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RELATIVE POTENTIAL HAZARDS OF RADIOACTIVE WASTE IN VARIOUS WATER SYSTEMS

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ABSTRACT

The potential hazard to man arising from the hypothetical release of radioactive spent fuel waste into various water systems has been evaluated. Radionuclide transport and human exposure were simulated for six water systems: a large North-western river, a small Northeastern river, a small Northwestern river, a large Central Region river, a lake with no outflow in an arid region, and an aquifer discharging directly into an ocean.

TABLE OF CONTENTS

	<u>Page No.</u>
ABSTRACT	ii
List of Figures	v
List of Tables	vii
1. INTRODUCTION	1-1
2. BIDOSE MODEL	2-1
2.1 Derivation of Compartment Equations	2-2
2.2 Model Assumptions	2-4
3. NORTHWESTERN RIVER (BASELINE CASE)	3-1
3.1 Quasi-Steady-State Solution	3-1
3.2 Steady-State Solution	3-5
3.3 Time-Varying Solution	3-6
4. NORTHEASTERN RIVER	4-1
4.1 Introduction	4-1
4.2 Compartmental Model of the Northeastern River	4-1
4.3 Potential Hazard Predictions	4-3
5. SMALL NORTHWESTERN RIVER	5-1
5.1 Model Assumptions	5-1
5.2 Potential Hazard Predictions	5-2
6. LONG, LARGE RIVER IN CENTRAL UNITED STATES	6-1
6.1 Introduction	6-1
6.2 Compartmental Model of the Upper Segment	6-2
6.3 Compartmental Model of the Lower Segment	6-3
6.4 Potential Hazard Predictions	6-5
7. DESERT LAKE WITH NO OUTFLOW	7-1
7.1 Model Assumptions and Predictions	7-1
7.2 Desert Lake Model with Hypothetical Irrigation	7-5
8. AQUIFER INTO THE OCEAN	8-1
8.1 Model Assumptions	8-1
8.2 Potential Hazard Predictions	8-5
9. DISCUSSION	9-1

TABLE OF CONTENTS (Continued)

	<u>Page No.</u>
10. CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK	10-1
APPENDIX A SOLUTION OF COMPARTMENT EQUATIONS	A-1
APPENDIX B COMPARTMENT EQUATIONS FOR NORTHWESTERN RIVER	B-1
APPENDIX C RADIONUCLIDE LIST	C-1
REFERENCES	R-1

LIST OF FIGURES

<u>Figure No.</u>		<u>Page No.</u>
3.1-1	Potential Population Hazard of Spent Fuel for the Large Northwestern River: (a) Quasi-Steady-State Solution, (b) Time-Varying Solution	3-3
3.1-2	Potential Individual Hazard for the Large Northwestern River: (a) Quasi-Steady-State Solution, (b) Time-Varying Solution and (c) Steady-State Solution	3-4
4.3-1	The Potential Individual Hazard for the Northeastern River Case	4-4
4.3-2	The Potential Population Hazard for the Northeastern River Case	4-4
4.3-3	Contours of Equal Peak 50-Year Whole-Body-Equivalent Dose to an Average Individual	4-7
5.2-1	Potential Population Hazard for the Small Northwestern River for (a) Time-Varying Solution and (b) Steady-State Solution and (c) Time-Varying Solution with No Suspended Sediment in Irrigation Water	5-4
5.2-2	Potential Individual Hazard from the Small Northwestern River for (a) Time-Varying Solution, (b) Steady-State Solution and (c) Time-Varying Solution with No Suspended Sediment in Irrigation Water	5-4
6.1-1	Assumed Interface Between Platte-Niobrara and Mississippi River Systems	6-2
6.4-1	The Potential Individual Hazard for the Central River	6-6
6.4-2	The Potential Population Hazard for the Central River	6-6
7.1-1	Potential Population Hazard for the Desert Lake for: (a) Steady-State with No Irrigation, and (b) Time-Varying Topsoil Concentrations	7-3

LIST OF FIGURES (Continued)

<u>Figure No.</u>		<u>Page No.</u>
7.1-2	Potential Individual Hazard for the Desert Lake for: (a) Steady-State with No Irrigation, and (b) Time-Varying Topsoil Concentrations	7-4
8.1-1	Southwestern Portion of the International Commission for the Northwest Atlantic Fishery Area	8-4
8.2-1	Potential Population Hazard from an Aquifer Discharging into the Ocean	8-6
8.2-2	Potential Hazard to an Average Individual from an Aquifer Discharging into the Ocean	8-6

LIST OF TABLES

Table No.		Page No.
3-1	Water System Parameters (Northwestern River)	3-2
3.1-1	Relative Contributions to Population Potential Hazard for the Northwestern River	3-4
3.1-2	Relative Contributions to Individual Potential Hazard for the Northwestern River	3-5
4.2-1	Water System Parameters (Northeastern River)	4-2
4.2-2	Aquatic Food Harvest (Edible kg)	4-3
4.3-1	Critical Pathways (Average Individual)	4-6
4.3-2	Critical Pathways (Population)	4-6
5.1-1	Simulation Parameters for Small Northwestern River	5-3
5.2-1	Relative Contributions to Population Potential Hazard for the Small Northwestern River	5-5
5.2-2	Relative Contributions to Individual Hazard Potential for the Small Northwestern River	5-6
6.2-1	Water System Parameters (Upper Segment)	6-3
6.3-1	Water System Parameters (Lower Segment)	6-4
6.3-2	Aquatic Food Harvest (Lower Segment)	6-5
6.4-1	Critical Pathways (Average Individual)	6-8
6.4-2	Critical Pathways (Population)	6-9
7.2-1	Relative Contributions of Various Pathways to Potential Population Hazard for the Desert Lake	7-7
7.2-2	Relative Contributions to Potential Individual Hazard for the Desert Lake	7-7
8.1-1	Parameter Values for Simulation of Aquifer into the Ocean	8-5

LIST OF TABLES (Continued)

<u>Table No.</u>		<u>Page No.</u>
9-1	Potential Hazard to the Population from Spent Fuel: Sensitivity to Water System	9-1
9-2	Potential Hazard to an Individual from Spent Fuel: Sensitivity to Water System	9-2

1.

INTRODUCTION

This report presents the results of BIODOSE program simulations of various surface water systems. The purpose of the work was to compare the potential hazard to man resulting from possible releases of spent fuel into the various water systems. Sensitivities of the various simulation models to parameter values and to simplifying assumptions were also examined. The BIODOSE model is described in Appendix G of Ref. 1.

The following water system scenarios were investigated:

- Large river in the Northwest (baseline case)
- Typical river in the Northeast
- Small river in the Northwest
- Very long, large river in the Central U.S.
- Lake with no outflow in an arid region
- Aquifer discharging directly into the ocean.

These scenarios were chosen to be representative of a variety of water systems which could receive releases from a radioactive waste repository. The results presented herein are intended for use in evaluating the relative magnitudes of potential hazards for different types of water systems. Even though in most cases parameters from specific water bodies were used, the models are not intended to represent specific

existing water bodies and their proximity to possible repositories. Also the models were developed principally for comparative purposes, and the assumptions are not necessarily conservative, in the sense of predicting an upper bound to hazards in the light of uncertainties. Consequently, there is less uncertainty in comparing predicted hazards of one simulated water system to those of another than in comparing one water system simulation to any actual water system that might receive waste.

The assumptions and internal structure used in the basic BIDOSE model were also examined. Specifically, the sufficient mathematical conditions for the solution method used in the model for the treatment of the decay of the over-all radionuclide inventory rather than the decay of the radionuclides present in each compartment (soil or water body) were analyzed. Expressions for time-varying radionuclide concentration in all compartments were derived, and the results for some water systems were compared to the steady-state concentrations.

In all of the cases studied, the predicted potential hazards are the doses that would result from a yearly input to the river or lake of spent fuel from one MWe-yr of power production. This unit was chosen merely as a normalization factor, not as an estimate of the rate at which waste will be released to surface waters. To convert potential hazards to expected doses, the predicted inputs must be taken into account. All barriers which might impede such releases are ignored, and therefore the results of these calculations are not to be taken as estimates of future doses to man. The individual potential hazards are expressed as fifty-year doses in man-rem due to fifty years of exposure resulting from an input rate of one MWe-yr/yr. The population potential hazards are expressed as annual doses (averaged over fifty years due to a fifty-year exposure) in man-rem resulting from an input rate of one MWe-yr/yr.

2.

BIODOSE MODEL

The basic BIODOSE model predicts doses to humans from releases of radionuclides to the surface environment. It simulates soil and water bodies as perfectly mixed compartments with many dose pathways to man including aquatic food, crops, animal products, drinking water and ground exposure. Air pathways were not considered. The model is described in more detail in Appendix G of Ref. 1. It is similar in basic structure to other models having a similar purpose (Refs. 2 through 4).

The time frame of the model simulations is five million years. The basic conditions and parameters (such as physical flow rates between compartments, diet factors and usage rates) are assumed to be unchanged during this time period. Different hypothesized scenarios can be modeled and tested with the program, however.

The BIODOSE model was developed initially to simulate a large river in the Northwestern United States. A quasi-steady-state compartment model was appropriate for the parameters used (Ref. 1). However, for some of the cases considered in this study, it was found necessary to use time-varying solutions to the compartment equations due to the large times required for concentrations of radionuclides in topsoil to reach a steady state. The derivation of the general compartment equations and their time-varying solutions are described below.

2.1 DERIVATION OF COMPARTMENT EQUATIONS

The general system of equations describing the amount of nuclide r in each compartment can be expressed as follows:

$$V \frac{dC_r}{dt} = -\lambda_r VC_r + A_r C_r + Q_r + \sum_s \lambda_r VC_s \quad (2.1-1)$$

where

C_r is a vector of dimension n whose components are the concentrations of nuclide r in the n compartments (C_i/m^3)

λ_r is the radioactive decay constant for nuclide r (yr^{-1}). Note that λ_s does not enter into the equation for nuclide r because concentrations are given in curies

A_r is the matrix of volumetric flow rates with the off-diagonal elements a_{ij} representing transfer from compartment j to compartment i and the diagonal elements a_{ii} being the flow rates out of compartment i (m^3/yr)

Q_r is the vector of inputs to the compartments (C_i/yr)

V is a diagonal matrix whose elements are the compartment volumes (m^3)

s is a subscript labeling those nuclides which decay into nuclide r .

