eqs. A.2-3 and A.2-4 is:

$$\tau_{iq}^F = 3 \text{ yr for all waste forms.} \quad (\text{C.2-4})$$

In Appendix A it was assumed that the calcines do not enter interim storage until the age of five years. Therefore, their probability of failure in an interim storage pool drainage accident is zero for any age disaggregation scenario involving an inter-canister spacing of 1.5 ft or greater.

Definition of Extreme Scenarios - The age-segregated configuration for interim storage was shown in Appendix B to exhibit little sensitivity to changes in pool configuration parameters. Therefore, the alternative concept of waste age aggregation was investigated in order to complete the sensitivity analysis of expected dose from pool drainage accidents.

With uniform age aggregation of wastes in the storage pool, there are two possible consequences of a pool drainage accident that are consistent with the assumptions made in this analysis:

- If the mean steady-state temperature of the waste ensemble is less than the failure temperature for the waste form, no canisters of any age fail.

- If the mean ensemble temperature exceeds the failure temperature for the waste form, all canisters in the pool will fail regardless of age. Even older wastes that were not subject to failure in the age-segregated scenario would fail due to the heat given off by the younger wastes in the ensemble.

There are bands of uncertainty associated with both the steady-state canister ensemble temperature following an accident (typically $\pm 200^{\circ}\text{F}$ about the estimated value, per Appendix B) and the failure threshold temperature for each waste form ($2192 \pm 90^{\circ}\text{F}$ for glass and $2372 \pm 180^{\circ}\text{F}$ for multibarrier waste, per Ref. C.1). Unfortunately, this limits the ability to make precise statements on whether or not the entire age-aggregated inventory of waste fails following a pool drainage accident.

Figures C.2-1 and C.2-2 contain plots of the age-aggregated waste temperatures corresponding to the various canister spacings and pool loading strategies previously discussed, along with failure temperatures for glass and multibarrier waste. The aggregated waste temperatures for each spacing and loading configuration are shown as vertical solid or dotted lines with three marks: the middle mark in each case is the nominal waste temperature (as determined in Appendix B) and the upper and lower marks represent the assumed $\pm 200^{\circ}\text{F}$ band of uncertainty about this nominal value. (Batch loading of multibarrier waste was not investigated.) The assumed nominal waste failure temperatures and limits of uncertainty are similarly indicated for each waste form by a crosshatched area on the graph.

When the range of waste temperatures for a particular spacing-loading configuration lies entirely above the failure temperature uncertainty band, the probability of failure is

Figure C.2-1 Age-Aggregated Waste Temperatures and Failure Thresholds for Interim Storage Pool Drainage Accidents Involving Borosilicate Glass Waste

one. When the line lies entirely below the failure temperature uncertainty band (e.g., for continuous loading of glass waste with 2-ft canister separations), the probability of failure is zero. When overlap of the two regions exists, which is most often the case, the probability of failure is more difficult to determine. However, an estimate can be made if probability distributions are assumed for the canister and failure temperatures.

Let T_1 be a random variable denoting the assumed failure temperature for each waste form and T_2 be a random variable denoting the steady-state post-accident canister

Figure C.2-2 Age-Aggregated Waste Temperatures and Failure Thresholds for Interim Storage Pool Drainage Accidents Involving Multibarrier Waste

ensemble temperature for a certain spacing and loading. Then the probability of all canisters failing following a pool drainage accident is:

$$P(T_2 \geq T_1) = \int_{T=0}^{\infty} P(T_1 \leq T) p(T_2) dT \quad (C.2-5)$$

The first term in the integrand is a cumulative distribution function (cdf) of T_1 and the second term is a probability density function (pdf) of T_2 . As a first approach, a simple uniform probability distribution will be assumed for both T_1 and T_2 :

$$P(T_1 \leq T) = \begin{cases} 0, & T \leq \bar{T}_1 - \frac{a}{2} \\ \frac{1}{a} \left[T - \bar{T}_1 + \frac{a}{2} \right], & \bar{T}_1 - \frac{a}{2} < T \leq \bar{T}_1 + \frac{a}{2} \\ 1, & T > \bar{T}_1 + \frac{a}{2} \end{cases} \quad (C.2-6)$$

$$p(T_2) = \begin{cases} 0, & T < \bar{T}_2 - \frac{b}{2} \\ \frac{1}{b}, & \bar{T}_2 - \frac{b}{2} \leq T \leq \bar{T}_2 + \frac{b}{2} \\ 0, & T > \bar{T}_2 + \frac{b}{2} \end{cases} \quad (C.2-7)$$

where

$\bar{T}_1$ = the mean failure temperature for each waste form (for glass, $\bar{T}_1 = 2192^\circ\text{F}$; for multibarrier waste, $\bar{T}_1 = 2372^\circ\text{F}$).

a = the total width of the uncertainty band about $\bar{T}_1$ (for glass, $a = 180^\circ\text{F}$; for multibarrier waste, $a = 360^\circ\text{F}$).

$\bar{T}_2$ = the mean steady-state post-accident canister ensemble temperature for each spacing and loading configuration (the middle mark in the ranges shown in Figs. C.2-1 and C.2-2).

b = the total width of the uncertainty band about $\bar{T}_2$ (400°F for all spacings and loadings).

Performing the operations of Eq. C.2-5 yields the canister failure probability values shown in Figs. C.2-1 and C.2-2. These probabilities can now be rank-ordered and used to determine ranges of expected dose from both glass and multibarrier waste.

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Nominal and Extreme Expected Doses - Table C.2-2 summarizes the configurations chosen from Figs. C.2-1 and C.2-2 as extreme accident scenarios, along with their associated failure probabilities and expected doses. For all aggregated scenarios, the failure threshold age is set to 10 yr for use in Eqs. A.2-3 and A.2-4 and the resulting expected dose is multiplied by the high and low failure probabilities, respectively, to obtain the high and low expected doses. A failure threshold age of 10 yr applies to both extreme scenarios because if the waste fails at all in an accident involving age-aggregated waste, all ages of waste in the pool fail. The reader is cautioned that the high and low failure probabilities and expected doses shown are completely dependent on the form of the probability distributions assumed for T_1 and T_2 . Future analysis should explore the effect of substituting other probability distributions, such as a Gaussian. For uniform distributions, the expected doses shown are the high and low values of risk with respect to those parameters whose perturbation affects risk in a nonlinear manner.

TABLE C.2-2
SUMMARY OF NOMINAL AND EXTREME CASES:
INTERIM STORAGE POOL DRAINAGE ACCIDENTS

T-1889

WASTE FORM	EXPECTED DOSE COMPUTED	AGE AT ENTRY INTO INTERIM STORAGE (yr)	AGE AT REMOVAL FROM INTERIM STORAGE (yr)	THRESHOLD FAILURE AGE (yr)	PROBABILITY OF WASTE FAILURE, GIVEN AN ACCIDENT	FACTORS CONTROLLING THE PROBABILITY AND THRESHOLD AGE OF FAILURE			EXPECTED WHOLE-BODY DOSE $\frac{mR}{hr \cdot yr}$
						INTER-CANISTER SPACING (ft)	WASTE AGE SEPARATION OPTION	CANISTER LOADING SCHEME	
Borosilicate Glass	High	1	10	10	0.72	1.5	Aggregation	Batch	2.5
	Nominal	1	10	3	1	1.5	Segregation	Batch	0.89
	Low	1	10	10	0	2.0	Aggregation	Continuous	0
Multi-barrier	High	0.4	10	10	0.4	1.5	Aggregation	Continuous	1.5
	Nominal	0.4	10	3	1	1.5	Segregation	Batch	1.3
	Low	0.4	10	10	0.016	2.0	Aggregation	Continuous	0.061

C.2.3 Summary

This section has shown the linear sensitivity of total expected pre-emplacment dose to changes in multiplicative parameters in the interim storage pool drainage accident equation. Additionally, the sensitivity of risk to changes in parameters such as the failure threshold age and probability of failure of waste in pool drainage accidents has been evaluated using extreme scenarios. The latter approach was adopted because of the nonlinear nature of these sensitivity relationships and the lack of distributional data for these parameters. A scenario was said to have low or high risk based on these nonlinear sensitivity analyses alone. Table C.2-2 lists the parameter values corresponding to each of these scenarios. One can use these extreme risk values and the aforementioned linear sensitivity relationships to simultaneously perturb the nonlinear and linear parameters using any ranges of values for the linear parameters.

The following conclusions can be drawn concerning the sensitivity of risk from interim storage pool drainage accidents:

- For spray and fluidized bed calcine waste entering interim storage at an age of five years or more, the probability of failure in this accident is zero for all scenarios -- hence, expected dose is also zero in each case. Thus, transportation accidents are the dominant component of risk from these waste forms.
- For borosilicate glass waste entering interim storage at the age of one year:
 - Total expected dose from all pre-emplacment accidents is almost proportional to any multiplicative (linear) pool drainage

accident parameter, since risk from this accident is the dominant component of total pre-emplacment risk (see Table C.2-1). Such linear parameters include the probability of a severe earthquake and the probability of pool drainage given an earthquake.

- Using the failure threshold temperatures given in Ref. C.1 and the post-accident mean waste ensemble temperature derived in Appendix B, there is no release from borosilicate glass in the best-case configuration.
- Expected dose from this waste form is very sensitive to the choice of the pool design factors enumerated in Table C.2-2.
- For multibarrier waste entering interim storage at the age of 150 days:
 - Total expected dose from all pre-emplacment accidents is almost proportional to any linear pool drainage accident parameter, for the same reasons as were listed above under borosilicate glass (see Table C.2-1).
 - Expected dose from this waste form is moderately sensitive to the choice of the pool design factors discussed in Table C.2-2.

C.3 TRANSPORTATION ACCIDENTS

Impact and fire accidents involving the shipment of waste by truck or train were shown in Appendix A to provide a significant contribution to total expected pre-emplacment dose. Transportation accidents were shown in Section A.6 to provide the dominant component of risk from both spray and fluidized bed calcine and the second-greatest component of risk from borosilicate glass. This section analyzes the sensitivity of total expected pre-emplacment dose to changes in parameters affecting probability and release fraction calculations for specific transportation accidents.

C.3.1 Sensitivity of Expected Dose to Accident and Pathway Probabilities

An expression showing the sensitivity of total expected pre-emplacement volatilization, dispersion or dissolution dose from each waste form to variations in the accident and pathway probabilities of each truck and train accident can be derived using the same methods presented in Section C.2.1. This general sensitivity relationship is

$$D' = D + D_T \left(\frac{P'}{P} - 1 \right) \quad (C.3-1)$$

where

D, D' = baseline and perturbed values, respectively, of total expected pre-emplacement dose due to radionuclides released via a given mechanism from a given waste form. This measure is computed by summing expected dose over all non-transportation accidents and then separately over either truck or train accidents. Units are man-rem/MWe-yr.

D_T = baseline value of expected dose from the specific truck or train accident, release mechanism and solid form for which the sensitivity relationship is to apply.

P, P' = the baseline and perturbed values, respectively, of the accident or pathway probability in the truck or train accident of interest.

It should be noted that some transportation accidents have no release via one or more of the assumed mechanisms (e.g., there is no release of volatiles in truck and train impact accidents). Therefore, the sensitivity of total expected pre-emplacement dose from these mechanisms to parameter value changes in such accidents is zero.

A separate sensitivity equation must be developed for each combination of release mechanism, waste form and transportation accident type; this would require 108 separate versions of Eq. C.3-1. Due to the great number of equations that would result, such an analysis is not performed here. Rather, the reader is referred to Tables A.3-3, A.3-4 and A.6-1 to A.6-4 in Appendix A, which provide all data necessary for evaluating Eq. C.3-1 given any combination of accident, release mechanism and waste form.

C.3.2 Sensitivity of Expected Dose to Release Fraction Parameters

The expected biosphere release fraction was shown in Eqs. A.3-12 and A.3-13 of Appendix A to be a product of the pathway probability and waste release fraction. Section C.3.1 has already treated the sensitivity of expected dose to perturbation of the pathway probabilities, so the emphasis here will be on analysis of the effects of perturbing the parameters used in evaluating waste release fractions.

The factors of interest in the release fraction calculations are:

- Probability density functions (pdf's) of accident severity
- Release functions of accident severity
- Failure threshold temperatures and loci (fire accidents).

Figure C.3-1 gives an overview of the types of perturbations considered in the analysis:

- 95% confidence intervals about pdf tails. These are computed only for those pdf's for which identifiable data points (instead of

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Figure C.3-1 Release Fraction Parameters Perturbed in Transportation Accident Sensitivity Analysis

smooth curves) are available -- i.e., for pdf's of truck fire time and train impact velocity.

- Upper and lower bounds on release functions. These are used for all dispersion, volatilization and dissolution release functions which depend on impact velocity or fire temperature.
- Estimated upper-risk and lower-risk bounds on the failure threshold temperature for each waste form. Each combination of failure temperature and transportation mode has its own associated failure time vs. fire temperature locus. (See Appendices A and B for details.)

The methodology followed in the sensitivity analysis involves computing the possible ranges of expected dose by simultaneously perturbing all of the above factors (pdf's, release functions and failure criteria) to either their best- or worst-case representations. Results of these runs then serve as extreme bounds on expected dose from release fraction perturbation alone.

Computation of 95% Confidence Intervals about pdf's of Accident Severity - The computation of confidence intervals about a function fit to empirical data requires a knowledge of the individual data values used. Such data were available for pdf's of

- Train impact velocity at collisions with trucks during railroad crossings
- Train impact velocity at collisions with extremely rigid fixed objects
- Truck fire times.

In each case, the raw data were tabulated in formats most easily transformable into cumulative distribution functions

(cdf's). The resulting cdf's were then graphically or analytically differentiated to form their associated pdf's for use in the expected release fraction calculations.

Computing confidence intervals about the pdf's began by taking the general two-parameter Weibull cumulative distribution function assumed in Appendix A:

$$F(v) = 1 - \exp\left[-(v/\alpha_1)^{\alpha_2}\right] \quad (C.3-2)$$

and transforming it as follows:

$$\ln[-\ln(1-F(v))] = \alpha_2 \ln v - \alpha_2 \ln \alpha_1 \quad (C.3-3)$$

Then, letting

$$x = \ln v \quad (C.3-4)$$

$$g(v) = \ln[-\ln(1-F(v))] \quad (C.3-5)$$

$$h(x) = g(v(x)) \quad (C.3-6)$$

Equation C.3-3 becomes

$$\begin{aligned} h(x) &= \alpha_2 x - \alpha_2 \ln \alpha_1 \\ &= A_1 x + A_2 \end{aligned} \quad (C.3-7)$$

This is now an estimation problem amenable to solution by linear regression analysis after transforming each of the original data points $(v_i, F(v_i))$ to $(x_i, h(x_i))$ via Eqs. C.3-4 to C.3-6. Least-squares estimates $\hat{A}_1$ and $\hat{A}_2$ were then obtained and transformed to the estimates $\hat{\alpha}_1$ and $\hat{\alpha}_2$:

$$\hat{\alpha}_1 = \left[-\hat{A}_2 / \hat{A}_1 \right] \quad (\text{C.3-8})$$

$$\hat{\alpha}_2 = \hat{A}_1 \quad (\text{C.3-9})$$

The standard error of the estimate, s , was also calculated.

Next, the 95% confidence intervals about $h(x)$ at each independent observation x_k were computed (Ref. C.2):

$$h(x_k) = \hat{h}(x_k) \pm t(n-2, 0.95) s \left[1 + \frac{1}{n} + \frac{(x_k - \sum x_i / n)^2}{\sum x_i^2 - \frac{1}{n} (\sum x_i)^2} \right]^{1/2} \quad (\text{C.3-10})$$

where

$$\hat{h}(x_k) = \hat{\alpha}_2 x_k - \hat{\alpha}_1 \ln \hat{\alpha}_1 \quad (\text{C.3-11})$$

and

$t(n-2, 0.95)$ = the 95 percentage point of the t -distribution having $n-2$ degrees of freedom (two-sided test).

n = the number of data points used to estimate $\hat{\alpha}_1$ and $\hat{\alpha}_2$.

i = index of a data point used to estimate $\hat{\alpha}_1$ and $\hat{\alpha}_2$.

x_i = $\ln v_i$, the transformed value of the i^{th} data observation.

k = index of an independent data point not used in the estimation of $\hat{\alpha}_1$ and $\hat{\alpha}_2$.

x_k = $\ln v_k$, the transformed value of the k^{th} independent observation.

Solving Eq. C.3-5 for $F(v)$ and substituting the equality $h(x) = g(v)$:

$$F(v) = 1 - \exp[-e^{h(x)}] \quad (C.3-12)$$

Equation C.3-12 can be used to map the confidence intervals about $h(x)$ at each point x_k into confidence intervals about $F(v)$ at each point v_k , as follows:

$$F^{\pm}(v_k) = 1 - \exp[-e^{h^{\pm}(x_k)}] \quad (C.3-13)$$

where the $\pm$ designation refers to the high (+) and low (-) confidence bounds about each function. Note that the high bound $h^+(x_k)$ maps into high bound $F^+(v_k)$, and the low bound $h^-(x_k)$ maps into low bound $F^-(v_k)$.

A simple graphical differentiation technique can be used to compute the desired pdf confidence bounds $p^+(v)$ and $p^-(v)$ on a pointwise basis from $F^-(v)$ and $F^+(v)$, respectively:

$$p\left(\frac{v_k + v_{k+1}}{2}\right) \approx \frac{F(v_{k+1}) - F(v_k)}{v_{k+1} - v_k} \approx \frac{dF}{dv} \bigg|_{v = \frac{v_k + v_{k+1}}{2}} \quad (C.3-14)$$

Thus, confidence intervals for the pdf's can be generated over any severity range on a point-by-point basis. Straight line segments can then be used to connect these points to form a piecewise-linear continuous function for use in release fraction calculations. It is believed that these numerical calculations are accurate to three decimal places, which is sufficient precision for use in the remaining analysis.

Release Functions - Table C.3-1 and C.3-2 summarize the parameter values used to generate the lower and upper release functions for impact and fire accidents, as depicted in Fig. C.3-1. Appendix A contains the generic release function equations whose parameters are referenced in these tables.

Failure Loci - The parameters α and β of the failure time vs. fire temperature locus (Eq. A.3-21, Appendix A) vary as the assumed failure temperature varies between its limits of uncertainty for each waste form. These limits are (Ref. C.1):

- For spray and fluidized bed calcine:
2372 $\pm$ 90°F (canister failure)
- For borosilicate glass:
2192 $\pm$ 90°F (canister failure)
- For multibarrier waste:
2372 $\pm$ 180°F (failure of
waste coating).

The values of α and β for the loci corresponding to each of the lower-risk (high) and upper-risk (low) failure temperatures listed above can be found in Tables B.1-4 and B.2-3 of Appendix B for train and truck fire accidents, respectively.

Results of Analyses Performed - Tables C.3-3 through C.3-10 present summaries of ranges of values of expected dose from transportation accidents involving each of the four reference waste forms.

The high and low expected doses presented here are based on simultaneous perturbation of all nonlinear release fraction parameters (but not the linear accident or pathway probabilities). These extreme risks can be compared with the

TABLE C.3-1

UPPER AND LOWER WASTE RELEASE FUNCTIONS FOR TRUCK AND TRAIN IMPACT ACCIDENTS

T-1819

RELEASE MECHANISM	WASTE FORM	ESCAPING RADIONUCLIDES	APPENDIX A EQUATION SHOWING FORM OF RELEASE FUNCTION	RELEASE FUNCTION PARAMETER VALUES ¹			RADIONUCLIDES HAVING ZERO RELEASE AT ALL ACCIDENT SEVERITIES
				LOWER UPPER V ₀	A	B	
Airborne Particulate Dispersion	Spray Calcine	All	A.3-19	87	1.6 E-1	1.0 E-2	None
				47	9.0	6.0 E-1	
	Borosilicate Glass	All	A.3-18	87	2.0 E-5	7.60 E-6	None
				47	1.0 E-3	7.60 E-5	
	Fluidized Bed Calcine	All	A.3-19	87	8.0 E-1	1.0 E-2	None
				47	4.0 E-1	5.0 E-1	
	Multibarrier Waste Form	All	A.3-18	87	1.0 E-7	7.60 E-8	None
				47	1.0 E-5	7.60 E-7	
Volatilization	All	None	--	--	--	--	All
Dissolution	Spray Calcine	Sr and Cs	A.3-20	87	2.5 E-1	--	All <u>except</u> Sr and Cs
				47	1.0	--	
	Borosilicate Glass	All	A.3-18	87	1.0 E-5	3.08 E-5	None
				47	1.0 E-3	3.08 E-4	
	Fluidized Bed Calcine	Sr and Cs	A.3-20	87	1.0 E-1	--	All <u>except</u> Sr and Cs
				47	1.0	--	
	Multibarrier Waste Form	All	A.3-18	87	1.0 E-7	3.08 E-7	None
				47	1.0 E-5	3.08 E-6	

*Note: • For airborne particulate dispersion, the release function represents the fraction of escaping radionuclides released as particulates less than 10 μ in diameter.
 • For dissolution, the release function represents the fraction of escaping radionuclides released to water in one day.

Source: Ref. C.1.

TABLE C.3-2
UPPER AND LOWER WASTE RELEASE FUNCTIONS FOR TRUCK AND TRAIN FIRE ACCIDENTS

T-1820

RELEASE MECHANISM*	WASTE FORM	ESCAPING RADIONUCLIDES	APPENDIX A EQUATION SHOWING FORM OF RELEASE FUNCTION	RELEASE FUNCTION PARAMETER VALUES†			RADIONUCLIDES HAVING ZERO RELEASE AT ALL ACCIDENT SEVERITIES
				(LOWER) (UPPER) T ₀	A	B	
Airborne Particulate Dispersion	Spray and Fluidized Bed Calcine	All	A.3-27	2402	1.0 E-3	--	None
				2282	1.0 E-1	--	None
	Borosilicate Glass	None	--	--	--	--	All
Volatilization	Multibarrier Waste Form	All	A.3-27	2552	1.0 E-6	--	None
				2192	1.0 E-2	--	None
	Spray and Fluidized Bed Calcine	Cs	A.3-26	2462	1.74 E-3	7.0 E3	All <u>except</u> Cs
				2282	1.74 E1	7.6 E3	All <u>except</u> Cs
		Ru	A.3-26	2462	2.36 E3	2.79 E4	All <u>except</u> Ru
				2282	2.36 E7	2.79 E4	All <u>except</u> Ru
	Borosilicate Glass	Cs	A.3-26	2282	8.13 E3	2.92 E4	All <u>except</u> Cs
				2192	8.13 E7	2.92 E4	All <u>except</u> Cs
Dissolution	Multibarrier Waste Form	Cs	A.3-26	2552	5.89 E3	3.37 E4	All <u>except</u> Cs
				2192	5.89 E7	3.37 E4	All <u>except</u> Cs
	Spray and Fluidized Bed Calcine	Sr and Cs	A.3-27	2462	1.0 E-1	--	All <u>except</u> Sr and Cs
				2282	1.0	--	All <u>except</u> Sr and Cs
	Borosilicate Glass	All	A.3-27	2282	1.0 E-7	--	None
				2402	1.0 E-3	--	None
	Multibarrier Waste Form	All	A.3-27	2552	1.0 E-7	--	None
				2192	1.0 E-4	--	None

- *Note: • For airborne particulate dispersion, the release function represents the fraction of escaping radionuclides released as particulates less than 10μ in diameter.
- For volatilization, the release function represents the fraction of escaping radionuclides released to the air in four hours.
- For dissolution, the release function represents the fraction of escaping radionuclides released to water in one day.

†Source: Ref. C.1.

nominal values found in Tables A.6-1 through A.6-4 of Appendix A. This comparison indicates that the high risk, as defined above, is generally about 1 to 2 orders of magnitude greater than nominal risk. The sensitivity analysis was truncated at this point -- an in-depth look at the contributions of individual parameters can be made at a later time.

C.3.3 Summary

This section has developed relationships showing the linear sensitivity of total expected pre-employment dose to changes in multiplicative parameters in the transportation accident risk equation. Additionally, the nonlinear sensitivity of nominal risk to changes in release fraction parameters (probability density functions, release functions and failure threshold temperatures and loci) was assessed. Extreme scenarios were constructed based on simultaneous perturbation of all the latter parameters to their lower-risk or upper-risk representations, per the discussion of Section C.3.2. These scenarios did not include the effects of perturbing the multiplicative (linear) risk parameters. However, one can use the high and low expected dose values and the linear sensitivity relationships to simultaneously perturb the nonlinear and linear parameters using any ranges of values for the linear parameters.

In conclusion, expected dose from transportation accidents is very sensitive to the choice of release function amplitudes and failure thresholds and to the probability density functions used. The sensitivity of total expected dose ranges between 1 to 4 orders of magnitude above nominal and between 2 to 4 orders of magnitude below nominal. Further work should include additional refinement of these functions to reduce their uncertainties.

TABLE C.3-3
LOW VALUES OF EXPECTED DOSE FROM TRANSPORTATION ACCIDENTS -- SPRAY CALCINE

		EXPECTED DOSE -- MAN-REM/MWE-YR											
INDEX	ACCIDENT TYPE	VOLATILIZATION				DISPERSION				DISSOLUTION			
		WHOLE BODY	WHOLE BODY EQ	CRIT. ORGAN	ORGAN NAME	WHOLE BODY	WHOLE BODY EQ	CRIT. ORGAN	ORGAN NAME	WHOLE BODY	CRIT. ORGAN	ORGAN NAME	AGE
6	TRUCK-IMPCT-ERFO-UR	0.0	0.0	0.0		9.1E-04	1.0E-03	1.6E-03	80	1.7E-04	6.6E-04	80	10Y
7	TRUCK-IMPCT-ERFO-RU	0.0	0.0	0.0		5.4E-05	6.2E-05	9.4E-05	80	1.7E-04	6.6E-04	80	10Y
8	TRUCK-CROSSNG AC-UR	0.0	0.0	0.0		6.0E-05	6.0E-05	1.0E-04	80	1.1E-05	4.2E-05	80	10Y
9	TRUCK-CROSSNG AC-RU	0.0	0.0	0.0		3.5E-05	4.0E-05	6.1E-05	80	1.1E-05	4.2E-05	80	10Y
10	TRUCK-FIRE-URBAN	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
11	TRUCK-FIRE-RURAL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
12	TRUCK-PUNCTUR-URBAN	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
13	TRUCK-PUNCTUR-RURAL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
	TRUCK TOTAL	0.0	0.0	0.0		1.0E-03	1.2E-03	1.8E-03	80	3.6E-04	1.4E-03	80	
14	TRAIN-IMPCT-ERFO-UR	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
15	TRAIN-IMPCT-ERFO-RU	0.0	0.0	0.0		2.0E-06	2.3E-06	3.4E-06	80	6.2E-06	2.4E-05	80	10Y
16	TRAIN-FIRE-URBAN	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
17	TRAIN-FIRE-RURAL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
18	TRAIN-PUNCTUR-URBAN	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
19	TRAIN-PUNCTUR-RURAL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
	TRAIN TOTAL	0.0	0.0	0.0		2.0E-06	2.3E-06	3.4E-06	80	6.2E-06	2.4E-05	80	

TABLE C.3-4
HIGH VALUES OF EXPECTED DOSE FROM TRANSPORTATION ACCIDENTS -- SPRAY CALCINE

EXPECTED DOSE -- MAN-REM/MWE-YR													
INDEX		VOLATILIZATION				DISPERSION				DISSOLUTION			
		WHOLE BODY	WHOLE BODY EQ	CRIT. ORGAN	ORGAN NAME	WHOLE BODY	WHOLE BODY EQ	CRIT. ORGAN	ORGAN NAME	WHOLE BODY	CRIT. ORGAN	ORGAN NAME	AGE
1	ACCIDENT TYPE												
6	TRUCK-IMPCT-ERFO-UR	0.0	0.0	0.0		1.2E+01	1.3E+01	2.0E+01	80	2.0E-01	7.7E-01	80	10Y
7	TRUCK-IMPCT-ERFO-RU	0.0	0.0	0.0		6.9E-01	7.8E-01	1.2E+00	80	2.0E-01	7.7E-01	80	10Y
8	TRUCK-CROSSNG AC-UR	0.0	0.0	0.0		1.0E-01	1.2E-01	1.8E-01	80	1.6E-03	6.3E-03	80	10Y
9	TRUCK-CROSSNG AC-RU	0.0	0.0	0.0		6.2E-03	7.1E-03	1.1E-02	80	1.6E-03	6.3E-03	80	10Y
10	TRUCK-FIRE-URBAN	1.2E-02	1.2E-02	1.2E-02	LI	1.1E-02	1.3E-02	2.0E-02	80	1.1E-04	4.2E-04	80	10Y
11	TRUCK-FIRE-RURAL	6.6E-04	7.1E-04	7.0E-04	LI	6.6E-04	7.5E-04	1.1E-03	80	1.1E-04	4.2E-04	80	10Y
12	TRUCK-PUNCTUR-URBAN	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
13	TRUCK-PUNCTUR-RURAL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
	TRUCK TOTAL	1.2E-02	1.3E-02	1.3E-02	LI	1.2E+01	1.4E+01	2.1E+01	80	4.0E-01	1.5E+00	80	
14	TRAIN-IMPCT-ERFO-UR	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
15	TRAIN-IMPCT-ERFO-RU	0.0	0.0	0.0		2.8E-01	3.2E-01	4.9E-01	80	7.6E-02	2.9E-01	80	10Y
16	TRAIN-FIRE-URBAN	1.4E-03	1.5E-03	1.5E-03	LI	1.3E-03	1.5E-03	2.3E-03	80	1.3E-05	4.9E-05	80	10Y
17	TRAIN-FIRE-RURAL	8.1E-05	8.4E-05	8.4E-05	LI	7.6E-05	8.7E-05	1.3E-04	80	1.3E-05	4.9E-05	80	10Y
18	TRAIN-PUNCTUR-URBAN	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
19	TRAIN-PUNCTUR-RURAL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
	TRAIN TOTAL	1.5E-03	1.5E-03	1.5E-03	LI	2.6E-01	3.2E-01	4.9E-01	80	7.6E-02	2.9E-01	80	

TABLE C.3-5

LOW VALUES OF EXPECTED DOSE FROM TRANSPORTATION ACCIDENTS -- BOROSILICATE GLASS

INDEX	ACCIDENT TYPE	VOLATILIZATION				DISPERSION				DISSOLUTION			
		WHOLE BODY	WHOLE BODY EO	CRIT. ORGAN	ORGAN NAME	WHOLE BODY	WHOLE BODY EO	CRIT. ORGAN	ORGAN NAME	WHOLE BODY	CRIT. ORGAN	ORGAN NAME	AGE
6	TRUCK-IMPCT.ERFO-UR	0.0	0.0	0.0		4.7E-06	5.3E-06	8.1E-06	80	8.9E-08	3.4E-07	80	10Y
7	TRUCK-IMPCT.ERFO-RU	0.0	0.0	0.0		2.8E-07	3.2E-07	4.8E-07	80	8.9E-08	3.4E-07	80	10Y
8	TRUCK-CROSSNG AC-UR	0.0	0.0	0.0		6.3E-07	7.2E-07	1.1E-06	80	1.5E-08	6.0E-08	80	10Y
9	TRUCK-CROSSNG AC-RU	0.0	0.0	0.0		3.8E-08	4.3E-08	6.5E-08	80	1.5E-08	6.0E-08	80	10Y
10	TRUCK-FIRE-URBAN	1.6E-14	1.7E-14	1.7E-14	LI	0.0	0.0	0.0		2.7E-20	1.0E-19	80	10Y
11	TRUCK-FIRE-RURAL	9.3E-16	9.7E-16	9.6E-16	LI	0.0	0.0	0.0		2.7E-20	1.0E-19	80	10Y
12	TRUCK-PUNCTUR-URBAN	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
13	TRUCK-PUNCTUR-RURAL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
	TRUCK TOTAL	1.7E-14	1.8E-14	1.8E-14	LI	5.6E-06	6.4E-06	9.7E-06	80	2.1E-07	8.1E-07	80	
14	TRAIN-IMPCT.ERFO-UR	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
15	TRAIN-IMPCT.ERFO-RU	0.0	0.0	0.0		1.0E-08	1.2E-08	1.8E-08	80	3.2E-09	1.3E-08	80	10Y
16	TRAIN-FIRE-URBAN	6.4E-07	6.7E-07	6.7E-07	LI	0.0	0.0	0.0		1.3E-12	4.9E-12	80	10Y
17	TRAIN-FIRE-RURAL	3.7E-08	3.9E-08	3.8E-08	LI	0.0	0.0	0.0		1.3E-12	4.9E-12	80	10Y
18	TRAIN-PUNCTUR-URBAN	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
19	TRAIN-PUNCTUR-RURAL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
	TRAIN TOTAL	6.8E-07	7.1E-07	7.0E-07	LI	1.0E-08	1.2E-08	1.8E-08	80	3.2E-09	1.3E-08	80	

TABLE C.3-6

HIGH VALUES OF EXPECTED DOSE FROM TRANSPORTATION ACCIDENTS -- BOROSILICATE GLASS

		EXPECTED DOSE -- MAN-REM/MWE-YR											
INDEX	ACCIDENT TYPE	VOLATILIZATION				DISPERSION				DISSOLUTION			
		WHOLE BODY	WHOLE BODY EQ	CRIT. ORGAN	ORGAN NAME	WHOLE BODY	WHOLE BODY EQ	CRIT. ORGAN	ORGAN NAME	WHOLE BODY	CRIT. ORGAN	ORGAN NAME	AGE
6	TRUCK-IMPCT.ERFO-UR	0.0	0.0	0.0		4.9E-02	5.6E-02	8.4E-02	BD	8.3E-04	3.2E-03	BD	10Y
7	TRUCK-IMPCT.ERFO-RU	0.0	0.0	0.0		2.9E-03	3.3E-03	5.9E-03	BD	8.3E-04	3.2E-03	BD	10Y
8	TRUCK-CROSSNG AC-UR	0.0	0.0	0.0		5.3E-04	6.0E-04	9.1E-04	BD	1.1E-05	4.1E-05	BD	10Y
9	TRUCK-CROSSNG AC-RU	0.0	0.0	0.0		3.2E-05	3.6E-05	5.4E-05	BD	1.1E-05	4.1E-05	BD	10Y
10	TRUCK-FIRE-URBAN	2.3E-01	2.4E-01	2.3E-01	LI	0.0	0.0	0.0		7.9E-07	3.0E-06	BD	10Y
11	TRUCK-FIRE-RURAL	1.3E-02	1.4E-02	1.3E-02	LI	0.0	0.0	0.0		7.9E-07	3.0E-06	BD	10Y
12	TRUCK-PUNCTUR-URBAN	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
13	TRUCK-PUNCTUR-RURAL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
	TRUCK TOTAL	2.4E-01	2.5E-01	2.5E-01	LI	5.2E-02	5.9E-02	9.0E-02	BD	1.7E-03	6.5E-03	BD	
14	TRAIN-IMPCT.ERFO-UR	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
15	TRAIN-IMPCT.ERFO-RU	0.0	0.0	0.0		1.4E-03	1.6E-03	2.5E-03	BD	4.8E-04	1.9E-03	BD	10Y
16	TRAIN-FIRE-URBAN	1.5E-01	1.6E-01	1.5E-01	LI	0.0	0.0	0.0		4.8E-07	1.9E-06	BD	10Y
17	TRAIN-FIRE-RURAL	8.4E-03	8.8E-03	8.7E-03	LI	0.0	0.0	0.0		4.8E-07	1.9E-06	BD	10Y
18	TRAIN-PUNCTUR-URBAN	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
19	TRAIN-PUNCTUR-RURAL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
	TRAIN TOTAL	1.5E-01	1.6E-01	1.6E-01	LI	1.4E-03	1.6E-03	2.5E-03	BD	4.9E-04	1.9E-03	BD	

