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Assessment of Effectiveness of
Geologic Isolation Systems

**Test Case Release
Consequence Analysis
for a Spent Fuel
Repository in Bedded Salt**

January 1980

Prepared for the
Office of Nuclear Waste Isolation
under its Contract with the
U.S. Department of Energy

Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute

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Assessment of Effectiveness of
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TEST CASE RELEASE
CONSEQUENCE ANALYSIS
FOR A SPENT FUEL
REPOSITORY IN BEDDED SALT

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SUMMARY

Geologic and geohydrologic data for the Paradox Basin have been used to simulate movement of ground water and radioactive contaminants from a hypothetical nuclear reactor spent fuel repository after an assumed accidental release. The pathlines, travel times and velocity of the ground water from the repository to the discharge locale (river) were determined after the disruptive event by use of a two-dimensional finite difference hydrologic model. The concentration of radioactive contaminants in the ground water was calculated along a series of flow tubes by use of a one-dimensional mass transport model which takes into account convection, dispersion, contaminant/media interactions and radioactive decay.

For the hypothetical site location and specific parameters used in this demonstration, it is found that Iodine-129 (I-129) is the only isotope reaching the Colorado River in significant concentration. The I-129 is transported to the river at a maximum concentration of about 1.84×10^{-8} microcuries per milliliter ($\mu\text{Ci/ml}$). This concentration occurs about 8.0×10^5 years after the repository has been breached. This I-129 ground-water concentration is about 0.3 of the drinking water standard for uncontrolled use. The ground-water concentration would then be diluted by the Colorado River (mean flow of $7,000 \text{ ft}^3/\text{sec}$ to about $2.13 \times 10^{-13} \mu\text{Ci/ml}$.

None of the actinide elements reach more than half the distance from the repository to the Colorado River in the two-million year model run time. As an example, Radium-226, at a maximum concentration, has travelled 0.46 of the distance to the river in two million years. Radium-226 concentration in the ground water at that point in space and time is $1.02 \times 10^{-7} \mu\text{Ci/ml}$.

This exercise demonstrates that the WISAP model system is applicable for analysis of contaminant transport. The results presented in this report, however, are valid only for one particular set of parameters. A complete sensitivity analysis must be performed to evaluate the range of effects from the release of contaminants from a breached repository.

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This report is the result of a cooperative effort between Bechtel National, Inc., (BNI) and Pacific Northwest Laboratory (PNL) to test and demonstrate hydrologic and geologic transport modeling technology for nuclear release consequence analysis as applied to a hypothetical, yet site-specific spent fuel geologic repository.

The following Battelle Pacific Northwest Laboratory staff and Bechtel National, Inc. contributed to this project:

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In addition, J. T. Christian and L. W. Picking of Stone and Webster Engineering Corporation served as observers and contributed significantly to the conceptual modeling effort. Stone and Webster is ONWI's Geologic Project Manager for the Paradox Basin.

PART I. GENERAL DISCUSSION

I.1 INTRODUCTION

The National Waste Terminal Storage (NWTs) Program is concerned with developing methods and techniques for using geologic formations to safely dispose of spent fuel from commercial nuclear power reactors and/or high level radioactive waste. Part of this program is managed for the Department of Energy by Battelle Memorial Institute's Office of Nuclear Waste Isolation (ONWI). Under ONWI sponsorship, the Pacific Northwest Laboratory, is responsible for the Waste Isolation Safety Assessment Program (WISAP). WISAP's mission is to develop and implement methods to assess the post-closure safety of geologic repositories. Assessment of geologic isolation safety is unique relative to safety assessments for other engineered systems because of the uncertainties resulting from the long time periods involved in the assessments, the hypothetical nature and low probabilities of the nuclide release scenarios and the limits on the ability to characterize the geohydrologic systems. The safety assessment methods will be applied to support site-specific repository selection, qualifications, and licensing.

One task (TASK 3) under WISAP is to develop modeling systems to predict the transport of radioactive contaminants from NWTs repositories to the biosphere and to evaluate the potential dose to humans. Existing technology is being used and available hydrologic, transport, and dose models are being adapted and/or extended to estimate the consequences of accidental release of radioactivity from waste isolation repositories.