Equation 2.1-1 can be simplified in a manner similar to that described in Section F.2.1 of Ref. 1 for the transport equations in a stream tube. The nuclide concentrations in each compartment can be expressed as ratios to the total inventory of that nuclide, viz.,

$$c_r = C_r / I_r \quad (2.1-2)$$

where I_r is the total amount (Ci) of nuclide r from the waste in existence anywhere at a given time. The differential equation for I_r can be written as

$$\frac{dI_r}{dt} = -\lambda_r I_r + \sum_s \lambda_s I_s \quad (2.1-3)$$

Combining the above equations yields

$$V \frac{dc_r}{dt} = A_r c_r + \frac{Q_r}{I_r} + \sum_s \lambda_r \frac{I_s V}{I_r} (c_s - c_r) \quad (2.1-4)$$

Assume that $c_r(0) = c_s(0) = 0$; that is, nuclide r and its parents are not present in the compartments at time zero. By the uniqueness theorem for differential equations, $c_r = c_s$ if the compartment flow matrix is the same for both nuclide r and nuclide s . Therefore, if $A_r = A_s$ for any s (which is assumed in all the cases which follow),

$$\frac{dc_r}{dt} = V^{-1} A_r c_r + V^{-1} g_r \quad (2.1-5)$$

where $g_r = \frac{Q_r}{I_r}$. The compartment equations are thus simplified by expressing the radionuclide concentrations as proportions of total inventory and thereby avoiding analysis of decay chains. The assumption that the compartment flow matrices are identical for every nuclide in a decay chain is not strictly true. The distribution coefficients for the sediment compartments, the retardation factors for the topsoil (see Appendix B for detailed definitions) and the crop removal rates are included in the compartment flow matrix, A_r , and vary for each

nuclide considered in the BIDOSE program. One important decay chain, $^{230}\text{Th} \rightarrow ^{226}\text{Ra}$, has a difference of two orders of magnitude in the soil retardation factors used in the BIDOSE program (5×10^4 vs 5×10^2 , respectively). Since ^{226}Ra is the major contributor to the potential hazard of spent fuel and HLW from uranium fuels beyond 50,000 years, the error introduced by the above assumption of equality of the A_r and A_s matrices may be significant. It is recommended that the sensitivity to the above assumption be investigated. The solution method discussed in Appendix A could easily be extended to cover compartment equations involving decay chains.

2.2 MODEL ASSUMPTIONS

Several key assumptions of this study, which should be noted in interpreting the simulation results, and which are explained in more detail at various appropriate points in the report, are summarized here for convenience:

- Water and soil bodies are modeled as perfectly-mixed compartments with first-order transfer rates
- Radionuclide doses are linear functions of concentration
- The annual rate at which spent fuel enters the water body is normalized to be the waste from one MWe-yr of power production
- The potential population hazard predictions are expressed as whole-body-equivalent doses to the population per unit of waste entering the water system in units of man-rem per yr per MWe-yr/yr
- The potential individual hazard predictions are expressed as fifty-year

whole-body-equivalent doses to individuals eating an average diet of food, all of which is from contaminated areas, per unit of waste entering the water system per year, in units of rem per MWe-yr/yr

- To convert potential hazards to doses, the rate at which waste enters the water system must be taken into account.

3. NORTHWESTERN RIVER (BASELINE CASE)

The baseline case of a large river in the Northwest (modeled after the Columbia River) has been described previously (Refs. 1 and 5). In this section, the sensitivity of predicted hazard to the earlier assumption of quasi-steady-state conditions in the compartments and limited irrigation periods is evaluated.

The equations and parameter values used in this study were the same as those described in Refs. 1 and 5 except that topsoil erosion was added as a pathway from the topsoil compartment to the river or lake compartment. For convenience and completeness, the compartment equations are repeated in Appendix B in vector form and key parameters are given in Table 3-1. A list of the radionuclides considered in the study are given in Appendix C.

Three different solutions to the set of compartment equations were compared: quasi-steady-state with the topsoil radionuclide buildup over a relatively short time period, steady-state, and time-varying for all the compartments with continuous topsoil nuclide buildup.

3.1 QUASI-STEADY-STATE SOLUTION

The quasi-steady-state solution takes into account the effect of nuclide buildup in the topsoil. The topsoil buildup time is long compared with changes in the input. This solution also assumes that irrigation occurs for a relatively short time period as explained in Ref. 1. In this simulation

TABLE 3-1
WATER SYSTEM PARAMETERS
(NORTHWESTERN RIVER)

T-1431a

PARAMETER	VALUE
River Flow Rate	$1.2 \times 10^{11} \text{ m}^3/\text{yr}$
Estuary Volume	$2.6 \times 10^9 \text{ m}^3$
Estuary Flushing Time	2.5 day
Ocean Volume	$6 \times 10^{12} \text{ m}^3$
Ocean Flushing Time	122 days
Irrigation Rate	4% of Flow
Topsoil Area	$4.8 \times 10^9 \text{ m}^2$
Topsoil Volume	$7.2 \times 10^8 \text{ m}^3$
Rainfall, Evapotranspiration	Equal Values
Population Density	$50/\text{km}^2$

it was assumed that irrigation took place every year to a maximum of one thousand years.* For times later than one thousand years, it was assumed that irrigation took place only over the preceeding one thousand years. The equations used here were very similar to those of Ref. 1 except that a topsoil erosion pathway was included and that the ocean compartment was redefined to exclude the plume compartment. The resulting equations are given in Appendix B. The parameter values used in the quasi-steady-state solution are, in addition to those listed in Ref. 1, the following:

*In Ref. 1, irrigation took place one tenth of the time up to one thousand years and then over the previous 100 years thereafter. Irrigation every year was assumed here to make comparison to the time-varying solution easier.

$$S_t = 6.1 \times 10^{-5} \text{ m/yr (erosion rate)}$$

$$v_w = 0.001 \text{ m/yr (river sedimentation rate)}$$

$$v_e = 0.1 \text{ m/yr (estuary sedimentation rate)}$$

This solution gave rise to the potential hazards indicated in Figs. 3.1-1 and 3.1-2. Changing the maximum irrigation period from one thousand years to millions of years in the quasi-steady-state case resulted in virtually no change in the total predicted hazard. The relative contributions to the potential population hazard from the different dose pathways are summarized in Table 3.1-1. Irrigated crops are responsible for the major proportion of potential hazard. For the individual potential hazard the relative contributions are similar in rank to those for the population, as indicated in Table 3.1-2. The exception is that animal products make up the major pathway

Figure 3.1-1 Potential Population Hazard of Spent Fuel for the Large Northwestern River: (a) Quasi-Steady-State Solution, (b) Time-Varying Solution (Note assumptions in Section 2.2)

Figure 3.1-2 Potential Individual Hazard for the Large Northwestern River: (a) Quasi-Steady-State Solution, (b) Time-Varying Solution and (c) Steady-State Solution (Note assumptions in Section 2.2)

TABLE 3.1-1
RELATIVE CONTRIBUTIONS TO POPULATION POTENTIAL HAZARD FOR THE
NORTHWESTERN RIVER (QUASI-STEADY-STATE SOLUTION)

T-3005a

NUCLIDE CLASS (TIME)	PATHWAY (COMPARTMENT)	CONTRIBUTION	
		man-rem/MWe-yr	PERCENT
Fission Products (At 100 Years)	Vegetables (Topsoil)	6.2×10^4	73
	Vegetables (River)	1.2×10^4	14
	Drinking Water (River)	6.6×10^3	8
Actinides (At 200,000 Years)	Vegetables (River)	1.7×10^2	30
	Vegetables (Topsoil)	1.6×10^2	28
	Animal Products (River)	1.4×10^2	24
	Drinking Water (River)	9.0×10^1	16

TABLE 3.1-2
RELATIVE CONTRIBUTIONS TO INDIVIDUAL POTENTIAL HAZARD FOR
THE NORTHWESTERN RIVER (QUASI-STEADY-STATE SOLUTION)

T-3005b

NUCLIDE CLASS (TIME)	PATHWAY (COMPARTMENT)	CONTRIBUTION	
		rem/MWe	PERCENT
Fission Products (At 100 Years)	Vegetables (Topsoil)	1.5×10^{-1}	54
	Vegetables (River)	3.1×10^{-2}	11
	Drinking Water (River)	2.7×10^{-2}	10
	Animal Products (River)	2.5×10^{-2}	9
	Ground Exposure (Topsoil)	2.1×10^{-2}	7
	Animal Products (Topsoil)	1.1×10^{-2}	4
	Aquatic Food (River)	8.4×10^{-3}	3
Actinides (At 200,000 years)	Animal Products (River)	8.2×10^{-4}	36
	Vegetables (River)	4.2×10^{-4}	18
	Vegetables (Topsoil)	4.0×10^{-4}	17
	Drinking Water (River)	3.7×10^{-4}	16
	Aquatic Food (Estuary)	1.8×10^{-4}	8

for actinides at 200,000 years. All references in subsequent text to the baseline case or Northwestern river case are to the quasi-steady-state solution.

3.2 STEADY-STATE SOLUTION

The steady-state solution to Eq. 2.1-5 is:

$$c_r = -A_r^{-1} q_r \quad (3.2-1)$$

This solution was evaluated using the same parameter values as for quasi-steady-state solution of Section 3.1. The predicted population hazard is essentially indistinguishable from the time-varying results discussed in Section 3.3. The individual potential hazard for fission products is slightly above the time-varying solution, as depicted in Fig. 3.1-2.

3.3 TIME-VARYING SOLUTION

The time-varying solution described in Appendix A was also computed for this water system. To prevent numerical difficulties associated with having too large a range of eigenvalues of the $(V^{-1}A_r)$ matrix, the system was decoupled and two sets of equations were solved sequentially. The $(V^{-1}A_r)$ matrix in Eq. 2.1-5 has a structure which readily lends itself to decoupling. The equations for the first three compartments can be solved independently of the last four compartment equations. Then, the system of equations for the last four compartments can be solved with the input to the estuary compartment being $(F_{c_{rw}})$. The mathematical structure of each of the two subsystems is thus identical.