TABLE C.3-7
LOW VALUES OF EXPECTED DOSE FROM TRANSPORTATION ACCIDENTS --
FLUIDIZED BED CALCINE

INDEX	ACCIDENT TYPE	VOLATILIZATION				DISPERSION				DISSOLUTION			
		WHOLE	WHOLE	CRIT.	ORGAN	WHOLE	WHOLE	CRIT.	ORGAN	WHOLE	CRIT.	ORGAN	
		BODY	BODY EQ	ORGAN	NAME	BODY	BODY EQ	ORGAN	NAME	BODY	ORGAN	NAME	AGE
6	TRUCK-IMPCT-ERFD-UR	0.0	0.0	0.0		8.5E-04	9.6E-04	1.5E-03	80	6.8E-05	2.6E-04	80	10Y
7	TRUCK-IMPCT-ERFD-RU	0.0	0.0	0.0		5.1E-05	5.7E-05	8.7E-05	80	6.8E-05	2.6E-04	80	10Y
8	TRUCK-CROSSNG AC-UR	0.0	0.0	0.0		5.8E-05	6.4E-05	1.0E-04	80	4.4E-06	1.7E-05	80	10Y
9	TRUCK-CROSSNG AC-RU	0.0	0.0	0.0		3.5E-06	3.9E-06	6.0E-06	80	4.4E-06	1.7E-05	80	10Y
10	TRUCK-FIRE-URBAN	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
11	TRUCK-FIRE-RURAL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
12	TRUCK-PUNCTUR-URBAN	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
13	TRUCK-PUNCTUR-RURAL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
	TRUCK TOTAL	0.0	0.0	0.0		9.6E-04	1.1E-03	1.7E-03	80	1.5E-04	5.6E-04	80	
14	TRAIN-IMPCT-ERFD-UR	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
15	TRAIN-IMPCT-ERFD-RU	0.0	0.0	0.0		1.8E-06	2.1E-06	3.2E-06	80	2.5E-06	9.6E-06	80	10Y
16	TRAIN-FIRE-URBAN	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
17	TRAIN-FIRE-RURAL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
18	TRAIN-PUNCTUR-URBAN	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
19	TRAIN-PUNCTUR-RURAL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
	TRAIN TOTAL	0.0	0.0	0.0		1.8E-06	2.1E-06	3.2E-06	80	2.5E-06	9.6E-06	80	

TABLE C.3-8
HIGH VALUES OF EXPECTED DOSE FROM TRANSPORTATION ACCIDENTS --
FLUIDIZED BED CALCINE

		EXPECTED DOSE -- MAN-REM/MWF-YR											
INDEX	ACCIDENT TYPE	VOLATILIZATION				DISPERSION				DISSOLUTION			
		WHOLE BODY	WHOLE BODY ED	CRIT. ORGAN	ORGAN NAME	WHOLE BODY	WHOLE BODY ED	CRIT. ORGAN	ORGAN NAME	WHOLE BODY	CRIT. ORGAN	ORGAN NAME	AGE
6	TRUCK-IMPCT.ERFO-UR	0.0	0.0	0.0		3.5E-01	4.0E-01	6.1E-01	BD	2.0E-01	7.7E-01	BD	10Y
7	TRUCK-IMPCT.ERFO-RU	0.0	0.0	0.0		2.1E-02	2.4E-02	3.6E-02	BD	2.0E-01	7.7E-01	BD	10Y
8	TRUCK-CROSSNG AC-UR	0.0	0.0	0.0		4.6E-02	5.2E-02	8.0E-02	BD	1.6E-03	6.3E-03	BD	10Y
9	TRUCK-CROSSNG AC-RU	0.0	0.0	0.0		2.7E-03	3.1E-03	4.7E-03	BD	1.6E-03	6.3E-03	BD	10Y
10	TRUCK-FIRE-URBAN	1.2E-02	1.2E-02	1.2E-02	LI	1.1E-02	1.3E-02	2.0E-02	BD	1.1E-04	4.2E-04	BD	10Y
11	TRUCK-FIRE-RURAL	6.8E-04	7.1E-04	7.0E-04	LI	6.6E-04	7.5E-04	1.1E-03	BD	1.1E-04	4.2E-04	BD	10Y
12	TRUCK-PUNCTUR-URBAN	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
13	TRUCK-PUNCTUR-RURAL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
	TRUCK TOTAL	1.2E-02	1.3E-02	1.3E-02	LI	4.4E-01	5.0E-01	7.5E-01	BD	4.0E-01	1.5E+00	BD	
14	TRAIN-IMPCT.ERFO-UR	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
15	TRAIN-IMPCT.ERFO-RU	0.0	0.0	0.0		1.2E-01	1.4E-01	2.1E-01	BD	7.6E-02	2.9E-01	BD	10Y
16	TRAIN-FIRE-URBAN	1.4E-03	1.5E-03	1.5E-03	LI	1.3E-03	1.5E-03	2.3E-03	BD	1.3E-05	4.9E-05	BD	10Y
17	TRAIN-FIRE-RURAL	8.1E-05	8.4E-05	8.4E-05	LI	7.6E-05	8.7E-05	1.3E-04	BD	1.3E-05	4.9E-05	BD	10Y
18	TRAIN-PUNCTUR-URBAN	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
19	TRAIN-PUNCTUR-RURAL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
	TRAIN TOTAL	1.5E-03	1.5E-03	1.5E-03	LI	1.2E-01	1.4E-01	2.1E-01	BD	7.6E-02	2.9E-01	BD	

TABLE C.3-9
LOW VALUES OF EXPECTED DOSE FROM TRANSPORTATION ACCIDENTS --
MULTIBARRIER WASTE FORM

EXPECTED DOSE -- MAN-REM/MWE-YR

INDEX	ACCIDENT TYPE	VOLATILIZATION				DISPERSION				DISSOLUTION			
		WHOLE BODY	WHOLE BODY ED	CRIT. ORGAN	ORGAN NAME	WHOLE BODY	WHOLE BODY ED	CRIT. ORGAN	ORGAN NAME	WHOLE BODY	CRIT. ORGAN	ORGAN NAME	AGE
6	TRUCK-IMPCT.ERFO-UR	0.0	0.0	0.0		3.7E-08	4.2E-08	6.5E-08	80	6.9E-10	3.4E-09	80	10Y
7	TRUCK-IMPCT.ERFO-RU	0.0	0.0	0.0		2.2E-09	2.5E-09	3.8E-09	80	6.9E-10	3.4E-09	80	10Y
8	TRUCK-CROSSNG AC-UR	0.0	0.0	0.0		5.8E-09	6.5E-09	9.9E-09	80	1.5E-10	6.0E-10	80	10Y
9	TRUCK-CROSSNG AC-RU	0.0	0.0	0.0		3.4E-10	3.9E-10	5.9E-10	80	1.5E-10	6.0E-10	80	10Y
10	TRUCK-FIRE-URBAN	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
11	TRUCK-FIRE-RURAL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
12	TRUCK-PUNCTUR-URBAN	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
13	TRUCK-PUNCTUR-RURAL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
	TRUCK TOTAL	0.0	0.0	0.0		4.6E-08	5.2E-08	7.9E-08	80	2.1E-09	8.1E-09	80	
14	TRAIN-IMPCT.ERFO-UR	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
15	TRAIN-IMPCT.ERFO-RU	0.0	0.0	0.0		6.1E-11	9.2E-11	1.4E-10	80	3.2E-11	1.3E-10	80	10Y
16	TRAIN-FIRE-URBAN	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
17	TRAIN-FIRE-RURAL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
18	TRAIN-PUNCTUR-URBAN	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
19	TRAIN-PUNCTUR-RURAL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
	TRAIN TOTAL	0.0	0.0	0.0		6.1E-11	9.2E-11	1.4E-10	80	3.2E-11	1.3E-10	80	

TABLE C.3-10
HIGH VALUES OF EXPECTED DOSE FROM TRANSPORTATION ACCIDENTS --
MULTIBARRIER WASTE FORM

EXPECTED DOSE -- MAN-REM/MWE-YR													
INDEX		VOLATILIZATION				DISPERSION				DISSOLUTION			
		WHOLE BODY	WHOLE BODY ED	CRIT. ORGAN	ORGAN NAME	WHOLE BODY	WHOLE BODY ED	CRIT. ORGAN	ORGAN NAME	WHOLE BODY	CRIT. ORGAN	ORGAN NAME	AGE
6	TRUCK-IMPCT,ERFO-UR	0.0	0.0	0.0		4.9E-04	5.6E-04	5.4E-04	80	8.3E-06	3.2E-05	80	10Y
7	TRUCK-IMPCT,ERFO-RU	0.0	0.0	0.0		2.9E-05	3.3E-05	5.0E-05	80	8.3E-06	3.2E-05	80	10Y
8	TRUCK-CROSSNG AC-UR	0.0	0.0	0.0		5.3E-06	6.0E-06	9.1E-06	80	1.1E-07	4.1E-07	80	10Y
9	TRUCK-CROSSNG AC-RU	0.0	0.0	0.0		3.2E-07	3.6E-07	5.4E-07	80	1.1E-07	4.1E-07	80	10Y
10	TRUCK-FIRE-URBAN	6.2E-03	6.5E-03	6.4E-03	L1	4.9E-03	5.4E-03	6.2E-03	80	4.3E-08	1.6E-07	80	10Y
11	TRUCK-FIRE-RURAL	3.6E-04	3.7E-04	3.7E-04	L1	2.7E-04	3.1E-04	4.7E-04	80	4.3E-08	1.6E-07	80	10Y
12	TRUCK-PUNCTUR-URBAN	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
12	TRUCK-PUNCTUR-RURAL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
	TRUCK TOTAL	6.6E-03	6.9E-03	6.6E-03	L1	5.6E-03	6.3E-03	9.6E-03	80	1.7E-05	6.6E-05	80	
14	TRAIN-IMPCT,ERFO-UR	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
15	TRAIN-IMPCT,ERFO-RU	0.0	0.0	0.0		1.4E-05	1.6E-05	2.5E-05	80	4.6E-06	1.9E-05	80	10Y
16	TRAIN-FIRE-URBAN	1.9E-03	1.9E-03	1.9E-03	L1	1.2E-03	1.4E-03	2.1E-03	80	1.2E-08	4.3E-08	80	10Y
17	TRAIN-FIRE-RURAL	1.0E-04	1.1E-04	1.1E-04	L1	7.1E-05	8.1E-05	1.2E-04	80	1.2E-08	4.3E-08	80	10Y
18	TRAIN-PUNCTUR-URBAN	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
19	TRAIN-PUNCTUR-RURAL	0.0	0.0	0.0		0.0	0.0	0.0		0.0	0.0		10Y
	TRAIN TOTAL	1.9E-03	2.0E-03	2.0E-03	L1	1.3E-03	1.5E-03	2.3E-03	80	4.6E-06	1.9E-05	80	

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APPENDIX D
WASTE TRANSPORT IN A STREAM TUBE

The basic model used in this study for flow through porous media consists of a series of interconnected one-dimensional flow paths. The complicated problem of solving two- or three-dimensional transport equations for a variety of changing parameters and geologic states is thus avoided. The simplification is justified on both pragmatic and mathematical grounds. It is not practical to do extensive sensitivity analysis on multi-state generic repository models without such simplification. Further, there is considerable conceptual advantage to modeling flow as a series of linear pathways. The dynamics are decomposed into a fundamental form so that a physical understanding of the processes involved is facilitated.

Mathematically the flow paths are stream tubes and the complexity of the fluid flow defines their number and positioning. For the initial models, fairly simple flow fields were chosen. More complicated and more realistic flow fields will be determined by two- and three-dimensional hydrology programs.

Under certain constraints the transport equation for dispersive flow reduces to a simple one-dimensional flow model in stream coordinates. Quite generally, transport of radionuclides in porous media is described by a diffusion equation (Ref. D.1). Hence, if the concentration of nuclide r in the interstitial water is $C_r(\underline{x}, t)$ and the interstitial fluid velocity is $\underline{v}$ then

$$\frac{\partial C_r}{\partial t} = \frac{\partial}{\partial x_i} D_{ij} \frac{\partial}{\partial x_j} C_r - \frac{\partial}{\partial x_i} (v_i C_r) - \lambda_r C_r + \sum_{s \neq r} \lambda_s^r C_s - \frac{\partial m_r}{\partial t} - \lambda_r m_r + \sum_{s \neq r} \lambda_s^r m_r \quad (D-1)$$

Here D_{ij} is the coefficient of convective dispersion, λ_r is the radioactive decay constant, λ_s^r is the production rate of nuclide r from decay of nuclide s , m_r is the amount of ion adsorbed on the solid per unit volume, and the subscripts i and j refer to the three Cartesian coordinates. The convention has been adopted that when subscripts referring to coordinate axes are repeated, they are to be summed over. This equation may be simplified (see Appendix F), dropping the r subscript, as

$$B \frac{\partial c}{\partial t} = \frac{\partial}{\partial x_i} D_{ij} \frac{\partial c}{\partial x_j} - \frac{\partial}{\partial x_i} (v_i c) \quad (D-2)$$

where B is the retardation factor, and $c(\underline{x}, t)$ is C_r divided by the amount of nuclide r from repository waste in existence at time t .

We now assume that D_{ij} reduces to a linear function of the flow velocity in the one-dimensional case (Refs. D.2, D.3, and D.4). This assumption requires some additional comment. We have implicitly assumed that flow due to diffusion is negligible when compared to dispersion. In this regime a linear relation between D_{ij} and $|\underline{v}|$ is acceptable. If diffusion becomes important our equations become inapplicable. However, for such a case no waste would ever have time to migrate to the biosphere.

The simplest form of D_{ij} must now be

$$D_{ij} = \frac{a_{ijlm} v_l v_m}{v} \quad (D-3)$$

where $v = |\underline{v}|$. (Ref. D.1).

The tensor a_{ijklm} is called the dispersivity tensor of the porous medium. If it is now assumed that a_{ijklm} is an isotropic tensor, then its most general form is

$$a_{ijklm} = (\alpha - 2\nu)\delta_{ij}\delta_{klm} + \mu(\delta_{il}\delta_{jm} + \delta_{jl}\delta_{im}) + \nu(\delta_{il}\delta_{jm} - \delta_{jl}\delta_{im}) \quad (D-4)$$

Because of Onsager's relation (Ref. D.5), D_{ij} can be postulated to be symmetric and the last term in the above equation is set equal to zero. Hence

$$D_{ij} = (\alpha - 2\nu)\delta_{ij}V + \frac{2\nu v_i v_j}{V}$$

and

$$B \frac{\partial c}{\partial t} + \frac{\partial}{\partial x_i} (v_i c) = (\alpha - 2\nu) \frac{\partial}{\partial x_i} V \frac{\partial c}{\partial x_i} + 2\nu \frac{\partial}{\partial x_i} \frac{v_i v_j}{V} \frac{\partial c}{\partial x_j} \quad (D-5)$$

For steady incompressible flow $\nabla \cdot \underline{v} = 0$ and the above equation simplifies to

$$B \frac{\partial c}{\partial t} + \underline{v} \cdot \nabla c = (\alpha - 2\nu) \nabla \cdot (V \nabla c) + 2\nu (\underline{v} \cdot \nabla) \frac{1}{V} (\underline{v} \cdot \nabla) c \quad (D-6)$$

We now rewrite this equation in coordinates determined by the velocity field. The natural coordinates (S, N, T) are those where S represents the distance along a streamline in the direction of stream flow. The equation reduces to

$$B \frac{\partial c}{\partial t} + V \frac{\partial c}{\partial S} = \alpha V \frac{\partial^2 c}{\partial S^2} + \frac{(\alpha - 2\nu)}{h_1 h_3} \frac{\partial}{\partial N} (h_1 h_3 V) \frac{\partial c}{\partial N} + \frac{(\alpha - 2\nu)}{h_1 h_2} \frac{\partial}{\partial T} (h_1 h_2 V) \frac{\partial c}{\partial T} \quad (D-7)$$

Here h_1 , h_2 , and h_3 are the scale factors. The similarity is apparent between this equation and the familiar result for $\underline{v} = V\hat{i}$ and V constant, i.e.,

$$B \frac{\partial c}{\partial t} + V \frac{\partial c}{\partial x} = \alpha V \frac{\partial^2 c}{\partial x^2} + (\alpha - 2u) V \left(\frac{\partial^2 c}{\partial y^2} + \frac{\partial^2 c}{\partial z^2} \right) \quad (D-8)$$

We now wish to average Eq. D-7 across the stream tube. The area over which to integrate is determined by the rate at which the velocity and the concentration gradient decrease in the N and T directions. For example, if a source inputs an impulse at time zero into a path in which V is a constant, then the concentration will fall off in the radial direction, r , as $\exp(-r^2/4L(\alpha - 2u))$. Here L represents the distance the pulse has traveled. For a path 200 meters long and with $(\alpha - 2u) = 10$ meters the pulse would spread about 180 meters by the time it exited the path segment.

Returning to Eq. D-7 we note that in this formulation S , N , and T represent distances along coordinate axes. Hence the order of differentiation cannot in general be interchanged. Introducing coordinates (S^*, N^*, T^*) where $dS = h_1 dS^*$, $dN = h_2 dN^*$, and $dT = h_3 dT^*$ and integrating over the cross-sectional area of the stream tube, we have

$$\begin{aligned} B \frac{\partial}{\partial t} \iint_A c h_1 h_2 h_3 dN^* dT^* + \frac{\partial}{\partial S^*} \iint_A V c h_2 h_3 dN^* dT^* \\ = \alpha \frac{\partial}{\partial S^*} \iint_A \frac{V}{h_1} \frac{\partial c}{\partial S^*} h_2 h_3 dN^* dT^* \end{aligned} \quad (D-9)$$

The area of the stream tube, the mean velocity and the mean concentrations with and without weighting by velocity can now be defined as

$$\begin{aligned}
 W &= \iint_A h_2 h_3 dN^* dT^* \\
 \tilde{V} &= \iint_A v h_2 h_3 dN^* dT^* / W \\
 \tilde{c} &= \iint_A v c h_2 h_3 dN^* dT^* / W \tilde{V} \\
 \langle c \rangle &= \iint_A c h_2 h_3 dN^* dT^* / W
 \end{aligned}
 \tag{D-10}$$

If h_1 is, to a first order approximation, independent of N^* and T^* across the stream tube then it may be taken outside of the integrals and we have approximately

$$B \frac{\partial \langle c \rangle}{\partial t} + \tilde{V} \frac{\partial \tilde{c}}{\partial S} = a \tilde{V} \frac{\partial^2 \tilde{c}}{\partial S^2}
 \tag{D-11}$$

The constraint on h_1 is equivalent to requiring the integral of the curvature across the stream to be much less than one.

There are several situations for which the averaged equation may not be a good representation of transport. Figure D-1 shows a situation where a stream tube branches into

Figure D-1 Branching of a Stream Tube

two parts. Since the concentration is averaged over the width of the stream the initial concentration in each branch is the same. In order to represent situations in which the mixing is not expected to be complete at a given node, mixing factors can be included in the program. For example, the concentration of waste entering a borehole at the repository may not be the same as the mean concentration of waste over the entire repository.

Figure D-2 illustrates a possible situation which is not currently handled by the WASTE program. Here the majority of waste flows laterally in a layer which only partially leads to the biosphere. The upper faster-moving layer leads directly to a river or lake. Waste can migrate upwards from the lower layer due to dispersion and enter the biosphere. Since in this case our stream tube consists only of the lower layer, the amount of waste entering the river is underestimated. Furthermore since the upper layer is moving faster than the lower layer waste will reach the river more quickly. It can be seen that this situation occurs only when a large fraction of the waste in the lower layer does not go directly into the river. Therefore this mechanism for release is in general of less concern than one in which all the waste in the lower layer enters the river.

Figure D-2 Dispersive Flow Into a River

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APPENDIX E
PROBABILISTIC ANALYSIS OF GEOLOGIC EVENTS

E.1 INTRODUCTION

The migration of radioactive waste in the ground may be affected by future events, such as faulting or dissolution of engineered seals. The occurrence of such events can usually be predicted only on a probabilistic basis. The consequences of the events will depend on their sequence and timing. A scenario-by-scenario study of waste transport would therefore require study not merely of the possible events, but of the far greater number of possible histories which a repository might experience as it passes from state to state.

To measure the overall hazard of a waste repository, it is necessary to calculate expected values of radionuclide releases. The method derived in this appendix has been developed for that purpose.

In this approach, the model analyzes waste repositories on two levels. A total system, composed of the repository, the waste, and the various pathways by which the waste might reach the biosphere, is described by a geologic state and a waste distribution. The geologic state is defined by the condition of the strata in which the repository is located and by the escape pathways. For a given geologic state, all the system variables which will govern waste transport, such as the permeability and porosity of different rock layers and the velocity field of ground water, will be

uniquely defined. The waste distribution describes the actual concentration of radioactive waste in the repository and the different pathways at any given time. The purpose of this appendix is to derive an equation for the expected value of the waste distribution in terms of the equations for waste flow in each geologic state and the rates of transition between geologic states.

E.2 MATHEMATICAL DERIVATION

The derivation begins with the observation that the concentration of waste nuclides in groundwater at any point may depend on the whole history of the repository area from emplacement to the time being considered. Concentration at time t therefore depends not only on the current geologic state $g(t)$, but on the entire evolution of the geologic state from zero to t . The history of the geologic system will be denoted by h ; each value of h is an entire realization of the stochastic process whose value at time t is the random variable $g(t)$. The expected value of the concentration of any radionuclide r at point $\underline{x}$, $C_r(\underline{x};h,t)$, will be given by integrating over all histories

$$E(C_r(\underline{x},t)) = \int C_r(\underline{x};h,t) p(h) dh \quad (E.2-1)$$

where $p(h)$ is the probability density of history h .

We assume that waste transport is described by an equation of the form

$$\frac{\partial}{\partial t} C_r(\underline{x};h,t) = L^{(h)} C_r(\underline{x};h,t) + \sum_{s \neq r} \lambda_s^r C_s(\underline{x};h,t) \quad (E.2-2)$$

where, for any h , $L^{(h)}$ is an operator which operates on the spatial coordinates of C_r . λ_s^r is the rate at which nuclide s decays into nuclide r . λ_s^r is equal to $\ln 2$ divided by the half-life of nuclide s if nuclide s always decays into r . This assumption is consistent with the usual equation for flow of dissolved material in groundwater (Appendix D), which in one dimension takes the form

$$\frac{\partial C_r}{\partial t} = \left[-V_{ion} \frac{\partial}{\partial x} + \alpha V_{ion} \frac{\partial^2}{\partial x^2} - \lambda_r \right] C_r \quad (E.2-3)$$

where V_{ion} is the advection velocity of the ions, α is the dispersion constant and λ_r is the decay rate of nuclide r .

We wish to obtain an equation for waste transport which does not involve the history h , but only the current state g . In order to do so, we define a quantity ϕ_r by integrating over all histories h which reach state g at time t

$$\phi_r(\underline{x};g,t) = \int_{\Omega: \{h(t)=g\}} C_r(\underline{x};h,t) p(h) dh \quad (E.2-4)$$

The integral is over all realizations h of the random process which take the value g at time t . In subsequent equations this integration will be understood and the Ω and brackets will be omitted. ϕ_r may be interpreted physically as the expected value of concentration of nuclide r at point $\underline{x}$ given that the system is in state g , multiplied by the probability that the system is in g . This quantity is analogous to the quantity $F_r(l,m,n)$ defined in Appendix F; F_r is related to mass flux

integrated over interval l in the same way as ϕ_r is related to concentration. By comparing Eq. E.2-4 and Eq. E.2-1, it is seen that expected concentrations may be calculated from the relationship

$$E(C_r(\underline{x}, t)) = \sum_g \phi_r(\underline{x}; g, t) \quad (E.2-5)$$

In order for this definition to be useful, we must derive an equation for the evolution of ϕ_r which does not depend on h . We begin by taking the time derivative of Eq. E.2-4. In order to deal with the summation over histories, we must explicitly use the definition of the derivative:

$$\begin{aligned} \frac{\partial}{\partial t} \phi_r(\underline{x}; g, t) &= \lim_{\Delta t \rightarrow 0} \frac{1}{\Delta t} \left\{ \int_{h(t+\Delta t)=g} C_r(\underline{x}; h, t+\Delta t) p(h) dh \right. \\ &\quad \left. - \int_{h(t)=g} C_r(\underline{x}; h, t) p(h) dh \right\} \end{aligned} \quad (E.2-6)$$

In order to separate out the time dependence of C_r , we add and subtract identical terms.

$$\begin{aligned} \frac{\partial}{\partial t} \phi_r(\underline{x}; g, t) &= \lim_{\Delta t \rightarrow 0} \frac{1}{\Delta t} \left\{ \int_{h(t+\Delta t)=g} C_r(\underline{x}; h, t+\Delta t) p(h) dh \right. \\ &\quad - \int_{h(t+\Delta t)=g} C_r(\underline{x}; h, t) p(h) dh + \int_{h(t+\Delta t)=g} C_r(\underline{x}; h, t) p(h) dh \\ &\quad \left. - \int_{h(t)=g} C_r(\underline{x}; h, t) p(h) dh \right\} \end{aligned} \quad (E.2-7)$$

The first two terms are integrals over the same range of values of h and thus can be combined and simplified by using Eq. E.2-2.

$$\begin{aligned}
 & \lim_{\Delta t \rightarrow 0} \int_{h(t+\Delta t)=g} p(h) \frac{C_r(\underline{x}; h, t+\Delta t) - C_r(\underline{x}; h, t)}{\Delta t} dh \\
 &= \int_{h(t)=g} p(h) \frac{\partial}{\partial t} C_r(\underline{x}; h, t) dh \\
 &= \int_{h(t)=g} p(h) L^{(h)} C_r(\underline{x}; h, t) dh \\
 &+ \sum_{s \neq r} \int_{h(t)=g} p(h) \lambda_s^r C_s(\underline{x}; h, t) dh \quad (E.2-8)
 \end{aligned}$$

In order to simplify the two remaining terms of Eq. E.2-7, we must assume the range of possible states g is countable. Canceling terms which appear in both integrals, we then obtain

$$\begin{aligned}
 & \lim_{\Delta t \rightarrow 0} \frac{1}{\Delta t} \left\{ \int_{\substack{h(t+\Delta t)=g \\ \text{and } h(t) \neq g}} C_r(\underline{x}; h, t) p(h) dh \right. \\
 & \quad \left. - \int_{\substack{h(t)=g \text{ and} \\ h(t+\Delta t) \neq g}} C_r(\underline{x}; h, t) p(h) dh \right\} \\
 &= \lim_{\Delta t \rightarrow 0} \frac{1}{\Delta t} \left\{ \sum_{g' \neq g} \int_{\substack{h(t+\Delta t)=g \\ \text{and } h(t)=g'}} C_r(\underline{x}; h, t) p(h) dh \right. \\
 & \quad \left. - \sum_{g' \neq g} \int_{\substack{h(t)=g \text{ and} \\ h(t+\Delta t)=g'}} C_r(\underline{x}; h, t) p(h) dh \right\} \quad (E.2-9)
 \end{aligned}$$

In order to proceed further, we must examine more closely the role of h . The variable h represents the geologic history over the entire time period of concern in the analysis. We define two partial histories, e and f , as the histories from time zero through times t and $t+\Delta t$ respectively. If each value of h is thought of as a sequence of states, each value

of e or f will be a shorter sequence. Each sequence e or f will be included in many different h 's. Different partial histories f which are identical through time t and then reach different states at time $t+\Delta t$ will all include the same partial history e .

Now, it is reasonable to assume causality; i.e., that the concentration of waste at a given time will depend only on the previous geologic states of the system and not on what happens at subsequent times. Since the partial history f includes a specification of the geologic state at all times prior to t , $C_r(\underline{x};h,t)$ will be the same for all histories h which include the same f . All the terms of Eq. E.2-9 which correspond to the same f can be grouped together, and the right hand side of that equation can be written as:

$$\lim_{\Delta t \rightarrow 0} \frac{1}{\Delta t} \left\{ \sum_{g' \neq g} \int_{S_{g'g}} C_r(\underline{x};f,t) p(f) df - \sum_{g' \neq g} \int_{S_{gg'}} C_r(\underline{x};f,t) p(f) df \right\}$$

We have denoted the space of partial histories f which pass through state a at time t and through b at time $t+\Delta t$ as S_{ab} . The membership of S_{ab} will, of course, change when the value of Δt is varied.

Each space S_{ab} may be partitioned into subspaces S_{ab}^e . Each subspace S_{ab}^e is composed of all those partial histories f which follow a particular partial history e from time zero to t , at which time they have reached state a , and then reach state b at time $t+\Delta t$, as shown schematically in Fig. E.2-1. Since S_{ab} is equal to the union of all the S_{ab}^e corresponding to different e which reach state a at time t , we may rewrite our integrals to obtain

Figure E.2-1 Schematic Representation of Some Partial Histories Belonging to the Subspace S_{ab}^e

$$\lim_{\Delta t \rightarrow 0} \frac{1}{\Delta t} \left\{ \sum_{g' \neq g} \int_{e(t)=g'} de \int_{S_{g'g}^e} df C_r(\underline{x}; f, t) p(f) \right. \\ \left. - \sum_{g' \neq g} \int_{e(t)=g} de \int_{S_{gg'}^e} df C_r(\underline{x}; f, t) p(f) \right\}$$

We now invoke causality again to make concentration C_r at time t a function only of e and not of f . Since only the integral over f depends on Δt , the order of operations can be altered to obtain

$$\sum_{g' \neq g} \int_{e(t)=g'} de C_r(\underline{x}; e, t) \lim_{\Delta t \rightarrow 0} \frac{1}{\Delta t} \int_{S_{g',g}^e} p(f) df$$

$$- \sum_{g' \neq g} \int_{e(t)=g} de C_r(\underline{x}; e, t) \lim_{\Delta t \rightarrow 0} \frac{1}{\Delta t} \int_{S_{gg'}^e} p(f) df$$

Now the integral of $p(f)$ over S_{ab}^e is simply $p(e)$ multiplied by the conditional probability $P(b, t+\Delta t|e)$ that the system, having experienced partial history e and having reached state a at time t , will reach state b at time $t+\Delta t$. We therefore have

$$\sum_{g' \neq g} \int_{e(t)=g'} de C_r(\underline{x}; e, t) p(e) \lim_{\Delta t \rightarrow 0} \frac{1}{\Delta t} P(g, t+\Delta t|e)$$

$$- \sum_{g' \neq g} \int_{e(t)=g} de C_r(\underline{x}; e, t) p(e) \lim_{\Delta t \rightarrow 0} \frac{1}{\Delta t} P(g', t+\Delta t|e)$$

We may now define the transition rate from a to b , Γ_{ba} , by

$$\Gamma_{ba}(e) = \lim_{\Delta t \rightarrow 0} \frac{1}{\Delta t} P(b, t+\Delta t|a, t; e) \quad (E.2-10)$$

In this definition the transition rate has been written so as to show that it may be a function of past history e ; in what follows we will not explicitly show this dependence. In the cases we are considering, the value of e at time t is defined by the restrictions on the integrals over e , and so we can substitute the definition directly to obtain

$$\sum_{g' \neq g} \int_{e(t)=g'} C_r(\underline{x}; e, t) p(e) \Gamma_{gg'} de$$

$$- \sum_{g' \neq g} \int_{e(t)=g} C_r(\underline{x}; e, t) p(e) \Gamma_{g'g} de$$

In order to restore simplicity of notation, the integrals over e may be expanded back into integrals over h . Substituting into Eq. E.2-7 the values we have obtained for its terms, a formula for the derivative of ϕ_r is obtained.

$$\frac{\partial}{\partial t} \phi_r(\underline{x}; g, t) = \int_{h(t)=g} p(h) L^{(h)} C_r(\underline{x}; h, t) dh$$

$$+ \sum_{g' \neq g} \int_{h(t)=g'} \Gamma_{gg'} p(h) C_r(\underline{x}; h, t) dh$$

$$- \sum_{g' \neq g} \int_{h(t)=g} \Gamma_{g'g} p(h) C_r(\underline{x}; h, t) dh$$

$$+ \sum_{s \neq r} \int_{h(t)=g} \lambda_s^r p(h) C_s(\underline{x}; h, t) dh \quad (E.2-11)$$

The first term in this equation represents the flow through space and decay of radionuclide r . The second term represents the increase in ϕ_r due to transitions into g from other states, and the third term represents transitions out of state g . The fourth term describes the creation of nuclide r by the decay of parent nuclides.

We now make two assumptions about the transport operator L : that L depends only on g and not on h , and that it operates linearly on C_r . We may then move it outside the integral so that

$$\begin{aligned}
 & \int_{h(t) \approx g} p(h) L^{(h)} C_r(\underline{x}; h, t) dh \\
 &= L^{(g)} \int_{h(t) \approx g} p(h) C_r(\underline{x}; h, t) dh \\
 &= L^{(g)} \phi_r(\underline{x}; g, t)
 \end{aligned} \tag{E.2-12}$$

At this point we make the further assumption that the system described by the geologic states is a Markov process. The transition rates Γ will now be independent of the past history. They, like the decay rates λ , also may be moved outside the sum. Eq. E.2-11 for the evolution of ϕ_r reduces to

$$\begin{aligned}
 \frac{\partial}{\partial t} \phi_r(\underline{x}; g, t) &= L^{(g)} \phi_r(\underline{x}; g, t) \\
 &+ \sum_{g' \neq g} \Gamma_{gg'} \phi_r(\underline{x}; g', t) - \sum_{g' \neq g} \Gamma_{g'g} \phi_r(\underline{x}; g, t) \\
 &+ \sum_{s \neq r} \lambda_s^r \phi_s(\underline{x}; g, t)
 \end{aligned} \tag{E.2-13}$$

Equation E.2-13 involves only the current state g and may be solved for the ϕ_r ; Eq. E.2-5 may then be used to calculate expected values of concentration.