This report describes the initial use of the WISAP hydrologic and transport models for assessment of the consequences of radiocontaminant releases from a disrupted geologic repository containing nuclear power reactor spent fuel. This work demonstrates the model use for a specific site where a moderate amount of actual data on the boundaries and parameters of the geohydrologic system is available. The Office of Nuclear Waste Isolation requested that data from the Paradox Bedded Salt Region be used for this exercise. The Paradox Region is one of several regions of salt deposits in the U.S. under

study to determine suitability for possible repository sites. However, the siting of a repository in the Paradox Region is strictly a hypothesis made in order to demonstrate WISAP modeling technology. There is no intent, either actual or implied, to qualify or disqualify the site as a candidate nuclear waste/spent fuel repository in this exercise.

Most of the geohydrologic data used for the exercise were derived from the draft report by Bechtel National, Inc., (BNI) on characterization of the Paradox Bedded Salt Region.¹ BNI is the regulatory Project Manager for the Paradox Region.

I.2 SITE LOCATION

The Paradox Basin bedded salt region is situated in southeastern Utah and southwestern Colorado. The Region, as used in this report, is defined at the surface by the zero isopleth of the Pennsylvanian salt beds. Commonly called the "zero-salt" line, this line circumscribes the outer perimeter of the salt, i.e., where salt thickness decreases to zero. Figure I.1 is the location map for the region and shows the zero-salt line in a generalized form as defined by Wengard.² The salt beds exceed 4,000 feet in thickness at some locations within the region and provide the location for the hypothetical repository.

There are approximately 10,000 square miles within the zero-salt line, of which about 6,000 square miles are in Utah and 4,000 square miles are in Colorado. In Utah the zero-salt line encompasses portions of counties-- San Juan, Grand, Wayne, and Emery County. About 50% of the Utah portion of the basin lies in the northeastern half of San Juan County, and 35% to 40% in the southern half of Grand County. The remainder is divided about equally between southeastern Emery and eastern Wayne counties.

Figure I.2 shows the base map of the model area within the Paradox Basin Region selected for the release consequence analysis exercise. The model area lies between the Green and Colorado rivers, extending about 100 miles northward from the confluence of the two rivers. Figure I.2 also shows the location of the hypothetical repository about 35 miles north of the river junction. The

FIGURE I.1. Paradox Basin Bedded Salt Region

repository is located, more than 3,000 feet below ground surface in a thick section of interbedded salt and shale layers (Paradox formation) that separate upper and lower aquifer systems.

FIGURE 1.2. Base Map of the Paradox Model Region

I.2.1 Geology

Table I.1 shows the geologic formations that are involved in the model area, their thickness, age, and role:

TABLE I.1. Geologic Formations in the Modeled Area

	<u>Formation</u>	<u>Thickness (Ft)</u>	<u>Geologic Age</u>	<u>Role</u>
1.	Moenkopi	400	Triassic	Aquiclude
2.	Cutler	200	Permian	Upper Aquifer
3.	Rico	400	Pennsylvanian	Upper Aquifer
4.	Honaker Trail	400	Pennsylvanian	Upper Aquifer
5.	Paradox	4,300	Pennsylvanian	Aquiclude*
6.	Pinkerton Trail	100	Pennsylvanian	Aquiclude
7.	Molas	100	Pennsylvanian	Aquiclude
8.	Leadville	500	Mississippian	Lower Aquifer

Note: From R. J. Hite and J. A. Liming (Geologic Atlas of the Rocky Mountain Region³ and Geologic Map State of Utah⁴).

* Location of hypothetical repository.

The Leadville limestone consists of limestone overlying dolomite. The limestone is dense, fine-grained, and massive. The dolomite is massive and coarsely crystalline. Fractures within the formation provide its transmissive capabilities.

The Molas formation consists of calcareous shales and sandstone with lenses of limestone.