The input q_r was set equal to one for all time periods, which is conceptually equivalent to assuming that all nuclides in the waste go into solution in the river. The waste from one MWe-yr of power production enters the river each year.

The time-varying solution resulted in potential population hazard predictions that were within 25 percent of the steady-state predictions at 100 years and within one percent of the steady-state levels by the 5000 year point. The time-varying potential hazards are indicated in Figs. 3.1-1 and 3.1-2. These hazards differ little from the quasi-steady-state

predictions except for actinides in the earlier time periods. The differences in the predictions of actinide hazard at early times are due to lower predicted river concentrations in the quasi-steady-state solution and to delays in sediment buildup in the time-varying solution compared to steady-state. The quasi-steady-state solution neglects certain terms in the equation for river concentration, which appear to cause the minor differences.

The differences in the three solutions for this water body case are relatively small. However, in several of the cases which follow, the differences are not minor.

4. NORTHEASTERN RIVER

4.1 INTRODUCTION

The second case study of various water systems was for a Northeastern River. The Connecticut River was selected as representative. Two distinct scenarios were considered. In the first, the river discharge was assumed to flow into and mix with a large volume of the Atlantic Ocean. The second case considered the more conservative assumption that the radionuclides from the river were entirely contained within Long Island Sound. The next section outlines the assumed model for the river and the final section discusses the results of the potential hazard calculations.

4.2 COMPARTMENTAL MODEL OF THE NORTHEASTERN RIVER

The BIODOSE program, as described in Chapter 2 of this report and Appendix G of Ref. 1, consists of a compartmental model of a river-estuary-ocean system. Since the Connecticut River is this type of system, no changes were necessary to the basic structure of the model. However, the water system parameters and aquatic harvest data for the Connecticut are significantly different from the baseline system described in Section 3.1 and Ref. 1. Tables 4.2-1 and 4.2-2 contain the relevant values assumed in this study. Any parameters not specified in either table were taken to be the same as in Ref. 1.

TABLE 4.2-1
WATER SYSTEM PARAMETERS (NORTHEASTERN RIVER)

T-2984

PARAMETER	VALUE	REFERENCE
Flow Rate	$1.77 \times 10^{10} \text{ m}^3/\text{yr}$	6
Irrigation Rate	4 Percent of Flow Rate	1
Estuary Volume	$1.1 \times 10^8 \text{ m}^3$	7
Estuary Flushing Time	$7.95 \times 10^{-3} \text{ yr}$	7
Ocean Volume	$\left\{ \begin{array}{l} 1.9 \times 10^{12} \text{ m}^3 \\ (6.2 \times 10^{10} \text{ m}^3)^* \end{array} \right.$	$\begin{array}{l} 5 \\ 8 \end{array}$
Ocean Flushing Time	$\left\{ \begin{array}{l} 0.333 \text{ yr} \\ (0.263 \text{ yr})^* \end{array} \right.$	$\begin{array}{l} 9 \\ 7 \end{array}$
Plume Volume	$2.4 \times 10^7 \text{ m}^3$	10
Plume Depth	1 m	10
Areas:		
River	$9.7 \times 10^7 \text{ m}^2$	**
Estuary	$5.1 \times 10^7 \text{ m}^2$	7
Plume	$2.4 \times 10^7 \text{ m}^2$	10
Ocean	$\left\{ \begin{array}{l} 3.8 \times 10^{10} \text{ m}^2 \\ (3.2 \times 10^9 \text{ m}^2)^* \end{array} \right.$	$\begin{array}{l} \dagger \\ 8 \end{array}$
Topsoil	$2.1 \times 10^9 \text{ m}^2$	††
River Sediment	$9.7 \times 10^7 \text{ m}^2$	**
Estuary Sediment	$5.1 \times 10^7 \text{ m}^2$	7
Shoreline Length	$1.25 \times 10^5 \text{ m}$	--

*Values for Long Island Sound only (assumes river outflow does not leave Long Island Sound)

†Approximate value for International Commission for the Northwest Atlantic Fisheries (ICNAF) area 5ZW (Ref. 12).

**Approximate value for length of $4.8 \times 10^5 \text{ m}$ (300 naut. miles).

††Assumes $1/3 \text{ m}^3$ of irrigation water per 1 m^2 of topsoil irrigated.

TABLE 4.2-2
AQUATIC FOOD HARVEST (EDIBLE kg)

AQUATIC FOOD TYPE	RIVER*	ESTUARY*	OCEAN (REF. 12)	LONG ISLAND SOUND (REF. 13)
Fish	4.8×10^4	2.6×10^4	3.9×10^7	2.4×10^5
Mollusk	--	--	4.3×10^6	9.1×10^3
Crustacean	--	--	4.2×10^5	8.9×10^4

*Estimates, see Table D-8 of Ref. 11.

4.3 POTENTIAL HAZARD PREDICTIONS

The quasi-steady-state solution was used for this case. The potential hazard to an average individual for the Northeastern river system is shown in Fig. 4.3-1 as a function of time since removal from the reactor. This data may be compared with the result for the baseline case depicted as curve (a) in Fig. 3.1-2. The potential hazard (to an average individual) arising from nuclear waste entering the Northeastern river is at least a factor of three greater than that of the baseline system. The higher dose is the result of the lower flow rate of the Northeastern river ($1.8 \times 10^{10} \text{ m}^3/\text{yr}$ vs $1.2 \times 10^{11} \text{ m}^3/\text{yr}$ for the baseline system).

The population potential hazard is shown in Fig. 4.3-2. These results are similar to those shown in Fig. 3.1-1. This similarity is not surprising since the population dose is based upon the capability of the water system to support a group of adults consuming an average diet. That is, the total size of the population is determined by the ratio of the total quantity of vegetable (and animal) products produced via irrigation to the amount of these products consumed in the average diet.

Figure 4.3-1 The Potential Individual Hazard for the Northeastern River Case (Note assumptions in Section 2.2)

Figure 4.3-2 The Potential Population Hazard for the Northeastern River Case (Note assumptions in Section 2.2)

For the assumed Northeastern river, the lower flow rate results in less available irrigation water and consequently smaller yields. The number of individuals in the population supported by the river is thus lower, but coupled with the higher individual dose, the total population dose remains relatively unchanged.

The second case investigated assumed that all of the river outflow was restricted to Long Island Sound. No noticeable change in the potential hazard was found. This relative insensitivity is readily explained by examining the critical exposure pathways. Tables 4.3-1 and 4.3-2 list the critical pathways for the average and population dose respectively. From the tables it is obvious that river water is the dominant contributor to dose. Thus, changes in the water system model parameters below the estuary should not have a significant impact.

An alternative method of presenting the above information is to plot contour lines of constant dose as a function of lumped parameters. Figure 4.3-3 is a plot of contours of equal peak 50-year whole-body-equivalent dose to an average individual as a function of the total flow time and total pulse width defined in Section 3.1.1 of Ref. 5. Sorption retardation (see Appendix B for definition) was included in the calculations resulting in differing flow velocities for each nuclide class. The assumed retardation factors were: 1 for ^{129}I and ^{99}Tc , 100 for other fission products, and 10,000 for actinides.

Comparing the potential hazard for the Northeastern river to the baseline system (see Chapter 3) yields the following observations:

5.

SMALL NORTHWESTERN RIVER

The third water system simulated with BIODOSE was that of a relatively small river with irrigation withdrawals and large suspended sediment loads. The Missouri River above Fort Peck Reservoir in Montana was chosen as representative of such a water body system. The river, river sediment and irrigated topsoil were considered. Any effects downstream of the river section modeled were not taken into account.

5.1 MODEL ASSUMPTIONS

The previous compartment equations were altered to take into account the mechanism of suspended sediment being carried in irrigation water. Furthermore, eroded topsoil was assumed to go back into the river sediment compartment rather than the water compartment, as in the previous formulation. All sediment is considered to originate in, or return to, the sediment compartment, for consistency. Since only three compartments were modeled, the compartment flow matrix A_r was reduced to a 3×3 matrix consisting of the first three rows and columns of the matrix of Eq. B-2 with the following element changes:

$$a_{12} = (I+R-E)/(\theta B_{rt} V_w) \quad (5.1-1)$$

$$a_{32} = A_t S_t / V_s \quad (5.1-2)$$

$$a_{33} = - \left[\frac{DA_s}{dK_{rs}} + A_s v_w + IR_s \right] / V_s \quad (5.1-3)$$

$$a_{23} = IR_s / V_t \quad (5.1-4)$$

where R_s is the ratio of suspended sediment volume to irrigation water volume.

The parameter values used in the simulation were the same as for the Northwestern river except for those values listed in Table 5.1-1. The irrigation withdrawal as a fraction of river flow rate was roughly the same as for the baseline case (4 percent); however, the river flow rate itself in this case was only 7 percent of the baseline case. The concentration of radionuclides in the river, and consequently in the irrigation water, was therefore predicted to be much higher than in the baseline case, resulting in the topsoil becoming a relatively more important pathway to man. In addition, the sediment in the irrigation water was assumed to contribute significantly to topsoil concentration buildup. Consequently, the time-varying solution for this case was thought to represent a more realistic and less conservative prediction than the steady-state.