With this result, one need not calculate the motion of of waste for each history, but may instead solve for the quantities $\phi_r(\underline{x}; g, t)$, which were defined as the expected value of concentration of radionuclide r at point $\underline{x}$, given that the system is in geologic state g , multiplied by the probability of the system being in state g . These quantities represent an aggregation of the various histories which could lead to state g at time t . It is not necessary to solve an infinite number of partial differential equations corresponding to an infinity of possible histories. Instead

one only need solve a system of as many equations as there are geologic states and radionuclides.

E.3 DISCUSSION

The principal assumptions made in the above derivation are as follows:

- The operator describing motion of waste must depend only on the current geologic state and not on past geologic states
- The operator describing waste motion in any given state must be linear in waste concentration
- The transition rates between geologic states cannot depend on the past history of the system
- The geologic system is restricted to a countable set of states.

The first two of these assumptions restrict waste transport to flows which can be described by linear instantaneous operators. These assumptions are satisfied by the most commonly used transport equation, as described above in the discussion of Eq. E.2-3.

The other two assumptions govern the geologic states. They require that the system of geologic states form a Markov chain. Whether this requirement is satisfied depends on the particular set of states used in a model.

APPENDIX F
SUBSURFACE WASTE TRANSPORT MODEL

F.1 GENERAL APPROACH

As discussed in Appendix D, the transport model approximates the groundwater flow pattern around a repository by a network of one-dimensional flow paths, or "pipes". The variables which describe each path are listed in Table F.1-1.

TABLE F.1-1
 VARIABLES DESCRIBING FLOW PATHWAYS

$B(j, m_1, m_2, n)$	The retardation factor for nuclide type j in the path from node m_1 to m_2 , in state n (dimensionless). A state implies a set of geological properties.
$W(m_1, m_2, n)$	The cross-sectional area of path m_1, m_2 in state n in square meters.
$\alpha(m_1, m_2)$	The dispersion constant in meters.
$K(m_1, m_2, n)$	The permeability in cm/sec.
$HEAD(m, n)$	The hydraulic head at node m in meters.
$Z(m_1, m_2)$	The distance from m_1 to m_2 in meters.
$\epsilon(m_1, m_2, n)$	The effective porosity (dimensionless).

Each point in the network at which flow paths branch, or at which any of the variables listed in Table 2-1 changes value, is defined as a node. The nodes are numbered in such a way that water flow is always from lower-numbered to higher-numbered nodes.*

*This would appear to preclude situations where flow reverses when state changes. But this restriction may be avoided by artificially placing more than one node at the same location.

Initially the program calculates the amount of waste leaving the repository (node 1) as a function of geologic state and time (see Section F.6). The calculation then proceeds to each node in the system of pipes in sequence. The rate at which waste arrives at a given node is calculated from the amounts of waste which had earlier left lower-numbered nodes.

In order to carry out digital calculations, time must be divided into discrete intervals. The program calculates a quantity $F_j(l,m,n)$, which is the amount of waste type j passing through node m during time interval l , given that the system is in state n , multiplied by the probability of the system being in state n .

The following equation is used to calculate F for nodes other than the repository itself:

$$F(l,m,n) = \sum_{m' < m} \sum_{l' \leq l} \sum_{n'} F(l',m',n') \\ \times \Theta(m',m,n') G(l',l,m',m,n') \Psi(l',l,n',n) \quad (F.1-1)$$

In this formula, $F(l',m',n')$ represents the amount of waste leaving node m' in state n' during interval l' . This is multiplied by Θ , the fraction of the waste leaving m' which enters a path segment leading directly from m' to m . (If there is no such pipe, Θ is zero.) G is the fraction of the waste entering the path during interval l' which reaches the end of the pipe (node m) during interval l . This is calculated under the assumption that the system is always in the same state, n' , as it was in when the waste entered the path. Thus the waste does not react to the system's change of state until it reaches a node. The state changes are accounted for

when the waste reaches node m by the factor Ψ ; Ψ is the probability that the system, having been in state n' during interval ℓ' , will be in state n during interval ℓ . The effect of multiplying by Ψ is to take the waste, which migrated through the path from m' to m on the assumption that the system was still in state n' , and distribute it among all the states (including n') in proportion to the probability that while the waste was in the path segment the system went from state n' to state n .

The mathematical approximation (as compared to an exact solution of Eq. E.2-13) of delaying the effect of state changes on waste until the waste reaches a node greatly simplifies calculations. Its effect may be reduced by inserting intermediate nodes in paths. Waste will react to state changes when reaching these intermediate nodes and then proceed through the remainder of the path at a velocity appropriate to the new state. The overall effect of the approximation may be analyzed by measuring the effect of adding such intermediate nodes; such tests are planned as a part of model validation.

The assumptions and methods used to calculate the factors G , θ , and Ψ are described in the following sections.

F.2 TECHNIQUES FOR SOLVING THE TRANSPORT EQUATION

The problem of predicting nuclide transport in groundwater in three-dimensional space may be reduced by the method derived in Appendix D to that of estimating stream flow lines and then formulating a transport equation for a one-dimensional "pipe" that follows the flow path. The water flow lines and velocities can be predicted with a two- or three-dimensional hydrology model using the finite element technique,

given the spatial distribution of particular geological structures and properties. Such calculations can often be carried out by such two-dimensional programs as that developed by Taylor (Ref. F.1); a three-dimensional code may sometimes be needed to depict particular situations accurately.

In this section, the one-dimensional nuclide transport equation (given in the next section) is solved explicitly with a Green's function (impulse response) approach (Ref. F.2). The resulting integral equation allows the use of a simple numerical integration technique which avoids the inherent difficulties of numerical dispersion associated with finite difference schemes. This approach is illustrated graphically in Fig. F.2-1.

F.2.1 The Hydrological Equations

A fundamental equation governing transport and dispersion of ions in one-dimensional flow through porous media is

$$\frac{\partial m_r}{\partial t} + \frac{\partial C_r}{\partial t} + V \frac{\partial C_r}{\partial x} = \alpha V \frac{\partial^2 C_r}{\partial x^2} - \lambda_r C_r + \sum_{s \neq r} \lambda_s^r C_s - \lambda_r m_r + \sum_{s \neq r} \lambda_s^r m_s \quad (\text{F.2-1})$$

Here λ_r is the radioactive decay constant of nuclide r (equal to $\ln 2$ divided by the half-life), λ_s^r is the production rate of nuclide r from decay of nuclide s , V is the interstitial water flow velocity, C_r is the concentration of nuclide r in the interstitial water, α is the longitudinal dispersion constant, and m_r is the amount of ion r sorbed on the solid per unit volume.

The third term on the left side of F.2-1 represents simple advection, while the first term on the right side is a hydrodynamic dispersion term where the dispersion constant is assumed to be a linear function of fluid velocity. The

THE INPUT TO THE PATH SEGMENT IS DIVIDED INTO DISCRETE TIME INTERVALS.

THE INPUT IS APPROXIMATED BY IMPULSES ENTERING AT THE MIDPOINT OF EACH TIME INTERVAL.

THE GREEN CURVE GIVES THE OUTPUT RESULTING FROM EACH OF THESE IMPULSE INPUTS.

THE OUTPUT OF THE IMPULSES IS INTEGRATED OVER A TIME INTERVAL.

THE CONTRIBUTIONS FROM DIFFERENT IMPULSE INPUTS ARE SUMMED TO GIVE THE TOTAL OUTPUT DURING THE TIME INTERVAL. THIS IS USED AS THE INPUT TO THE NEXT SEGMENT.

Figure F.2-1 Procedure for Calculating the Output of a Path Segment

velocity V can be estimated from the hydrology program or from Darcy's law if the pressure differences in the flow path are known. The flow direction can be estimated from the hydrology program also. Appendix D gives a justification of the one-dimensionality of the model; also, Refs. F.3, F.4 and F.5 discuss the advection, dispersion, decay and sorption terms.

The following additional assumptions are now made:

- Flow is slow enough so that instantaneous ion exchange equilibrium results, and the exchange adsorption isotherm is linear.
That is, $m_r = \frac{\rho}{\epsilon} K_d C_r$, where ρ is the bulk density, ϵ is the effective porosity and K_d is the distribution coefficient
- The dissolution rate $R(t)$ of the waste form is the same for all nuclides in the same decay chain
- The retardation factor, B_r , is the same for all nuclides in the same decay chain
($B_r = 1 + \frac{\rho}{\epsilon} K_d$)
- All path segments are considered to be infinite or semi-infinite in extent for the purpose of setting boundary conditions.

The first assumption allows us to write (Ref. F.1)

$$B_r \frac{\partial C_r}{\partial t} + V \frac{\partial C_r}{\partial x} = \alpha V \frac{\partial^2 C_r}{\partial x^2} - B_r \lambda_r C_r + \sum_{s \neq r} B_s \lambda_s^r C_s \quad (F.2-2)$$

Let $I_r(t)$ be the total amount of radionuclide r at time t in the waste which was originally emplaced in the repository. Then using the rest of the assumptions and defining $c_r = C_r/I_r$, we have for nuclides in the same decay chain

$$\frac{\partial c_r}{\partial t} + \frac{V}{B} \frac{\partial c_r}{\partial x} = \frac{\alpha V}{B} \frac{\partial^2 c_r}{\partial x^2} + \sum_s \lambda_s^r \frac{I_s}{I_r} (c_s - c_r) \quad (F.2-3)$$

with boundary conditions

$$c_r = 0 \text{ at } t = 0$$

$$c_r = 0 \text{ at } x = \infty$$

$$Q \left(c_r - \alpha \frac{\partial c_r}{\partial x} \right) = R(t) + Q\alpha \frac{\partial c_r}{\partial x} \text{ at } x = 0$$

where Q is the flow rate of water through the repository. The last boundary condition results from conservation of mass flux across the boundary. Equation F.2-3 is derived by substituting $c_r I_r$ for C_r in Eq. F.2-2 and using the decay equation for I_r

$$\frac{\partial I_r}{\partial t} = -\lambda_r I_r + \sum_s \lambda_s^r I_s$$

By the uniqueness theorem for differential equations, $c_r = c_s$, and the subscripts may be replaced with a single subscript j denoting a group of nuclides which have the same retardation factor. In the remainder of this appendix we will omit the subscript j . This simplification allows us to eliminate from our model a detailed analysis of nuclide decay chains. The assumption that the retardation factor is the same for all parent-daughter combinations is very reasonable in light of our imprecise knowledge of these parameters. That this causes only minor perturbations in our results is discussed in Appendix L.

The final set of equations is:

$$\frac{\partial c}{\partial t} + \frac{V}{B} \frac{\partial c}{\partial x} = \frac{\alpha V}{B} \frac{\partial^2 c}{\partial x^2} \quad x > 0 \quad (\text{F.2-4})$$

$$c = 0 \quad t = 0$$

$$c = 0 \quad x = \infty$$

$$Q \left(c - \alpha \frac{\partial c}{\partial x} \right) = R(t) + Q\alpha \frac{\partial c}{\partial x} \quad x = 0$$

For the next segment in the network, where the beginning of the path is at a distance z from the repository, we would have

$$\begin{aligned} \frac{\partial c'}{\partial t} + \frac{V'}{B'} \frac{\partial c'}{\partial x} &= \frac{\alpha' V'}{B'} \frac{\partial^2 c'}{\partial x^2} & x > z \\ c' &= 0 & t = 0 \\ c' &= 0 & x = \infty \\ \left(c' - \alpha' \frac{\partial c'}{\partial x} \right) \Big|_{x=z+0} &= \left(c - \alpha \frac{\partial c}{\partial x} \right) \Big|_{x=z-0} \end{aligned} \quad (F.2-5)$$

The last equation follows from conservation of mass flux across the boundary at z .

F.2.2 Formulas for Discrete Time Intervals

The solution of Eq. F.2-4 can be written as

$$c(x,t) = \frac{V}{BQ} \int_0^t R(\tau) G'(x,t-\tau) d\tau \quad (F.2-6)$$

where $R(\tau)$ is the rate at which waste enters the path segment and the Green's function, or impulse response, is

$$G'(x,t) = \frac{1}{\sqrt{4\pi\alpha\frac{V}{B}t}} \exp \left\{ -\frac{\left(x - \frac{V}{B}t\right)^2}{4\alpha\frac{V}{B}t} \right\} \quad (F.2-7)$$

In order to solve our problem on the computer, this continuous-time solution must be modified to be compatible with discrete time intervals. The means by which this is done is illustrated graphically in Fig. F.2-1. This procedure will be developed mathematically in the remainder of this section.

We first define

$$F(l) = \int_{T(l)}^{T(l+1)} Q c(z, t) dt \quad (F.2-8)$$

where Q is the volumetric water flow rate. Equation F.2-8 represents approximately the amount of waste leaving the pipe at $x = z$ during the time period $(T(l), T(l+1))$. Substitution of Eq. F.2-6 into Eq. F.2-8 and reversal of the order of integration yields the following:

$$\begin{aligned} F(l) = & \frac{V}{B} \int_0^{T(l)} \int_{T(l)}^{T(l+1)} R(\tau) G'(z, t-\tau) dt d\tau \\ & + \frac{V}{B} \int_{T(l)}^{T(l+1)} \int_{\tau}^{T(l+1)} R(\tau) G'(z, t-\tau) dt d\tau \end{aligned} \quad (F.2-9)$$

We now move $R(\tau)$ outside the t integral and integrate the Green's function over a single time interval. Let

$$G_1(z, \tau, l) = \frac{V}{B} \int_{T(l)}^{T(l+1)} G'(z, t-\tau) dt \quad \tau \leq T(l) \quad (F.2-10a)$$

and

$$G_2(z, \tau, l) = \frac{V}{B} \int_{\tau}^{T(l+1)} G'(z, t-\tau) dt \quad T(l) < \tau < T(l+1) \quad (F.2-10b)$$

These functions give the fraction of an impulse of waste entering the path segment at time τ which would leave it during the time interval $(T(l), T(l+1))$. The integrals of Eq. F.2-10 can be carried out explicitly, giving

$$G_1(z, \tau, l) = \frac{1}{2} \left[g(z, T(l+1) - \tau) - g(z, T(l) - \tau) \right]$$

and

$$G_2(z, \tau, l) = \frac{1}{2} g(z, T(l+1) - \tau)$$

where

$$g(z, t) = \operatorname{erfc} \left\{ \frac{z - \frac{V}{B} t}{\sqrt{\frac{4\alpha V t}{B}}} \right\} - \operatorname{erfc} \left\{ \frac{z + \frac{V}{B} t}{\sqrt{\frac{4\alpha V t}{B}}} \right\} e^{\frac{z}{B}} \quad (\text{F.2-11})$$

The quantity $F(l)$ from Eqs. F.2-9 and F.2-11 can now be used as the input to the next path. A new set of integrated Green's functions will then tell us the fraction of waste leaving the second path. This procedure, as generalized to more complicated networks, is described by Eq. F.1-1.

In order to calculate $F(l)$ we break time up into discrete steps. The steps have been chosen to begin at times $T(l)$ where

$$T(l) = 10 + \frac{4.5(l-1)}{l_{\max}} - 100 \quad (\text{F.2-12})$$

This choice of step size corresponds to our choice to display the output on a log-log scale. This also puts greater emphasis on earlier times when releases may be more critical. The equation for the output of a given path becomes

$$\begin{aligned}
 F(l) \cong & \sum_{i=1}^{l-1} \int_{T(i)}^{T(i+1)} R(\tau) G_1(z, \tau, l) d\tau \\
 & + \int_{T(l)}^{T(l+1)} R(\tau) G_2(z, \tau, l) d\tau
 \end{aligned} \tag{F.2-13}$$

where $R(\tau)$ is the rate at which waste enters the segment.

The integrals are usually evaluated using the midpoint rule. The computer program takes each input to a path segment and computes the fraction that comes out at all time intervals.

When the Green's function is narrower than the time steps, G' may be approximated by a delta function

$$G'(z, t) = \delta(z - \frac{V}{B} t) \tag{F.2-14}$$

If the midpoint rule were then used to integrate Eq. F.2-13 with changing time steps, for some values of l the sum would contain two non-zero terms and for other values of l it would only contain one non-zero term. Numerical noise would result, as illustrated in Fig. F.2-2. In such cases, it is more accurate to use Eq. F.2-14 directly to solve Eq. F.2-9. The precise conditions under which this is done are discussed in the next section.

An additional procedure is necessary to avoid round-off errors. Both $g(z, t)$ and $G_1(z, \tau, l)$ involve differences of complementary error functions. When these differences are small the error functions are expanded so that accuracy may be maintained. The methods used in these calculations are discussed in the next section.

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a) ENTERING PATH

TWO PULSES IN
ONE TIME INTERVAL

b) LEAVING PATH

Figure F.2-2 Numerical noise arises when the Green's function is narrower than the time interval and the duration of time intervals is not constant. In b, note the arrival of two pulses during the same time interval.

The program is written so that as few calls as possible are made to the complementary error function routine. The net result is an accurate and efficient calculation of nuclide migration.

F.3 NUMERICAL TECHNIQUE FOR CALCULATION OF INTEGRATED GREEN'S FUNCTION

As shown in Section F.2.2, the fraction of waste entering a path of length z at time τ which leaves the path between $\tau+t$ and $\tau+t+\Delta t$ is given by

$$G = g(z, t+\Delta t) - g(z, t) \quad (\text{F.3-1})$$

where $g(z, t)$ represents the fraction of waste which passes through the path segment in less time than t . The exact formula for g , derived in Section F.2.2, will be denoted g_A :

$$g_A(t) = \frac{1}{2} \left[\text{erfc}(\phi_-(t)) - e^{z/\alpha} \text{erfc}(\phi_+(t)) \right] \quad (\text{F.3-2})$$

where

$$\phi_{\pm}(t) = \frac{z \pm \frac{V}{B} t}{\sqrt{4\alpha \frac{V}{B} t}} \quad (\text{F.3-3})$$

A number of numerical problems can arise if Eqs. F.3-1 and F.3-2 are used directly to calculate G . These problems may be resolved by judicious use of the asymptotic expansion of the complementary error function

$$\text{erfc}(u) \xrightarrow{u \rightarrow \infty} \frac{e^{-u^2}}{\sqrt{\pi} u} \left(1 - \frac{1}{2u^2} + \frac{3}{4u^4} - \dots \right) \quad (\text{F.3-4})$$

This expansion possesses the useful property that the error is always less than the first excluded term.

Consider first the case $z/\alpha \gg 1$. If z/α is sufficiently large, the exponentiation in Eq. F.3-2 will yield a number that exceeds the machine's storage capacity. The

actual criterion used is $z/\alpha > 144$. By expanding $\text{erfc}(\phi_+(t))$, we obtain

$$g_B(t) = \frac{1}{2} \left[\text{erfc}(\phi_-(t)) - \frac{e^{-\phi_-^2(t)}}{\sqrt{\pi} \phi_+(t)} \right] \quad (\text{F.3-5})$$

The fractional error introduced by dropping terms of order ϕ_+^{-2} and higher will always be less than $\alpha/2z$.

Round-off errors can occur in the subtraction operation of either Eq. F.3-2 or Eq. F.3-5. Both complementary error functions must then be expanded and large terms occurring in both expansions canceled. The formula which results is

$$g_C(t) = \frac{e^{-\phi_-^2(t)}}{\sqrt{4\pi\alpha B/(Vt)}} \frac{1}{\phi_+(t) \phi_-(t)} \times \left[1 - \frac{1}{2} \left(\frac{1}{\phi_+^2(t)} + \frac{1}{\phi_+(t)\phi_-(t)} + \frac{1}{\phi_-^2(t)} \right) \right] \quad (\text{F.3-6})$$

Roundoff errors will exceed 1% when the computer calculates using six-digit numbers and

$$\frac{g(t)}{\text{erfc} \phi_-(t)} \leq 10^{-5}$$

When Eqs. F.3-4 and F.3-6 are substituted into this relation, one obtains the criterion

$$\frac{1}{1 + \frac{zB}{Vt}} \left[\frac{1 - \frac{1}{2}(\phi_+^{-2}(t) + \phi_+^{-1}(t)\phi_-^{-1}(t) + \phi_-^{-2}(t)) + \dots}{1 - \frac{1}{2}\phi_-^{-2}(t) + \dots} \right] < 10^{-5}$$

As long as $\phi_-(t) > 1$, this can only be satisfied when $Vt/zB \leq 10^{-5}$. For $z \geq \alpha$, this implies $\phi_- \geq 10^2$, and the error in Eq. F.3-6 due to dropping additional terms will be much less than 1%.

For large times when $Vt/Bz \gg 1$, on the other hand, round-off errors can arise in Eq. F.3-1. To deal with this, we rewrite Eq. F.2-11 as follows.

$$\begin{aligned} G &= g_A(T(\ell+1)-\tau) - g_A(T(\ell)-\tau) \\ &= \frac{1}{2} \left\{ \operatorname{erfc}(\phi_-(T(\ell+1)-\tau)) - \operatorname{erfc}(\phi_-(T(\ell)-\tau)) \right. \\ &\quad \left. + e^{z/\alpha} [\operatorname{erfc}(\phi_+(T(\ell)-\tau)) - \operatorname{erfc}(\phi_+(T(\ell+1)-\tau))] \right\} \\ &= g'_A(T(\ell+1)-\tau) - g'_A(T(\ell)-\tau) \end{aligned} \quad (F.3-7)$$

where

$$g'_A(\tau) = \frac{1}{2} [-\operatorname{erfc}(-\phi_-(t)) - e^{z/\alpha} \operatorname{erfc}(\phi_+(t))] \quad (F.3-8)$$

In the limit $\frac{Vt}{zB} \rightarrow \infty$, one has $\phi_- \rightarrow -\infty$ and $\phi_+ \rightarrow +\infty$, and use of the asymptotic expansion yields Eq. F.3-6 as the formula for $g'_A(t)$. This formula is used when

$$\frac{G}{g_A(T(\ell)-\tau)} < 10^{-5}$$

and its precision will be governed by considerations similar to those of the preceding case.

When $\ell = \ell'$, this round-off problem cannot arise because the subtraction of Eq. F.3-1 is not carried out. Equation F.3-2 or F.3-5 is then used as appropriate.

Finally, we have the case discussed in Section F.2.2 when the dispersion time $\frac{B}{V} \sqrt{4\alpha z}$ is much less than the time interval $T(l+1) - T(l)$. In this case, G is calculated ignoring dispersion altogether, but taking account of the width of the input pulse. Defining $T_f = zB/V$, we may write the formulas used as:

if $T(l') + T_f < T(l)$ and $T(l'+1) + T_f > T(l)$:

$$G(l', l) = \frac{T(l'+1) + T_f - T(l)}{T(l'+1) - T(l')} \quad (F.3-9a)$$

$$G(l', l-1) = 1 - G(l', l) \quad (F.3-9b)$$

if $T(l') + T_f > T(l)$ and $T(l'+1) + T_f < T(l+1)$:

$$G(l', l) = 1 \quad (F.3-9c)$$

$$\text{otherwise } G = 0 \quad (F.3-9d)$$

The formulas of Eq. F.3-9 are used whenever, from an impulse input into the path, 95% of the output will emerge during a single time interval. This will occur when the time interval is longer than four times the variance of the Gaussian output pulse, i.e., when

$$4 \frac{B}{V} \sqrt{2\alpha z} < T(l+1) - T(l) \quad (F.3-10)$$

However, dispersion cannot be neglected when the input pulse is narrower than the Green's function. For that reason, Eq. F.3-9 is not used when

$$\frac{F(l', m', n')}{F(l'+1, m', n')} < 0.05$$

or

$$\frac{F(l'+1, m', n')}{F(l', m', n')} < 0.05$$

The different cases discussed in this appendix, their defining conditions, and the formulas used in them, are summarized in Table F.3-1.

In this table:

$$g_A(t) = \frac{1}{2} \left[\operatorname{erfc} \phi_-(t) - e^{z/\alpha} \operatorname{erfc} \phi_+(t) \right]$$

$$g_B(t) = \frac{1}{2} \left[\operatorname{erfc} \phi_-(t) - \frac{e^{-\phi_-^2(t)}}{\sqrt{\pi} \phi_+(t)} \right]$$

$$g_C(t) = \frac{e^{-\phi_-^2(t)}}{\sqrt{\frac{4\pi\alpha B}{Vt}} \phi_+(t) \phi_-(t)} \left[1 - \frac{1}{2} \left(\frac{1}{\phi_+^2(t)} + \frac{1}{\phi_+(t)\phi_-(t)} + \frac{1}{\phi_-^2(t)} \right) \right]$$

$$\phi_{\pm}(t) = \frac{z \pm \frac{V}{B} t}{\sqrt{4\alpha \frac{V}{B} t}}$$

$$T_f = \frac{zB}{V}$$

and l_{opt} is defined by $T(l_{\text{opt}}-1) < T(l') + T_f \leq T(l_{\text{opt}})$.

TABLE F.3-1
FORMULAS FOR INTEGRATED GREEN'S FUNCTION G

T-1300

CASE NO.	CONDITIONS	FORMULA
0.1	$l \neq l'$ $z/a < 144$ not Case 5	$G = g_A(T(l'+1) - T(l'))$
0.2	$l = l'$ $z/a \geq 144$ not Case 5	$G = g_B(T(l'+1) - T(l'))$
1	$l \neq l'$ $c_-(T(l'+1) - T(l')) > 1$ $\frac{g_A(T(l'-1) - T(l'))}{\operatorname{erfc}(c_-(T(l'+1) - T(l'))))} < 10^{-5}$ not Case 5	$G = g_C(T(l'+1) - T(l'))$ $- g_C(T(l) - T(l'))$
2	$l \neq l'$ $c_-(T(l) - T(l')) < -2$ $\frac{G}{g_A(T(l) - T(l'))} < 10^{-5}$ not Case 5	$G = g_C(T(l'+1) - T(l'))$ $- g_C(T(l) - T(l'))$
3	$l \neq l'$ $z/a \geq 144$ not Cases 1, 2, or 5	$G = g_B(T(l'+1) - T(l'))$ $- g_B(T(l) - T(l'))$
4	$l \neq l'$ $z/a < 144$ not Cases 1, 2, or 5	$G = g_A(T(l'+1) - T(l'))$ $- g_A(T(l) - T(l'))$
5.1	$\frac{5}{\sqrt{2az}} < T(l_{\text{opt}}) - T(l_{\text{opt}}-1)$	$G(l', l_{\text{opt}}-2) = \frac{T(l_{\text{opt}}-1) - T(l') - T_f}{T(l'+1) - T(l')}$ $G(l', l_{\text{opt}}-1) = \frac{T(l'+1) + T_f - T(l_{\text{opt}}-2)}{T(l'+1) - T(l')}$
5.2	$\frac{F(l'+1, m', n')}{F(l', m', n')} > 0.05$ $\frac{F(l'+1, m', n')}{F(l'+1, m', n')} > 0.05$	$G(l', l_{\text{opt}}) = \frac{T(l'+1) + T_f - T(l_{\text{opt}})}{T(l'+1) - T(l')}$ $G(l', l_{\text{opt}}-1) = \frac{T(l_{\text{opt}}) - T(l') - T_f}{T(l'+1) - T(l')}$
5.3	$T(l') + T_f > T(l_{\text{opt}}-1)$ $T(l'+1) + T_f < T(l_{\text{opt}})$	$G(l', l_{\text{opt}}-1) = 1$

F.4 TREATMENT OF NODES WHERE FLOW PATHS BRANCH

At some nodes flow paths will branch and there will be more than one route by which waste can proceed from that point. For example, in our baseline models waste may leave the repository through the fracture zone around the shaft and tunnel, through the bulk permeability of the surrounding rock and sometimes through other pathways. In these cases it is necessary to determine how much of the waste enters each open flow path.

The model divides the waste in proportion to the volumetric flow of water in each pathway. The proportion of the waste leaving node m_1 in state n which proceeds toward node m_2 is given by

$$\theta(m_1, m_2, n) = \frac{V(m_1, m_2, n) W(m_1, m_2, n) \epsilon(m_1, m_2, n)}{\sum_{m'} V(m_1, m', n) W(m_1, m', n) \epsilon(m_1, m', n)} \quad (F.4-1)$$

where V is the water velocity in each pathway, W is the cross-section of the pathway and ϵ is the effective porosity.

It will be noted that retardation factors do not enter into this formula; the velocity used is the water velocity rather than the velocity of the waste. This requires some comment. In situations where streamlines branch in an area where rock chemistry, water impurities, etc. are homogeneous and retardation factors change only after the waste has been irrevocably committed to a particular pathway, the waste transport will simply be proportional to the water flow. This situation leads directly to Eq. F.4-1.

The situation where streamlines branch in an area of inhomogeneous sorption is more complicated. The applicability of Eq. F.4-1 to this case will be the subject of additional analysis in the future.

F.5 METHOD OF CALCULATING PROBABILITIES OF TRANSITION

The quantity $\Psi(\ell', \ell, n', n)$ used in Eq. F.1-1 is defined as the conditional probability that the system, having been in state n' at time $T(\ell')$, is in state n at time $T(\ell)$. (n' may be equal to n .)

When the program is used to analyze deterministic scenarios, Ψ is equal to unity if the system is in state n' at time $T(\ell')$ and is also in state n at time $T(\ell)$. Otherwise Ψ is equal to zero.

When the transitions among states are stochastic processes, more complicated formulas for Ψ must be used. The simplest case arises when the transition rates Γ (defined in Appendix G) are constant. For given ℓ' and ℓ , a matrix of $\Psi(n', n)$ may be calculated from the equation

$$\Psi = e^{-M[T(\ell) - T(\ell')]}$$

where M is a matrix whose elements are the transition rates.

When transition rates are not constant, formulas for Ψ must be derived by solving the appropriate differential equations.

F.6 LEACHING CALCULATION

The model assumes that no waste leaves the repository until the void space left by mining operations has been re-saturated by groundwater. The interval required for this to occur (designated T_{fill}) is an input to the program.

Once the mine has resaturated, the rate at which waste leaves is assumed to be proportional to the amount remaining in the repository. The rate at which waste leaves the repository is therefore given by

$$R(t) = \Lambda q(t) \quad (F.6-1)$$

where Λ is the fractional dissolution rate (in yr^{-1}) of the waste and $q(t)$ is the amount of waste in the repository at time t in MWe-yr.

The quantity actually used by our program is the input to the first flow pathways, $F(l,1,n)$, which represents the expected amount of waste leaving the repository during time interval l if the system is in state n , multiplied by the probability of the system being in state n . Since Eq. F.6-1 is linear in q , the expected rate of release will simply be the expected amount in the repository multiplied by Λ . Integrating over a time interval, we have

$$F(l,1,n) = Q(l,n) \left\{ 1 - \exp(-\Lambda(j,n)[T(l+1) - T(l)]) \right\} \quad (F.6-2)$$

Here $Q(l,n)$ is the expected amount of waste remaining in the repository at time $T(l)$ if the system is in state n , multiplied by the probability of the system being in state n . The following equation for $Q(l,n)$ may be derived from Eq. E.2-13:

$$Q(l,n) = \sum_{n'} \psi(l-1,l,n',n) [Q(l-1,n') - F(l-1,l,n')] \quad (F.6-3)$$

The initial values $Q(1,n)$ are inputs to the program. If the total amount of waste is normalized to one MWe-yr, then $Q(1,n)$ is the probability that the system is in state n at time $T(1)$.

It will be noted that in Eq. F.6-2, the dissolution rate A was written as a function of both nuclide type j and geologic state n . This notation gives the program the capability of handling dissolution rates which are affected by water flow, repository temperature, or other geologic state variables, or by chemical properties of different nuclides. However, as noted in Section F.2.1, parent and daughter nuclides in any single decay chain are represented as having the same dissolution rate if both are present in the waste at the time it is dissolving.

The program can easily be modified to represent dissolution processes which do not satisfy Eq. F.6-1.

F.7 CALCULATION OF MAXIMUM CONCENTRATIONS

The maximum concentrations of selected radionuclides in the interstitial water at each node are calculated by the subprogram WSCONS. These concentrations may be of interest for regulatory purposes. Also, they may be used to check the consistency of our physical assumptions as to the degree of ion solubility and the rate of ion-exchange reactions. These computations are made only for deterministic models, as for these purposes actual concentrations and not expected concentrations are required.

The formula used to compute the interstitial concentration at node m_1 at time $T(\ell)$ is

$$C_r(\ell, m_1, 1) = \frac{F(\ell, m_1, 1) I_r(T(\ell)) \Theta(m_1, m_2, 1)}{(T(\ell+1) - T(\ell)) V(m_1, m_2, 1) W(m_1, m_2, 1) \epsilon(m_1, m_2, 1)} \quad (F.7-1)$$

where m_2 may be any node connected to m_1 by a single flow path segment. This formula is just the flow rate of waste, $F/(T(\ell+1) - T(\ell))$, multiplied by the inventory of nuclide r , I_r , and the fraction of waste flowing into path (m_1, m_2) , Θ , and divided by the flow rate of water in the path, $VW\epsilon$.

The concentrations in the aquifer given in Appendix I were calculated from this formula, assuming mixing through an area equal to the height of the aquifer times the width of the repository. The method used to calculate explicitly the horizontal distribution of waste in the aquifer from both point and plane sources is detailed in the next section.

F.8 CALCULATION OF CONCENTRATIONS IN THE AQUIFER

Concentrations are calculated in the aquifer overlying the depository to assess the hazard to man from wells. The following simplifying assumptions are made:

- The aquifer is homogeneous and extends uniformly in the horizontal directions.
- The horizontal velocity in the aquifer is constant.
- The waste in the aquifer is bounded between two horizontal planes.

This model is illustrated in Fig. F.8-1, for an aquifer of thickness b and horizontal velocity V .