The Pinkerton Trail formation consists mainly of crystalline limestone and interbedded shale.

The Paradox formation in this area consists mainly of interbedded sodium salt, shale, and potassium salt beds. A salt anticline accounts for the great thickness of the unit in this region.

The Honaker Trail formation consists of crystalline-to-granular limestone with interbeds of chert and calcareous siltstone. Fractures within the formation provide its transmissive capabilities.

The Rico formation consists of interbedded sandstone, limestone, conglomerate and interbedded shale.

The Cutler formation consists mainly of cross-bedded sandstone with interbeds of siltstone, shale, and limestone.

The Moenkopi formation consists of shale, siltstone, and limestone. For the purposes of this exercise, the formation is assumed to be an aquiclude.

Figure I.3 shows the relationship of these formations in the generalized geologic column of the Paradox Basin bedded salt region.

I.2.2 Geohydrology

Potentiometric maps of the Mississippian (Leadville), Pinkerton Trail, Paradox, Honaker Trail, and the Permian (Cutler) formations are available.⁵ The Mississippian, Honaker Trail, and Permian maps are used for this exercise. In addition, 30 oil well drill stem test analyses were acquired from Roger L. Hoeger, consulting geologist, Denver, Colorado. Twenty-five tests have been analyzed in the Mississippian aquifer, three in the Paradox formation, and one each in the Honaker Trail (Hermosa) and Permian formations.

The potentiometric maps provide the hydraulic head and gradients of the upper and lower aquifer systems used in the hydrologic model. Information provided by Hanshaw and Hill consultants points out that little difference exists between the Honaker Trail and Permian potentials, which indicates that the Rico Formation does not act as a hydraulic barrier. Thus, these three formations comprise the upper aquifer. The Mississippian formation is the lower aquifer. The potentiometric maps indicate that the potential of the lower aquifer ranges from 250 to 400 feet. A 250-foot head difference appears more common and is used for this exercise. It should be noted that the potentials have been corrected to fresh water densities. Faults in the northern part of this area locally disrupt the ground-water contours. The specific test site is located south of the faults to avoid these disruptions.

The drill stem test data provide permeabilities and transmissivities of the two aquifers. Permeabilities in the lower system range from 0.4 to 190 ft/yr. The average of this range is about 45 ft/yr and is used for the initial runs of this exercise.

ERA	SYSTEM	SERIES	FORMATION	THICKNESS (ft)	LITHOLOGY	TIME (BP) (my)
CENOZOIC	QUATERNARY AND TERTIARY		Unnamed Quaternary Tertiary Intrusives Wasatch Formation	0-?	Quaternary and Tertiary fluvial and aeolian deposits; Tertiary volcanics and intrusive rocks; gravel; dunes.	70
MESOZOIC	CRETACEOUS	UPPER	Mesaverde Group	0-500	Sandstone, siltstone, shale	135
			Mancos Shale Ferrun Member	1000-3500	Shale and siltstone Carboniferous shale	
			Dakota Sandstone	100-150	Conglomerate, sandstone and shale	
		LOWER	Burro Canyon Formation	100-200	Conglomerate, sandstone and shale	
	JURASSIC		Morrison Formation Brushy Basin Member Salt Wash Member	300-400	Varicolored claystone, siltstone and sandstone Siltstone Siltstone	180
			Summerville Formation	25-100	Red shale and siltstone	
			Entrada Sandstone	100-500	Dune sandstone	
		? - ? - ?	Carmel Formation	75-100	Red shale and siltstone	
			Navajo Sandstone	100-400	Dune sandstone	
	TRIASSIC		Kayenta Formation	0-500	Red shale and sandstone	225
			Wingate Sandstone	0-450	Dune sandstone	
			Chinle Formation Moss Back Formation Moenkapi Formation	(?) - 2000	Red siltstone Sandstone Red shale and siltstone	
					Dolores Fm. of Hite (1972)	
PALEOZOIC	PERMIAN		White Rim De Chelly Organ Rock Cedar Mesa Halgeito	1500-2000	Sandstone Dune sandstone Red shale and sandstone grading into Arkose and conglomerate (Rico)	270
			Cutler Group Rico	300-500	Sandstone Red shale and siltstone	
	PENNSYLVANIAN	VIRGIL-MISSOURI	Honaker Trail Fm.	1000-2000	Dolomite and black shale	305
		DES MOINES	Hermosa Group Paradox Formation	0-6000	Carbonates Saline deposits Grading into Arkose and conglomerate	
		ATOKA-MORROW	Pinkerton Trail	0-200	Dolomite and black shale	
	MISSISSIPPIAN		Molas Formation	0-150	Red shale, siltstone, rubble (regolith)	350
			Leadville Limestone	200-300	Limestone and dolomite	
	DEVONIAN		Ouray Limestone	75-100	Limestone	400
			Elbert Dolomite McCracken Ss. Member	200-350	Dolomite and limestone with marine sandstone at base	
			Aneth Dolomite	0-200	Dolomite and minor sandstone and shale	
	CAMBRIAN		Lynch Dolomite	0-400	Brown dolomite	600
			Maxfield Limestone	(?) - 660	Limestone and shale	
			Ophir Shale	0-500	Shale	
			Ignacio Quartzite	0-200	Quartzitic sandstone and conglomerate	
PRECAMBRIAN			Unnamed	18,000(?)	Sediments and metasediments	
					Schists, gneisses, quartzites, intrusives	