5.2 POTENTIAL HAZARD PREDICTIONS

The resulting predicted potential hazards for the population and average individual are shown in Figs. 5.2-1 and 5.2-2. The potential hazards are roughly of the same order of magnitude as the Northwestern river hazards for the population but up to a factor of fifteen higher for the individual. The relative contributions to the whole-body-equivalent potential population hazard for the various pathways are summarized in Table 5.2-1. The early fission product hazard is due mainly to the topsoil contribution with 77 percent of the total coming from soil water being taken up into crops. In comparison, for the baseline Northwestern river the vegetables (topsoil) accounted for 73 percent of the fission hazard at 100 years. The actinide hazard peak at 200,000 years also results

TABLE 5.1-1
SIMULATION PARAMETERS FOR SMALL NORTHWESTERN RIVER

T-2994

PARAMETER	VALUE	REFERENCE
A_s, A_r (area of sediment and river)	$1.65 \times 10^9 \text{ m}^2$	14
V_w (volume of water in river, assumed 1.3 feet deep)	$1.0 \times 10^9 \text{ m}^3$	14
V_s (volume of sediment, assumed 12 inches deep)	$5.0 \times 10^8 \text{ m}^3$	14
I (irrigation withdrawal)	$3.42 \times 10^8 \text{ m}^3/\text{yr}$	14
v_w (sedimentation rate, assumed equal to one-tenth the sediment load of the river divided by the river area)	$2.5 \times 10^{-4} \text{ m/yr}$	14
A_t (area of topsoil, calculated by dividing the reported irrigation volumetric rate by the reported irrigation depth rate average)	$6.23 \times 10^8 \text{ m}^2$	14
R (rainfall, 15.25 inches/yr times A_t)	$2.4 \times 10^8 \text{ m}^3/\text{yr}$	14
E (evapotranspiration, 29.85 inches/yr times A_t)	$4.7 \times 10^8 \text{ m}^3/\text{yr}$	14
V_t (volume of topsoil, assumed 12 inches deep)	$2.3 \times 10^8 \text{ m}^3$	14
F (flow of river, assume equal to flow into Fort Peck Reservoir)	$8.8 \times 10^9 \text{ m}^3/\text{yr}$	14
Fish Harvest (commercial plus recreational national average times 0.28 edible fraction)	$3.4 \times 10^5 \text{ kg/yr}$	11
R_s (ratio of suspended sediment to irrigation water, assumed equal to sedimentation load/flow of river)	7.8×10^{-4}	14
E_r (topsoil erosion rate, assumed equal to suspended sediment load to topsoil necessary to achieve mass balance)	$2.7 \times 10^5 \text{ m}^3/\text{yr}$	14

mainly from the vegetable (topsoil) pathway. The relative contributions to the individual potential hazard, as shown in Table 5.2-2, are very similar to those for the Northwestern river (Table 3.1-2). The vegetable and animal product pathways again dominate.

The steady-state solutions are shown in Figs. 5.2-1 and 5.2-2 for comparison. The differences between the time-varying and steady-state solutions for both the potential population and individual hazard predictions are due almost entirely to topsoil pathways. Also indicated in Figs. 5.2-1

Figure 5.2-1 Potential Population Hazard for the Small Northwestern River for (a) Time-Varying Solution and (b) Steady-State Solution and (c) Time-Varying Solution with No Suspended Sediment in Irrigation Water (Note Assumptions in Section 2.2)

Figure 5.2-2 Potential Individual Hazard from the Small Northwestern River for (a) Time-Varying Solution, (b) Steady-State Solution and (c) Time-Varying Solution with No Suspended Sediment in Irrigation Water (Note Assumptions in Section 2.2)

TABLE 5.2-1
RELATIVE CONTRIBUTIONS TO POPULATION POTENTIAL HAZARD FOR
THE SMALL NORTHWESTERN RIVER (TIME-VARYING SOLUTION)

T-2995

NUCLIDE CLASS (TIME)	PATHWAY (COMPARTMENT)	CONTRIBUTION	
		man-rem/MWe-yr	PERCENT
Fission Products (At 100 Years)	Vegetables (Topsoil)	7.0×10^4	77
	Vegetables (River Irrigation Water)	9.8×10^3	11
	Animal Products (River)	4.8×10^4	3
	Animal Products (Topsoil)	2.8×10^4	1
Actinides (At 200,000 Years)	Vegetables (Topsoil)	1.9×10^2	37
	Vegetables (River Irrigation Water)	1.4×10^2	26
	Animal Products (River)	1.1×10^2	21
	Drinking Water (River)	7.4×10^1	14

and 5.2-2 are the time-varying solution estimates with the suspended sediment parameters set equal to zero. For the individual, the differences in the actinide potential hazard result almost entirely from the topsoil ground exposure difference; while for the population, the vegetable (topsoil) pathway accounts for the difference.

The conclusions are summarized as follows:

- The predicted potential population hazards for this water body system are roughly comparable to those of the two previous cases.
- The potential individual hazards are significantly higher than those of the Northwestern river case.

TABLE 5.2-2
RELATIVE CONTRIBUTIONS TO INDIVIDUAL HAZARD POTENTIAL FOR
THE SMALL NORTHWESTERN RIVER (TIME-VARYING SOLUTION)

T-3005c

NUCLIDE CLASS (TIME)	PATHWAY (COMPARTMENT)	CONTRIBUTION	
		rem/MWe	PERCENT
Fission Products (At 100 Years)	Vegetables (Topsoil)	2.5×10^0	55
	Aquatic Food (River)	8.6×10^{-1}	19
	Vegetables (River)	3.5×10^{-1}	8
	Drinking Water (River)	3.1×10^{-1}	7
	Animal Products (River)	2.7×10^{-1}	6
	Animal Products (Topsoil)	1.7×10^{-1}	4
Actinides (At 200,000 Years)	Animal Products (River)	9.4×10^{-3}	31
	Vegetables (Topsoil)	6.7×10^{-3}	22
	Vegetables (River)	4.8×10^{-3}	16
	Drinking Water (River)	4.2×10^{-3}	14
	Aquatic Food (River)	4.1×10^{-3}	13
	Ground Exposure (Topsoil)	9.5×10^{-4}	3

- The suspended sediment in the irrigation water is an important pathway.
- The time-varying solution appears to give more realistic and less conservative predictions in that it allows for nuclide buildup times, but it also may be subject to more uncertainty in that it is sensitive to more parameters, particularly ones that are highly variable in nature (such as distribution coefficients). Suitable caution should be used in the interpretation of these results.

6. LONG, LARGE RIVER IN CENTRAL UNITED STATES

6.1 INTRODUCTION

The fourth study of a water system simulated with BIDOSE was that of a long, large river in the central United States. The representative river was assumed to consist of two segments: a tributary of the main river from which significant withdrawals are made for purposes of irrigation, and the main river with high flow rate. The first segment was based upon the characteristics of the Platte and Niobrara rivers located in the Missouri River basin. This choice was motivated by the relatively large agricultural area under irrigation (Ref. 15). The second segment was chosen to be the main stem of the Mississippi River from Cairo, Illinois to the Gulf of Mexico. As of 1974 there were no current or planned agricultural diversions of water from the main stream of the Mississippi River (Ref. 16, Appendix C). However, frequent flooding of the Mississippi does provide a small pathway for the deposition of nuclides on cropland. This pathway is discussed in more detail in Section 6.3. The assumed interface between the Platte-Niobrara River system and the lower Mississippi River is depicted in Fig. 6.1-1.

Compartmental models for the upper (Platte-Niobrara) and lower (lower Mississippi River) segments are discussed in Sections 6.2 and 6.3 respectively. Results of BIDOSE calculations of the potential hazard to man of spent fuel entering the combined river system are presented in Section 6.4.

R-41188

Figure 6.1-1 Assumed Interface Between Platte-Niobrara and Mississippi River Systems

6.2 COMPARTMENTAL MODEL OF THE UPPER SEGMENT

The upper system was modeled with three compartments:

- River water
- Topsoil
- River sediment.

Potential nuclide concentrations and doses were calculated via two different methods: the time-varying solution discussed in Appendix A was employed to evaluate the potential hazard in the upper segment, and the quasi-steady-state solution described in Section 3.1 was used to calculate hazards in the lower segment. The time-varying solution was chosen for the upper segment so that the exact nuclide flow rate ($F_{c_{rw}}$) would be input to the lower segment. The water system parameter values for this case are given in Table 6.2-1.

TABLE 6.2-1
WATER SYSTEM PARAMETERS (UPPER SEGMENT)

T-2987

PARAMETER	VALUE	REFERENCE
Flow Rate	$5.1 \times 10^9 \text{ m}^3/\text{yr}$	15
Irrigation Rate	15 Percent of Flow Rate	15
Areas:		
River	$1 \times 10^8 \text{ m}^2$	15
Topsoil	$1.6 \times 10^9 \text{ m}^2$	15
River Sediment	$1 \times 10^8 \text{ m}^2$	15
Volumetric Ratio of Suspended Sediment to River Water	2.4×10^{-3}	14
River Sedimentation Rate	$1.0 \times 10^{-3} \text{ m/yr}$	1
Topsoil Erosion Rate*	$1.38 \times 10^{-3} \text{ m/yr}$	--
Rainfall	$7.8 \times 10^8 \text{ m}^3/\text{yr}$	14
Evapotranspiration	$1.3 \times 10^9 \text{ m}^3/\text{yr}$	14
Harvest (Estimated Edible Finfish from River Only)	$1.4 \times 10^4 \text{ kg/yr}$	11

*Chosen to balance topsoil volume (i.e., deposition via suspended sediment must equal loss via erosion).

6.3 COMPARTMENTAL MODEL OF THE LOWER SEGMENT

The lower segment was modeled as consisting of all eight compartments in the baseline model. The Mississippi River delta consists of several passes (or branches, see Ref 17), three of which - Pass a Loutre, South Pass and Southwest Pass - account for over 70 percent of the discharge into the Gulf of Mexico. Since detailed data is available for South Pass (Refs. 17 and 18), it was assumed that the parameters for the other passes could be scaled in proportion to their respective discharge percentages. The estuary-plume pairs for each of the passes were combined into a single estuary and plume consistent with the BIDOSE compartment model.

As noted in Section 6.1, water from this segment is normally not used for irrigation. There is, however, a pathway for river water to reach cropland. The almost annual spring flooding along the main stem of the river (Ref. 16, Appendix E), has the effect of irrigating cropland adjacent to the river banks. This is the only agricultural pathway modeled for the lower segment. Suspended sediment was not included in the simulated flood water since the potential hazard from the lower segment was so low (Table 6.4-1) compared to the upper segment that the added hazard from the suspended sediment was considered negligible. The effect of suspended sediment in irrigation (or flood) water was studied independently in the small Northwestern river case (Chapter 5). Table 6.3-1 contains the relevant water system parameter values.