Figure F.8-1 Aquifer Model for Computing Concentrations Due to Waste Migration from an Underground Depository

F.8.1 Transport Equations

The basic equation governing waste transport in the aquifer is given by (Appendix D, Eq. D-8)

$$\frac{\partial c}{\partial t} + \frac{V}{B} \frac{\partial c}{\partial x} = \frac{\alpha V}{B} \frac{\partial^2 c}{\partial x^2} + \frac{(\alpha - 2\mu)V}{B} \left(\frac{\partial^2 c}{\partial y^2} + \frac{\partial^2 c}{\partial z^2} \right) \quad (\text{F.8-1})$$

where $(\alpha-2\mu)$ is the coefficient of transverse dispersivity.
The boundary conditions are assumed to be:

$$\begin{aligned} c &= 0 \text{ at } t = 0 \\ c &= 0 \text{ at } x = \pm\infty \\ c &= 0 \text{ at } y = \pm\infty \\ \frac{\partial c}{\partial z} &= 0 \text{ at } z = 0 \text{ and } z = b \end{aligned} \quad (F.8-2)$$

The Green's function solution for a point source with release rate $f(t)$ at $x=y=z=0$ is (Ref. F.6):

$$\begin{aligned} c(x,y,z,t) = & \int_0^t \frac{f(t-\tau) \exp \left[\frac{-\left(x - \frac{v}{B}\tau\right)^2}{\frac{4\alpha V\tau}{B}} - \frac{\frac{y^2}{4(\alpha-2\mu)V\tau}}{B} \right]}{4\epsilon\pi t b V \sqrt{\alpha(\alpha-2\mu)}} \\ & \times \left[1 + 2 \sum_{m=1}^{\infty} \exp \left[\frac{-m^2 \pi^2 (\alpha-2\mu) V\tau}{B b^2} \right] \cos \frac{m\pi z}{b} \right] d\tau \end{aligned} \quad (F.8-3)$$

Since wells would be expected to mix the water over the vertical extent of the aquifer, Eq. F.8-3 is integrated over z . The mean concentration in the interstitial water is then given by:

$$\langle c \rangle = \int_0^t \frac{f(t-\tau) \exp \left[\frac{-\left(x - \frac{v}{B}\tau\right)^2}{\frac{4\alpha V\tau}{B}} - \frac{\frac{y^2}{4(\alpha-2\mu)V\tau}}{B} \right]}{4\epsilon\pi t b V \sqrt{\alpha(\alpha-2\mu)}} d\tau \quad (F.8-4)$$

The concentration per unit volume of rock and interstitial water can be obtained from Eq. F.8-4 by multiplying by the effective porosity and the retardation factor.

F.8.2 Technique for Solving the Two-Dimensional Transport Equation

The formula used to compute the interstitial concentration of radionuclide r at a selected point (x,y) in the aquifer at time $T(\ell)$ is:

$$C_r(\ell) = \sum_{m'} \sum_{\ell'=1}^{\ell-1} F(\ell', m', 1) \times \bar{G}(\ell', \ell, m') \times I_r(T(\ell)) \quad (\text{F.8-4})$$

where m' ranges over all point sources in the aquifer located at $x(m')$, $y(m')$ and the Green's function is given by:

$$\bar{G}(\ell', \ell, m') = \frac{\exp \left\{ \frac{-\left(x - x(m') - \frac{V}{B} [T(\ell) - T(\ell')]\right)^2}{4\alpha \frac{V}{B} [T(\ell) - T(\ell')]} \right\}}{4\pi \epsilon V b \sqrt{\alpha(\alpha - 2\mu)} [T(\ell) - T(\ell')]} \times \exp \left\{ \frac{-[y - y(m')]^2}{4 \frac{V}{B} (\alpha - 2\mu) [T(\ell) - T(\ell')]} \right\} \quad (\text{F.8-5})$$

This formula is obtained from the discretization of Eq. F.8-4 and is analogous to the fundamental relation given in Eq. F.1-1.

The numerical approach used is identical to that depicted in the first three portions of Fig. F.2-1. The program

takes each input to the aquifer, $F(l', m', 1)$, and computes the contributions to the concentration from that input at all subsequent time intervals. The maximum contribution from $F(l', m', 1)$ to the concentration at (x, y) occurs at approximately

$$t^* = \frac{B}{V} \sqrt{\frac{(x-x(m'))^2 + \frac{\alpha(y-y(m'))^2}{\alpha-2\mu}}{\alpha-2\mu}} + T(l') \quad (F.8-6)$$

In carrying out numerical calculations, computational considerations are treated in a manner similar to the approach for the stream tube described in Section F.3.

As a preliminary approach, plane and line sources are simulated by replacing them with several point sources. The stream tube from the depository to the aquifer is treated as a point source for the shaft and boreholes, as a plane source for the breccia pipe and as a line source for a fault. The general flow through the rock overlying the depository is treated as a plane source.

F.8.3 Continuous Source Solutions

The solution of Eq. F.8-1 for a continuous source located at $x=0$, $y=0$, and strength f is:

$$c = \frac{f e^{\frac{x}{2\alpha}} W(r, s)}{4\epsilon\pi bV\sqrt{\alpha(\alpha-2\mu)}} \quad (F.8-7)$$

where

$$r = \left(\frac{x^2}{\alpha} + \frac{y^2}{\alpha-2\mu} \right) / \frac{4Vt}{B}$$

$$s = \sqrt{\frac{x^2}{\alpha} + \frac{y^2}{\alpha-2\mu}} / \sqrt{4\alpha}$$

and $W(r,s)$ is known as the "well function for leaky aquifers" (Ref. F.2). It is defined by:

$$W(r,s) = \int_r^\infty (1/y) \exp(-y-s^2/4y) dy \quad (F.8-8)$$

and is extensively tabulated. The following relations are useful in practical computations (Ref. F.7):

$$\lim_{t \rightarrow \infty} W(r,s) = 2K_0(s) \quad (F.8-9)$$

$$W(r,s) = K_0(s) \text{ at } t = \frac{B}{V} \sqrt{x^2 + \frac{\alpha y^2}{\alpha - 2\mu}} \quad (F.8-10)$$

for $s > 5$,

$$K_0(s) \approx \sqrt{\frac{\pi}{2s}} \left(1 - \frac{1}{8s}\right) e^{-s} \quad (F.8-11)$$

where K_0 is the zeroth-order modified Bessel function. The time in Eq. F.8-10 is t^* which is the time it takes a narrow pulse to reach point (x,y) .

The peak concentration from a continuous source at $x=0$, $y=0$ is given approximately by:

$$c \approx \frac{f \exp \left\{ \frac{x^2}{2\alpha} - \sqrt{\frac{x^2}{4\alpha^2} + \frac{y^2}{4\alpha(\alpha-2\mu)}} \right\}}{4\epsilon b V \sqrt{\pi(\alpha-2\mu)} \left[x^2 + \frac{\alpha y^2}{\alpha-2\mu} \right]^{\frac{1}{4}}} \quad (F.8-12)$$

$$\text{for } \left(\frac{x^2}{\alpha^2} + \frac{y^2}{\alpha(\alpha-2\mu)} \right) > 100$$

When $y = 0$,

$$c \approx f/4\epsilon bV\sqrt{\pi(\alpha-2\mu)x} \quad (\text{F.8-13})$$

These two relations are illustrated in Fig. F.8-2 and Fig. F.8-3, respectively, for the baseline parameters in the aquifer. It is worth noting how swiftly concentration falls off with increasing y . Concentration falls off much more slowly in the x direction.

Figure F.8-2 Relative Aquifer Concentration for Several Downstream Points x as a Function of y , the Distance Perpendicular to the Axis of Flow

Figure F.8-3 Relative Aquifer Concentration as a Function of Downstream Distance Along the Axis of Flow

F.9 WASTE TRANSPORT IN AN AQUIFER WITH A CONTINUOUSLY OPERATING WELL

The concentration in the aquifer as calculated in the last section gives only a partial indication of the hazard to man from well water. This is because a continuously operating well will affect the flow rates within the aquifer and hence the transit time of the waste to the well. This can be important for nuclides with rates of decay comparable to their transit time. Furthermore, as a well flows it will mix water from greater and greater distances away from itself until the "radius of influence" is reached. Therefore concentrations calculated along the axis of the flow may be overestimated and concentrations calculated away from the axis may be underestimated.

The calculations in Section F.8 do not take into account either the mixing of waste in the aquifer or the removal of waste from the aquifer due to wells.

The ground water velocity for a single well located at $(\bar{x}, \bar{y})$ in the aquifer shown in Fig. F.8-1 is given by (Ref. F.8):

$$u = V - \frac{Q(x-\bar{x})}{2\pi b\epsilon [(x-\bar{x})^2 + (y-\bar{y})^2]} \quad (F.9-1)$$

$$v = - \frac{Q(y-\bar{y})}{2\pi b\epsilon [(x-\bar{x})^2 + (y-\bar{y})^2]} \quad (F.9-2)$$

where u is the velocity in the x direction, v is the velocity in the y direction, and Q is the discharge rate of the well. For this velocity field there is a limiting line outside of which water will not flow into the well but will bypass it. The equation for this line is given by (Ref. F.8):

$$\tan^{-1} \left[\frac{(y-\bar{y})}{(x-\bar{x})} \right] = \frac{2\pi b\epsilon V(y-\bar{y})}{Q} \quad (F.9-3)$$

The flow lines for a single well in a confined aquifer and the limit line defined above are illustrated in Fig. F.9-1.

The discharge rate for a single well ranges between roughly $2 \times 10^5 \text{ m}^3/\text{yr}$ and $2 \times 10^6 \text{ m}^3/\text{yr}$ (Ref. F.9). For a well with discharge $2 \times 10^5 \text{ m}^3/\text{yr}$ the width of the limit line would be $2.2 \times 10^3 \text{ m}$ at a distance of 550 m upstream from the well for the baseline repository. This is already large enough to encompass the depository.

Figure F.9-1 Flow to a Well Penetrating a Confined Aquifer

The only cases of interest are when the depository lies within the zone of influence of the well. The simplest case is a well located directly downstream of the depository, $\bar{y}=0$, and far enough away so that the depository is entirely within the zone of influence of the well. Less conservative assumptions may be possible for specific sites. It should be pointed out that additional wells in the aquifer would tend to reduce the concentration in the well water since the waste would be mixed with a greater volume of water.

The two dimensional transport equation can be approximated by a one-dimensional equation, Eq. F.2-4, by averaging across the streamlines leading to the well. For this analysis the one-dimensional equation is simplified by assuming a constant interstitial water velocity given by

$$V_c = \frac{\bar{x}\bar{v}}{\bar{x} - \frac{Q}{2\pi b\varepsilon V} \ln \left(1 + \frac{2\pi b\varepsilon V\bar{x}}{Q} \right)} \quad (\text{F.9-4})$$

This velocity is chosen so that the transit time to the well is equal to that of a particle with the velocity given in Eq. F.9-1. This approximation is very good if dispersion is small and transport is described primarily by simple convection.

Computer calculations are made by introducing a node in the aquifer for the well, using the velocity defined in Eq. F.9-4 and following the procedures discussed in Sections F.1 through F.3. The time period during which the well is assumed to operate can be either a deterministic or a probabilistic input.

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APPENDIX G

THE BIOSPHERE TRANSPORT AND DOSE MODEL

G.1 INTRODUCTION

The biosphere transport and dose program BIDOSE is used in conjunction with the waste transport program WASTE (Appendix F) to calculate expected doses to man from releases of radioactivity to the environment. The program WASTE calculates the expected aquifer concentrations and flow rates into the biosphere of high level waste (HLW) from an underground repository.

The possible water pathways which are considered in the dose program are water wells, lakes, and a river, estuary and ocean system. Figure G.1-1 illustrates the latter model and lists the exposure pathways considered.

Over the last ten years a large number of models have been developed to compute the consequences of radioactive releases to the environment (Refs. G.1 through G.4). The model is derived from these, following closely the methods outlined in NRC Regulatory Guide 1.109 (Ref. G.5). There are two major points of departure from the previous methods. First, since radionuclide releases can occur over a long time period -- 10,000 years and longer -- the problem of buildup in soils and sediment is addressed. Second, since future population statistics are unknown it is necessary to compute population doses without referring explicitly to the local demography.

Figure G.1-1 Water and Food Pathways Model:
River, Estuary and Ocean System

Due to the vast uncertainty about future conditions, the model's predictions for times far into the future must be considered carefully. The basic philosophy in developing the model was to provide a tool for evaluating the consequences of radionuclide release under conditions not far removed from those we experience today. The model is, however, sufficiently general to accommodate a wide variety of assumptions as to diet, irrigation usage, water pathway characteristics, etc.

G.2 TRANSPORT MODEL

The mean concentration of various radionuclides in sediment, topsoil and water subsystems is calculated approximately using a compartment or box model. Each compartment

refers to an enclosed section of the physical world. All relevant dynamic processes are parameterized into transfer coefficients between the compartments. The model is based on calculating the mass balance in each compartment.

G.2.1 The Compartment Model

The basic equation used is

$$V_p \frac{d}{dt} C_{rp} = \sum_j C_{rj} A_{jp} + V_p \lambda_r \sum_q C_{qp} + Q_{rp} - V_p \lambda_r C_{rp} \quad (G.2-1)$$

where

C_{rp} = the concentration of nuclide r in compartment p (Ci/m^3)

C_{qp} = the concentration of nuclide q decaying into nuclide r in compartment p (Ci/m^3)

A_{jp} = the flow rate from compartment j to compartment p for $p \neq j$

A_{pp} = minus the flow rate out of compartment p

λ_r = the radioactive decay constant for nuclide r (yr^{-1}). Note that λ_q does not enter the equations for nuclide r because concentrations are measured in curies.

Q_{rp} = the input rate of nuclide r into compartment p from outside the system (Ci/m^3)

V_p = the volume of compartment p .

The following dynamic processes which affect concentration in the water, sediment and topsoil are modeled:

- Dilution by mixing
- Diffusion between sediment and water
- Sedimentation

- Removal of water and food products by man
- Return flow from the topsoil to the water system
- Ion exchange and biogeochemical processes, which are parameterized by distribution coefficients.

Figure G.2-1 illustrates this compartment model. The equations for a river, estuary and ocean system are given in the next section. A version of this model suitable for lake or river calculations is incorporated in the program FLOW.

G.2.2 Concentration Equations for the River, Estuary and Ocean System

The notation used in this section is fully described following the final set of equations. The concentration of nuclide r in a river or lake is given by:

$$\begin{aligned}
 V_w \frac{d}{dt} C_{rw} = & - \left[\lambda_r V_w + F + I + \frac{DA_s}{d} + K_{rs} A_s V_w \right] C_{rw} \\
 & + Q_r + V_w \sum_q \lambda_r C_{qw} + \left[\frac{I + R - E}{K_{rt}} \right] C_{rt} \\
 & + \left[\frac{DA_s}{K_{rs} d} \right] C_{rs}
 \end{aligned} \tag{G.2-2}$$

where losses are due to radioactive decay, flow out of the system, irrigation withdrawals, diffusion into the sediment and sedimentation. Inputs to the river or lake are from the aquifer, radionuclide production, run-off and diffusion from the sediment.

Figure G.2-1 Model for Surface Water System

The concentration in the sediment is given by:

$$v_s \frac{d}{dt} C_{rs} = - \left[\lambda_r v_s + \frac{DA_s}{K_{rs} d} + A_s v_w \right] C_{rs} + \left[\frac{DA_s}{d} + K_{rs} A_s v_w \right] C_{rw} + v_s \sum_q \lambda_r C_{qs} \quad (G.2-3)$$

The concentration in the topsoil is given by:

$$v_t \frac{d}{dt} C_{rt} = - \left[\lambda_r v_t + \frac{I + R - E}{K_{rt}} + M_r \right] C_{rt} + I C_{rw} + v_t \sum_q \lambda_r C_{qt} \quad (G.2-4)$$

The concentration in the estuary is given by:

$$V_e \frac{d}{dt} C_{re} = - \left[\lambda_r V_e + \frac{V_e}{T_e} + \frac{DA_e}{d} + K_{rse} A_e V_e \right] C_{re} \\ + F C_{rw} + V_e \sum_q \lambda_r C_{qe} + \left[\frac{DA_e}{K_{rse} d} \right] C_{rse} \quad (G.2-5)$$

The concentration in the estuarine sediment is given by:

$$V_{se} \frac{d}{dt} C_{rse} = - \left[\lambda_r V_{se} + \frac{DA_e}{K_{rse} d} + A_e V_e \right] C_{rse} \\ + \left[\frac{DA_e}{d} + K_{rse} A_e V_e \right] C_{re} + V_{se} \sum_q \lambda_r C_{qse} \quad (G.2-6)$$

The concentration in the ocean is given by:

$$V_o \frac{d}{dt} C_{ro} = - \left[\lambda_r V_o + \frac{V_o}{T_o} \right] C_{ro} + V_o \sum_q \lambda_r C_{qo} + \frac{V_e}{T_e} C_{re} \quad (G.2-7)$$

The following notation has been adopted:

C_{rp} is the concentration of nuclide r in pathway p (Ci/m^3) where w, e, o, t, s and se represent the river (or lake), estuary, ocean, topsoil, river sediment and estuarine sediment pathways respectively

V_p is the effective volume of pathway p (m^3)

T_p	is the flushing time for the estuary or the residence time for coastal waters (yr)
A_p	is the area of the sediment (m^2)
K_{rp}	is the distribution coefficient for nuclide r in pathway p $\left(\frac{Ci/m^3 \text{ dry sediment}}{Ci/m^3 \text{ water}} \right)$
Q_r	is the input of nuclide r from the aquifer into the river or lake (Ci/yr)
λ_r	is the radioactive decay constant of nuclide r (yr^{-1})
v_p	is the net rate of sedimentation (m/yr)
F	is the flow rate of the river (m^3/yr)
I	is the average yearly rate at which water is withdrawn from the river for irrigation (m^3/yr)
D	is the diffusion coefficient (m^2/yr)
d	is the average diffusion depth for sediment and subsoil (m)
R	is the average yearly rainfall on the topsoil under irrigation (m^3/yr)
E	is the average yearly evaporation from the topsoil under irrigation (m^3/yr)
M_r	is the effective average yearly removal rate of nuclide r from topsoil that is taken up by plants and animals (m^3/yr). This is evaluated in Section G.4.2.

G.2.3 Quasi Steady-State Model

Calculations can be considerably simplified because the release of waste from the aquifer is expected to be constant over long time periods. The basic assumptions made for all compartments except topsoil are:

- The times V_p/A_{jp} associated with transfers between the compartments in the model, are much smaller than the time over which changes in Q_{rp} occur.
- The times V_p/A_{jp} are also much smaller than the times over which concentrations are affected by the combined processes of radionuclide production and decay.

These assumptions permit the use of a steady-state model in which all time dependence is contained in the input term for flow of waste from the aquifer into the water system. The terms in Eq. G.2-1 involving radioactive decay and the derivative of the concentration may now be neglected.

$$0 = \sum_j C_{rj} A_{jp} + Q_{rp}(t) \quad (G.2-8)$$

Buildup in the topsoil is not assumed to reach equilibrium. Instead, the topsoil is assumed to be irrigated at a constant rate for a fixed period of time. This time period was varied from 100 to 1000 years to test the sensitivity of the dose from direct exposure to the topsoil or from plant uptake. Except for ^{126}Sn the dose from the topsoil was always much smaller than doses from other pathways.

The computer program BIDOSE employs the quasi steady-state model in its transport calculations. The equations and the parameters used are given in the next section.

G.2.4 Steady-State Equations

The equations used in the program BIDOSE to compute concentrations in the water, topsoil and sediment are:

$$C_{rw} (F + I) = Q_r + \left(\frac{I + R - E}{K_{rt}} \right) C_{rt} \quad (G.2-9)$$

$$C_{re} \left(\frac{V_e}{T_e} \right) = F C_{rw} \quad (G.2-10)$$

$$C_{ro} \left(\frac{V_o}{T_o} \right) = \left(\frac{V_e}{T_e} \right) C_{re} \quad (G.2-11)$$

$$C_{rs} = K_{rs} C_{rw} \quad (G.2-12)$$

$$C_{rt} = C_{rw} \left(\frac{I}{V_t} \right) \left(\frac{1 - \exp(-L_r t_b)}{L_r} \right) \quad (G.2-13)$$

where

$$L_r = \frac{I + R - E}{K_{rt} V_t} + \frac{M_r}{V_t} \quad (G.2-14)$$

and t_b is time over which the topsoil is irrigated.

The notation is the same as in Section G.2.2. The input from Q_r measures the amount of waste flowing out of the aquifer from 1 MWe-yr of nuclear power production as a function of time.

The values assumed for the various parameters are given in Tables G.2-1 and G.2-2, along with their references. The water system characteristics used were based on data collected from the Columbia River and its estuary and ocean systems. It should be mentioned that the values of the distribution coefficients for sediment and topsoil have a wide range in nature. Experimentally measured values even within the same region can vary by several orders of magnitude. A more accurate and dynamic model of these phenomena must await additional experimental and theoretical work.

TABLE G.2-1
CONCENTRATION FACTORS

T-1432

ELEMENT	$K_{rs} \left(\frac{\text{Ci/m}^3 \text{ DRY SEDIMENT}^*}{\text{Ci/m}^3 \text{ WATER}} \right)$		REFERENCE ⁺	
	FRESH WATER	SALT WATER	FRESH	SALT
Sr	1.3×10^3	5.3×10^1	16	12,15
Y	5.3×10^2		10	
Zr	1.0×10^5	1.0×10^5	10	12
Nb	3.0×10^3	1.0×10^5	16	12
Tc [‡]	1.0×10^4			
Ru	2.0×10^3	1.6×10^4	16	12,15
Sn	5.4×10^4		10	
I	1.0×10^4		16	
Cs	4.8×10^5	1.0×10^3	16	11
Ce	6.0×10^4	2.0×10^5	10	15
Pm		1.0×10^5		11
Eu [‡]	1.0×10^4			
Pb	3.2×10^3			
Po	3.2×10^3			
Ra	3.2×10^3		16	
Th	5.0×10^3		16	
Pa [‡]	1.0×10^4			
U [‡]	1.0×10^4			
Np [‡]	1.0×10^4			
Pu	3.8×10^5	2.1×10^5	13	15
Am	8.4×10^4	1.0×10^5	14	
Cm [‡]	1.0×10^4			

*Sediment density assumed to be 1.6 kg/l.

⁺See References for Appendix G.

[‡]Arbitrarily assigned values. Net dose is virtually insensitive to the concentration factor for these nuclides.

TABLE G.2-2
DATA FOR WATER SYSTEM EQUATIONS

T-1431

PARAMETER	VALUE	UNITS	REFERENCE NUMBER*
F	1.2×10^{11}	m^3/yr	6
V_e	2.6×10^9	m^3	6
T_e	2.5	day	6
V_o	6×10^{12}	m^3	7
T_o	122	day	7
I	4% F	m^3/yr	8
A_t	$(1/1 \frac{m}{yr})$	m^2	8
V_t	$0.15 A_t$	m^3	5
R.E	$R = E$	m^3/yr	Chosen for simplicity
M_r	See Section G.4.2	m^3/yr	
K_{rt}	Western Desert Soil	Ci/m^3 Topsoil Ci/m^3 Water	9

*See References for Appendix G.

G.2.5 Concentration Equations for the Ocean

The spatial distribution of radionuclides in the ocean may become important if biological activity is not uniform. The fish harvest data from Ref. G.17 in Table G.2-3 shows how harvest falls off as distance from shore increases. Because of this the plume of semi-fresh water which flows from the estuary out to sea contributes disproportionately to the net dose from the ocean. Therefore, the ocean pathway is divided into two compartments: the coastal ocean region and the river plume region. The distribution of radionuclides in a plume may be calculated for a specific site using the following equation (Ref. G.18)

TABLE G.2-3
COMMERCIAL FISH HARVEST OF
THE UNITED STATES (g/m²-day)

DISTANCE FROM SHORE	T-1433		
	0-3 mi	3-12 mi	12-50 mi
AVERAGE HARVEST	0.0193	0.0022	0.0003

$$C_{rpl}(x,y) = \left[\frac{C_{re} V_e}{T_e} \right] \frac{\exp\left(\frac{-uy^2}{4D_L x}\right) \exp\left(\frac{-\lambda_r x}{u}\right)}{2d\sqrt{\pi u x D_L}} \quad (G.2-15)$$

where

- u is the ocean velocity, about 15 cm/sec for the Oregon and Washington coast
- d is the plume depth, about 20 m for the Columbia River plume
- D_L is the lateral dispersion coefficient
- x is the distance parallel to the current
- y is the distance normal to the current
- C_{rpl} is the concentration of nuclide r in the plume
- C_{re} is the concentration of nuclide r in the estuary
- V_e is the volume of the estuary, about 2.6×10^9 m³ for the Columbia River estuary
- T_e is the flushing time of the estuary, about 2.5 days for the Columbia River estuary.

Values for the Columbia River estuary and plume were found in Refs. G.6 and G.7.

For use in the model, a mean plume concentration was calculated on the basis of the data presented in Ref. G.7 for the Columbia River plume. For a plume area of about $1.25 \times 10^{10} \text{ m}^2$ the mean plume concentration would be,

$$C_{\text{rpl}} = \left[\frac{V_e}{10 T_e F} \right] C_{\text{re}} \quad (6.2-16)$$

where F is the yearly flow rate of the river (m^3/yr).

G.2.6 Steady-State Assumptions

The assumptions given in Section G.2.3 which permit the use of an equilibrium model deserve further discussion. The assumptions result in a conservative estimate of the peak individual dose. This is because water concentrations from a continuous input will rise from zero till they reach their equilibrium value while the model assumes them to always be at their equilibrium value.

A less conservative analysis would be possible if there was a thorough understanding of those processes which remove contaminants from the biosphere. The major processes in a river and estuary system which remove radionuclides are sedimentation and diffusion into the sediment. Radionuclides can reenter the ecosystem from the sediment by physical, chemical and biological means. Both the potential for remobilization and the time period over which it might occur are unknown for many of the radionuclides in HLW. Although it has been suggested that some radionuclides such as plutonium become irreversibly bound to the sediment, recent evidence suggests that remobilization can occur (Ref. G.19). Therefore, it is felt prudent in this analysis to adopt the following conservative assumptions:

- The water and sediment system are in dynamic equilibrium. For each radionuclide, the concentration in the sediment divided by the water concentration is given by the distribution coefficient.
- There are no irreversible losses from the water system to the sediment.
- The time period over which buildup in the sediment occurs is much less than the time over which changes in Q_{rp} occur.

G.2.7 Model Assumptions for the Population Dose Calculation

Population doses are calculated by integrating the individual dose over an entire population. The integrated population dose is obtained by integrating the population dose over the entire lifetime of the repository. Since doses are proportional to the concentrations in each compartment, Eq. G.2-1 can be integrated directly. This gives for a repository lifetime of 3×10^6 years:

$$V_p C_{rp} (t = 3 \times 10^6 \text{ yr}) = \sum_j [C_{rj}] A_{jp} + V_p \sum_q \lambda_r [C_{qp}] + V_p \lambda_r [C_{rp}] + [Q_{rp}] \quad (\text{G.2-17})$$

where [] is defined as:

$$[f] = \int_0^{3 \times 10^6 \text{ yr}} f \, dt \quad (\text{G.2-18})$$

The quantity on the left hand side of Eq. G.2-17 may be neglected for nuclides that have either decayed to negligible amounts or left the ecosystem by 3×10^6 years. If in

addition the terms involving radioactive decay are negligible then Eq. G.2-17 reduces in form to Eq. G.2-8. Equation G.2-17 is independent of the assumptions made in deriving the steady-state relation, Eq. G.2-8.

G.3 DOSE CALCULATIONS

The concentrations calculated for the five media: sediment, river, estuary, ocean and topsoil, are used with a simple ecosystem model to give radionuclide dose rates to man. Doses were assumed to be received by ingestion and external exposure. The ingestion pathways considered are drinking water, aquatic foods, irrigated crops and farm animals. The external exposure pathways considered are shoreline, boating, swimming and topsoil.

Each adult is assumed to drink all his water and eat all his aquatic food from the river or lake system into which radioactive material was released. Furthermore, each adult's diet is assumed to be composed solely of food products that were either directly or indirectly contaminated by the river or lake water. In addition, all water-related recreation time is assumed to be spent somewhere within the river, estuary and ocean system. These assumptions ensure that no important pathway for exposure is overlooked for each nuclide in the system.

G.3.1 Dose Equation

The basic equation used is (Ref. G.9),

$$D_{\text{rpu}} = C_{\text{rp}} U_{\text{p}} DF_{\text{rpu}} \quad (\text{G.3-1})$$

where

D_{rpu} = the dose rate to organ u from nuclide r via pathway p

C_{rp} = the concentration of nuclide r in pathway p

U_p = the usage rate associated with pathway p

DF_{rpu} = the radiation dose factor for nuclide r in pathway p for organ u.

The dose calculations for water withdrawn directly from the aquifer through a well are identical to those for wastes which flow into a river or lake except that the aquatic food, shoreline and swimming pathways are eliminated.

G.3.2 The Dose Factor

The dose factors that are used represent the accumulated dose over 50 years to an adult from chronic ingestion and exposure to radiation. The procedure has been to calculate dose factors using those already tabulated in Ref. G.9 and multiply by a dose accumulation factor. The dose factors tabulated represent one year's accumulated dose from a single intake of radionuclides on the first day of the year. The basic equations for the 1-year and 50-year dose factors for chronic ingestion of soluble radionuclides are*

$$DF1 = 18.7 \frac{f_w \epsilon}{m} \frac{1 - e^{-\lambda_e}}{\lambda_e} \quad (G.3-2)$$

$$DF50 = 18.7 \frac{f_w \epsilon}{m} \frac{50\lambda_e + e^{-50\lambda_e} - 1}{\lambda_e^2} \quad (G.3-3)$$

*J.K. Soldat, Battelle Pacific Northwest Laboratories, personal communication.

where

DF1 = the 1-year dose factor (mrem/pCi)

DF50 = the 50-year dose factor $\left(\frac{\text{mrem}}{\text{pCi/yr}} \right)$

f_w = the fraction of the ingested nuclide reaching the organ

m = mass of the organ in grams

ϵ = effective energy of the nuclide in the organ under consideration (MeV/disintegration)(rem/rad)

$\lambda_e \triangleq (0.693/T_B + 0.693/T_R)$

T_B = biological half-life for the nuclide in the organ (yr)

T_R = radioactive half-life for the nuclide (yr).

The appropriate dose accumulation factor is,

$$\text{DAF} = \frac{50 \lambda_e^{-1} + e^{-50 \lambda_e}}{(1 - e^{-\lambda_e}) \lambda_e} \quad (\text{G.3-4})$$

The values for λ_e were taken from Ref. G.9.

The same 50-year dose factor was used to calculate both individual and population dose. This results in a measure of the accumulated dose to a population over a 50 year period. The population dose per year was calculated by dividing the above measure by 50. This was used in our calculation of the integrated population dose. It effectively represents the population as consisting of adults evenly distributed over a 50 year age range.

Doses were calculated for the whole body and seven organs of interest: gastrointestinal and lower large intestine, thyroid, bone, liver, lung, kidney and skin. The means of exposure included immersion and surface irradiation as well as ingestion. A whole-body dose equivalent can also be calculated which combines the dose to all organs by using dose equivalent factors (Ref. G.20). These factors weight each organ dose according to cancer risk. This may provide a more meaningful and compact way of presenting the hazard from radioactive waste.

G.3.3 The Usage Rate

The average and maximum usage rates that are employed in the model for calculating individual doses are given in Tables G.3-1 and G.3-2. The tables give values for the intake of water and food products and the time per year spent in water-related recreation for an adult. The values used reflect those given in Ref. G.5; the number of food products considered, however, was expanded, based on the data given in Ref. G.9. Therefore, while the totals for a given category -- meat and poultry, for example -- are as given in the NRC regulatory guide, the breakdown within that category is determined from the data given in Ref. G.9.

The aquatic food diet for an individual was apportioned according to the contributions from the river, estuary and ocean pathways. This was done by multiplying the aquatic food intake in each pathway by F_{lp} , the fraction of food product l (fish, crustacean or mollusk) consumed in pathway p (river, estuary, plume or ocean). The sum of F_{lp} over all pathways for a fixed l was set equal to one. The values used for F_{lp} are listed in Table G.3-3. These values are an estimate based on the fish harvest data given in Section G.4.2.

TABLE G.3-1
STANDARD USAGE FACTORS FOR AN AVERAGE ADULT

T-1426

DIET AND RECREATION	USAGE RATE, U _p	UNITS
Milk	110	l/yr
Fish	6.9	kg/yr
Mollusk	0.5	kg/yr
Crustacean	0.5	kg/yr
Water	370	l/yr
Eggs	487	eggs/yr
Berries	5	kg/yr
Melons	7	kg/yr
Orchard Fruit	43	kg/yr
Wheat	50	kg/yr
Other Grains	4	kg/yr
Beef	39	kg/yr
Poultry	17	kg/yr
Pork	39	kg/yr
Leafy Vegetables	5	kg/yr
Other Above Ground Vegetables	5	kg/yr
Potatoes	44	kg/yr
Other Root Vegetables	26	kg/yr
Shoreline	8.3	hr/yr
Swimming and Boating*	5	hr/yr

*Ref. G.9

TABLE G.3-2
STANDARD MAXIMUM USAGE FACTORS FOR AN ADULT

T-1427

DIET AND RECREATION	USAGE RATE, U _p	UNITS
Milk	310	l/yr
Fish	21	kg/yr
Mollusk	2.5	kg/yr
Crustacean	2.5	kg/yr
Water	730	l/yr
Eggs	730	eggs/yr
Berries	10	kg/yr
Melons	14	kg/yr
Orchard Fruit	90	kg/yr
Wheat	113	kg/yr
Other Grains	12	kg/yr
Beef	45	kg/yr
Pork	45	kg/yr
Poultry	20	kg/yr
Leafy Vegetables	32	kg/yr
Other Above Ground Vegetables	32	kg/yr
Potatoes	131	kg/yr
Other Root Vegetables	86	kg/yr
Shoreline	12	hr/yr
Swimming and Boating*	200	hr/yr

*Ref. G.9

TABLE G.3-3
FRACTION OF FOOD PRODUCT CONSUMED

T-1428			
WATER SYSTEM	FISH	CRUSTACEAN	MOLLUSK
River	0.1	0	0
Estuary and Near Shore	0.4	1	1
Plume and Ocean	0.5	0	0

Other assumptions can easily be implemented but will not result in a substantial change in the final calculated dose.