TABLE 6.3-1
WATER SYSTEM PARAMETERS (LOWER SEGMENT)

T-2988

PARAMETER	VALUE	REFERENCE
Flow Rate	$5.1 \times 10^{11} \text{ m}^3/\text{yr}$	Ref. 16, Appendix C
Irrigation Rate*	1.6×10^{-4} Flow Rate	-
Estuary Volume	$3.6 \times 10^8 \text{ m}^3$	Refs. 17, 18
Estuary Flushing Time	$9.1 \times 10^{-4} \text{ yr}$	Refs. 17, 18
Ocean Volume†	$1.5 \times 10^{10} \text{ m}^3$	-
Ocean Flushing Time	0.27 yr	Ref. 9
Plume Volume	$1.1 \times 10^9 \text{ m}^3$	Refs. 17, 18
Plume Depth	1 m	Refs. 17, 18
Areas:		
River	$1.4 \times 10^9 \text{ m}^2$	Ref. 16, Appendix C
Estuary	$3.4 \times 10^7 \text{ m}^2$	Refs. 17, 18
Plume	$1.1 \times 10^8 \text{ m}^2$	Refs. 17, 18
Ocean†	$7.7 \times 10^8 \text{ m}^2$	-
Topsoil	$5.4 \times 10^8 \text{ m}^2$	Ref. 16, Appendix I
River Sediment	$1.4 \times 10^8 \text{ m}^2$	Ref. 16, Appendix C
Estuary Sediment	$3.4 \times 10^7 \text{ m}^2$	Refs. 17, 18
Shoreline Length	$1.6 \times 10^5 \text{ m}$	-

*Assumed to cover topsoil area to a depth of 0.15 m.

†Based on assumed size of $4.8 \text{ km} \times 160 \text{ km} \times 20 \text{ m}$.

Aquatic food harvest is shown in Table 6.3-2. Although no appreciable harvest is taken from the lower Mississippi River and estuary, there are a number of oxbow lakes which do provide for recreational fishing. The bulk of the aquatic food harvest was assumed to be taken from the near ocean (i.e., within 4.8 km of shore). A length of 160 km (100 miles) was chosen to define the ocean compartment.

TABLE 6.3-2
AQUATIC FOOD HARVEST* (LOWER SEGMENT)
T-3007

AQUATIC FOOD	RIVER†	ESTUARY	OCEAN‡
Fish	9.1×10^4	-	3.3×10^6
Mollusk	-	-	7.7×10^4
Crustacean	-	-	6.2×10^5

*Estimates in edible kg, see Tables D-2, D-7 and D-8 of Ref. 11.

†Based upon 16 oxbow lakes (25,000 acres) adjacent to river, Ref. 16, Appendix Q.

‡Based upon 4.8 km $\times$ 160 km area.

6.4 POTENTIAL HAZARD PREDICTIONS

The segmented structure of the river system assumed in this part of the study yields predicted hazards for each segment. In order to obtain the total population hazard, the contributions of each segment are simply added. However, since an individual is assumed to obtain all his food from a single river system, an individual exposed via pathways in one segment (e.g., the upper segment) will not be affected by the exposure pathways in the other segment (i.e., lower segment).

The potential hazard for this case is illustrated in terms of dose to an average individual and total population dose in Figs. 6.4-1 and 6.4-2 respectively.

Figure 6.4-1 The Potential Individual Hazard for the Central River (Note Assumptions in Section 2.2)

Figure 6.4-2 The Potential Population Hazard for the Central River (Note Assumptions in Section 2.2)

Comparison of Figs. 6.4-1 and 6.4-2 with the results for the baseline case reveals the following:

- The hazard to an average individual near the upper segment is approximately ten times higher than for the baseline case (see Chapter 3) at 100 years. The largest difference occurs for fission products.
- For the lower segment, the individual hazard is generally more than an order of magnitude lower than in the baseline system. The only exception is for the actinides which are a factor of seven lower.
- The population dose follows a similar pattern with the potential hazard for the upper segment approximately five times as large as the baseline value, while the lower segment has a potential hazard approximately one-tenth the baseline.

The potential hazard to an average individual is much higher for the first segment of the river system than for the second. This is a direct consequence of the higher flow rate of the lower segment compared to the upper (5.1×10^{11} vs 5.2×10^9 m³/yr). The critical dose pathways (for an average individual) for both segments are listed in Table 6.4-1. The major dose pathway at 100 years for the entire river system was fission products transported via river water and its uses (i.e., irrigation and consumption -- both human and animal). The significance of human water consumption would be reduced if it were assumed that radionuclides are removed during water treatment. At present, this is assumed not to occur. Note that the vegetable pathway includes both activity deposited during irrigation and uptake from topsoil. A secondary pathway for fission products at 100 years is consumption of aquatic food.

TABLE 6.4-1
CRITICAL PATHWAYS (AVERAGE INDIVIDUAL)

T-2989

NUCLIDE CLASS (TIME)	UPPER SEGMENT			LOWER SEGMENT		
	CRITICAL PATHWAYS (COMPARTMENT)	POTENTIAL HAZARD (rem/Hwe)	CONTRIBUTION (PERCENT)	CRITICAL PATHWAYS (COMPARTMENT)	POTENTIAL HAZARD (rem/Hwe)	CONTRIBUTION (PERCENT)
Fission Products (At 100 Years)	Vegetables (Topsoil)	7.1	63	Vegetables (Topsoil)	1.8×10^{-2}	41
	Aquatic Food (River)	1.6	14	Aquatic Food (Ocean)	8.1×10^{-3}	19
	Vegetables (River)	0.64	6	Vegetables (River)	5.3×10^{-3}	12
	Drinking Water (River)	0.56	5	Drinking Water (River)	4.7×10^{-3}	11
	Animal Products (River)	0.50	4	Animal Products (River)	4.1×10^{-3}	10
	Animal Products (Topsoil)	0.49	4			
Actinides (At 200,000 Years)	Animal Products (River)	1.8×10^{-2}	29	Aquatic Food (Ocean)	1.7×10^{-3}	84
	Vegetables (Topsoil)	1.6×10^{-2}	26	Animal Products (River)	1.5×10^{-4}	7
	Vegetables (River)	9.1×10^{-3}	15	Vegetables (River)	7.5×10^{-5}	4
	Drinking Water (River)	8.0×10^{-3}	13	Drinking Water (River)	6.7×10^{-5}	3
	Aquatic Food (River)	7.6×10^{-3}	12			

As was the case for the individual hazard, the major contributor to the population hazard is the upper segment. Table 6.4-2 lists the dose pathways to the population. In general, the pathways are the same as for the average individual; however, their relative importance varies due to finite resources. As an example, consider the potential hazard due to the actinides and daughters in the lower segment at 200,000 years. The aquatic food pathway accounts for 84 percent of the dose to an average individual but only 24 percent of the population dose. This is a result of the finite aquatic food harvest and the relatively unlimited supply of drinking water. A similar situation occurs with fission products in the lower

TABLE 6.4-2
CRITICAL PATHWAYS (POPULATION)

T-2990

NUCLIDE CLASS (TIME)	UPPER SEGMENT			LOWER SEGMENT		
	CRITICAL PATHWAYS (COMPARTMENT)	POTENTIAL HAZARD (man-rem /MWe-yr)	CONTRIBUTION (PERCENT)	CRITICAL PATHWAYS (COMPARTMENT)	POTENTIAL HAZARD (man-rem /MWe-yr)	CONTRIBUTION (PERCENT)
Fission Products (At 100 Years)	Vegetables (Topsoil)	5.4×10^5	88	Drinking Water (River)	4.8×10^3	90
	Vegetables (River)	4.9×10^4	8	Animal Products (River)	3.0×10^2	6
Actinides (At 200,000 Years)	Vegetables (Topsoil)	1.2×10^3	48	Drinking Water (River)	7.3×10^1	68
	Vegetables (River)	7.0×10^2	28	Aquatic Food (Ocean)	2.6×10^1	24
	Animal Products (River)	5.0×10^2	20	Animal Products (River)	2.2	2

segment, where the relatively small crop yield and aquatic food harvest result in a very low percentage contribution of these pathways to the population dose.

7. DESERT LAKE WITH NO OUTFLOW

The fifth study of a water body simulated with BIODOSE was that of a desert lake having no outflow. Walker Lake in Nevada was suggested as representative.*

7.1 MODEL ASSUMPTIONS AND PREDICTIONS

Information on Walker Lake parameters were obtained from Roger Jacobsen and Edward Lider of the Desert Research Institute at the University of Nevada. The lake area and sediment area are $1.5 \times 10^8 \text{ m}^2$. The sediment concentration factors, K_{rs} , used were those for the baseline Northwestern river. In the absence of other available information, the sedimentation rate, v_w , was assumed to be that estimated for the Fort Peck Reservoir (see Case 3): $2.5 \times 10^{-3} \text{ m/yr}$. The dose parameters took their baseline values. The only dose pathways were lake sediment exposure, water immersion and aquatic food. The fish harvest was assumed to be the national recreational and commercial fresh water average of 19.3 kg/ha/yr with a 28 percent edible portion (Ref. 11).

The long-term steady-state existence of this lake was assumed in the model; however, the very existence of the lake after millions of years (or even a few hundred years) can be validly questioned. The Walker Lake water level has been decreasing over the last one hundred years at an average of $0.5 \text{ m/yr}^\dagger$. If climatological patterns shift, however, the

*Steinborn, T., Lawrence Livermore Laboratory, personal communication. 1978.

†Lider, E., University of Nevada, personal communication, 1978.

trend may reverse. In the very long term, a cyclic pattern is possible, and long term existence of the lake may be possible. The assumed sedimentation rate implies that after three million years the equivalent of 7500 meters of sediment will have accumulated. This equivalent volume of sediment may be spread out over a larger area than the present water surface area, or the lake location may shift, so that this sedimentation rate is not inconsistent with the existence of the lake. If this scenario is to be investigated in more detail, the question of possible drying up of the lake and subsequent use of the potentially contaminated lake bed for various purposes, such as irrigated crop production, should be addressed, as well as the possibility of a lake coming into existence near a repository.

Two compartments of BIODOSE were utilized: the lake itself and lake sediment. The following equations for compartment nuclide concentrations were assumed:

$$V_w \frac{d c_{rw}}{dt} = - \left[\frac{DA_s}{d} + K_{rs} A_s v_w \right] c_{rw} + q_r + \left(\frac{DA_s}{K_{rs} d} \right) c_{rs} \quad (7.1-1)$$

$$V_s \frac{d c_{rs}}{dt} = - \left[\frac{DA_s}{d K_{rs}} + A_s v_w \right] c_{rs} + \left[\frac{DA_s}{d} + K_{rs} A_s v_w \right] c_{rw} \quad (7.1-2)$$

where the symbols are defined in Appendix B of this report and in Appendix G of Ref. 1. The terms on the right hand side of Eq. 7.1-1 are due to diffusion from water to sediment, sedimentation, repository input and diffusion from sediment to water. The terms in Eq. 7.1-2 are due to diffusion from sediment to water, sediment burial loss (equal to sedimentation rate) and diffusion and sedimentation from water to sediment. Since the dynamics of the compartment system are

fast compared to the dynamics of the input, the steady-state solution was used. The following equations result:

$$c_{rw} = q_r / K_{rs} A_s v_w \quad (7.1-3)$$

$$c_{rs} = K_{rs} c_{rw} \quad (7.1-4)$$

The whole-body-equivalent potential hazards over time to the population and average individual are shown in curve (a) of Figs. 7.1-1 and 7.1-2, respectively. The individual potential hazard from fission products is an order of magnitude higher than in the baseline case due to the smaller body of water and reduced exit pathways. However, the initial potential population hazard is more than two orders of magnitude

Figure 7.1-1 Potential Population Hazard for the Desert Lake for: (a) Steady-State with No Irrigation, and (b) Time-Varying Topsoil Concentrations (Note Assumptions in Section 2.2)

Figure 7.1-2 Potential Individual Hazard for the Desert Lake for: (a) Steady-State with No Irrigation, and (b) Time-Varying Topsoil Concentrations (Note Assumptions in Section 2.2)

lower than the baseline Northwestern river case because of the reduced number of dose pathways and the relatively small fish harvest.

The nuclide concentrations are very sensitive to, and inversely proportional to, the sedimentation rate. The sediment buildup is the only mechanism for removal of nuclides from the lake, as the water is too salty (one percent) for irrigation at present.* It was assumed that the drinking water was desalted but that no radionuclides were removed during the water treatment process.

Virtually the entire population hazard was due to the aquatic food pathway, while for the individual the aquatic

*Jacobsen, R., U. of Nevada, personal communication.

food and drinking water pathways contributed in roughly equal amounts to the total hazard.

7.2 DESERT LAKE MODEL WITH HYPOTHETICAL IRRIGATION

Under the supposition that irrigation with saline water may come into future use for certain crops, an irrigation pathway and a topsoil compartment were added to this simulation model. The following parameters were assumed: area of topsoil, A_t , $1.5 \times 10^6 \text{ m}^2$ (one percent of water area) and irrigation flow, I , $7.5 \times 10^5 \text{ m}^3/\text{yr}$ ($0.5 \text{ m}/\text{yr} \times A_t$). The sum of irrigation and rainfall were assumed to equal evapotranspiration from the topsoil. Erosion was neglected. The compartment equations for water and topsoil are

$$V_w \frac{dc_{rw}}{dt} = - \left[\frac{DA_s}{d} + K_{rs} A_s v_w + I \right] c_{rw} + q_r + \left(\frac{DA_s}{K_{rs} d} \right) c_{rs} \quad (7.2-1)$$

$$V_t \frac{dc_{rt}}{dt} = - [M_r] c_{rt} + I c_{rw} \quad (7.2-2)$$

where M_r is crop uptake.

All usage parameters and equations other than the above were as presented in Appendix G of Ref. 1, except that drinking water amount was assumed proportional to irrigation rate rather than river or lake flow. Implicit in the above is the very conservative assumption that the water purification process would not remove nuclides. The drinking water hazard pathway contributed very little to the overall dose, however, so that the results were not sensitive to this assumption.

To investigate nuclide buildup time in the topsoil as a hazard-limiting mechanism, a time-varying solution for the topsoil compartment was used:

$$c_{rt} = \frac{Ic_{rw}}{M_r} \left(1 - \exp - \left(\frac{M_r t}{V_t} \right) \right) \quad (7.2-3)$$

where V_t is the volume of the topsoil, which was assumed to be six inches (0.15 m) deep. The resulting average individual and population hazards are plotted in curve (b) of Figs. 7.1-1 and 7.1-2. The potential-hazards increase with time compared to those of the no-irrigation case mainly because nuclide concentrations in the topsoil build up since crop uptake is the only removal mechanism. These predictions with time-varying topsoil concentrations are undoubtedly more realistic for comparative purposes with other cases, given the irrigation assumption. Again, however, suitable cautions should be exercised because of probable increased sensitivity to parameter uncertainties in the estimates.

The relative contributions to potential hazard for the time-varying topsoil scenario are listed in Tables 7.2-1 and 7.2-2. As expected, the largest potential hazard resulted from the topsoil contamination.

The conclusions for this case study are summarized below:

- It appears that the desert lake case may result in higher individual potential hazards but lower population potential hazards than those of the Northwestern river because of the small water volume and small number of nuclide exit pathways.

TABLE 7.2-1

RELATIVE CONTRIBUTIONS OF VARIOUS PATHWAYS TO POTENTIAL
POPULATION HAZARD FOR THE DESERT LAKE
(WITH TIME-VARYING TOPSOIL CONCENTRATIONS)

T-2991

NUCLIDE CLASS (TIME)	PATHWAY (COMPARTMENT)	CONTRIBUTION	
		man-rem/MWe-yr	PERCENT
Fission Products (At 100 Years)	Vegetables (Topsoil)	7600	6
	Aquatic Food (Lake)	1860	19
	Vegetables (Lake Irrigation Water)	420	4
Actinides and Daughters (At 200,000 Years)	Vegetables (Topsoil)	162	86
	Animal Products (Topsoil)	14.6	8
	Aquatic Food (Lake)	8	4

TABLE 7.2-2

RELATIVE CONTRIBUTIONS TO POTENTIAL INDIVIDUAL HAZARD FOR
THE DESERT LAKE (WITH TIME-VARYING TOPSOIL CONCENTRATIONS)

T-2991a

NUCLIDE CLASS (TIME)	PATHWAY (COMPARTMENT)	CONTRIBUTION	
		rem/MWe	PERCENT
Fission Products (At 100 Years)	Vegetables (Topsoil)	1.2×10^2	77
	Aquatic Food (Lake)	7.8×10^0	5
	Vegetables (River)	6.8×10^0	4
	Drinking Water (River)	6.1×10^0	4
	Animal Products (River)	4.1×10^0	3
Actinides and Daughters (At 200,000 Years)	Vegetables (Topsoil)	2.6×10^0	64
	Animal Products (Topsoil)	6.0×10^{-1}	15
	Ground Exposure (Topsoil)	6.0×10^{-1}	15

- The simulation results are very sensitive to the sedimentation rate.
- Use of the lake water for irrigation would substantially increase the potential risk, particularly in the very long term.
- Future work on this type of water body scenario should include analysis of the disappearance of water in the lake and possible agricultural or recreation uses of the lake bed.

8. AQUIFER INTO THE OCEAN

The sixth study of a water system simulated with BLODOSE was that of an aquifer discharging directly into an ocean. Such discharges are known to exist off the Atlantic coast of the U.S., a dramatic example of which is a spring, off the northeast coast of Florida, having an estimated discharge of 1500 cubic feet per second ($1.34 \times 10^9 \text{ m}^3/\text{yr}$) (Ref. 19). Recent evidence of fresh ground water beneath the Continental Shelf off the Maryland-Massachusetts coast (Ref. 20) may be indicative of aquifers discharging offshore.

8.1 MODEL ASSUMPTIONS

In the BLODOSE simulation the "baseline" aquifer used in WASTE simulations of nuclide transport (Appendix H, Ref. 1) was adopted as a model for an aquifer discharging into the ocean. This aquifer has a cross-sectional area of $4 \times 10^5 \text{ m}^2$, a porosity of 0.1 and a steady-state interstitial velocity of 1.5 m/yr. Thus, the water outflow is $6.0 \times 10^4 \text{ m}^3/\text{yr}$. Only the cross-sectional area was utilized in this analysis because the waste flow rate, as was done throughout the analysis, was normalized to a value of one MWe-yr per year, independent of the water outflow. This simulation could be interpreted also as depicting seabed disposal of waste with a normalized dissolution rate.

Two compartments of the BLODOSE model were utilized: plume and ocean. Perfect mixing of the aquifer water and plume water was assumed, as lower-density fresh water would

tend to rise and mix well with sea water. The area of the plume compartment ($2.3 \times 10^6 \text{ m}^2$) was assumed to be that of a horizontal aquifer projected along a seabed which was at a ten degree angle from the horizontal.

The equations for nuclide concentrations in the plume and ocean are, respectively:

$$V_p \frac{d c_{rp}}{dt} = - \left(\frac{V_p}{T_p} \right) c_{rp} + q_r \quad (8.1-1)$$

$$V_o \frac{d c_{ro}}{dt} = - \left(\frac{V_o}{T_o} \right) c_{ro} + \left(\frac{V_p}{T_p} \right) c_{rp} \quad (8.1-2)$$

where V_p and V_o and T_p and T_o are the volumes and flushing times of the respective compartments. Steady-state conditions were assumed, since several modeling studies (Refs. 21 and 9) have indicated times for contaminants from point sources to reach steady-state which are very short (on the order of one year) compared with changes in the input. The following equations result:

$$c_{rp} = q_r / (V_p / T_p) \quad (8.1-3)$$

$$c_{ro} = q_r / (V_o / T_o) \quad (8.1-4)$$

The flushing times were estimated on the basis of mid-depth steady-state current predictions for the Middle Atlantic continental shelf (0.3 cm/sec) by Stommel and Leetmaa (Ref. 9). The following relationship was used:

$$V/T = vWD \quad (8.1-5)$$

where v is the current speed, W is the width of the compartment perpendicular to the current and D is the average water depth of the compartment.

Two different cases were considered for the ocean compartment area. The first scenario assumed the ocean compartment width equaled the average width of the continental shelf below Cape Cod, and the value of 140 km estimated by Stommel and Leetmaa (Ref. 9) was used. The total area of the compartment was chosen to be equal to that of Area 5ZW (Fig. 8-1) of the International Commission for the Northwest Atlantic Fisheries (ICNAF) (Ref. 12) for which fish harvest statistics are available. These fish harvest estimates for the year 1976 were used in the model with an edible portion of 53 percent (Ref. 11) and are indicated in Table 8.1-1. The compartment was assumed not to go beyond the continental shelf, while the ICNAF Area 5ZW includes about one-third nonshelf area. Consequently, the fish harvest may be somewhat underestimated. The plume fish harvest was estimated as explained for scenario (b) below. A conservative value of 0.1 was chosen for the fraction of fish consumed from the plume. An average depth of 50 m was assumed (Ref. 9). Equation 8.1-5 was used to estimate the flushing time. The resulting parameters are indicated in Table 8.1-1.