G.3.4 Concentrations in the Environment

The method used to calculate concentrations in irrigated foods was taken from Refs. G.9 and G.21. It is essentially the same as that detailed in NRC Regulatory Guide 1.109. The equations used were

$$C_{rv} = \left[IR_v \frac{r C_{rw} T_v (1 - e^{-\lambda E_r t_e})}{Y_v \lambda E_r} 1000 + \frac{C_{rt} B_{rv}}{D_T} \right] \quad (G.3-5)$$

$$C_{ra} = S_{ra} [C_{rf} Q_F + C_{rw} Q_{Aw}] \quad (G.3-6)$$

where

C_{rv} is the concentration of nuclide r in plant v (Ci/kg)

C_{ra} is the concentration of nuclide r in animal product a (Ci/unit)

C_{rF}	is the concentration of nuclide r in feed or forage calculated from C_{rv} (Ci/kg)
C_{rw}	is the concentration of nuclide r in the fresh water used for irrigation (Ci/m ³)
C_{rt}	is the concentration of nuclide r in the topsoil (Ci/m ³)
IR_v	is the irrigation rate during the growing season for vegetable v (l/m ² -day)
r	is the fraction of deposited activity retained on crops, taken to be 0.25
T_v	is the fraction of deposited activity which ends up in the edible portion of the plant. It is taken to be 1 for leafy vegetables and fresh forage and 0.1 for all other produce.
λ_{Er}	is the weathering removal constant = 0.693/14 (day ⁻¹)
t_e	is the time of above-ground exposure of crops to contamination during the growing season (day)
Y_v	is the plant yield (kg/m ²)
B_{rv}	is the plant concentration factor (Ci/kg)/(Ci/kg)
D_T	is the topsoil density (kg/m ³). It is taken to be 1600 kg/m ³
S_{rA}	is the transfer coefficient for nuclide r from daily intake of animal to edible portion of animal product [day/l (milk)] or [day/kg (animal product)]
Q_F	is the consumption rate of contaminated feed or forage by an animal (kg/day)
Q_{Aw}	is the consumption rate of water by an animal (l/day)
1000	is a factor to convert m ³ to liters.

The values of B_{rv} , S_{ra} , Q_F , and Q_{Aw} are taken from Ref. G.5. The values of IR_v , Y_v , and t_e are given in Table G.3-4.*

TABLE G.3-4
IRRIGATION RATE, PLANT YIELD AND GROWING PERIOD

T-1440

PLANT PRODUCT	IR_v (l/m^2 -day)	Y_v (kg/m^2)	t_e (day/yr)
Leafy Vegetables	5.0	1.5	90
Other Above Ground Vegetables	5.3	0.7	60
Potatoes	6.0	4.0	90
Other Root Vegetables	5.0	5.0	90
Berries	5.0	2.7	60
Melons	5.0	0.8	90
Orchard Fruit	5.0	1.7	90
Wheat	5.0	0.7	90
Other Grain	5.0	1.4	90
Grass	5.0	1.3	30

The concentrations of radionuclides in the edible portions of aquatic foods are found using the bioaccumulation factors given in NRC Regulatory Guide 1.109. The bioaccumulation factor measures the ratio of the concentration in the biota to the radionuclide concentration in water at equilibrium. Fresh water bioaccumulation factors were used for the river to calculate fish, mollusk and crustacean concentrations. Salt water bioaccumulation factors were used for the estuary and ocean calculations.

*The source of Table G.3-4 is a personal communication with H.C. Burkholder, Battelle Pacific Northwest Laboratories.

The shoreline concentrations were modified in order to take account of the geometry of exposure using the shore-width factor as given in Ref. G.5. Topsoil concentrations were multiplied by a shielding factor of 0.33 (Ref. G.3) to take account of housing. Topsoil exposure was conservatively expected to occur year-round.

G.4 POPULATION DOSE MODEL

Population dose is often calculated for a real or assumed population within a 50 mile radius of the contaminated region. For calculations of population doses far into the future it is very difficult to make realistic population estimates. However, the total dose from some pathways will be essentially independent of the size of the neighboring population. The aquatic food pathway depends on the net fish harvest and the vegetable and animal pathways primarily depend on the yearly irrigation rate. The population dose from these pathways will be independent of how these products are distributed. The population dose model described below is based on parameters that are essentially independent of the size of the population living near the river system.

G.4.1 Equations for Calculating Population Dose

The intake rate from irrigated crops is given by:

$$p_r^{veg} = \frac{f^{veg} \sum_v \frac{F_v U_v C_{rv}}{Y_v IR_v t_e}}{1000} \quad (G.4-1)$$

where

- p_r^{veg} is the intake rate from all plant products (Ci/yr)
- f^{veg} is the fraction of the river or well flow rate that is used for irrigating crops for human consumption
- F is the average yearly flow rate of a river or well (m^3/yr)
- U_v is the average yearly consumption of food crop v by an individual (kg/yr)
- C_{rv} is the concentration of nuclide r in plant v (Ci/kg) as calculated in Eq. G.3-5
- IR_v is the irrigation rate during the growing season for vegetable v (l/m^2 -day)
- Y_v is the plant yield (kg/m^2)
- t_e is the time of above-ground exposure of crops to contamination during the growing season (day)
- 1000 is a factor to convert m^3 to liters.

Vegetables were assumed to be grown in proportion to their usage in an average diet as given in Table G.3-1. The population was assumed to consist solely of adults.

The intake rate from consumption of milk and beef products is given by:

$$p_r^{milk} = (1000 f^{milk_F}) \frac{C_{rF} Y_F}{IR_F t_e} S_{rA} A^{milk} + f^{cow} F C_{rw} S_{rA} A^{milk} \quad (G.4-2)$$

$$p_r^{\text{beef}} = (1000 f^{\text{beef}}_F) \frac{C_{rF} Y_F}{IR_F t_e} S_{rA} A^{\text{beef}} + f^{\text{cattle}}_F C_{rF} S_{rA} A^{\text{beef}} \quad (\text{G.4-3})$$

where

- $p_r^{\text{milk}}, p_r^{\text{beef}}$ is the intake rate from consumption of milk or beef (Ci/yr)
- $f^{\text{milk}}, f^{\text{beef}}$ is the fraction of the river or well flow rate that is used for irrigating crops for consumption by dairy cows or beef cattle
- $f^{\text{cow}}, f^{\text{cattle}}$ is the fraction of the river or well flow rate that serves as drinking water for dairy cows or beef cattle
- C_{rF}, IR_F, Y_F are as defined following Eq. G.4-1, and the subscript F refers to feed or forage
- S_{rA} is the transfer coefficient for nuclide r from daily intake of animal to edible portion of animal product [day/l(milk)] or [day/kg (beef)]
- $A^{\text{milk}}, A^{\text{beef}}$ is the production rate of milk or beef per animal per day [l/day (milk)] or [kg/day (beef)]
- 1000 is a factor to convert m^3 to liters.

It is assumed that

$$I = [f^{\text{milk}} + f^{\text{beef}} + f^{\text{veg}}] F$$

where I is the average yearly rate at which water is withdrawn from the river or well for irrigation.

It is now possible to obtain a relationship for M_r , the effective removal rate from topsoil, which is required in Section G.2.2.

$$M_r = \left\{ \frac{B_{rF} S_{rA} Y_F A^{\text{milk}}}{D_T I R_F t_e} f^{\text{milk}} + \frac{B_{rF} S_{rA} Y_F A^{\text{beef}}}{D_T I R_F t_e} f^{\text{beef}} + \frac{\sum_v B_{rv} U_v}{D_T \sum_v \frac{U_v I R_v t_e}{Y_v}} f^{\text{veg}} \right\} 1000 F \quad (G.4-4)$$

where B_{rv} and D_T are defined in Section G.3.4 and B_{rF} is the value of B_{rv} for feed or forage.

The value of A^{beef} was obtained from Ref. G.4 which quoted a production rate of 0.4 kg/day for a fattening steer. The value of A^{milk} was obtained by dividing the total U.S. milk production by the total number of dairy cows in the U.S. (Ref. G.22). This gives a value of about 15 liters of milk produced per cow per day.

The fraction of river water used for irrigation was obtained by dividing the amount of water used for irrigation in the U.S. by the total runoff per year (Ref. G.8). Account was taken of the fraction of irrigation water which comes from underground sources (Ref. G.23). An estimated 4% of the yearly runoff in the U.S. is used for the purpose of irrigation.

A similar calculation is necessary for ground water. Based on Ref. G.23, 85% of the ground water used in the Western United States is for irrigation. Therefore $I/F = 0.04$ for rivers and $I/F = 0.85$ for wells.

The population dose from the aquatic food pathway was calculated using the harvest data in Table G.4-1. The harvests for the river, estuary and ocean pathways were based on data from the Columbia River system, Ref. G.24. The lake harvest

TABLE G.4-1
AQUATIC FOOD HARVEST

AQUATIC FOOD	RIVER	ESTUARY AND NEAR-SHORE	OCEAN	LAKE
Fish	1.5×10^5	1.2×10^7	2.0×10^8	7.5×10^6
Mollusk	—	4.5×10^6	—	—
Crustacean	1.0×10^4	1.7×10^6	—	—
All weights expressed in edible lb.				

data came from Ref. G.25 and typified the Great Lakes. Since the productivity of aquatic life is limited, substantial increases in these yields are not expected.

The population doses from the swimming, shoreline and topsoil exposure pathways were based on the following assumptions.

- Swimming and boating population usage was 0.14 user-hr/acre of water system per day (Ref. G.25)
- Shoreline population usage was 0.5 user-hr/acre of water system per day (Ref. G.25)
- The topsoil was assumed to be occupied 100% of the time. A shielding factor of 1/3 was included to take account of housing (Ref. G.3). The area of the topsoil was estimated from the irrigation rate by assuming 1 cubic meter of water for every square meter of land (Ref. G.8).

A population density of 500 people/km² was chosen to test the importance of the topsoil exposure pathway.

The population dose from drinking water is calculated by using an assumed usage rate for the river system. This was obtained by dividing the total quantity of drinking water used from above-ground resources in the U.S. per year by the annual runoff. This figure, 3.7×10^{-5} , was then multiplied by the river flow rate in our system to obtain the total quantity of water consumed.

The population dose from drinking water from underground resources is calculated by using an assumed usage rate for wells. About 7% of well flow is used for municipal supplies (Ref. G.23). Only about 0.2% of this is used for drinking purposes assuming a 125 gal/day/capita water usage for urban centers. Therefore $W/F = 3.7 \times 10^{-5}$ for rivers and $W/F = 1.4 \times 10^{-4}$ for wells, where W is the quantity of drinking water used per year.

G.4.2 Sensitivity of Population Dose to Flow Rate

The population dose will quite generally be independent of the flow rate of the water system, in sharp contrast to the individual dose which is inversely proportional to the flow rate. This conclusion is based on the following assumptions:

- The potential usage of the water system is proportional to the average flow rate.
- The actual usage is equal to the potential usage.
- The concentrations within the water system are roughly inversely proportional to the flow rate.

The usage rates which can be expected to be dependent on river flow are drinking water and irrigation usage. The aquatic food and recreational pathways depend on the area and volume of the water system and hence only indirectly on the flow rate. However, except for ^{126}Sn and $^{93\text{m}}\text{Nb}$ these pathways are of only secondary importance in determining the total dose.

The maximum potential usage rate of the water system is difficult to estimate. Theoretically it could amount to more than 100% of the water flow if there was considerable recycling. The following factors mitigate against high usage rates.

- Extensive water reuse implies the removal of waste products. Presumably radio-nuclides would also be removed during water treatment.
- Approximately 60% of the water which is used for irrigation is consumed and does not return to the water system. This water is not available for reuse.
- Approximately 30% of the water which is used for municipal supplies is consumed and does not return to the water system. Furthermore only a small fraction (0.2%) of municipal water is used for drinking.

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APPENDIX H
PARAMETERS FOR SENSITIVITY ANALYSES

The following tables and figures contain a description of the parameter values used in obtaining the sensitivity analysis results listed in Appendix I. The rationale for use of these values may be found in Refs. H.1 through H.3. Figures H-1 through H-4 illustrate schematically the flow pathways in the different cases which were analyzed. Tables H-1 through H-7 list baseline parameter values. Tables H-8 through H-14 describe parameter values tested in the sensitivity analysis when space does not permit their inclusion in the tables of Appendix I. The "run index number" of Tables H-8 through H-14 refers to a reference number appearing on the appropriate table of Appendix I.

Table H-15 is an index showing which figures and tables of Appendix H relate to each table of Appendix I.

The following variables had the same baseline, or "preferred," values in all cases:

- The dissolution rate of the waste was 10^{-4} per year
- The time required for resaturation of the depository was 100 years
- The hydraulic head of the lower aquifer was 60 m greater than the head of the upper aquifer at the same location.
- The horizontal hydraulic gradient of the upper aquifer was 0.005.

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The radionuclide source terms were calculated using the standard reactor parameters for a light water reactor given in Ref. H.4. A fuel of uranium enriched to 3.3% ^{235}U was exposed for 1100 days at an average power of 30 MW/MT. The neutron flux ϕ and the reactor spectrum parameters THERM, RES, and FAST were 2.92×10^{13} n/cm²-sec, 0.632, 0.333, and 2.0 respectively.

Consideration was limited to the following nuclides which were chosen by LLL as the list of biologically significant radionuclides to be considered in this study (Ref. H.5):

^{89}Sr	^{210}Pb
^{90}Sr	^{210}Po
^{90}Y	^{226}Ra
^{91}Y	^{229}Th
^{93}Zr	^{230}Th
^{95}Zr	^{231}Pa
$^{93\text{m}}\text{Nb}$	^{233}U
^{95}Nb	^{237}Np
^{99}Tc	^{238}Pu
^{106}Ru	^{239}Pu
^{126}Sn	^{240}Pu
^{125}Sb	^{241}Pu
^{129}I	^{241}Am
^{134}Cs	^{243}Am
^{137}Cs	^{242}Cm
^{144}Ce	^{244}Cm
^{147}Pm	
^{154}Eu	

In future analyses, ^{59}Ni , ^{135}Cs and ^{225}Ra will also be included. The omission of these nuclides has little effect on the calculated peak individual doses; however inclusion of

^{135}Cs would have increased the calculated integrated population doses in some cases by a factor not exceeding 4. This correction has no effect on the qualitative conclusions of the study.

Figure H-1 Flow Pathways for Unflawed Repository
(Tables I-1 through I-6)

Figure H-2 Flow Pathways for Repository With
Deteriorated Backfill (Tables I-7
and I-8)

Figure H-3 Flow Pathways for Repository With Failed Boring Seals (Tables I-9 and I-10)

Figure H-4 Flow Pathways for Repository With Fault (Table I-11) or Breccia Pipe (Table I-12)

TABLE H-1
BASELINE PARAMETERS FOR UNFLAWED SHALE REPOSITORY
(TABLES I-1 AND I-2)

T-1550

PATHWAY	LENGTH (m)	CROSS SECTION (m ²)	EFFECTIVE POROSITY	PERMEABILITY (cm/sec)	RETARDATION FACTOR	DISPERSION (m)
1 st Segment of Tunnel Fracture Zone	1200	316	0.1	0.1	¹²⁹ I, ⁹⁹ Tc: Other Fission Products: 10^2 Actinides: 10^4	50
2 nd Segment of Tunnel Fracture Zone	440	18.96	0.1	0.1	¹²⁹ I, ⁹⁹ Tc: Other Fission Products: 10^2 Actinides: 10^4	50
Fracture Zone Around Shaft in Depository Layer	100	10	10^{-3}	10^{-4}	¹²⁹ I, ⁹⁹ Tc: Other Fission Products: 10^2 Actinides: 10^4	50
Fracture Zone Around Shaft in Shale Barrier Layer	200	5	10^{-3}	10^{-4}	¹²⁹ I, ⁹⁹ Tc: Other Fission Products: 10^2 Actinides: 10^4	50
Depository Layer	100	5×10^6	0.05	10^{-9}	¹²⁹ I, ⁹⁹ Tc: Other Fission Products: 10^2 Actinides: 10^4	50
Barrier Layer	200	5×10^6	0.05	10^{-7}	¹²⁹ I, ⁹⁹ Tc: Other Fission Products: 10^2 Actinides: 10^4	50
Aquifer	1.6×10^4	4×10^5	0.1	10^{-4}	¹²⁹ I, ⁹⁹ Tc: Other Fission Products: 10^2 Actinides: 10^4	50

TABLE H-2
BASELINE PARAMETERS FOR UNFLAWED SALT REPOSITORY
(TABLES I-3 AND I-4)

T-1551

PATHWAY	LENGTH (m)	CROSS SECTION (m ²)	EFFECTIVE POROSITY	PERMEABILITY (cm/sec)	RETARDATION FACTOR	DISPERSION (m)
1 st Segment of Tunnel Fracture Zone	1200	3300	10^{-3}	10^{-6}	1	50
2 nd Segment of Tunnel Fracture Zone	440	198	10^{-3}	10^{-6}	1	50
Fracture Zone Around Shaft in Depository Layer	100	60	10^{-3}	10^{-6}	1	50
Fracture Zone Around Shaft in Shale Barrier Layer	200	5	10^{-3}	10^{-4}	1	50
Depository Layer	100	5×10^6	10^{-2}	10^{-9}	1	50
Barrier Layer	200	5×10^6	0.05	10^{-7}	1	50
Aquifer	1.6×10^4	4×10^5	0.1	10^{-4}	¹²⁹ I, ⁹⁹ Tc: Other Fission Products: 10^2 Actinides: 10^4	50

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TABLE H-3
BASELINE PARAMETERS FOR SHALE WITH FRACTURE FLOW
(TABLES I-5 AND I-6)

T-1553

PATHWAY	LENGTH (m)	CROSS SECTION (m ²)	EFFECTIVE POROSITY	PERMEABILITY (cm/sec)	RETARDATION FACTOR	DISPERSION (m)
Depository Layer	100	5×10^6	10^{-5}	10^{-8}	SAME	50
Barrier Layer	200	5×10^6	10^{-4}	10^{-6}	SAME	50

TABLE H-4
ADDITIONAL BASELINE PARAMETERS FOR FAILED BACKFILL CASES
(TABLES I-7 AND I-8)

T-1552

PATHWAY	LENGTH (m)	CROSS SECTION (m ²)	EFFECTIVE POROSITY	PERMEABILITY (cm/sec)	RETARDATION FACTOR	DISPERSION (m)
1 st Segment of Tunnel Backfill	1200	3100	10^{-2}	10^{-4}	¹²⁹ I, ⁹⁹ Tc: Other Fission Products: 10^2 Actinides: 10^4	50
2 nd Segment of Tunnel Backfill	440	150	10^{-2}	10^{-4}	SAME	50
Shaft Backfill	300	64	10^{-2}	10^{-4}	SAME	50

TABLE H-5
ADDITIONAL BASELINE PARAMETERS FOR CASES WITH FAILED BORING SEALS
(TABLES I-9 AND I-10)

T-1551

PATHWAY	LENGTH (m)	CROSS SECTION (m ²)	EFFECTIVE POROSITY	PERMEABILITY (cm/sec)	RETARDATION FACTOR	DISPERSION (m)
Borehole Path Less Than 500 Years	300	0.1	10^{-2}	10^{-4}	¹²⁹ I, ⁹⁹ Tc: Other Fission Products: 10^2 Actinides: 10^4	50
Borehole Path Between 500 and 1000 Years	300	0.3	10^{-2}	10^{-4}	SAME	50
Borehole Path After 1000 Years	300	0.5	10^{-2}	10^{-4}	SAME	50

TABLE H-6
BASELINE PARAMETERS FOR CASE WITH FAULT
(TABLE I-11)

T-1555

PATHWAY	LENGTH (m)	CROSS SECTION (m ²)	EFFECTIVE POROSITY	PERMEABILITY (cm/sec)	RETARDATION FACTOR	DISPERSION (m)
Change from Table H-1						
Depository Layer	100	4.9×10^6	0.05	10^{-8}	SAME	50
Barrier Layer	200	4.9×10^6	0.05	10^{-7}	SAME	50
Add						
*Fault Open in Barrier Layer	200	10^5	10^{-3}	10^{-4}	120. ⁹⁰ Tc: Other Fission Products: 10^2 Actinides: 10^4	50
Fault Closed in Barrier Layer	200	10^5	10^{-3}	10^{-6}	SAME	50
Fault Open in Depository Layer	100	10^5	10^{-3}	10^{-5}	SAME	50
Fault Closed in Depository Layer	100	10^5	10^{-3}	10^{-7}	SAME	50

*The probability of a fault is 5×10^{-7} per year

TABLE H-7
BASELINE PARAMETERS FOR CASE WITH BRECCIA PIPE
(TABLE I-12)

T-1556

PATHWAY	LENGTH (m)	CROSS SECTION (m ²)	EFFECTIVE POROSITY	PERMEABILITY (cm/sec)	RETARDATION FACTOR	DISPERSION (m)
Change from Table H-2						
Depository Layer	100	4.9×10^6	10^{-2}	10^{-9}	1	50
Barrier Layer	200	4.9×10^6	0.05	10^{-7}	1	50
Add:						
*Breccia Pipe	300	10^5	0.3	10^{-2}	1	50

*The probability of a breccia pipe formation is 5×10^{-7} per year.

TABLE H-8
PARAMETERS VARIED IN TABLE I-1

T-1582

RUN INDEX NUMBER	VARIED PARAMETER	BASELINE VALUE	NEW VALUE
(1)	Retardation Factor of Fission Products other than I and Te Retardation Factor of Actinides	10^2 10^4	1 10^2
(2)	Porosity of the Tunnel Fracture Zone Porosity of the Shaft Fracture Zone Porosity of the Depository Layer Porosity of the Barrier Layer Porosity of the Aquifer	10^{-1} 10^{-3} 5×10^{-2} 5×10^{-2} 10^{-1}	10^{-2} 10^{-4} 10^{-2} 10^{-2} 2×10^{-2}
(3)	Porosity of the Tunnel Fracture Zone Porosity of the Shaft Fracture Zone	10^{-1} 10^{-3}	10^{-2} 10^{-4}
(4)	Cross Section of the 1 st Segment of the Tunnel Fracture Zone (m^2) Cross Section of the 2 nd Segment of the Tunnel Fracture Zone (m^2) Permeability of the Tunnel Fracture Zone (cm/sec)	316 18.91 10^{-1}	580 34.8 10^{-4}
(5)	Cross Section of the 1 st Segment of the Tunnel Fracture Zone (m^2) Cross Section of the 2 nd Segment of the Tunnel Fracture Zone (m^2) Cross Section of the 1 st Segment of the Shaft Fracture Zone (m^2) Cross Section of the 2 nd Segment of the Shaft Fracture Zone (m^2)	316 18.91 10 5	785 47.1 100 100
(6)	Permeability of the Depository Layer (cm/sec) Permeability of the Barrier Layer (cm/sec)	10^{-9} 10^{-7}	10^{-7} 10^{-5}
(7)	Permeability of the Tunnel Fracture Zone (cm/sec) Permeability of the Shaft Fracture Zone (cm/sec)	10^{-1} 10^{-4}	1 10^{-3}

TABLE H-9
PARAMETERS VARIED IN TABLE I-2

T-1583

RUN INDEX NUMBER	VARIED PARAMETER	BASELINE VALUE	NEW VALUE
(1)	Permeability of the Tunnel Fracture Zone (cm/sec) Permeability of the Shaft Fracture Zone (cm/sec) Permeability of the Aquifer (cm/sec)	10^{-1} 10^{-4} 10^{-4}	1 10^{-3} 10^{-2}
(2)	Permeability of the Tunnel Fracture Zone (cm/sec) Permeability of the Shaft Fracture Zone (cm/sec) Permeability of the Aquifer (cm/sec) Actinide Retardation Factor	10^{-1} 10^{-4} 10^{-4} 10^4	1 10^{-3} 10^{-2} 10^2
(3)	Permeability of the Aquifer (cm/sec) Permeability of the Depository Layer (cm/sec) Permeability of the Barrier Layer (cm/sec)	10^{-4} 10^{-9} 10^{-7}	10^{-2} 10^{-7} 10^{-5}
(4)	Permeability of the Tunnel Fracture Zone (cm/sec) Permeability of the Shaft Fracture Zone (cm/sec) Permeability of the Aquifer (cm/sec) Permeability of the Depository Layer (cm/sec) Permeability of the Barrier Layer (cm/sec)	10^{-1} 10^{-4} 10^{-4} 10^{-9} 10^{-7}	1 10^{-3} 10^{-2} 10^{-7} 10^{-5}
(5)	Permeability of the Shaft Fracture Zone (cm/sec) Permeability of the Aquifer (cm/sec) Porosity of the Tunnel Fracture Zone	10^{-4} 10^{-4} 10^{-1}	10^{-3} 10^{-2} 10^{-2}
(6)	Permeability of the Aquifer (cm/sec) Permeability of the Depository Layer (cm/sec) Permeability of the Barrier Layer (cm/sec)	10^{-4} 10^{-9} 10^{-7}	10^{-2} 10^{-11} 10^{-9}

TABLE H-10
PARAMETERS VARIED IN TABLE I-3

T-1564

RUN INDEX NUMBER	VARIED PARAMETER	BASELINE VALUE	NEW VALUE
(1)	Retardation Factor of Fission Products (Except I, Tc) in Aquifer Retardation Factor of Actinides in Aquifer	10^2 10^4	1 10^2
(2)	Porosity of the Tunnel and Shaft Fracture Zone Porosity of the Depository Layer Porosity of the Barrier Layer	10^{-3} 10^{-2} 5×10^{-2}	10^{-4} 4×10^{-3} 10^{-2}
(3)	Porosity of the Depository Layer Porosity of the Barrier Layer	10^{-2} 5×10^{-2}	4×10^{-3} 10^{-2}
(4)	Porosity of the Tunnel and Shaft Fracture Zone	10^{-3}	10^{-4}
(5)	Cross Section of the 1st Segment of the Tunnel Fracture Zone (m^2) Cross Section of the 2nd Segment of the Tunnel Fracture Zone (m^2)	3.3×10^3 198	190 11.4
(6)	Cross Section of the 1st Segment of the Tunnel Fracture Zone (m^2) Cross Section of the 2nd Segment of the Tunnel Fracture Zone (m^2) Cross Section of the 1st Segment of the Shaft Fracture Zone (m^2) Cross Section of the 2nd Segment of the Shaft Fracture Zone (m^2)	3.3×10^3 198 60 5	6.4×10^3 384 110 100
(7)	Permeability of the Depository Layer (cm/sec) Permeability of the Barrier Layer (cm/sec)	10^{-9} 10^{-7}	10^{-7} 10^{-5}
(8)	Permeability of the Depository Layer (cm/sec) Permeability of the Barrier Layer (cm/sec)	10^{-9} 10^{-7}	10^{-5} 10^{-5}
(9)	Permeability of the Shaft Fracture Zone (cm/sec) Permeability of the Tunnel Fracture Zone (cm/sec)	10^{-6} 10^{-6}	10^{-5} 10^{-5}

TABLE H-11
PARAMETERS VARIED IN TABLE I-4

T-1568

RUN INDEX NUMBER	VARIED PARAMETER	BASELINE VALUE	NEW VALUE
(1)	Permeability of the Aquifer (cm/sec) Permeability of the Depository Layer (cm/sec) Permeability of the Barrier Layer (cm/sec)	10^{-4} 10^{-9} 10^{-7}	10^{-2} 10^{-5} 10^{-5}
(2)	Permeability of the Shaft Fracture Zone (cm/sec) Porosity of the Tunnel Fracture Zone Permeability of the Aquifer (cm/sec)	10^{-6} 10^{-3} 10^{-4}	10^{-5} 10^{-4} 10^{-2}
(3)	Permeability of the Shaft Fracture Zone (cm/sec) Permeability of the Tunnel Fracture Zone (cm/sec) Permeability of the Aquifer (cm/sec)	10^{-6} 10^{-6} 10^{-4}	10^{-6} 10^{-5} 10^{-2}
(4)	Permeability of the Shaft Fracture Zone (cm/sec) Permeability of the Tunnel Fracture Zone (cm/sec) Permeability of the Depository Layer (cm/sec) Permeability of the Barrier Layer (cm/sec) Permeability of the Aquifer (cm/sec)	10^{-6} 10^{-6} 10^{-9} 10^{-7} 10^{-4}	10^{-5} 10^{-5} 10^{-5} 10^{-5} 10^{-2}

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TABLE H-12
PARAMETERS VARIED IN TABLE I-5

T-1565

RUN INDEX NUMBER	VARIED PARAMETER	BASELINE VALUE	NEW VALUE
(1)	Aquifer Length (m) Head Gradient	1.6×10^4 5×10^{-3}	1.6×10^3 5×10^{-2}
(2)	Permeability of the Aquifer (cm/sec) Actinide Retardation Factor	10^{-4} 10^4	10^{-2} 10^2
(3)	Permeability of the Aquifer (cm/sec) Actinide Retardation Factor Leach Rate (yr ⁻¹)	10^{-4} 10^4 10^{-4}	10^{-2} 10^2 10^{-1}

TABLE H-13
PARAMETERS VARIED IN TABLE I-7

T-1566

RUN INDEX NUMBER	VARIED PARAMETER	BASELINE VALUE	NEW VALUE
(1)	Permeability of Backfill in the Tunnel (cm/sec) Permeability of Backfill in the Shaft (cm/sec) Porosity of Backfill in the Shaft and T.	10^{-4} 10^{-4} 10^{-2}	10^{-3} 10^{-3} 10^{-1}
(2)	Permeability of Backfill in the Tunnel (cm/sec) Permeability of Backfill in the Shaft (cm/sec) Porosity of Backfill in the Shaft and Tunnel	10^{-4} 10^{-4} 10^{-2}	10^{-3} 10^{-6} 10^{-1}
(3)	Permeability of Backfill in the Tunnel (cm/sec) Permeability of Backfill in the Shaft (cm/sec) Porosity of Backfill in the Shaft and Tunnel	10^{-4} 10^{-4} 10^{-2}	10^{-1} 10^{-6} 10^{-1}

TABLE H-14
PARAMETERS VARIED IN TABLE I-8

T-1567

RUN INDEX NUMBER	VARIED PARAMETER	BASELINE VALUE	NEW VALUE
(1)	Permeability of Backfill in the Tunnel (cm/sec) Permeability of Backfill in the Shaft (cm/sec) Porosity of Backfill in the Shaft and Tunnel	10^{-4} 10^{-4} 10^{-2}	10^{-3} 10^{-3} 10^{-1}
(2)	Permeability of Backfill in the Tunnel (cm/sec) Permeability of Backfill in the Shaft (cm/sec) Porosity of Backfill in the Shaft and Tunnel	10^{-4} 10^{-4} 10^{-2}	10^{-3} 10^{-6} 10^{-1}
(3)	Permeability of Backfill in the Tunnel (cm/sec) Permeability of Backfill in the Shaft (cm/sec) Porosity of Backfill in the Shaft and Tunnel	10^{-4} 10^{-4} 10^{-2}	10^{-1} 10^{-6} 10^{-1}
(4)	Permeability of Backfill in the Tunnel (cm/sec) Permeability of Backfill in the Shaft (cm/sec) Porosity of Backfill in the Shaft and Tunnel	10^{-4} 10^{-4} 10^{-2}	10^{-1} 10^{-1} 10^{-1}

TABLE H-15
CROSS-REFERENCING INDEX TO TABLES

T-1569

RESULTS	FLOW PATHWAYS (FIGURE)	BASELINE PARAMETER VALUES	INPUTS TO SENSITIVITY ANALYSIS
I-1	H-1	H-1	H-8
I-2	H-1	H-1	H-9
I-3	H-1	H-2	H-10
I-4	H-1	H-2	H-11
I-5	H-1	H-1, H-3	H-12
I-6	H-1	H-2, H-3	--
I-7	H-2	H-1, H-4	H-13
I-8	H-2	H-2, H-4	H-14
I-9	H-3	H-1, H-5	--
I-10	H-3	H-2, H-5	--
I-11	H-4	H-1, H-6	--
I-12	H-4	H-2, H-7	--

REFERENCES

- H.1 "Documentation Information for Peer Group Review Report-Site Suitability Criteria Study," Golder Associates, Inc., Lawrence Livermore Laboratory Report No. WM77-525, October 1977.
- H.2 "Final Report on Geological Studies Pertinent to Site Suitability Criteria for High Level Waste Repositories," Geotechnical Engineers, Inc., U.S.D.O.E. Report No. UCRL-13741, May, 1977, and "Final Report on Geologic Studies Pertinent to Site Selection Criteria for High Level Waste Repositories - Phase 2," Geotechnical Engineers, Inc., U.S.D.O.E. Report No. UCRL-13741-2, July, 1977.
- H.3 Holdsworth, T., Towse, D.F., Isherwood, D., Harvey, T., and Heckman, R.A., "Site Suitability Criteria for Solidified High Level Waste Repositories" (Draft), Lawrence Livermore Laboratory, in press.
- H.4 Bell, M.T., "ORIGEN - The ORNL Isotope Generation and Depletion Code," Oak Ridge National Laboratory, ORNL-4628, 1973.
- H.5 Cohen, J.J., et al, "Determination of Performance Criteria for High Level Nuclear Waste," Lawrence Livermore Laboratory, NUREG-0279, July 1977.

APPENDIX I
TABLES OF SENSITIVITY

Tables I-1 through I-12 summarize the results of the sensitivity analyses conducted on generic bedded salt and shale repositories with an overlying aquifer and an underlying aquifer under pressure.

Five different baseline cases were defined for the sensitivity analysis of each repository, corresponding to the following situations:

- An unflawed repository (except for the fracture zone caused by construction) with interstitial flow in the undisturbed portion of all strata
- An unflawed repository with fracture flow in shale (for the salt repository, this refers to a shale barrier layer)
- A repository with deteriorated backfill
- A repository with failed boring seals
- A repository in which breccia pipe formation (in the salt case) or fault movement (in the shale case) may occur.

The first row of each table gives results for one of the baseline cases. In the baseline cases, all parameters assume their preferred values. The subsequent rows present cases in which one or more parameters have been varied from the baseline value in the direction of poorer performance. If space permits, the values of the parameters being varied are given in the first two columns of the table. Otherwise,

a reference number is given and the values may be found in the appropriate table of Appendix H.

For each case analyzed, the integrated population dose and the peak 50 year dose to an individual eating an average diet are given for both the whole body and the critical organ. The time of occurrence of peak doses is also given. For cases in which geologic state transitions do not occur, peak concentrations of ^{99}Tc , ^{126}Sn , ^{226}Ra , and ^{239}Pu in the aquifer are also given with the time of occurrence of the peak. Concentrations were not calculated beyond three million years; therefore peak concentrations are omitted from the table when the peak occurs beyond three million years.

Assumptions of Tables I-1 and I-2 - Tables I-1 and I-2 describe a shale repository with flow paths to the aquifer through a fracture zone surrounding the tunnel and shaft and through the two overlying layers of shale. It is assumed that the flow through the shale is interstitial flow. Flow pathways are shown in Fig. H-1 and baseline parameter values are given in Table H-1. Changes in parameters varied in sensitivity analysis, when not shown, are listed in Tables H-8 and H-9.

Assumptions of Tables I-3 and I-4 - Tables I-3 and I-4 describe a bedded salt repository with flow paths to the aquifer through a fracture zone surrounding the tunnel and shaft and through the overlying salt and shale layers. It is assumed that the flow through both the salt and a shale barrier layer is interstitial flow. Flow pathways are shown in Fig. H-1 and baseline parameter values are given in Table H-2. Changes in parameters varied in sensitivity analysis, when not shown, are listed in Tables H-10 and H-11.