For the second scenario, a very small ocean compartment was assumed in order to test the sensitivity of the potential hazard to the size of this compartment. The area of the ocean compartment down-current of the plume compartment was assumed to be four times that of the plume compartment. The average water depth of both compartments was set at 50 feet (15.2 m), which was obtained from USGS maps of the Massachusetts coastline 16 km from shore. This distance was in the range offshore that fresh groundwater has been found (Ref. 20).

Figure 8.1-1 Southwestern Portion of the International Commission for the Northwest Atlantic Fishery Area (from Ref. 12)

TABLE 8.1-1
PARAMETER VALUES FOR SIMULATION OF
AQUIFER INTO THE OCEAN

PARAMETER	LARGE OCEAN COMPARTMENT (a)	SMALL OCEAN COMPARTMENT (b)
Volume/Flushing Time of Plume (V_p/T_p)	$2.3 \times 10^9 \text{ m}^3/\text{yr}$	$2.3 \times 10^9 \text{ m}^3/\text{yr}$
Volume/Flushing Time of Ocean (V_o/T_o)	$6.6 \times 10^{11} \text{ m}^3/\text{yr}$	$4.4 \times 10^9 \text{ m}^3/\text{yr}$
Fish Harvest - Plume*	$1.7 \times 10^3 \text{ kg/yr}$	$1.7 \times 10^3 \text{ kg/yr}$
Fish Harvest - Ocean*	$8.8 \times 10^7 \text{ kg/yr}$	$7.7 \times 10^3 \text{ kg/yr}$
Mollusk Harvest - Ocean*	$6.5 \times 10^6 \text{ kg/yr}$	0
Crustacean Harvest - Ocean*	$1.5 \times 10^6 \text{ kg/yr}$	0
Fraction of Fish Diet from Plume	0.1	0.2
Fraction of Fish Diet from Ocean	0.9	0.8

*Edible portion.

Aquatic food was assumed to consist of fish only. Harvest estimates were taken for the 5 to 19 km range offshore from Table 4.3-5 of Ref. 11 as 7.3 kg/ha/yr total weight of commercial and recreational catches. With an edible portion of 53 percent (Ref. 11), the fish harvests were $1.7 \times 10^3 \text{ kg/yr}$ and $7.7 \times 10^3 \text{ kg/yr}$ for the plume and ocean compartments, respectively. No shellfish were assumed to be harvested that far offshore. One-fifth of the individual's fish diet was assumed to originate in the plume while the other four fifths came from the ocean compartment. The assumptions of the relatively small compartments and of all the fish in the diet coming from these compartments make the individual hazard estimates very conservative. Use of Eq. 8.1-5 and the assumption of square

compartment geometry resulted in the scenario (b) values listed in Table 8.1-1.

8.2 POTENTIAL HAZARD PREDICTIONS

The simulation results are indicated in Figs. 8.2-1 and 8.2-2 for population and individual potential hazards for the first scenario. For the larger ocean compartment scenario, the population hazard from actinides is roughly an order of magnitude lower than that for the baseline Northwestern river; the iodine and technetium hazards are two orders of magnitude lower than the baseline; and the hazard due to other fission products starts two orders of magnitude lower, and after 1000 years reaches approximately the same value as that for the baseline case. Note that the hazard after 200,000 years is almost as great as that after 200 years. For the hazard to an individual, the contribution of the actinides is at a level similar to the baseline while the fission products are roughly an order of magnitude lower than the baseline.

For the scenario with the very small ocean compartment, the potential hazard to an individual consuming an average diet is approximately of the same order of magnitude as that for the baseline. The concentrations in the plume and ocean compartments are high, but the only pathway to man is via aquatic food. The ocean compartment contributes twice the potential hazard as the plume. The potential hazard to the population is roughly three to four orders of magnitude lower than the baseline river. The scenario with the larger ocean compartment is considered to be a more realistic representation of the water system for the purpose of predicting hazards.

Figure 8.2-1 Potential Population Hazard from an Aquifer Discharging into the Ocean (Note Assumptions in Section 2.2)

Figure 8.2-2 Potential Hazard to an Average Individual from an Aquifer Discharging into the Ocean (Note Assumptions in Section 2.2)

In summary:

- A simple two-compartment model of an aquifer discharging directly into the ocean predicted hazards that initially were approximately two orders of magnitude lower than for the baseline river for the population and later one order of magnitude lower.
- The potential individual hazard starts an order of magnitude lower but then becomes higher than the baseline case by a factor of three.
- Further study of this water system should include analysis of convection and dispersion mechanisms of nuclide movement in the water as well as possible sediment interactions.

9.

DISCUSSION

Simulations of radioactive nuclide transport through various water body systems have been performed to predict potential hazards to the population and to an individual eating an average diet. In this chapter the potential hazards of the various water bodies are compared. Tables 9-1 and 9-2 summarize the maximum population and individual potential hazards at 100 years and at 200,000 years after emplacement of spent nuclear fuel. The potential population hazards are considered to be relatively more accurate predictions than the individual hazards because of the structure of the simulation model (see discussions in Ref. 1). Individual hazards are also listed because they are relatively high in some cases where the population hazards are not relatively high (the desert lake and the aquifer case) and vice-versa.

TABLE 9-1
POTENTIAL HAZARD TO THE POPULATION FROM SPENT FUEL:
SENSITIVITY TO WATER SYSTEM

T-2997

WATER SYSTEM	MAXIMUM POTENTIAL HAZARD (man-rem/MWe-yr)	
	AT 100 YEARS	AT 200,000 YEARS
Northwestern River (Quasi-Steady-State)	8×10^4	6×10^2
Northeastern River	3×10^4	1×10^3
Small Northwestern River (Time-Varying)	9×10^4	5×10^2
Large Central River	6×10^5	2×10^3
Desert Lake (No Irrigation)	2×10^3	8×10^0
Aquifer into Ocean (Large Ocean Compartment)	2×10^2	5×10^1

TABLE 9-2
 POTENTIAL HAZARD TO AN INDIVIDUAL FROM SPENT FUEL:
 SENSITIVITY TO WATER SYSTEM

T-2998

WATER SYSTEM	MAXIMUM POTENTIAL HAZARD (rem/MWe)	
	AT 100 YEARS	AT 200,000 YEARS
Northwestern River (Quasi-Steady-State)	3×10^{-1}	2×10^{-3}
Northeastern River	9×10^{-1}	5×10^{-2}
Small Northwestern River (Time-Varying)	5×10^0	3×10^{-2}
Large Central River	1×10^1	5×10^{-2}
Desert Lake (No Irrigation)	1×10^1	7×10^{-2}
Aquifer into Ocean (Large Ocean Compartment)	1×10^{-2}	6×10^{-3}

In terms of population hazard, the four river systems are all roughly comparable, although the river with very high irrigation withdrawals (the Central river) is somewhat higher because of its larger crop yield. The desert lake is relatively low in population hazard, even though the lake radionuclide concentration predictions are high, because the relatively small aquatic food harvest limits the exposure pathways. When irrigation of topsoil is added to the simulation, however, the population hazards are comparable to those of the other river water systems. In general, for river or lake systems the potential population hazards appear to be relatively less dependent on the water outflow rate of the river or lake but more dependent on the proportion of the flow removed as irrigation water. In a given water body system, a self-compensating phenomenon occurs if the flow rate changes, in that the major exposure pathways (such as crop yields and aquatic food harvest) increase with flow rate but the radionuclide concentrations decrease. The proportion of the flow withdrawn for

irrigation does appear to influence potential hazard directly, however. Thus, it appears that the hypothetical case of a river or lake with all or most of its flow used for irrigating a relatively large topsoil area would result in the highest potential hazard for the population. Real examples of such a water system are the Rio Grande and Colorado Rivers.

The aquifer into the ocean represents a categorically different water system from the others considered. The potential population hazards appear to be substantially lower than those for the river systems because of the absence of other major exposure pathways besides aquatic food. This simulation may be of some use in evaluating schemes for seabed disposal of nuclear waste.

The BIODOSE simulation model appears to be a valid tool for comparison of radionuclide transport through various types of surface water body systems and exposure mechanisms. For an evaluation of a specific disposal site, however, refinement of model structure and better estimates of parameter values would be required before predictions of potential hazard could be made.

10. CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

In this study a simulation model was used to evaluate various types of water body systems with respect to their relative effectiveness in retarding the transport of radionuclides to man. Spent fuel was assumed to be released into the water system at a fixed annual rate. The following preliminary conclusions are drawn from the comparison of the predicted potential hazards:

- The river systems studied appear to be roughly comparable in potential population hazard.
- For the four river systems studied, potential population hazards are relatively insensitive to water system parameter changes (such as river flow rate), except for irrigation rates and suspended sediment concentrations in irrigation water.
- The potential population hazard of the desert lake with no outflow appears to be very low relative to the river systems. The individual potential hazard is predicted to be comparable to or higher than that of the river systems, however. The individual potential hazard of a small river or lake system with high irrigation withdrawals would appear to be very high relative to that of any other type of water system.
- The potential population hazard of the aquifer discharging into the ocean appears to be substantially lower than that for the river systems.
- The time-varying solution to the compartment radionuclide concentration equations

appears to be more appropriate and easier to use in some cases than previous methods. These cases are those for which the time constants associated with the river sediment and/or topsoil compartments are long relative to the half-life of any radio-nuclides which tend to accumulate in the sediment or topsoil.

For further research in this area it is suggested the following be considered (in order of importance):

- Investigate the sensitivity of the model to neglecting the differences in transport rates of nuclides in decay chains (the "reconcentration effect")
- Estimate the uncertainties in potential hazard estimates
- Improve modeling of the suspension-sedimentation processes in water bodies
- Extend the simulation model to include air pathways
- Include in the model the recycling in the water system of nuclides through animal-human waste disposal
- Model interstitial water of soil and sediment as separate compartments
- Evaluate the importance of contaminated soil residue on crops as a potential dose pathway to man.