TABLE I-1
SHALE REPOSITORY SENSITIVITY ANALYSIS
(INTERSTITIAL FLOW)

T-1578

VARIABLE PARAMETER	BASELINE VALUE	NEW VALUE	INTEGRATED POPULATION DOSE (MAN-REM/MW-YR)			PEAK INDIVIDUAL DOSE (REM/MW-YR)				
			WHOLE BODY DOSE	CRITICAL ORGAN DOSE	CRITICAL ORGAN	WHOLE BODY DOSE	TIME	CRITICAL ORGAN DOSE	TIME	CRITICAL ORGAN
BASELINE	-	-	1.30 E-3	1.60 E-1	GI-LLI	6.18 E-14	1.44 E 4	7.48 E-12	1.44 E 4	GI-LLI
ACTINIDE & FISSION PRODUCT SORPTION FACTORS	(1)		8.86 E-2	3.56 E-1	GI-LLI	2.78 E-12	1.24 E 6	2.21 E-11	1.44 E 4	GI-LLI
DISPERSION	50	10	1.53 E-3	1.80 E-1	GI-LLI	1.07 E-12	1.74 E 5	1.30 E-11	1.74 E 5	GI-LLI
LOW POROSITY EVERYWHERE	(2)		2.36 E-3	2.89 E-1	GI-LLI	2.94 E-13	4.52 E 4	3.58 E-11	4.52 E 4	GI-LLI
LOW POROSITY IN AQUIFER	0.1	0.02	1.35 E-3	1.65 E-1	GI-LLI	6.55 E-14	5.99 E 3	7.93 E-12	5.99 E 3	GI-LLI
POROSITY IN SHAPE	0.05	0.01	2.23 E-3	2.74 E-1	GI-LLI	2.94 E-13	5.85 E 4	3.56 E-11	5.85 E 4	GI-LLI
LOW POROSITY IN SHAFT & TUNNEL FRACTURE ZONE	(3)		1.30 E-3	1.60 E-1	GI-LLI	6.53 E-14	1.17 E 4	7.91 E-12	1.17 E 4	GI-LLI
FAST SATURATION	100	20	1.30 E-3	1.60 E-1	GI-LLI	6.19 E-14	1.44 E 4	7.48 E-12	1.44 E 4	GI-LLI
MIN. AREA FRACTURE ZONE IN TUNNEL	(4)		1.29 E-3	1.59 E-1	GI-LLI	6.9 E-14	1.17 E 4	7.91 E-12	1.17 E 4	GI-LLI
MAX. AREA FRACTURE ZONE IN SHAFT AND TUNNEL	(5)		1.32 E-3	2.47 E-1	GI-LLI	7.45 E-13	1.17 E 4	9.85 E-11	1.17 E 4	GI-LLI
SHAPE PERMEABILITY	(6)		2.73 E-3	4.14 E-1	GI-LLI	1.58 E-12	1.57 E 4	1.83 E-10	1.52 E 4	GI-LLI
ARTESIAN HEAD	60	150	1.83 E-3	2.37 E-1	GI-LLI	1.42 E-13	9.85 E 4	1.71 E-11	9.85 E 4	GI-LLI
AQUIFER PERMEABILITY	10 ⁻⁴	10 ⁻²	1.39 E-3	1.87 E-1	GI-LLI	6.37 E-14	3.86 E 3	7.95 E-12	3.86 E 3	GI-LLI
FRACTURE ZONE PERMEABILITY	(7)		1.60 E-3	2.23 E-1	GI-LLI	5.82 E-13	1.17 E 4	6.80 E-11	1.17 E 4	GI-LLI
HEAD GRADIENT IN AQUIFER	0.005	0.05	1.37 E-3	1.66 E-1	GI-LLI	6.84 E-14	4.87 E 3	8.04 E-12	4.87 E 3	GI-LLI
THICKNESS OF DEPOSITORY LAYER	200	20	2.44 E-3	3.12 E-1	GI-LLI	9.35 E-13	3.31 E 4	6.48 E-11	3.31 E 4	GI-LLI
THICKNESS OF BARRIER LAYER	200	20	1.76 E-3	2.35 E-1	GI-LLI	2.43 E-13	1.24 E 4	2.94 E-11	1.24 E 4	GI-LLI
LENGTH OF TUNNEL (INCREASE)	400	6000	1.30 E-3	1.60 E-1	GI-LLI	8.22 E-14	1.52 E 4	7.52 E-12	1.52 E 4	GI-LLI
LENGTH OF TUNNEL	440	200	1.30 E-3	1.60 E-1	GI-LLI	6.19 E-14	1.45 E 4	7.49 E-12	1.45 E 4	GI-LLI
DISSOLUTION RATE OF WASTE	10 ⁻⁴	0.1	1.34 E-3	1.65 E-1	GI-LLI	2.95 E-13	1.23 E 4	3.57 E-11	1.23 E 4	GI-LLI
FISSION PRODUCT SORPTION FACTORS	10 ²	1	3.38 E-3	3.08 E-1	GI-LLI	6.52 E-13	1.12 E 4	2.30 E-11	1.12 E 4	GI-LLI
ACTINIDE SORPTION FACTORS	10 ⁴	10 ²	8.78 E-2	8.78 E-2	WHOLE BODY	2.78 E-12	1.24 E 6	3.91 E-11	1.24 E 6	BONE
AQUIFER LENGTH	1.6 E 4	1.6 E 3	1.37 E-3	1.65 E-1	GI-LLI	6.92 E-14	6.19 E 3	7.89 E-12	5.19 E 3	GI-LLI

TABLE I-1
SHALE REPOSITORY SENSITIVITY ANALYSIS
(INTERSTITIAL FLOW) (CONTINUED)

T-1578a

VARIABLE PARAMETER	PEAK AQUIFER CONCENTRATION ($\text{GCM}^{-3} \cdot \text{MM}^{-3} \cdot \text{YR}$)							
	10^{-10}		10^{-11}		10^{-12}		10^{-13}	
	CONCENTRATION	TIME	CONCENTRATION	TIME	CONCENTRATION	TIME	CONCENTRATION	TIME
BASELINE	$2.02 \text{ E } -11$	$3.96 \text{ E } 3$	$1.31 \text{ E } -14$	$2.14 \text{ E } 5$	-	-	-	-
ACTINIDE & FISSION PRODUCT SORPTION FACTORS	$2.02 \text{ E } -11$	$3.96 \text{ E } 3$	$7.50 \text{ E } -13$	$3.75 \text{ E } 3$	$2.23 \text{ E } -15$	$2.25 \text{ E } 5$	$1.26 \text{ E } -14$	$1.65 \text{ E } 5$
DISPERSION	$3.44 \text{ E } -11$	$1.65 \text{ E } 5$	$2.80 \text{ E } -14$	$2.37 \text{ E } 5$	-	-	-	-
LOW POROSITY EVERYWHERE	$9.13 \text{ E } -11$	$4.29 \text{ E } 4$	$3.07 \text{ E } -13$	$2.83 \text{ E } 4$	$2.07 \text{ E } -17$	$1.79 \text{ E } 6$	$8.25 \text{ E } -18$	$2.20 \text{ E } 6$
LOW POROSITY IN AQUIFER	$2.02 \text{ E } -11$	$3.96 \text{ E } 3$	$1.30 \text{ E } -14$	$2.14 \text{ E } 5$	-	-	-	-
POROSITY IN SHAPE	$5.13 \text{ E } -11$	$4.29 \text{ E } 4$	$1.30 \text{ E } -14$	$2.14 \text{ E } 5$	-	-	-	-
LOW POROSITY IN SHAFT & TUNNEL FRACTURE ZONE	$2.37 \text{ E } -11$	$5.82 \text{ E } 2$	$3.07 \text{ E } -13$	$2.83 \text{ E } 4$	$2.07 \text{ E } -17$	$1.79 \text{ E } 6$	$2.44 \text{ E } -21$	$2.20 \text{ E } 6$
FAST SATURATION	$2.02 \text{ E } -11$	$3.96 \text{ E } 3$	$1.31 \text{ E } -14$	$2.14 \text{ E } 5$	-	-	-	-
MINIMUM AREA FRACTURE ZONE IN TUNNEL	$2.15 \text{ E } -11$	$2.18 \text{ E } 2$	$5.67 \text{ E } -13$	$7.37 \text{ E } 3$	$8.22 \text{ E } -16$	$4.85 \text{ E } 5$	$4.81 \text{ E } -15$	$3.78 \text{ E } 5$
MAXIMUM AREA FRACTURE ZONE IN SHAFT AND TUNNEL	$2.68 \text{ E } -10$	$9.28 \text{ E } 2$	$2.18 \text{ E } -12$	$4.52 \text{ E } 4$	-	-	-	-
SHALE PERMEABILITY	$5.04 \text{ E } -10$	$4.82 \text{ E } 3$	$3.45 \text{ E } -13$	$1.41 \text{ E } 5$	-	-	-	-
ARTESIAN HEAD	$4.45 \text{ E } -11$	$7.99 \text{ E } 4$	$7.4 \text{ E } -14$	$5.33 \text{ E } 4$	-	-	-	-
AQUIFER PERMEABILITY	$2.02 \text{ E } -13$	$3.86 \text{ E } 3$	$1.30 \text{ E } -16$	$2.14 \text{ E } 5$	-	-	-	-
FRACTURE ZONE PERMEABILITY	$2.04 \text{ E } -10$	$5.82 \text{ E } 2$	$2.84 \text{ E } -12$	$2.83 \text{ E } 4$	$1.73 \text{ E } -16$	$1.79 \text{ E } 6$	$8.88 \text{ E } -18$	$1.98 \text{ E } 6$
HEAD GRADIENT IN AQUIFER	$2.02 \text{ E } -12$	$3.96 \text{ E } 3$	$1.30 \text{ E } -15$	$2.14 \text{ E } 5$	-	-	-	-
THICKNESS OF DEPOSITORY LAYER	$1.74 \text{ E } -10$	$2.43 \text{ E } 4$	$1.71 \text{ E } -15$	$2.25 \text{ E } 5$	-	-	-	-
THICKNESS OF BARRIER LAYER	$6.58 \text{ E } -11$	$1.20 \text{ E } 3$	$4.91 \text{ E } -13$	$5.16 \text{ E } 4$	-	-	-	-
LENGTH OF TUNNEL (INCREASE)	$2.05 \text{ E } -11$	$4.97 \text{ E } 3$	$1.08 \text{ E } -14$	$2.77 \text{ E } 5$	-	-	-	-
LENGTH OF TUNNEL	$2.02 \text{ E } -11$	$3.96 \text{ E } 3$	$1.32 \text{ E } -14$	$2.14 \text{ E } 5$	-	-	-	-
DISSOLUTION RATE OF WASTE	$1.48 \text{ E } -10$	$2.24 \text{ E } 3$	$1.40 \text{ E } -14$	$1.83 \text{ E } 5$	-	-	-	-
FISSION PRODUCT SORPTION FACTORS	$2.02 \text{ E } -11$	$3.96 \text{ E } 3$	$7.50 \text{ E } -13$	$3.75 \text{ E } 3$	-	-	-	-
ACTINIDE SORPTION FACTORS	$2.02 \text{ E } -11$	$3.96 \text{ E } 3$	$1.30 \text{ E } -14$	$2.14 \text{ E } 5$	$2.23 \text{ E } -15$	$2.25 \text{ E } 5$	$1.26 \text{ E } -14$	$1.65 \text{ E } 5$
AQUIFER LENGTH	$2.02 \text{ E } -11$	$3.96 \text{ E } 3$	$1.30 \text{ E } -14$	$2.14 \text{ E } 5$	-	-	-	-

TABLE I-2
SHALE REPOSITORY SENSITIVITY ANALYSIS - MULTIPLE PARAMETER
(INTERSTITIAL FLOW)

T-1579

VARIABLE PARAMETER	INTEGRATED POPULATION DOSE (MAN-REM/MW-YR)			PEAK INDIVIDUAL DOSE (REM/MW-YR)				
	WHOLE BODY DOSE	CRITICAL ORGAN DOSE	CRITICAL ORGAN	WHOLE BODY DOSE	TIME	CRITICAL ORGAN DOSE	TIME	CRITICAL ORGAN
BASILINE	1.30 E-3	1.80 E-1	GI-LLI	6.19 E-14	1.44 E 4	7.48 E-12	1.44 E 4	GI-LLI
PERMEABILITY OF FRACTURE ZONE AND AQUIFER (1)	1.07 E-1	3.4 E-1	GI-LLI	2.17 E-12	3.87 E 4	6.54 E-11	3.87 E 4	GI-LLI
PERMEABILITY OF FRACTURE ZONE & AQUIFER AND ACTINIDE SORPTION FACTOR (2)	1.75	1.75	WHOLE BODY	4.49 E-10	4.07 E 4	4.49 E-10	4.07 E 4	WHOLE BODY
SHALE AND AQUIFER PERMEABILITY (3)	4.66 E-3	4.78 E-1	GI-LLI	1.84 E-12	2.59 E 2	1.89 E-10	2.59 E 2	GI-LLI
PERMEABILITY EVERYWHERE (4)	6.55 E-3	4.78 E-1	GI-LLI	1.84 E-12	4.87 E 3	1.96 E-10	4.87 E 3	GI-LLI
SHAFT FRACTURE ZONE AND AQUIFER PERMEABILITY AND TUNNEL FRACTURE ZONE POROSITY (5)	6.80 E-1	8.80 E-1	WHOLE BODY	2.12 E-11	1.24 E 6	1.40 E-10	1.45 E 4	GI-LLI
REDUCED SHALE PERMEABILITY AND INCREASED AQUIFER PERMEABILITY (6)	2.47 E-3	1.63 E-1	GI-LLI	1.27 E-12	8.6 E 2	1.53 E-10	8.5 E 3	GI-LLI

T-1579a

VARIABLE PARAMETER	PEAK AQUIFER CONCENTRATION ($\mu\text{Ci}/\text{cm}^3$ -MW-YR)							
	^{99}Tc		^{129}I		^{235}Pu		^{239}Pu	
	CONCENTRATION	TIME	CONCENTRATION	TIME	CONCENTRATION	TIME	CONCENTRATION	TIME
BASILINE	2.02 E-11	4.00 E 3	1.31 E-14	2.14 E 5	-	-	-	-
PERMEABILITY OF FRACTURE ZONE AND AQUIFER	2.04 E-12	5.82 E 2	2.64 E-14	2.83 E 4	1.72 E-16	1.78 E 6	2.21 E-22	1.98 E 5
PERMEABILITY OF FRACTURE ZONE AND AQUIFER AND ACTINIDE SORPTION FACTOR	2.94 E-12	5.82 E 2	2.64 E-14	2.83 E 4	5.42 E-16	3.14 E 4	1.26 E-13	2.69 E 4
SHALE AND AQUIFER PERMEABILITY	5.04 E-12	4.62 E 3	3.45 E-15	1.47 E 5	-	-	-	-
PERMEABILITY EVERYWHERE	5.02 E-12	4.87 E 3	3.29 E-15	1.41 E 5	3.44 E-20	1.61 E 6	3.04 E-24	1.98 E 6
SHAFT FRACTURE ZONE AND AQUIFER PERMEABILITY AND TUNNEL FRACTURE ZONE POROSITY	1.97 E-12	5.25 E 2	5.86 E-14	4.17 E 2	1.54 E-16	2.88 E 5	5.13 E-16	1.83 E 5
REDUCED SHALE PERMEABILITY AND INCREASED AQUIFER PERMEABILITY	3.80 E-12	9.01 E 3	2.72 E-16	4.18 E 5	-	-	-	-

TABLE I-3
SALT REPOSITORY SENSITIVITY ANALYSIS
(INTERSTITIAL FLOW)

T-1580

VARIABLE PARAMETER	BASELINE VALUE	NEW VALUE	INTEGRATED POPULATION DOSE (MAN-REM/MW-YR)			PEAK INDIVIDUAL DOSE (REM/MW-YR)				
			WHOLE BODY DOSE	CRITICAL ORGAN DOSE	CRITICAL ORGAN	WHOLE BODY DOSE	TIME	CRITICAL ORGAN DOSE	TIME	CRITICAL ORGAN
BASISLINE	-	-	1.63 E-3	2.81 E-1	GI-LLI	8.15 E-14	1.49 E 5	8.86 E-12	1.49 E 5	GI-LLI
ACTINIDE & FISSION PRODUCT SORPTION FACTOR	(1)		2.61	2.61	WHOLE BODY	7.48 E-11	1.12 E 6	7.48 E-11	1.12 E 6	WHOLE BODY
DISPERSION	50	10	1.83 E-3	3.14 E-1	GI-LLI	1.70 E-13	1.27 E 5	2.06 E-11	1.27 E 5	GI-LLI
LOW POROSITY EVERYWHERE	(2)		4.19 E-3	4.36 E-1	GI-LLI	4.05 E-13	3.67 E 4	4.80 E-11	3.67 E 4	GI-LLI
LOW POROSITY IN ROCK	(3)		2.37 E-3	3.82 E-1	GI-LLI	3.87 E-13	4.61 E 4	4.68 E-11	4.52 E 4	GI-LLI
LOW POROSITY IN SHAFT & TUNNEL FRACTURE ZONE	(4)		1.63 E-3	2.81 E-1	GI-LLI	8.15 E-14	1.49 E 5	8.86 E-12	1.49 E 5	GI-LLI
MINIMUM AREA FRACTURE ZONE IN TUNNEL	(5)		1.63 E-3	2.81 E-1	GI-LLI	8.21 E-14	1.15 E 5	9.83 E-12	1.15 E 5	GI-LLI
MAXIMUM AREA FRACTURE ZONE IN SHAFT AND TUNNEL	(6)		1.84 E-3	2.87 E-1	GI-LLI	8.08 E-14	1.15 E 5	9.77 E-12	1.15 E 5	GI-LLI
SALT PERMEABILITY	10 ⁻⁵	10 ⁻⁵	2.78 E-3	4.28 E-1	GI-LLI	1.46 E-12	1.60 E 4	1.77 E-10	1.60 E 4	GI-LLI
ROCK PERMEABILITY MODERATELY PERMEABLE SALT	(7)		2.78 E-3	4.31 E-1	GI-LLI	1.88 E-12	1.37 E 4	2.03 E-10	1.37 E 4	GI-LLI
ROCK PERMEABILITY EXTREMELY PERMEABLE SALT	(8)		2.77 E-3	4.32 E-1	GI-LLI	1.85 E-12	1.17 E 4	2.87 E-10	1.17 E 4	GI-LLI
ARTESIAN HEAD	60	150	2.17 E-3	3.57 E-1	GI-LLI	2.28 E-13	6.85 E 4	2.78 E-11	5.85 E 4	GI-LLI
AQUIFER PERMEABILITY	10 ⁻⁴	10 ⁻²	2.61	2.61	WHOLE BODY	7.48 E-11	1.12 E 6	7.48 E-11	1.12 E 6	WHOLE BODY
FRACTURE ZONE PERMEABILITY	(9)		1.66 E-3	2.90 E-1	GI-LLI	7.88 E-14	1.17 E 4	9.56 E-12	1.17 E 4	GI-LLI
THICKNESS OF DEPOSITORY LAYER	200	20	2.56 E-3	4.06 E-1	GI-LLI	6.53 E-13	2.99 E 4	7.80 E-11	2.89 E 4	GI-LLI
THICKNESS OF BARRIER LAYER	200	20	2.13 E-3	3.52 E-1	GI-LLI	1.97 E-13	4.76 E 4	2.38 E-11	4.76 E 4	GI-LLI
LENGTH OF TUNNEL (INCREASE)	440	6000	1.83 E-3	2.86 E-1	GI-LLI	8.20 E-14	1.15 E 5	9.92 E-12	1.15 E 5	GI-LLI
LENGTH OF TUNNEL	440	200	1.84 E-3	2.87 E-1	GI-LLI	8.12 E-14	1.15 E 5	9.83 E-12	1.15 E 5	GI-LLI
DISSOLUTION RATE OF WASTE	10 ⁻⁴	0.1	1.88 E-3	2.93 E-1	GI-LLI	8.57 E-14	1.08 E 5	1.04 E-11	1.08 E 5	GI-LLI
FISSION PRODUCT SORPTION FACTORS	10 ⁻²	1	4.45 E-3	3.57 E-1	GI-LLI	6.72 E-13	1.08 E 6	3.51 E-11	1.21 E 5	GI-LLI
ACTINIDE SORPTION FACTORS	10 ⁻⁴	10 ⁻²	2.61	2.61	WHOLE BODY	7.48 E-11	1.12 E 6	7.48 E-11	1.12 E 6	WHOLE BODY
AQUIFER LENGTH	1.6 E 4	1.6 E 3	3.28 E-3	3.42 E-1	GI-LLI	2.87 E-13	2.14 E 5	2.96 E-11	2.14 E 5	GI-LLI

TABLE I-3
SALT REPOSITORY SENSITIVITY ANALYSIS
(INTERSTITIAL FLOW) (CONTINUED)

T-1580a

VARIABLE PARAMETER	PEAK AQUIFER CONCENTRATION ($\text{GUM}^{-2}\text{MM}^{-3}\text{YR}^{-1}$)							
	99%		17%		22%		23%	
	CONCENTRATION	TIME	CONCENTRATION	TIME	CONCENTRATION	TIME	CONCENTRATION	TIME
BASISLINE	$2.58 \text{ E } -11$	$1.04 \text{ E } 5$	$7.04 \text{ E } -13$	$1.04 \text{ E } 5$	$5.67 \text{ E } -14$	$1.15 \text{ E } 5$	$1.04 \text{ E } -12$	$8.41 \text{ E } 4$
ACTINIDE & FISSION PRODUCT SORPTION FACTOR	$2.58 \text{ E } -11$	$1.04 \text{ E } 5$	$7.04 \text{ E } -13$	$1.04 \text{ E } 5$	$5.67 \text{ E } -14$	$1.15 \text{ E } 5$	$1.04 \text{ E } -12$	$8.41 \text{ E } 4$
DISPERSION	$5.40 \text{ E } -11$	$1.21 \text{ E } 5$	$1.42 \text{ E } -12$	$1.15 \text{ E } 5$	$1.22 \text{ E } -13$	$1.21 \text{ E } 5$	$2.62 \text{ E } -12$	$1.15 \text{ E } 5$
LOW POROSITY EVERYWHERE	$1.36 \text{ E } -10$	$2.48 \text{ E } 4$	$4.18 \text{ E } -12$	$3.31 \text{ E } 4$	$1.20 \text{ E } -13$	$4.52 \text{ E } 4$	$1.84 \text{ E } -11$	$3.14 \text{ E } 4$
LOW POROSITY IN ROCK	$1.26 \text{ E } -10$	$3.48 \text{ E } 4$	$4.18 \text{ E } -12$	$3.31 \text{ E } 4$	$1.20 \text{ E } -12$	$4.52 \text{ E } 4$	$1.84 \text{ E } -11$	$3.14 \text{ E } 4$
LOW POROSITY IN SHAFT & TUNNEL FRACTURE ZONE	$2.58 \text{ E } -11$	$1.04 \text{ E } 5$	$7.04 \text{ E } -13$	$1.04 \text{ E } 5$	$5.67 \text{ E } -14$	$1.15 \text{ E } 5$	$1.84 \text{ E } -12$	$8.41 \text{ E } 4$
MINIMUM AREA FRACTURE ZONE IN TUNNEL	$2.80 \text{ E } -11$	$1.09 \text{ E } 5$	$7.08 \text{ E } -13$	$1.04 \text{ E } 5$	$5.70 \text{ E } -14$	$1.15 \text{ E } 5$	$1.84 \text{ E } -12$	$7.99 \text{ E } 4$
MAXIMUM AREA FRACTURE ZONE IN SHAFT AND TUNNEL	$2.56 \text{ E } -11$	$1.09 \text{ E } 5$	$5.97 \text{ E } -13$	$1.04 \text{ E } 5$	$5.62 \text{ E } -14$	$1.15 \text{ E } 5$	$1.87 \text{ E } -12$	$8.41 \text{ E } 4$
SALT PERMEABILITY	$4.57 \text{ E } -10$	$5.08 \text{ E } 3$	$1.60 \text{ E } -11$	$5.89 \text{ E } 3$	$7.51 \text{ E } -14$	$1.24 \text{ E } 4$	$1.13 \text{ E } -10$	$7.27 \text{ E } 3$
ROCK PERMEABILITY	$5.33 \text{ E } -10$	$3.57 \text{ E } 3$	$2.00 \text{ E } -11$	$3.39 \text{ E } 3$	$6.21 \text{ E } -14$	$1.06 \text{ E } 4$	$1.13 \text{ E } -10$	$4.87 \text{ E } 3$
EXTREMELY PERMEABLE SALT	$7.10 \text{ E } -10$	$2.68 \text{ E } 3$	$2.74 \text{ E } -11$	$2.68 \text{ E } 3$	$5.17 \text{ E } -14$	$1.17 \text{ E } 4$	$1.07 \text{ E } -10$	$1.73 \text{ E } 3$
ARTESIAN HEAD	$6.89 \text{ E } -11$	$5.29 \text{ E } 4$	$2.26 \text{ E } -12$	$5.01 \text{ E } 4$	$9.89 \text{ E } -14$	$6.13 \text{ E } 4$	$8.51 \text{ E } -12$	$4.07 \text{ E } 4$
AQUIFER PERMEABILITY	$2.58 \text{ E } -10$	$1.09 \text{ E } 5$	$7.04 \text{ E } -13$	$1.04 \text{ E } 5$	$5.67 \text{ E } -14$	$1.15 \text{ E } 5$	$1.84 \text{ E } -14$	$8.41 \text{ E } 4$
FRACTURE ZONE PERMEABILITY	$7.87 \text{ E } -11$	$5.25 \text{ E } 2$	$1.11 \text{ E } -12$	$5.25 \text{ E } 2$	$5.34 \text{ E } -14$	$1.21 \text{ E } 5$	$4.48 \text{ E } -12$	$4.17 \text{ E } 3$
THICKNESS OF DEPOSITORY LAYER	$2.12 \text{ E } -10$	$1.87 \text{ E } 4$	$7.23 \text{ E } -12$	$1.97 \text{ E } 4$	$1.11 \text{ E } -13$	$2.68 \text{ E } 4$	$4.48 \text{ E } -11$	$1.52 \text{ E } 4$
THICKNESS OF BARRIER LAYER	$6.28 \text{ E } -11$	$3.31 \text{ E } 4$	$2.14 \text{ E } -12$	$3.31 \text{ E } 4$	$6.87 \text{ E } -14$	$5.01 \text{ E } 4$	$1.02 \text{ E } -11$	$2.83 \text{ E } 4$
LENGTH OF TUNNEL (INCREASE)	$2.80 \text{ E } -11$	$1.09 \text{ E } 5$	$7.08 \text{ E } -13$	$1.04 \text{ E } 5$	$5.80 \text{ E } -14$	$1.15 \text{ E } 5$	$1.85 \text{ E } -12$	$7.96 \text{ E } 4$
LENGTH OF TUNNEL	$2.57 \text{ E } -11$	$1.09 \text{ E } 5$	$7.81 \text{ E } -13$	$1.04 \text{ E } 5$	$5.85 \text{ E } -14$	$1.15 \text{ E } 5$	$1.83 \text{ E } -12$	$8.42 \text{ E } 4$
DISSOLUTION RATE OF WASTE	$2.70 \text{ E } -11$	$9.83 \text{ E } 4$	$8.42 \text{ E } -13$	$1.92 \text{ E } 3$	$5.77 \text{ E } -14$	$1.09 \text{ E } 5$	$3.87 \text{ E } -12$	$2.02 \text{ E } 3$
FISSION PRODUCT SORPTION FACTORS	$2.58 \text{ E } -11$	$1.04 \text{ E } 5$	$7.04 \text{ E } -13$	$1.04 \text{ E } 5$	$5.65 \text{ E } -14$	$1.15 \text{ E } 5$	$1.84 \text{ E } -12$	$8.41 \text{ E } 4$
ACTINIDE SORPTION FACTORS	$2.58 \text{ E } -11$	$1.09 \text{ E } 5$	$7.04 \text{ E } -13$	$1.04 \text{ E } 5$	$5.87 \text{ E } -14$	$1.15 \text{ E } 5$	$1.84 \text{ E } -12$	$8.41 \text{ E } 4$
AQUIFER LENGTH	$2.58 \text{ E } -11$	$1.09 \text{ E } 5$	$7.04 \text{ E } -13$	$1.04 \text{ E } 5$	$5.87 \text{ E } -14$	$1.15 \text{ E } 5$	$1.84 \text{ E } -12$	$8.41 \text{ E } 4$

TABLE I-4
SALT REPOSITORY SENSITIVITY ANALYSIS - MULTIPLE PARAMETER
(INTERSTITIAL FLOW)

T-1581

VARIED PARAMETER	INTEGRATED POPULATION DOSE (MAN-REM/MW-YR)			PEAK INDIVIDUAL DOSE (REM/MW-YR)				
	WHOLE BODY DOSE	CRITICAL ORGAN DOSE	CRITICAL ORGAN	WHOLE BODY DOSE	TIME	CRITICAL ORGAN DOSE	TIME	CRITICAL ORGAN
BASILINE	1.63 E -3	2.88 E -1	GI-LLI	8.15 E -14	1.16 E 5	9.88 E -12	1.16 E 5	GI-LLI
PERMEABILITY OF ROCK AND AQUIFER (1)	3.17	3.17	WHOLE BODY	1.22 E -10	9.81 E 5	1.56 E -9	1.01 E 6	BONE
PERMEABILITY OF SHAFT & AQUIFER POROSITY OF TUNNEL (2)	2.61	2.61	WHOLE BODY	7.45 E -11	1.12 E 6	7.45 E -11	1.12 E 6	WHOLE BODY
PERMEABILITY OF SHAFT TUNNEL & AQUIFER (3)	2.63	2.63	WHOLE BODY	7.24 E -11	1.12 E 6	7.24 E -11	1.12 E 6	WHOLE BODY
HIGH PERMEABILITY EVERYWHERE (4)	3.17	3.17	WHOLE BODY	1.22 E -10	9.81 E 5	1.56 E -9	1.01 E 6	BONE

T-1581a

VARIED PARAMETER	PEAK AQUIFER CONCENTRATION (CU/M ³ -MW-YR)							
	⁹⁰ Fc CONCENTRATION	TIME	¹²⁶ Ca CONCENTRATION	TIME	²²⁶ Ra CONCENTRATION	TIME	²³⁸ Pu CONCENTRATION	TIME
BASILINE	2.94 E -11	1.09 E 5	7.84 E -13	1.04 E 5	5.97 E -14	1.15 E 5	1.84 E -12	8.41 E 4
PERMEABILITY OF ROCK & AQUIFER	7.10 E -12	2.68 E 2	2.74 E -13	2.88 E 2	5.17 E -16	1.17 E 4	1.07 E -12	1.73 E 3
PERMEABILITY OF SHAFT & AQUIFER POROSITY OF TUNNEL	2.57 E -13	1.08 E 5	7.00 E -15	1.04 E 5	5.84 E -16	1.16 E 5	1.63 E -14	8.41 E 4
PERMEABILITY OF SHAFT TUNNEL & AQUIFER	2.87 E -13	5.25 E 2	1.11 E -14	5.26 E 2	5.34 E -16	1.21 E 5	4.38 E -14	4.17 E 3
HIGH PERMEABILITY EVERYWHERE	7.10 E -12	2.68 E 2	2.74 E -13	2.87 E 2	5.17 E -16	1.17 E 4	1.07 E -12	1.73 E 3

Assumptions of Table I-5 - Table I-5 describes a shale repository with flow paths to the aquifer through a fracture zone surrounding the tunnel and shaft and through the overlying layers of shale. It is assumed that the flow through both shale layers is fracture flow. Flow pathways are shown in Fig. H-1. Baseline parameter values are as given in Table H-1, except for flow through the two shale layers, which is described by the values given in Table H-3. Changes in parameters varied in sensitivity analysis, when not shown, are listed in Table H-12.

TABLE I-5
SHALE REPOSITORY SENSITIVITY ANALYSIS
(FRACTURE FLOW)

T-1582

VARIABLE PARAMETER	BASELINE VALUE	NEW VALUE	INTEGRATED POPULATION DOSE (MAN-REM/MW-YR)			PEAK INDIVIDUAL DOSE (REM/MW-YR)				
			WHOLE BODY DOSE	CRITICAL ORGAN DOSE	CRITICAL ORGAN	WHOLE BODY DOSE	TIME	CRITICAL ORGAN DOSE	TIME	CRITICAL ORGAN
BASLINE	-	-	2.77 E-3	4.32 E-1	GI-LLI	1.86 E-12	1.17 E 4	2.26 E-10	1.17 E 4	GI-LLI
AQUIFER LENGTH	1.6 E 4	1.6 E 3	6.76 E-3	5.15 E-1	GI-LLI	2.08 E-12	1.92 E 3	2.53 E-10	1.92 E 3	GI-LLI
DISPERSION DOWN	60	10	2.77 E-3	4.33 E-1	GI-LLI	2.93 E-12	1.12 E 4	2.48 E-10	1.12 E 4	GI-LLI
ACTINIDE SORPTION	10 ⁴	10 ²	3.14	3.14	WHOLE BODY	1.10 E-10	9.51 E 5	1.57 E-8	1.01 E 6	BONE
AQUIFER LENGTH HEAD GRADIENT, SIMULTANEOUSLY		(1)	1.32	1.32	WHOLE BODY	2.86 E-11	1.24 E 6	3.63 E-10	1.69 E 4	GI-LLI
PERMEABILITY & ACTINIDE SORPTION SIMULTANEOUSLY		(2)	3.53	3.53	WHOLE BODY	1.47 E-9	1.60 E 4	1.47 E-8	1.60 E 4	WHOLE BODY
DISPERSION UP	50	100	2.77 E-3	4.31 E-1	GI-LLI	1.74 E-12	1.24 E 4	2.11 E-10	1.24 E 4	GI-LLI
ACTINIDE SORPTION, LEACH RATE + AQUIFER PERMEABILITY		(3)	2.49	2.49	WHOLE BODY	4.84 E-9	1.28 E 4	5.16 E-8	2.29 E 2	GI-LLI

T-1582a

VARIABLE PARAMETER	PEAK AQUIFER CONCENTRATION (G/M ³ -MW-YR)							
	56 _{Yc}		126 _{Sh}		228 _{Ra}		239 _{Pu}	
	CONCENTRATION	TIME	CONCENTRATION	TIME	CONCENTRATION	TIME	CONCENTRATION	TIME
BASLINE	6.84 E-10	2.29 E 2	1.86 E-11	5.89 E 3	2.92 E-14	1.93 E 5	4.14 E-13	1.27 E 5
AQUIFER LENGTH	6.84 E-10	2.29 E 2	1.86 E-11	5.89 E 3	2.92 E-14	1.93 E 5	4.14 E-13	1.27 E 5
DISPERSION DOWN	6.84 E-10	2.29 E 2	1.85 E-11	5.89 E 3	2.92 E-14	1.82 E 5	4.14 E-13	1.27 E 5
ACTINIDE SORPTION	6.84 E-10	2.29 E 2	1.85 E-11	5.89 E 3	7.36 E-14	1.17 E 4	1.12 E-10	7.37 E 3
AQUIFER LENGTH HEAD GRADIENT, SIMULTANEOUSLY	6.84 E-11	2.29 E 2	1.85 E-12	5.89 E 3	2.92 E-15	1.93 E 5	4.14 E-14	1.27 E 5
PERMEABILITY & ACTINIDE SORPTION SIMULTANEOUSLY	6.84 E-12	2.79 E 2	1.86 E-13	5.89 E 3	7.36 E-16	1.17 E 4	1.12 E-12	7.37 E 3
DISPERSION UP	6.84 E-10	2.29 E 2	1.85 E-11	5.89 E 3	2.92 E-14	1.93 E 5	4.14 E-13	1.27 E 5
ACTINIDE SORPTION, LEACH RATE + AQUIFER PERMEABILITY	1.46 E-9	1.23 E 2	7.33 E-13	2.02 E 3	6.70 E-16	2.57 E 3	3.38 E-12	2.18 E 3

Assumptions of Table I-6 - Table I-6 describes a bedded salt repository with flow paths to the aquifer through a fracture zone surrounding the tunnel and shaft and through the overlying salt and shale layers. It is assumed that the flow through the shale barrier layer is fracture flow, and the flow through the salt layer is interstitial flow. Flow pathways are shown in Fig. H-1. Baseline parameter values are as given in Table H-2, except for flow through the shale barrier layer, which is described by the values given in the "barrier layer" row of Table H-3.

TABLE I-6
SALT REPOSITORY SENSITIVITY ANALYSIS
(FRACTURE FLOW)

T-1583

VARIED PARAMETER	BASELINE VALUE	NEW VALUE	INTEGRATED POPULATION DOSE (MAN-REM/MW-YR)			PEAK INDIVIDUAL DOSE (REM/MW-YR)				
			WHOLE BODY DOSE	CRITICAL ORGAN DOSE	CRITICAL ORGAN	WHOLE BODY DOSE	TIME	CRITICAL ORGAN DOSE	TIME	CRITICAL ORGAN
BASILINE	-	-	2.58 E -3	4.06 E -1	GI-LLI	5.84 E -13	2.58 E 4	7.07 E -11	2.56 E 4	GI-LLI
SALT PERMEABILITY	10 ⁸	10 ⁵	2.77 E -3	4.32 E -1	GI-LLI	1.88 E -12	1.17 E 4	2.27 E -10	1.17 E 4	GI-LLI
DISPERSION	50	10	2.64 E -3	4.18 E -1	GI-LLI	1.00 E -12	2.58 E 4	1.12 E -10	2.58 E 4	GI-LLI

T-1583a

VARIED PARAMETER	PEAK AQUIFER CONCENTRATION (CUM ³ -ANN-YR)							
	99 _{FC}		125 _{CD}		226 _{RA}		238 _{PO}	
	CONCENTRATION	TIME	CONCENTRATION	TIME	CONCENTRATION	TIME	CONCENTRATION	TIME
BASILINE	1.89 E -10	1.89 E 4	6.5 E -12	1.89 E 4	8.94 E -14	2.88 E 4	4.97 E -11	1.17 E 4
SALT PERMEABILITY	6.82 E -10	3.13 E 2	2.94 E -11	3.13 E 2	5.17 E -14	1.17 E 4	1.12 E -10	1.73 E 3
DISPERSION	3.15 E -10	1.80 E 4	1.11 E -11	1.52 E 4	1.27 E -13	1.97 E 4	7.88 E -11	1.37 E 4

Assumptions of Tables I-7 and I-8 - Tables I-7 and I-8 assume the same flow paths as in the shale and salt repositories of Tables I-1 and I-3 respectively with an additional flow path to the aquifer through the deteriorated backfill in the tunnel and shaft. Partial mixing between the backfill and the surrounding fracture zone is assumed. Flow pathways are shown in Fig. H-2. Baseline parameter values for the deteriorated backfill are given in Table H-4; base-lines for other pathways are given in Table H-1 for Table I-7 and in Table H-2 for Table I-8. Changes in parameters varied in sensitivity analysis are listed in Tables H-13 and H-14 respectively.

TABLE I-7
SHALE REPOSITORY DETERIORATED BACKFILL - SENSITIVITY ANALYSIS
(INTERSTITIAL FLOW)

T-1584

VARIABLE PARAMETER	INTEGRATED POPULATION DOSE (MAN-REM/MG-YR)			PEAK INDIVIDUAL DOSE (REM/MG-YR)			
	WHOLE BODY DOSE	CRITICAL ORGAN DOSE	CRITICAL ORGAN	WHOLE BODY DOSE	TIME	CRITICAL ORGAN DOSE	CRITICAL ORGAN
BASLINE	1.40 E-3	2.23 E-3	GI-LLI	5.70 E-13	1.10 E-4	6.90 E-11	1.10 E-4
FURTHER DETERIORATED BACKFILL (1)	2.31 E-3	3.54 E-3	GI-LLI	1.30 E-12	1.10 E-4	1.80 E-10	1.10 E-4
IMPERMEABLE SHAFT (2)	1.30 E-3	1.00 E-3	GI-LLI	6.70 E-14	1.45 E-4	8.20 E-12	1.45 E-4
IMPERMEABLE SHAFT & HIGHLY PERMEABLE TUNNEL (3)	1.29 E-3	1.56 E-3	GI-LLI	4.22 E-14	1.74 E-5	5.10 E-12	1.74 E-5

T-1584a

VARIABLE PARAMETER	PEAK AQUIFER CONCENTRATION (G/GM ³ DMG-YR)							
	15 ₁₀ CONCENTRATION	TIME	125 ₅₀ CONCENTRATION	TIME	275 ₂₅ CONCENTRATION	TIME	275 ₂₅ CONCENTRATION	TIME
BASLINE	2.30 E-10	5.26 E-2	2.84 E-12	2.89 E-4	1.50 E-10	2.32 E-6	2.09 E-10	2.32 E-6
FURTHER DETERIORATED BACKFILL	8.15 E-10	2.64 E-2	1.20 E-11	1.00 E-4	1.10 E-14	6.25 E-5	1.10 E-15	4.42 E-5
IMPERMEABLE SHAFT	2.20 E-11	3.75 E-3	1.00 E-14	1.83 E-6	-	-	-	-
IMPERMEABLE SHAFT & HIGHLY PERMEABLE TUNNEL	1.34 E-11	1.97 E-6	1.70 E-10	1.51 E-6	-	-	-	-

TABLE I-8
SALT REPOSITORY DETERIORATED BACKFILL - SENSITIVITY ANALYSIS
(INTERSTITIAL FLOW)

T-1585

VARIABLE PARAMETER	INTEGRATED POPULATION DOSE (MAN-REM/MG-YR)			PEAK INDIVIDUAL DOSE (REM/MG-YR)				
	WHOLE BODY DOSE	CRITICAL ORGAN DOSE	CRITICAL ORGAN	WHOLE BODY DOSE	TIME	CRITICAL ORGAN DOSE	TIME	CRITICAL ORGAN
BASILINE	1.79 E -3	3.66 E -1	GI-LLI	3.24 E -13	1.75 E 4	4.53 E -11	1.18 E 4	GI-LLI
FURTHER DETERIORATED BACKFILL (1)	2.26 E -3	3.64 E -1	GI-LLI	1.32 E -12	1.24 E 4	1.61 E -10	1.24 E 4	GI-LLI
IMPERMEABLE SHAFT (2)	1.63 E -3	2.86 E -1	GI-LLI	8.28 E -14	1.15 E 5	1.00 E -11	1.15 E 5	GI-LLI
IMPERMEABLE SHAFT HIGHLY PERMEABLE TUNNEL (3)	1.63 E -3	2.86 E -1	GI-LLI	8.28 E -14	1.15 E 5	9.99 E -12	1.15 E 5	GI-LLI
PERMEABLE TUNNEL & SHAFT (4)	2.75 E -3	4.30 E -1	GI-LLI	1.84 E -12	1.18 E 4	2.23 E -10	1.18 E 4	GI-LLI

T-1585a

VARIABLE PARAMETER	PEAK ADJUVANT CONCENTRATION (CM ³ -L/MG-YR)							
	⁹⁹ Tc		¹²⁹ Xe		²²⁶ Ra		²²⁶ Pb	
	CONCENTRATION	TIME	CONCENTRATION	TIME	CONCENTRATION	TIME	CONCENTRATION	TIME
BASILINE	1.35 E -10	8.37 E 2	5.20 E -12	8.37 E 2	4.02 E -14	1.27 E 5	2.13 E -11	2.02 E 3
FURTHER DETERIORATED BACKFILL	4.63 E -10	1.48 E 3	1.78 E -11	1.48 E 3	4.09 E -14	1.52 E 5	7.89 E -11	2.02 E 3
IMPERMEABLE SHAFT	2.81 E -11	1.09 E 5	7.16 E -13	9.83 E 4	5.73 E -14	1.27 E 5	1.67 E -12	8.41 E 4
IMPERMEABLE SHAFT HIGHLY PERMEABLE TUNNEL	2.81 E -11	1.04 E 5	7.16 E -13	9.83 E 4	5.70 E -14	1.15 E 5	1.68 E -12	7.89 E 4
PERMEABLE TUNNEL & SHAFT	6.61 E -10	9.28 E 2	2.55 E -11	9.28 E 2	5.37 E -14	9.07 E 3	1.06 E -10	2.01 E 3

Assumptions of Tables I-9 and I-10 - Tables I-5 and I-10 assume the same flow paths as in the baseline shale and salt repositories of Tables I-1 and I-3 respectively, with an additional flow path to the aquifer through borings on which the seal has failed. It is assumed that initially 10% of the borings have failed. After 500 yr, 30% have failed, and after 1000 yr, 50% have failed. Flow pathways are shown in Fig. H-3. Baseline parameter values for the failed borings are given in Table H-5; baselines for other pathways are given in Table H-1 for Table I-9 and in Table H-2 for Table I-10.

TABLE I-9
SHALE REPOSITORY BORING SEAL DISSOLUTION - SENSITIVITY ANALYSIS
(INTERSTITIAL FLOW)

T-1566

VARIED PARAMETER	BASELINE VALUE	NEW VALUE	INTEGRATED POPULATION DOSE (MAN-REM/MW-YR)			PEAK INDIVIDUAL DOSE (REM/MW-YR)				
			WHOLE BODY DOSE	CRITICAL ORGAN DOSE	CRITICAL ORGAN	WHOLE BODY DOSE	TIME	CRITICAL ORGAN DOSE	TIME	CRITICAL ORGAN
BASELINE	-	-	1.28 E-3	1.58 E-1	GI-LLI	5.11 E-14	1.45 E 4	2.29 E-12	1.45 E 4	GI-LLI
COMPLETE MIXING	-	-	1.28 E-3	1.58 E-1	GI-LLI	5.08 E-14	1.45 E 4	2.37 E-12	1.45 E 4	GI-LLI
MAXIMUM PERMEABILITY IN BORING	10 ⁻⁶	10 ⁻²	1.37 E-3	1.78 E-1	GI-LLI	2.44 E-13	1.30 E 4	2.95 E-11	1.30 E 4	GI-LLI

TABLE I-10
SALT REPOSITORY BORING SEAL DISSOLUTION - SENSITIVITY ANALYSIS
(INTERSTITIAL FLOW)

T-1537

VARIED PARAMETER	BASELINE VALUE	NEW VALUE	INTEGRATED POPULATION DOSE (MAN-REM/MW-YR)			PEAK INDIVIDUAL DOSE (REM/MW-YR)				
			WHOLE BODY DOSE	CRITICAL ORGAN DOSE	CRITICAL ORGAN	WHOLE BODY DOSE	TIME	CRITICAL ORGAN DOSE	TIME	CRITICAL ORGAN
BASELINE	-	-	1.63 E-3	2.85 E-1	GI-LLI	7.39 E-14	1.21 E 5	9.67 E-12	1.21 E 5	GI-LLI
COMPLETE MIXING	-	-	1.63 E-3	2.85 E-1	GI-LLI	7.39 E-14	1.21 E 5	9.66 E-12	1.21 E 5	GI-LLI
MAXIMUM PERMEABILITY IN BORING	10 ⁻⁶	10 ⁻²	1.65 E-3	2.88 E-1	GI-LLI	1.58 E-13	1.24 E 4	1.93 E-11	1.24 E 4	GI-LLI

Assumptions of Table I-11 - Table I-11 describes a shale repository with the possibility of the occurrence of a fault. The probability of the occurrence of a fault in any given year is assumed to be 5×10^{-7} in the baseline case. It is further assumed that when a fault does occur it will close almost completely after a mean time of 70 yr. The opening is assumed to be along an existing fault; creation of new faults was dropped from the analysis because it was less probable and would result in lesser consequences than movement along an existing fault. Fault pathways are shown in Fig. H-4. Baseline parameter values are as given in Table H-1, with the additions and changes in Table H-6.

TABLE I-11
SHALE REPOSITORY FAULTING - SENSITIVITY ANALYSIS
(INTERSTITIAL FLOW)

T-1506

VARIED PARAMETER	BASELINE VALUE	NEW VALUE	INTEGRATED POPULATION DOSE (MAN-REM/MW-YR)			PEAK INDIVIDUAL DOSE (REM/MW-YR)				
			WHOLE BODY DOSE	CRITICAL ORGAN DOSE	CRITICAL ORGAN	WHOLE BODY DOSE	TIME	CRITICAL ORGAN DOSE	TIME	CRITICAL ORGAN
BASILINE	-	-	1.27 E-3	1.57 E-1	GI-LLI	6.87 E-14	1.45 E 4	7.32 E-12	1.45 E 4	GI-LLI
FAULT STAYS OPEN AND A HIGHER PROBABILITY OF OCCURRENCE	5 E-7	5 E-5	1.27 E-3	1.57 E-1	GI-LLI	6.34 E-14	1.45 E 4	7.70 E-12	1.45 E 4	GI-LLI

Assumprions of Table I-12 - Table I-12 describes a salt repository with some probability of a breccia pipe forming between the repository and the aquifer. The probability that a breccia pipe will open in a given year is assumed to be 5×10^{-7} in the baseline case. Flow pathways are shown in Fig. H-4. Baseline parameter values are as given in Table H-2, with the additions and changes in Table H-7.

TABLE I-12
SALT REPOSITORY BRECCIA FORMATION - SENSITIVITY ANALYSIS
(INTERSTITIAL FLOW)

T-1577

VARIED PARAMETER	BASELINE VALUE	NEW VALUE	INTEGRATED POPULATION DOSE (MAN-REM/MW-YR)			PEAK INDIVIDUAL DOSE (REM/MW-YR)				
			WHOLE BODY DOSE	CRITICAL ORGAN DOSE	CRITICAL ORGAN	WHOLE BODY DOSE	TIME	CRITICAL ORGAN DOSE	TIME	CRITICAL ORGAN
BASILINE	-	-	1.62 E-3	2.84 E-1	GI-LLI	8.15 E-14	1.15 E 5	9.74 E-12	1.15 E 5	GI-LLI
HIGH PROBABILITY OF BRECCIA FORMATION	5 E-7	5 E-4	1.18 E-3	1.94 E-1	GI-LLI	1.72 E-13	2.43 E 4	2.08 E-11	2.43 E 4	GI-LLI
BRECCIA PIPE INITIALLY PRESENT	-	-	2.75 E-3	4.28 E-1	GI-LLI	1.48 E-12	1.80 E 4	1.75 E-10	1.80 E 4	GI-LLI

APPENDIX J
EFFECT OF CONSECUTIVE BARRIERS

J.1 INTRODUCTION

Consecutive barriers to migration of waste from the repository to the biosphere are central to current concepts of safe disposal of nuclear waste. In this appendix, the effects of consecutively operative barriers on the maximum concentration of waste in an aquifer are studied. (Note that any physical phenomenon which can reduce the value of the concentration is a potential barrier.)

The effects are first investigated within the context of two specific barriers -- the time over which a pulse of waste is released into the aquifer and the dispersion of the pulse as it moves down the aquifer. For a given quantity of waste, the peak concentration is computed as a function of both these variables. The result is then generalized to more than two such barriers, given that they act consecutively.

J.2 FLOW IN THE AQUIFER

The motion of a nuclide through an aquifer is considered neglecting radioactive decay. This is justified for times exceeding 500 years after removal from the reactor because the potential hazard of the waste is dominated by the actinides, and they do not appreciably decay before a million years. The waste moves at velocity V/B_r , where V is the velocity of water in the aquifer and B_r is the sorption

retardation factor for the nuclide in question. In the aquifer, hydraulic dispersion causes narrow pulses to spread. Only longitudinal spreading will be considered; lateral spreading will affect the peak value of the concentration but not appreciably alter its time dependence. We therefore treat motion in one dimension only and describe it by a diffusion-type differential equation (see Appendix D):

$$\frac{\partial C}{\partial t} = - \frac{V}{B_r} \frac{\partial C}{\partial x} + \frac{\alpha V}{B_r} \frac{\partial^2 C}{\partial x^2} \quad (J-1)$$

where

t = time

x = position in the aquifer

$C(x,t)$ = the concentration of the nuclide
in the interstitial water as a
function of position and time

α = the dispersion constant

V = the velocity of water in the aquifer

If we consider the aquifer to be infinite in both directions, Eq. J-1 can be solved by using the Green's function, G , which is given by

$$G(x,t;x',t') = \sqrt{\frac{B_r}{4\pi\alpha V(t-t')}} \exp \left\{ - \frac{\left(x-x' - \frac{V}{B_r}(t-t') \right)^2}{\frac{4\alpha V}{B_r}(t-t')} \right\} \quad (J-2)$$

The Green's function is the value of the total nuclide concentration in the aquifer at position x and time t given a unit impulse instantaneously injected at position x' at time t' .

If we define $C_{in}(t)$ as the input concentration to the aquifer

at a particular spatial point ($x=0$) as a function of time, then the total concentration of nuclide r as a function of position and time will be given by:

$$C(x,t) = \frac{V}{B_r} \int_0^t G(x,t; 0,t') C_{in}(t') dt' \quad (J-3)$$

Equivalently, if the input pulse is assumed to have entered the aquifer before $t=0$, then the input spatial profile for the concentration of nuclide r at $t=0$ can be designated $C_{in}(x)$ and the concentration at any later time as a function of position will be given by

$$C(x,t) = \int_{-\infty}^{\infty} G(x,t; x', 0) C_{in}(x') dx' \quad (J-4)$$

Without a detailed knowledge of the dissolution rate of the nuclide in the depository as a function of time and a valid model for the hydrology in the intervening layers between the depository and the aquifer, it is not possible to know C_{in} accurately. However, after most of the waste has dissolved and entered the aquifer, the shape of the spatial concentration profile will exhibit a single maximum provided that

- The retardation factor is approximately the same for all nuclides.
- The dissolution rates of the various nuclides are the same.
- The composition of the matrix into which the waste is imbedded is uniform.
- No events occur to significantly increase the surface area of waste exposed to ground water flow (such as crack formation).

- No changes occur in the rock layers after emplacement.
- No multiple flow paths of differing velocities exist.

If any of these assumptions fails (as is actually expected -- especially the first and last), multiple maxima can be expected in the spatial aquifer profile. However, it is possible to apply the following analysis to each of the profile peaks individually or to the pulse as a whole in the extreme limits of very short or very long release times. For that reason it is assumed that only one peak is present. For ease of computation, it is further assumed that the distribution is not too skewed so that it can be approximated by a gaussian distribution:

$$C_{in}(x) = Q_r \frac{\gamma B_r}{\sqrt{\pi}} \exp \left\{ -\frac{\gamma^2 x^2 B_r^2}{v^2} \right\} \quad (t=0)$$

where Q_r is the total amount of nuclide r in the repository, γ^{-1} is the width (standard deviation) of the pulse entering the aquifer, and the origin of coordinates has been chosen so that the peak occurs at $x=0$ when $t=0$. It will be shown that the final answer is not particularly sensitive to the shape of the pulse.

Performing the integration in Eq. J-4 gives

$$C(x,t) = \frac{Q_r}{\sqrt{\pi \left(\frac{4\alpha Vt}{B_r} + \frac{v^2}{B_r^2 \gamma^2} \right)}} \exp \left\{ \frac{-\left(x - \frac{vt}{B_r} \right)^2}{\frac{v^2}{\gamma^2 B_r^2} + \frac{4\alpha Vt}{B_r}} \right\}$$

The maximum value for $C(x,t)$ is obtained when

$$\frac{tV}{B_r \bar{x}} = -\left(\frac{1}{\bar{x}} + \xi\right) + \sqrt{(1+\xi)^2 + 1/\bar{x}^2}$$

where $\bar{x} = x/\alpha$ and $\xi = \frac{v^2}{4\alpha x \gamma^2 B_r^2}$.

Provided that $\bar{x} \gg 1$ (i.e., $x \gg \alpha$), this gives $t_{\max} = \frac{B_r x}{V}$ to lowest order in $1/\bar{x}$. The value of the concentration at this time is given by

$$C^{\max} = \frac{Q_r}{\sqrt{\pi \left(4\alpha x + \frac{v^2}{B_r^2 \gamma^2}\right)}}$$

If we define the time over which dispersion spreads a pulse as

$$T_D = \sqrt{4\alpha x} \frac{B_r}{V}$$

then $C^{\max}$ can be written as:

$$C^{\max} = \frac{Q_r B_r}{\sqrt{\pi} V} \frac{1}{\sqrt{\frac{1}{\gamma^2} + T_D^2}} \quad (J-5)$$

This is to be compared with an input pulse maximum of

$$C_{in}^{\max} = \frac{Q_r B_r}{V \sqrt{\pi}} \frac{1}{\sqrt{\frac{1}{\gamma^2}}} \quad (J-6)$$

The effect of dispersion on Eq. J-6 is to change $1/\gamma$ to

$$\sqrt{\frac{1}{\gamma^2} + T_D^2}.$$

In the limit where $\frac{1}{\gamma} \gg T_D$, then $C^{\max}$ is proportional to γ , while in the case where $\frac{1}{\gamma} \ll T_D$, $C^{\max}$ is proportional to $\frac{1}{T_D}$. For the baseline case without sorption -- $\alpha = 50$ m, $x = 16$ km, $B_r = 1$ and $V = 1.58$ m/year -- $T_D \approx 10^3$ years. If sorption is included with $B_r = 100$, then $T_D \approx 10^5$ years.

The behavior of pulse shapes in the two limiting cases does not depend on the shape of the input pulse.

Consider first the case where $T_D \gg 1/\gamma$. The input pulse will then be relatively narrow. Its shape will be greatly altered by the spreading due to hydraulic dispersion, and the shape of the output pulse will depend only on how much waste is in the input pulse. This situation is represented mathematically by a Green's function which is much wider than the input pulse. The input pulse may be approximated by a constant times a delta function with the constant equal to the area of the input pulse. The output will then have the same time dependence as the Green's function, with its amplitude proportional to the total amount of waste in the input pulse.

In the case where $T_D \ll 1/\gamma$, the input pulse is wide (and smooth). Hydraulic dispersion will have little effect and the output will have approximately the same shape as the input. This situation corresponds to an input pulse much wider than the Green's function. The amplitude of the output in this case will simply be equal to the amplitude of the input.

As mentioned, the duration of release into the aquifer is a function of other time scales. As an example of the relationship between these time scales, the waste may be considered to smoothly leach from the repository into a flow path

leading to the aquifer. In that case, the preceding analysis applies in its entirety, but with $C_{in}(t)$ considered a gaussian with a spread given by the dissolution time of the waste. $C(x,t)$ computed with this input pulse could then be used as an input pulse into the aquifer. The value of the spread at the entry point to the aquifer would then be:

$$\sqrt{\frac{1}{\Lambda^2} + T_{D1}^2}$$

where Λ is the dissolution rate of the waste and T_{D1} is the effective dispersion time for the path between the depository and the aquifer. In the aquifer, the spread of the final (output pulse) would then be:

$$\sqrt{\frac{1}{\Lambda^2} + T_{D1}^2 + T_{D2}^2}$$

where T_{D2} is the dispersion time for the aquifer. This can be generalized directly to more complicated situations.

In summary,

- For a given quantity of waste, the peak concentration is inversely proportional to the width (in time at a given position, or in space at a given time) of the concentration curve.
- The effect of a series of barriers is to replace the width of the initiating pulse with another effective width. The latter is computed by adding in quadrature the widths associated with each of the physical phenomena.

APPENDIX K
PARAMETERS FOR UNCERTAINTY ANALYSIS

The monte carlo routine (WSRAND) has been designed to incorporate a variety of constraints and correlations into the generated sets of random input parameters for the waste migration model. Each randomly generated variate, U , is assumed to have a lognormal distribution and is thus characterized by its median value, M , and scale factor uncertainty, V .

The scale factor uncertainty, V , has the property that $\log_{10}(V)$ is the standard deviation of the normal random variable $\log_{10}(U)$ with mean $\log_{10}(M)$. The constraints incorporated into the monte carlo routine in some cases have the effect of modifying the sample distributions so that they deviate significantly from the assumed population distributions. This effect is discussed in Section 3.5 of Volume I. The remainder of this appendix describes the model constraints. The baseline shale repository used in this study is described in Appendix H.

The scale factor uncertainties used reflect the assumed uncertainty in estimation of the input parameters that exist after the moderate pre-excavation phase exploration of the repository has been performed (from Ref. K.1).

K.1 DISPERSION CONSTANTS

Table K.1-1 lists the median value and scale factor for the randomly generated dispersion constants. The

TABLE K.1-1
ASSUMED STATISTICS FOR DISPERSION CONSTANTS

T-1418

PATHWAY	MEDIAN VALUE (m)	SCALE FACTOR UNCERTAINTY
First Segment of Tunnel Fracture Zone	50	2
Depository Layer	50	2
Second Segment of Tunnel Fracture Zone	50	2
Shaft Fracture Zone in Depository Layer	50	2
Shaft Fracture Zone in Shale Layer	50	2
Barrier Layer Above Depository	50	2
Aquifer	50	2

dispersion constants were generated independently of each other and all other variates.

K.2 STREAM TUBE CROSS-SECTIONS

Table K.2-1 lists the median values and scale factor uncertainties for the cross-sections of the shaft and tunnel fracture zones.

TABLE K.2-1
ASSUMED STATISTICS FOR PATH CROSS-SECTIONS

T-1419

PATHWAY	MEDIAN VALUE (m ²)	SCALE FACTOR UNCERTAINTY
First Segment of Tunnel Fracture Zone	316	2.5
Second Segment of Tunnel Fracture Zone	18.96	2.5
Shaft Fracture Zone in Depository Layer	10.0	10.0
Shaft Fracture Zone in Shale Layer	5.0	10.0

K.3 NUCLIDE RETARDATION FACTORS

Table K.3-1 lists the assumed population statistics used to generate the random retardation factors. The retardation factor 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

We introduce the following notation:

- $B_S(j)$ = retardation factor for interstitial flow of the nuclide group j through shale;
 $j = 1, 2, 3$.

TABLE K.3-1
ASSUMED RETARDATION FACTOR STATISTICS

T-1420

PATHWAY	NUCLIDE GROUP	MEDIAN VALUE	SCALE FACTOR UNCERTAINTY
Aquifer	1	1.0	0*
	2	1.0×10^2	3.16
	3	1.0×10^4	3.16
Fracture Zone (Shaft and Tunnel)	1	1.0	3.16
	2	1.0×10^2	3.16
	3	1.0×10^4	3.16
Shale (Depository and Barrier)	1	1.0	3.16
	2	1.0×10^2	3.16
	3	1.0×10^4	3.16

*The retardation factor for group 1 was constrained to unity in the aquifer but is listed here for the sake of completeness.

- $B_A(j)$ = retardation factor for flow of the nuclide group j through the aquifer; $j = 1, 2, 3$.
- $B_F(j)$ = retardation factor for flow of the nuclide group j through the fracture zone (shaft and tunnel); $j = 1, 2, 3$.

A number of constraints* were imposed on the retardation factors which are described here.

K.3.1 Constraints for Iodine and Technetium Retardation Factors

The following constraints apply to the retardation factors for ^{129}I and ^{99}Tc (nuclide group 1):

*Personal communication with Dana Isherwood, Lawrence Livermore Laboratory, 14 July 1977.

$$B_S(1) \geq 1.0 \quad (K.3-1)$$

$$B_F(1) \geq 1.0 \quad (K.3-2)$$

$$B_A(1) = 1.0 \quad (K.3-3)$$

$$B_F(1) \leq B_S(1) \quad (K.3-4)$$

K.3.2 Fission Products and Actinides

The following constraints apply to the retardation factors for fission products (group 2) and actinides (group 3):

$$B_S(2) \geq B_S(1) \quad (K.3-5)$$

$$B_S(3) \geq B_S(1) \quad (K.3-6)$$

$$B_F(2) \geq B_F(1) \quad (K.3-7)$$

$$B_F(3) \geq B_F(1) \quad (K.3-8)$$

$$B_A(2) \geq B_A(1) \quad (K.3-9)$$

$$B_A(3) \geq B_A(1) \quad (K.3-10)$$

$$B_A(2) \leq B_S(2) \quad (K.3-11)$$

$$B_A(3) \leq B_S(3) \quad (K.3-12)$$

$$B_F(2) \leq B_S(2) \quad (K.3-13)$$

$$B_F(3) \leq B_S(3) \quad (K.3-14)$$

In addition to the above constraints it was assumed that the fission product and actinide retardation factors are correlated random variables. Thus, variates $\log_{10}(B_S(2))$ and $\log_{10}(B_S(3))$ were generated using an assumed bivariate normal distribution with a correlation coefficient, $\rho = 0.5$.

K.3.3 Sample Histogram

Figure K.3-1 is a normalized histogram of 1000 random retardation factors for Group 1 (^{129}I , ^{99}Tc) in shale, generated to satisfy the constraints specified in Sections K.3.1 and K.3.2 of this memorandum.

Figure K.3-1 Sample Probability Density Function for Retardation Factors for ^{129}I , ^{99}Tc in Shale Obtained from 1000 Monte Carlo Trials

K.4 PERMEABILITIES AND EFFECTIVE POROSITIES

Since permeability and effective porosity are closely related quantities the values used in this study were generated jointly. The constraints specified here were obtained from Golder Associates (Ref. K.1).

K.4.1 Fracture Zones

Tables K.4-1 and K.4-2 list the assumed statistics used to generate the random permeabilities and effective porosities for the fracture zone. Within each pathway it was assumed that the random variates $\log_{10}(\text{permeability})$ and $\log_{10}(\text{porosity})$ have a bivariate normal distribution with a correlation coefficient $\rho = 0.8^*$.

TABLE K.4-1
ASSUMED PERMEABILITY STATISTICS FOR
FRACTURE ZONES

T-1421

PATHWAY LOCATION	MEDIAN VALUE (cm/sec)	SCALE FACTOR UNCERTAINTY
Tunnel	1.0×10^{-1}	10.0
Shaft in Depository Layer	1.0×10^{-4}	10.0
Shaft in Shale Barrier Layer	1.0×10^{-4}	10.0

*Personal communication with Jerry Rowe, Golder Associates,
13 July 1977.

TABLE K.4-2
ASSUMED EFFECTIVE POROSITY STATISTICS FOR
FRACTURE ZONES

T-1422

PATHWAY LOCATION	MEDIAN VALUE	SCALE FACTOR UNCERTAINTY
Tunnel	1.0×10^{-1}	2
Shaft in Depository Layer	1.0×10^{-3}	10
Shaft in Shale Barrier Layer	1.0×10^{-3}	10

K.4.2 Interstitial Flow

Table K.4-3 lists the statistics used to generate the random permeabilities for flow in the bulk undisturbed rock.

TABLE K.4-3
ASSUMED STATISTICS FOR PERMEABILITY
IN THE UNDISTURBED ROCK

T-1423

LAYER	MEDIAN VALUE (cm/sec)	SCALE FACTOR UNCERTAINTY
Repository Layer	1.0×10^{-9}	10.0
Shale Barrier Layer Above Repository	1.0×10^{-7}	10.0
Aquifer	1.0×10^{-4}	10.0
Barrier Layer Below Repository	$1.0 \times 10^{-5}^*$	10.0

*This value is based on an erroneous reading of Ref. K.2; however the error is in the direction of excess conservatism and has little impact on the results. The error was discovered after completion of the original draft of the report; it was not felt to be a worthwhile use of resources to redo the monte carlo calculations for such a small correction.

For this flow the effective porosities, ϵ , were generated from the horizontal permeabilities, k_H , by the relationship (Ref. K.1):

$$\epsilon = c \log_{10} \frac{k_H}{A} \quad (\text{K.4-1})$$

The constants c and A are dependent on the geologic layer and are listed in Table K.4-4.

TABLE K.4-4
CONSTANTS USED TO GENERATE EFFECTIVE
POROSITY FROM PERMEABILITY

T-1424

LAYER	c	A (sec/cm)
Aquifer	4.5×10^{-2}	4.0×10^{-7}
Shale Barrier Layer Above Depository	2.3×10^{-2}	4.0×10^{-9}
Depository Layer	2.3×10^{-2}	4.0×10^{-11}
Shale Barrier Layer Below Depository	2.3×10^{-2}	4.0×10^{-9}

In addition the interval constraint $0 < \epsilon < 1$ was imposed to yield physically meaningful values of porosity.

K.4.3 Sample Histogram

Figure K.4-1 is a normalized histogram of 1000 random permeabilities for the aquifer.

Figure K.4-1 Sample Probability Density Function for Aquifer Permeability Obtained from 1000 Monte Carlo Trials

K.5 ADDITIONAL VARIATES

Table K.5-1 lists the statistics used to generate the following random variates:

- Horizontal head gradient in the aquifer
- Vertical head of the underlying aquifer
- Dissolution rate of the waste (λ)
- Time required to saturate the depository void space (T_{fill}).