APPENDIX A
SOLUTION OF COMPARTMENT EQUATIONS

The dynamics of the assumed water body systems are rapid relative to input changes except for the topsoil and sediment compartments. That is, for all the compartments except topsoil, the time to reach a steady-state concentration was short compared with the time period over which past studies using the WASTE model (Ref. 1) indicate that changes take place in the waste input to the compartment system. The sediment compartments contributed a very minor amount to overall hazard. Consequently, a steady-state, or equilibrium, solution to the compartment equations is appropriate for simulations of those systems in which the topsoil compartment is not significant. The steady-state solution to Eq. 2.1-5 is:

$$c_r = -A_r^{-1} q_r \quad (A-1)$$

For water body systems with topsoil compartments a time-dependent solution is needed. In Ref. 1 a quasi-steady-state solution was utilized, where the topsoil compartment concentration was treated as time-varying, while the concentrations in the remainder of the compartments were considered to be in a steady state. Because of what appeared to be the potential importance of the topsoil contribution to overall hazard in the water body systems other than the Northwestern river case of Ref. 1, a time-varying solution to the compartment equations was considered to be a more accurate representation of the potential waste concentrations in the water and soil than a quasi-steady-state solution. Also, the time-varying

solution is easier to use, since an analytic quasi-steady-state solution need not be derived for each case.

The general solution to the compartment equation (Eq. 2.1-5) with zero initial conditions is the following (Ref. 22):

$$\underline{c}_r(t) = \exp(V^{-1}A_r t) \int_0^t \exp(-V^{-1}A_r \tau) V^{-1} \underline{q}_r d\tau \quad (A-2)$$

Since the nuclide input $\underline{q}_r$ is treated as a piecewise constant function and the nuclide amounts are evaluated at discrete time points for computational purposes, Eq. A-2 may be discretized:

$$\begin{aligned} \underline{c}_r(t_N) = \sum_{i=1}^N \left\{ \exp[V^{-1}A_r(t_N - t_{i-1})] \right. \\ \left. - \exp[V^{-1}A_r(t_N - t_i)] \right\} (V^{-1}A_r)^{-1} V^{-1} \underline{q}_r(t_i) \end{aligned} \quad (A-3)$$

where t_i is the i^{th} time point ($\underline{q}_r(t_i)$ is constant between t_{i-1} and t_i) and N is the index of the time at which $\underline{c}_r$ is to be evaluated.

Due to computational difficulties in the exponentiation of $V^{-1}A_r \Delta t$ for large values of Δt , an appropriate coordinate transformation of $\underline{c}_r$ was utilized to diagonalize the transformed $V^{-1}A_r$ matrix. Specifically, let

$$\underline{c}_r = P_r \underline{y}_r \quad (A-4)$$

where P_r is the matrix whose columns are eigenvectors of the matrix $(V^{-1}A_r)$. Substitution of Eq. A-4 into Eq. 2.1-5 yields:

$$\frac{dy_r}{dt} = D_r y_r + P_r^{-1} V^{-1} q_r \quad (A-5)$$

where $D_r = P_r^{-1} V^{-1} A_r P_r$, which is a diagonal matrix of eigenvalues corresponding to the eigenvectors of P_r if all the eigenvalues are distinct (see for example, Ref. 23). This condition holds for all the cases studied. Equation A-5 represents a set of n decoupled scalar differential equations instead of a system of n coupled differential equations as in Eq. 2.1-5.

The solution to Eq. A-5 (analogous to Eq. A-3) becomes:

$$y_r^j(t_N) = \sum_{i=1}^N \left\{ \exp[\lambda_j(t_N - t_{i-1})] - \exp[\lambda_j(t_N - t_i)] \right\} \frac{1}{\lambda_j} \left[P_r^{-1} V^{-1} q_r(t_i) \right]_j \quad (A-6)$$

where y_r^j is the j^{th} element of the vector y_r and λ_j is the corresponding eigenvalue and the notation $[x]_j$ denotes the j^{th} element of vector x . The original vector of nuclide concentrations, $c_r(t_N)$, can then be calculated via Eq. A-4.

This method of solving the time-dependent equation was used in several of the case studies where buildup time in the topsoil was significant to predicted hazard.

APPENDIX B
COMPARTMENT EQUATIONS FOR NORTHWESTERN RIVER

The set of compartment equations for the Northwestern river equation is:

$$\frac{d \underline{c}_r}{dt} = V^{-1} A_r \underline{c}_r + V^{-1} q_r \quad (B-1)$$

where

$$\underline{c}_r = [c_{rw} \ c_{rt} \ c_{rs} \ c_{re} \ c_{rse} \ c_{rp} \ c_{ro}]^T$$

and T denotes transpose and the subscripts w, t, s, e, se, p, and o represent river water, topsoil, river sediment, estuary water, estuary sediment, plume water and ocean water, respectively. The transfer coefficient matrix, $V^{-1} A_r$, is:

$$V^{-1} A_r = \begin{bmatrix} a_{11} & a_{12} & a_{13} & 0 & 0 & 0 & 0 \\ I/V_t & a_{22} & 0 & 0 & 0 & 0 & 0 \\ a_{31} & 0 & a_{33} & 0 & 0 & 0 & 0 \\ F/V_e & 0 & 0 & a_{44} & a_{45} & 0 & 0 \\ 0 & 0 & 0 & a_{54} & a_{55} & 0 & 0 \\ 0 & 0 & 0 & a_{64} & 0 & a_{66} & 0 \\ 0 & 0 & 0 & 0 & 0 & a_{76} & a_{77} \end{bmatrix} \quad (B-2)$$

where

$$a_{11} = - \left[F + I + \frac{DA_s}{d} + K_{rs} A_s V_w \right] / V_w$$

$$a_{12} = [(I+R-E)/(B_{rt}\theta) + A_t S_t]/V_w$$

$$a_{13} = \frac{DA_s}{dK_{rs}V_w}$$

$$a_{22} = -[(I+R-E)/B_{rt}\theta + M_r + A_t S_t]/V_t$$

$$a_{31} = \left[\frac{DA_s}{d} + K_{rs}A_s v_w \right] / V_s$$

$$a_{33} = - \left[\frac{DA_s}{dK_{rs}} + A_s v_w \right] / V_s$$

$$a_{44} = - \left[\frac{V_e}{T_e} + \frac{DA_e}{d} + K_{rse}A_e v_e \right] / V_e$$

$$a_{45} = \frac{DA_e}{dK_{rse}V_e}$$

$$a_{54} = \left[\frac{DA_e}{d} + K_{rse}A_e v_e \right] / V_{se}$$

$$a_{55} = - \left[\frac{DA_e}{K_{rse}d} + A_e v_e \right] / V_{se}$$

$$a_{64} = V_e / (T_e V_p)$$

$$a_{66} = - (10F) / V_p$$

$$a_{76} = [10F - V_p/T_o] / V_o$$

$$a_{77} = - [(1-A_p/A_o)/T_o]$$

and

$$V^{-1}q_r = [q_r/V_w \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0]^T$$

where

V_l is the effective volume of compartment l (m^3)

A_l is the surface area of compartment l (m^2)

K_{rl} is the distribution coefficient of compartment l , which is the ratio of the volumetric concentration in the sediment to that in the water (Ci/m^3 dry sediment/ Ci/m^3 water)

T_l is the flushing time of compartment l (yr)

q_r is the input of nuclide r from the aquifer connecting the repository to the water body (see Eq. 2.1-5) (Ci/yr from one MWe-yr of power production)

v_l is the net rate of sedimentation from compartment l (m/yr)

F is the outflow rate of the river (or lake) (m^3/yr)

I is the average yearly rate at which water is withdrawn from the river (or lake) for irrigation (m^3/yr)

D is the average diffusion coefficient (m^2/yr)

d is the average diffusion depth (m)

R is the average yearly rainfall on the topsoil (m^3/yr)

E is the average yearly evapotranspiration from the topsoil (m^3/yr)

M_r is the effective average yearly removal rate of nuclide r from the topsoil that is taken up by plants (m^3/yr)

S_t is the erosion rate of topsoil

θ is the volumetric water content of topsoil (m^3 water/ m^3 soil), set arbitrarily equal to one for all water systems for comparative purposes

B_{rt} is the soil retardation factor $(1+K_{rt}/\theta)$,
 where K_{rt} is the volumetric distribution
 coefficient for topsoil.

The quasi-steady-state solution to the compartment
 equations is the following:

$$c_{rw} = q_r \left\{ F + I - I [1 - \exp(-L_r t_b)] \right\}^{-1} \quad (B-3)$$

$$c_{re} = (F T_e / V_e) c_{rw} \quad (B-4)$$

$$c_{rp} = [(V_e / (T_e 10F))] c_{re} \quad (B-5)$$

$$c_{ro} = \frac{(V_e T_o / T_e) c_{re} - V_p c_{rp}}{V_o [1 - A_p / A_o]} \quad (B-6)$$

$$c_{rt} = (I c_{rw} / V_t) [1 - \exp(-L_r t_b)] / L_r \quad (B-7)$$

$$c_{rs} = K_{rs} c_{rw} \quad (B-8)$$

$$c_{rse} = K_{rse} c_{re} \quad (B-9)$$

where

$$L_r = \frac{I+R-E}{\theta B_{rt} V_t} + \frac{M_r}{V_t} + \frac{A_t S_t}{V_t}$$

and

$$t_b = \begin{cases} t & \text{if } t < 1000 \text{ years} \\ 1000 \text{ years} & \text{if } t \geq 1000 \text{ years} \end{cases}$$

APPENDIX C
RADIONUCLIDE LIST

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:

^{59}Ni	^{154}Eu
^{89}Sr	^{210}Pb
^{90}Sr	^{210}Po
^{90}Y	^{225}Ra
^{91}Y	^{226}Ra
^{93}Zr	^{229}Th
^{95}Zr	^{230}Th
$^{93\text{m}}\text{Nb}$	^{231}Pa
^{95}Nb	^{233}U
^{99}Tc	^{237}Np
^{106}Ru	^{238}Pu
^{126}Sn	^{239}Pu
^{129}I	^{240}Pu
^{134}Cs	^{241}Pu
^{135}Cs	^{241}Am
^{137}Cs	^{243}Am
^{144}Ce	^{242}Cm
^{147}Pm	^{244}Cm

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