TABLE K.5-1
STATISTICS OF RANDOM VARIATES

T-1425

VARIATE	MEDIAN VALUE	SCALE FACTOR UNCERTAINTY
Horizontal Head Gradient In the Aquifer	5.0×10^{-3}	1.2
Vertical Head of the Underlying Aquifer (m)	60.0	1.2
Λ (yr ⁻¹)	1.0×10^{-4}	10.0
T_{fill} (yr)	1.0×10^2	10.0

APPENDIX L
THE RECONCENTRATION EFFECT

L.1 INTRODUCTION

The waste transport model calculates the flow rate of nuclides to the biosphere under the assumption that the sorption retardation factors are equal for all members of a decay chain (Appendix F). This assumption is not always correct (Ref. L.1). As a result, the model may underestimate the flow rate of certain nuclides because of the "reconcentration effect" (Ref. L.2). In this appendix, the magnitude of the reconcentration effect is estimated for certain cases of interest for the performance of radioactive waste repositories.

Consider a two-member decay chain consisting of a parent nuclide and its decay product daughter whose sorption retardation factor is less than the retardation factor of the parent. Assume that an impulse of parent enters a long aquifer in which interstitial water is flowing. The water flows out of the aquifer directly into the biosphere. The impulse enters at the upstream end of the aquifer and flows with the water toward the downstream end. In the following discussion, the term "end" refers to the downstream, or discharge, end of the aquifer.

The impulse input of parent travels in the aquifer as a Gaussian pulse (Appendix F). As it moves it decays to daughter, which moves faster through the aquifer than the parent due to the difference in retardation factors. At any given time, the flow rate of daughter into the biosphere is

obtained by multiplying the velocity of the interstitial water by the concentration of daughter per unit volume of water at the end of the aquifer. The daughter flow rate into the biosphere is generally larger in this case than it would be if the retardation factors of parent and daughter were equal. This increase is due to the reconcentration effect.

The increase in daughter flow rate can be understood by considering the three mechanisms by which the daughter's retardation factor affects its concentration at the discharge of the aquifer.

First, the concentration of a nuclide in interstitial water is equal to the total amount of that nuclide (both dissolved and sorbed) present in a unit volume of rock, divided by the product of the retardation factor of the nuclide and the porosity of the rock. This definition reflects the fact that the retardation factor is a measure of the amount of nuclide in the interstitial water as compared to the total amount of nuclide either in solution or sorbed on the rock.

A reduction in the retardation factor of the daughter also affects the concentration of daughter at the discharge of the aquifer in two less apparent ways. The first effect is to change the point of origin of contributions of daughter which reach the exit at a given time. The distance an amount of daughter travels from the moment of its creation by decay until it reaches the end of the aquifer depends on its velocity. In the upper portion of Fig. L.1-1 a pulse of parent is shown at some time τ . The daughter created by decay at time τ is also shown. Two small pulses of the daughter curve are shaded. The distance of each pulse from the end of the aquifer is noted. If the daughter has retardation factor B_1 , the pulse on the right will reach the end of the aquifer at time t . If the

Figure L.1-1 Origin of Daughter Which Reaches Aquifer Exit at a Given Time

retardation factor is reduced to B_2 , the daughter moves more quickly and the pulse on the left reaches the end of the aquifer at time t . These two situations are depicted in the lower portions of the figure. Note that the decay of the daughter is neglected in Fig. L.1-1.

The concentration of daughter at the end of the aquifer also varies because a change in retardation factor produces a change in the amount the daughter decays for a given distance travelled. When the daughter's velocity increases, the daughter can travel a longer distance in a fixed amount of time. Hence, the daughter decays less for a given distance travelled. Figure L.1-2 shows the effect of a ten-fold reduction in retardation on the amount of decay for a nuclide travelling a given distance.

Figure L.1-2 Decay of Daughter With Distance for Different Retardation Factors

To summarize, a change in daughter retardation causes the flow rate of daughter to the biosphere to change due to three effects:

- The retardation explicitly enters into the expression for daughter concentration.
- As the daughter's velocity varies, different pulses of decay product will reach the aquifer discharge.
- The decay rate of the daughter with distance travelled is altered.

If the daughter's half-life is sufficiently short, the latter two effects tend to cancel each other and the net result of reducing the retardation factor is a proportional increase in the daughter flow rate. Consider Fig. L.1-3. The upper portion shows a hypothetical concentration of the parent as a function of distance along the aquifer at a time when the parent pulse is near the end of the aquifer. The pulse is fairly flat due to dispersion. The next frame shows the decay of the daughter with distance. The curve shown represents the daughter with reduced retardation factor. At the bottom of Fig. L.1-3, the decay curve is superimposed on several pulses which represent daughter created by decay of the parent pulse. Because of the short daughter half-life, pulses of daughter created far from the end of the aquifer will decay to insignificant levels before reaching the discharge. The pulses which contribute to the concentration of daughter at the exit come from a relatively flat part of the parent concentration curve. This follows because reconcentration is most important at the time of peak daughter flow rate. This peak coincides with the arrival of the peak of the parent pulse at the discharge. Near its peak, the parent pulse is nearly constant. Thus, the magnitudes of the contributions of daughter will be most nearly constant at the time of greatest interest.

Figure L.1-3 Effect of Short Daughter Half-Life on Daughter Concentration

If the retardation factor of the daughter increases, the contributions of daughter originate from closer to the discharge, as was depicted in Fig. L.1-1, and the daughter

decays in a much shorter distance, as was depicted in Fig. L.1-2. Consequently, the significant contributions to the daughter concentration at the end of the aquifer come from a relatively flat part of the parent curve. Hence, the pulses of daughter which contribute significantly have approximately constant magnitudes. They move a longer distance in the reduced retardation case, but they decay less. As a result, the effect of decay is about the same in both cases. The concentration of daughter at the end of the aquifer is therefore inversely proportional to the reduction in the daughter's retardation factor, provided the half-life of the daughter is sufficiently short. In Section L.2 of this appendix, the qualitative argument given in this paragraph is proven in mathematical detail.

For a long-lived daughter, the situation is more complicated because the daughter can travel a large distance with a small amount of decay. As a result, the shape of the parent pulse becomes important since the assumption of constant magnitude contributions of daughter is no longer valid. The increase in flow rate due to reconcentration becomes dependent on the position of the parent pulse, and becomes a complicated function of time.

There are two parent-daughter pairs in high level radioactive waste for which the reconcentration effect is of particular interest due to the large amount of these nuclides present: ^{230}Th with a half-life of 7.7×10^4 years decays to ^{226}Ra with a half-life of 1.6×10^3 years, and ^{93}Zr with a half-life of 1.5×10^6 years decays to ^{93m}Nb with a half-life of 14 years. Both of these daughters have sufficiently short half-lives that the effect of reconcentration will be to increase the flow rate to the biosphere by a factor given by the ratio of the parent retardation to the daughter retardation.

It is likely that inputs of thorium will not be able to traverse a long aquifer in three million years due to the large sorption retardation factor of thorium (Ref. L.1). The precursor of ^{230}Th in the decay chain is ^{234}U . The retardation factor of uranium seems to fall between those of thorium and radium (Ref. L.1). Hence, as ^{234}U moves through the aquifer it decays to slower ^{230}Th which in turn decays to the faster ^{226}Ra . As a result, the radium may overtake the uranium and produce a reconcentration. This three-member chain is analyzed in Section L.3.

L.2 THE RECONCENTRATION FACTOR FOR DECAY PAIRS WITH SHORT-LIVED DAUGHTERS

The reconcentration factor η is defined as the ratio of the flow rate of daughter entering the biosphere when retardation factor differences are present to the flow rate of daughter entering the biosphere when the retardation factor of the daughter is equal to the retardation factor of the parent. The waste transport model has to this point calculated the flow rate of the daughter assuming equal retardation factors. Multiplying the model output by η provides a correction for the reconcentration effect in a computationally simple manner.

The reconcentration factor computed here is based on several assumptions:

- The retardation factor of the daughter is much smaller than that of the parent.
- The half-life of the daughter is much shorter than that of the parent.

- The aquifer is sufficiently long that any original input of daughter to the aquifer will have decayed to an insignificant level in the time required for the daughter nuclide to traverse it.

The third assumption is particularly significant for the calculation. When a large amount of input daughter nuclide is flowing out of the aquifer the factor η will be small. The third assumption allows computation of the reconcentration factor without regard to the amount of input daughter, and guarantees that the retardation factor calculated will give the maximum effect.

In order to calculate the reconcentration factor, it is necessary to calculate the flow rate of daughter out of the aquifer. Let B denote the retardation factor and λ denote the decay constant, and let the subscripts 1 and 2 refer to parent and daughter respectively. Let x denote the distance coordinate along the aquifer.

The inputs to the aquifer in the waste transport model are sums of impulses. The response of the system to an impulse input is a Gaussian pulse traveling in the aquifer (Appendix F). In this analysis the concentration of parent in the aquifer is given as a single Gaussian pulse of unit height. The molar concentration of parent nuclide in the aquifer is given by

$$C_1(x,t) = \frac{1}{B_f \sqrt{4\pi\alpha \frac{V}{B_1} t}} \exp \left\{ -\frac{\left(x - \frac{V}{B_1} t\right)^2}{4\alpha \frac{V}{B_1} t} \right\} e^{-\lambda_1 t}; t > 0 \quad (L.2-1)$$

where V denotes the velocity of the interstitial water, ϵ denotes the porosity of the aquifer and α denotes the dispersion constant. The time scale is chosen so that $t=0$ refers to the time when the impulse enters the aquifer.

Let z denote the length of the aquifer. Let $f(z, t)$ denote the flow rate of the daughter to the biosphere. The flow rate is obtained by taking the product of the velocity of the interstitial water and the concentration of daughter at the end of the aquifer at time t . The concentration of daughter at $x = z$ and time t is obtained by summing up the daughter which is produced by decay of the parent which occurs at each time τ and position $z - V(t - \tau)/B_2$, since this decay product will reach discharge at time t . This sum must also take into account the decay of the daughter and the fact that the reduced daughter retardation factor causes the fraction of nuclide in solution to change. The resulting expression is

$$f(z, t) = \frac{VB_1}{B_2} \lambda_1 \int_0^t C_1 \left(z - \frac{V}{B_2}(t - \tau), \tau \right) e^{-\lambda_2(t - \tau)} d\tau \quad (L.2-2)$$

Equation L.2-2 will underestimate the flow rate of the daughter out of the aquifer when the input pulse is near the beginning of the aquifer, since the dispersion of the daughter has been neglected. However, the effect of the daughter's dispersion will become insignificant as the input nears the discharge. Therefore, Eq. L.2-2 will accurately represent the flow rate of the daughter when the reconcentration effect is most significant.

The result of the integration in Eq. L.2-2 has a complicated form. Let $T_{f2} = zB_2/V$. This is the transit time of an input of daughter through the aquifer. The formal expression for the result of the integration depends on whether the flow rate is being computed for a time before or after T_{f2} . Let

$$\sigma(t) = \begin{cases} 1 & \text{if } t < T_{f2} \\ -1 & \text{if } t \geq T_{f2} \end{cases}$$

Then

$$\begin{aligned}
 f(z, t) = & \sigma(t) \frac{VB_1}{B_2} \lambda_1 Q e^{-\lambda_2 t} \frac{1}{2\Omega} \exp \left\{ \frac{\left(\frac{V}{B_1} - \frac{V}{B_2} \right) \left(z - \frac{V}{B_2} t \right)}{2\alpha \frac{V}{B_1}} \right\} \\
 & \times \left[\exp \left\{ \frac{-\Omega \left(z - \frac{V}{B_2} t \right)}{2\alpha \frac{V}{B_1}} \right\} \operatorname{erfc} \left(\frac{\left| z - \frac{V}{B_2} t \right| - \sigma(t) \Omega t}{\sqrt{4\alpha \frac{V}{B_1} t}} \right) \right. \\
 & \left. - \exp \left\{ \frac{\Omega \left(z - \frac{V}{B_2} t \right)}{2\alpha \frac{V}{B_1}} \right\} \operatorname{erfc} \left(\frac{\left| z - \frac{V}{B_2} t \right| + \sigma(t) \Omega t}{\sqrt{4\alpha \frac{V}{B_1} t}} \right) \right]
 \end{aligned}
 \tag{L.2-3}$$

where

$$\Omega^2 = \left(\frac{V}{B_1} - \frac{V}{B_2} \right)^2 - 4\alpha \frac{V}{B_1} (\lambda_2 - \lambda_1)
 \tag{L.2-4}$$

Note that Ω^2 may be negative so that $\Omega = \sqrt{\Omega^2}$ may be imaginary.

Equation L.2-3 reduces to the much simpler form

$$f(z, t) = \frac{VB_1}{B_2} \lambda_1 C_1(z, t) \left[\lambda_2 - \lambda_1 + \frac{\left(\frac{V}{B_1} - \frac{V}{B_2} \right)^2}{4\alpha \frac{V}{B_1}} + \frac{\left(z - \frac{V}{B_2} t \right)^2}{4\alpha \frac{V}{B_1} t^2} \right]^{-1}
 \tag{L.2-5}$$

when the asymptotic expansion

$$\operatorname{erfc}(w) \approx \frac{e^{-w^2}}{\sqrt{\pi} w} \quad (\text{L.2-6})$$

is used.

The approximation of Eq. L.2-6 is valid for complex numbers w with large modulus satisfying $|\arg w| < \frac{3\pi}{4}$. (See Ref. L.4.)

In order to use Eq. L.2-5 in the waste transport model, it is necessary to show that the approximation is applicable to the complementary error functions occurring in Eq. L.2-3.

If

$$\left[\frac{V}{B_2} - \frac{V}{B_1} \left(\frac{z + \sqrt{4\alpha z}}{z - \sqrt{4\alpha z}} \right) \right]^2 \geq \Omega^2 \quad (\text{L.2-7})$$

the approximations will cause an error in the value of $\eta(t)$ which is no greater than 10%.

Equation L.2-7 reinforces the argument that the daughter decays quickly enough to guarantee that the shape of the parent pulse will not affect reconcentration.

In the special case $B_1 = B_2$,

$$f(z, t) = V \lambda_1 C_1(z, t) \left[(\lambda_2 - \lambda_1) + \frac{\left(z - \frac{V}{B_1} t \right)^2}{4\alpha \frac{V}{B_1} t^2} \right]^{-1} \quad (\text{L.2-8})$$

When the parent pulse is near the discharge, t is large and $z - (Vt/B_1)$ is small so the flow rate is approximately

$$f(z, t) = V \frac{\lambda_1 C_1(z, t)}{\lambda_2 - \lambda_1} \quad (\text{L.2-9})$$

Equation L.2-9 is the same result as would be obtained by assuming that the parent and daughter travel in secular equilibrium.

The reconcentration factor $\eta(t)$ is the ratio of Eq. L.2-5 to Eq. L.2-8.

$$\eta(t) = \frac{B_1}{B_2} \left\{ \frac{(\lambda_2 - \lambda_1) 4\alpha \frac{V}{B_1} t^2 + \left(z - \frac{V}{B_1} t\right)^2}{(\lambda_2 - \lambda_1) 4\alpha \frac{V}{B_1} t^2 - \left(\frac{V}{B_1} - \frac{V}{B_2}\right)^2 t^2 + \left(z - \frac{V}{B_2} t\right)^2} \right\} \quad (\text{L.2-10})$$

Let $T_{f1} = \frac{zB_1}{V}$. This is the time required for the parent pulse to traverse the aquifer. Writing Eq. L.2-10 as a Taylor series about T_{f1} and disregarding the terms of second order and higher yields

$$\eta(t) \approx \frac{B_1}{B_2} \left[1 - \frac{\frac{V}{B_1} \left(\frac{V}{B_2} - \frac{V}{B_1}\right) (t - T_{f1})}{2\alpha(\lambda_2 - \lambda_1) z} \right] \quad (\text{L.2-11})$$

with error less than 1%.

For times when the parent pulse is about one pulse width from the end of the aquifer ($|t - T_{f1}| \approx B_1 \sqrt{\alpha z}/V$)

$$\eta(t) \approx \frac{B_1}{B_2} \left[1 \pm \frac{\left(\frac{v}{B_2} - \frac{v}{B_1} \right)}{2\sqrt{\alpha z} (\lambda_2 - \lambda_1)} \right] \quad (L.2-12)$$

Suppose that the daughter half-life is much less than the time for the daughter to travel the width of the pulse, i.e.,

$$\frac{\ln 2}{\lambda_2} \ll \frac{\sqrt{\alpha z}}{\left(\frac{v}{B_2} \right)}$$

Then the second term in the braces in Eq. L.2-12 may be neglected. Hence

$$\eta(t) \approx \frac{B_1}{B_2} \quad (L.2-13)$$

The half-lives of ^{226}Ra and ^{93m}Nb are sufficiently small that Eq. L.2-13 may be used. Hence, in the cases of greatest interest, the reconcentration factor is approximately B_1/B_2 at all times near the transit time of the parent through the aquifer.

The effect of a broader input pulse of parent can be approximated by increasing the value of α in Eq. L.2-12. This increase will improve the accuracy of Eq. L.2-13.

The factor (Eq. L.2-13) will correct the flow rate of the daughter out of the aquifer for the reconcentration effect when the parent input is a single impulse. In general, the input is a sum of impulses. Equation L.2-13 may be used to correct the daughter flow rate for each impulse. Since the correction is linear, η may be used to correct the flow rate computed by the model.

Equation L.2-13 may be applied whenever a pulse of parent is near the discharge. Since no daughter input can traverse the aquifer any flow of daughter into the biosphere occurs because the parent pulse is near the discharge. Therefore, the reconcentration factor given by Eq. L.2-13 may be applied whenever there is daughter flowing out of the aquifer. If the daughter flow rate is zero, multiplication by η will not effect it. Hence the reconcentration factor η may be used at all times.

Since the integrated population dose (IPD) for the daughter is obtained by integrating its flow rate with respect to time over the life of the repository (Appendix G), the IPD for the daughter is increased by a factor of η .

L.3 THE RECONCENTRATION EFFECT FOR THE URANIUM CHAIN

In this section, the three-member decay chain $^{234}\text{U} \rightarrow ^{230}\text{Th} \rightarrow ^{226}\text{Ra}$ is analyzed in order to determine the effect of reconcentration on the flow rate of radium to the biosphere computed by TASC's waste transport model. The analysis is based on several assumptions:

- The retardation factor of radium is less than the retardation factor of uranium which, in turn, is less than or equal to the retardation factor of thorium.
- The waste transport model calculates the radium flow rate with the retardation factors of thorium and radium set equal to the retardation factor of uranium.
- The aquifer is sufficiently long that any original input of radium to the aquifer will have decayed to an insignificant level in the time required for the radium nuclide to traverse it.

- No thorium input is present.

The last assumption is a mathematical convenience. The effect of any thorium input can be calculated using the results of the previous section.

In the following, the notation of Section L.2 will be used with the exception that the subscripts 1, 2, and 3 will refer to ^{234}U , ^{230}Th , and ^{226}Ra , respectively.

The mathematical analysis presented in Section L.2 produced algebraically simple results because it was possible to use approximations to obtain Eq. L.2-5 and Eq. L.2-13. The error produced by these approximations was small because of the short half-life of the daughter.

In the uranium chain, the daughter nuclide is thorium whose half-life is 77,000 years. Because thorium is so long-lived, the approximations used in Section L.2 no longer apply. As a result, the expression for the thorium concentration in the aquifer is quite complicated and the reconcentration factor cannot be expressed in a simple way for the uranium chain except in the special case where thorium and uranium have the same retardation factor.

When we assume that uranium and its daughter thorium move with the same speed the following arguments can be applied. For an impulse of uranium which has entered the aquifer, the uranium concentration is given by Eq. L.2-1. The concentration of thorium produced by uranium decay will be:

$$C_2(x,t) = \frac{\lambda_1}{\lambda_2 - \lambda_1} \frac{B_1}{B_2} C_1(x,t) \left(1 - e^{-(\lambda_2 - \lambda_1)t} \right) \quad (\text{L.3-1})$$

Since the concentration of thorium is a linear combination of two decaying Gaussians, the results of Section L.2 may be applied in order to calculate the reconcentration factor. Thus, provided Eq. L.2-7 is satisfied, the reconcentration factor will be given by:

$$\eta = \frac{B_1}{B_3} \quad (\text{L.3-2})$$

The result of this special case is useful in examining the more general situation in which the thorium is slower than the uranium ($B_2 > B_1 > B_3$). In that general situation, the peak flow rate of radium will occur at the time when the peak of the uranium pulse exits the aquifer (Ref. L.3). This time is denoted as T_{f1} . However, since the thorium moves more slowly, the radium which leaves the aquifer must travel a longer distance as radium than in the special case. Hence, the radium will undergo more decay and the peak flow rate will be reduced. It follows that the peak flow rate of radium will be less than or equal to the peak flow rate calculated by the model times the η given by Eq. L.3-2. Let η_p denote the reconcentration factor at the time of peak radium flow. Then

$$\eta_p < \frac{B_1}{B_3} \quad (\text{L.3-3})$$

This argument establishes an upper bound on the reconcentration effect at the time of peak radium flow. However, this argument does not establish an upper bound at other times. It will be shown below (see Fig. L.3-1 and the accompanying discussion) that because of the higher retardation factor, a significant concentration of thorium will be found behind the

uranium pulse. As a result there will be a small, but significant, flow of radium long after the uranium pulse has left the aquifer. Since the current computer model will calculate an extremely small radium flow rate at such times, n will exceed n_p .

The actual value of n can be calculated as follows. Assume a uranium impulse input. Then Eq. L.2-1 gives the uranium concentration in the aquifer. The thorium concentration can be found by evaluating an integral analogous to Eq. L.2-2. The resulting thorium concentration $C_2(x,t)$ is given by $1/V$ times Eq. L.2-3 with x replacing z . However, Eq. L.2-7 is not satisfied because of thorium's long half-life. Hence, the concentration of thorium in the aquifer cannot be expressed in simple form.

Figure L.3-1 shows the general shape of the thorium concentration in the aquifer. In this figure, the variation of the uranium and thorium concentrations with distance from the entrance of the aquifer is shown for a given point in time. The shape of thorium concentration is due to thorium's small velocity and long half-life.

As the uranium pulse moves down the aquifer it decays to thorium which moves very slowly. However, the thorium is long-lived. Hence, the uranium pulse leaves a long "trail" of thorium behind it. There is very little thorium ahead of the uranium pulse. As the uranium pulse passes a point, the thorium concentration builds up quickly to its maximum value. As time increases, the qualitative features of Fig. L.3-1 are maintained with both curves moving to the right and undergoing decay.

Figure L.3-1 The Thorium Concentration

The flow rate of radium to the biosphere can be computed from the thorium concentration in the aquifer by an integration analogous to Eq. L.2-2. Because the approximation Eq. L.2-6 is not appropriate, this integral must be evaluated by numerical quadrature. The integral was evaluated in a test case with $V=80$ m/yr, $B_1=10^4$, $B_2=10^5$, $B_3=10^3$, $\alpha=50$ m, and $z=16$ km. Sorption retardation factors are taken from Ref. L.1 and α and z are taken from the baseline repository values of Appendix H, with a sufficiently large V to ensure that ^{234}U will be able to traverse the aquifer in 3 million years. In this case, the peak flow rate of radium was increased by a factor of 7.32 over the flow rate calculated in the $B_1=B_2=B_3=10^4$ case. This result agrees with Eq. L.3-3 which gives $\eta_p < 10$.

In order to evaluate the integrated population dose for radium it is necessary to proceed in a different manner, due to the difficulty in obtaining the radium flow rate with the previous approach. The process of flow in the aquifer is governed by the differential equations (Appendix F):

$$\frac{\partial C_1}{\partial t} = \frac{\alpha V}{B_1} \frac{\partial^2 C_1}{\partial x^2} - \frac{V}{B_1} \frac{\partial C_1}{\partial x} - \lambda_1 C_1 \quad (L.3-4)$$

$$\frac{\partial C_2}{\partial t} = \frac{\alpha V}{B_2} \frac{\partial^2 C_2}{\partial x^2} - \frac{V}{B_2} \frac{\partial C_2}{\partial x} - \lambda_2 C_2 + \frac{B_1}{B_2} \lambda_1 C_1 \quad (L.3-5)$$

$$\frac{\partial C_3}{\partial t} = \frac{\alpha V}{B_3} \frac{\partial^2 C_3}{\partial x^2} - \frac{V}{B_3} \frac{\partial C_3}{\partial x} - \lambda_3 C_3 + \frac{B_2}{B_3} \lambda_2 C_2 \quad (L.3-6)$$

subject to the boundary conditions

$$\begin{aligned} C_i &\rightarrow 0 \text{ as } x \rightarrow \infty, \quad i=1,2,3 \\ C_i &= 0 \text{ for } t=0, \quad i=1,2,3 \\ C_i &= 0 \text{ for } x=0, \quad t \geq 0, \quad i=2,3 \\ C_1 &= \delta(t) \text{ for } x=0, \quad t \geq 0 \end{aligned} \quad (L.3-7)$$

where

$\delta(t)$ denotes the Dirac delta function.

These boundary conditions describe the situation in which a unit impulse of uranium enters the aquifer at time $t=0$. The aquifer is assumed to be semi-infinite for the purpose of setting boundary conditions.

This system of equations (L.3-4 through L.3-7) can be solved explicitly by taking the Laplace transform in the time

domain of each equation and the boundary conditions. For each value of the Laplace parameter s , a system of three ordinary differential equations in the variable x and a set of initial values is obtained. These initial value problems can then be solved for the Laplace transform of $C_3(x,t)$ which is denoted $L(C_3(x,t))$. By linearity, the Laplace transform of the radium flow rate to the biosphere is

$$L(f(z,t)) = VL(C_3(z,t)) \quad (L.3-8)$$

The radium flow rate as a function of aquifer length and time can be obtained by taking the inverse Laplace transform. The total quantity of radium discharged from the aquifer can then be computed by integrating the flow rate over all time. This quantity is, as shown in Appendix G, directly proportional to the integrated population dose. The difficulty inherent in finding the inverse Laplace transform can be avoided by using two standard theorems for Laplace transforms (Ref. L.5):

$$L\left(\int_0^t g(u) du\right) = \frac{1}{s} L(g(t)) \quad (L.3-9)$$

and

$$\lim_{t \rightarrow \infty} g(t) = \lim_{s \rightarrow 0} s L(g(t)) \quad (L.3-10)$$

s is the Laplace transform variable. The net amount of radium leaving the aquifer over all time is:

$$[f] = \int_0^{\infty} f(z,t) dt \quad (L.3-11)$$

The following procedure can now be applied to solve for $[f]$.

$$\begin{aligned}
 [f] &= \int_0^{\infty} f(z,t) dt = \lim_{t \rightarrow \infty} \int_0^t f(z,u) du \\
 &= \lim_{s \rightarrow 0} s L \left(\int_0^t f(z,u) du \right) \\
 &= \lim_{s \rightarrow 0} s \left(\frac{1}{s} L(f(z,t)) \right)
 \end{aligned}$$

So,

$$[f] = \lim_{s \rightarrow 0} L(f(z,t))$$

It can be shown that the result is:

$$\begin{aligned}
 [f] &= \frac{B_1 \lambda_1 B_2 \lambda_2}{(B_1 \lambda_1 - B_2 \lambda_2)(B_2 \lambda_2 - B_3 \lambda_3)(B_1 \lambda_1 - B_3 \lambda_3)} \\
 &\times \left[(B_1 \lambda_1 - B_2 \lambda_2) e^{r_3 z} - (B_1 \lambda_1 - B_3 \lambda_3) e^{r_2 z} \right. \\
 &\quad \left. + (B_2 \lambda_2 - B_3 \lambda_3) e^{r_1 z} \right] \quad (L.3-13)
 \end{aligned}$$

where

$$r_j = \left(1 - \sqrt{1 + 4\alpha B_i \lambda_i / V} \right) / 2\alpha$$

The reconcentration factor for integrated population dose, η_{IPD} , is obtained by taking the ratio of $[f]$ to the value of $[\hat{f}]$ which is obtained by evaluating Eq. L.3-13 with all retardation factors equal. That is,

$$\eta_{IPD} = \frac{[f]}{[\hat{f}]} \quad (L.3-14)$$

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This result is not dependent on the ordering of the retardation factors and may be used for any combination of B_1 , B_2 , and B_3 . Furthermore these results are not dependent on the form of the input to the aquifer (taken here to be a delta function). Rather, the results depend only on the net integrated input to the aquifer.

The values of η_{IPD} found with Eq. L.3-13 and Eq. L.3-14 are in general agreement with results given earlier in this section. In particular, if the parameters are set at $B_1=B_2=10^4$, $B_3=10^3$, $z=16$ km, $\alpha=50$ m, and $V=80$ m/yr, Eq. L.3-2 may be applied. The result is $\eta=10$ at all times and hence, $\eta_{IPD}=10$. If the same parameters are used in Eqs. L.3-13 and L.3-14, the calculated result is $\eta_{IPD}=10.7$.

L.4 SUMMARY

The reconcentration factor has been computed and has been shown to cause the current waste migration model to underestimate certain nuclide flow rates. Methods for calculating the adjusted flow rates have been found in several cases of current interest.

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APPENDIX M

BUILDING AND TRUNCATING EVENT TREES

Event trees provide a useful formalism for analyzing both the relative and absolute importance of accidents that can take place in the nuclear fuel cycle. However, the detailed list of accidents, accident sequences and pathways to the biosphere is so large that a methodology is required to contain the analysis effort within the bounds of time and resources available. For efficiency's sake energies must be focused on the most critical accidents and pathways. This appendix describes an overall methodology which can be used for truncating the event trees developed in this study. Figure M-1 illustrates the steps involved. This description is intended as a conceptual overview of the processes involved in truncating event trees and not as a precise enumeration of the sequence of procedures used in the study. The following is a description of each of the actions listed in the figure.

Forming an Exhaustive List of Accidents - It is the purpose of the event tree methodology to consider at the outset all possible accidents and pathways which might lead to release of radionuclides to the biosphere and exposure of the general public. Therefore no potential accident event or pathway by which nuclides released in an accident can reach the general public is ignored. The list is composed by reference to previous work in the field and conversations with experts in the operations under consideration. The list, while large, can never be considered complete and the effort applied to compiling it is, of necessity,

Figure M-1 Steps Followed in the Development and Truncation of Event Trees

constrained by the time and resources available. The important thing is that the list is never considered closed; the analyst must always be prepared to scrutinize another accident scenario when one is put forward.

Computing Consequences - In order to achieve efficient use of time and resources available in analyzing accident consequences, elements of the exhaustive event tree must be eliminated. The process of elimination may take place even as

the event tree is being formed. However, at some point the analyst will want to apply a strictly mathematical approach to further truncation of the event tree; this is the process described here.

Since the goal of the analysis is to determine the dangers to the general public associated with all or portions of particular fuel cycles, emphasis must be placed on those accidents which provide the greatest danger. Accident scenarios and associated pathways which can be shown to provide consequences orders of magnitude lower than others can be eliminated, at least temporarily. Since most of the accident and release information is statistical in nature the expected value of consequence (risk) is a valid point of comparison.

Eliminating Events and Pathways - Collection of detailed data on all accidents and pathways in the exhaustive event tree is usually beyond the scope of the resources available and a quantitative means of eliminating portions of the tree is needed. The most logical measure of importance is the consequence, in terms of dose to individuals, dose to a population, etc, which results from a particular sequence of events.

While it would be preferable to eliminate events by comparing expected consequences, sufficient statistical data is not always available for all events. This is particularly true for some of the more obscure, and less important, accident sequences. Thus, at least for the initial rounds of elimination, worst-case consequences may be used as well. The important point is that scenarios for which the worst-case consequences are computed can be eliminated if worst-case actions are orders of magnitude less than the expected consequences from other scenarios, but not vice versa. Accidents

and pathways whose expected consequences are well below the worst-case consequences computed for others cannot be eliminated on that basis alone, since the latter set of accident scenarios might prove to have lower expected consequences when more detailed risk calculations are generated.

Attention must also be paid to the uncertainties in the risk calculations which may lead to incorrect elimination of events. This possibility requires reassessment of the outputs of the analysis to be sure that assumptions used in truncating the event tree at any time remain valid at the end of the study.

The comparison of expected consequences and worst-case consequences does not always complicate the analyst's efforts, since statistics are usually more available for those accidents which present the greatest risk. Those scenarios for which statistics are lacking are usually ones which can be eliminated without having to compute an expected consequence.

Improving Analysis of Events in the Truncated Tree -

The purpose of eliminating events and/or pathways from the event tree is to make the risk analysis more efficient by focusing resources on critical events and pathways. More precise descriptions of the statistics associated with accidents and the physical processes associated with release of radionuclides and their migration to contact with the general public can then be sought. In many instances considerable improvement can be gained in understanding the processes by which materials are released in an accident. A case in point is the improvement which has occurred in understanding release functions in transportation accidents during the current year's study.

At this point it is also desirable to be able to compute expected consequences for all events and pathways remaining on the truncated tree. Subsequent truncation should be made on the basis of expected consequences only, if possible.

As knowledge of the statistics of accidents and the mechanisms by which radionuclides are released improves, care must be taken that the resultant changes in expected consequences do not invalidate truncations of the event tree that were made previously.

Recomputing Consequences - It is desired to further reduce the complexity of the event tree, if possible, and to provide a more accurate comparison of risks from the various fuel cycle operations considered. Consequently, the risks resulting from the accidents and pathways remaining in the truncated tree must be recomputed using the improved information developed since the previous truncation. As stated above, the risks should be computed in a technically consistent manner -- i.e., all risks are expected consequences -- to provide the basis for further truncations of the tree.

Eliminating Additional Events or Pathways - After recomputing the risks associated with the accidents and pathways remaining on the event tree, it may be possible to eliminate additional elements of the tree based on risks which are orders of magnitude below those computed for other elements. Again the uncertainties associated with the risk calculations should be borne in mind lest too many events or pathways be eliminated.

As Fig. M-1 shows, the process of improving the accuracy of the data underlying the risk calculations, re-

computing the risks and truncating the event tree can be iterated several times as more and better information about the critical accidents and pathways is generated.

Checking Assumptions Key to Truncating the Tree -

Reducing the complexity of the event tree is a risky but usually necessary operation. In order to ensure that elements of the tree that were discarded might not actually be critical elements in the light of information developed subsequently, it is necessary to check the assumptions and data on which truncations were based. This can be a continuous process but it must be performed at least once -- prior to reporting the results of the risk analysis.

Any elements of the event tree which would not have been eliminated had the final set of assumptions and data been in use at the time of their elimination must be restored to the tree and subjected to the same level of analysis as those elements which were retained. It may turn out that an element restored to the tree can still be eliminated but the analysis based on the final assumptions and data must show this.

Reporting Expected Consequences - The output of the risk analysis can be reported after the above-described consistency check is completed. In addition to risk values associated with the various events and pathways on the truncated tree, careful attention should be given to stating the assumptions and data used in the calculations and the elements which were considered but eliminated. In addition, the uncertainties in the computed risks should be provided to the extent possible.