FIGURE 1.3. Generalized Geologic Column of the Paradox Basin Bedded Salt Region

The only values of permeability available for the upper aquifer are 0.3 and 102 ft/yr; 100 ft/yr is used for this exercise.

I.3 CONCEPTUAL MODEL

The first stage of any modeling effort involves examining the geohydrologic data and developing a conceptual model of the system. As noted earlier, the Paradox Basin in the region of interest can be represented by a two aquifer system. The lower aquifer which is at higher potential consists of the Mississippian aquifer (Leadville limestone). This lower aquifer system in the region of interest is separated from the upper aquifer system by the impermeable Paradox formation. The upper aquifer system consists of a combination of the Honaker Trail and Permian Formations (Cutler-Rico) which act essentially as a single aquifer. The generalized potentials for these systems are shown in Figures I.4. The formations which make up the upper aquifer system outcrop along the Colorado River as shown in Figures I.4, and the potentiometric map indicates that the Colorado River acts as a discharge site for these aquifers. The Green River lies above the upper aquifer system except near the confluence of the two rivers. Figure I.4 also shows the location of two geologic sections, Section A-A' and Section B-B'.

Figure I.5 shows the generalized geologic section along A-A'. The stratigraphic units have been grouped into a lower aquifer (Leadville limestone), central bedded salt and shale zone (Molas, Pinkerton Trail and Paradox formations), an upper aquifer (Honaker Trail, Rico and Cutler formations) and an upper aquitard (Moenkopi formation and above). Section A-A' parallels the length of the hypothetical repository and runs approximately perpendicular to the hydraulic gradients in both the upper and lower aquifer. Figure I.6 shows the generalized geologic section along B-B'. The section runs approximately parallel to the hydraulic gradient.

For modeling purposes, a composite potentiometric map for the upper aquifer in the region of interest was prepared. Based on this potentiometric map and the other details about the formation, the boundary conditions for the

FIGURE I.4. Potentiometric Map of Model Area

SECTION PERPENDICULAR TO HYDRAULIC GRADIENT

0 3000 6000

VERTICAL AND HORIZONTAL SCALE IN FEET

FIGURE I.5. Section Perpendicular to Hydraulic Gradient

SECTION PARALLEL TO HYDRAULIC GRADIENT

0 2000 FEET
VERTICAL SCALE

0 2 4 MILES
HORIZONTAL SCALE

FIGURE I.6. Section Parallel to Hydraulic Gradient

upper aquifer system were chosen. Figure I.7 shows the model boundaries and composite potential surface for the upper aquifer system. A no-flow boundary was chosen along the southwest part of the area which cut the potentials at right angles. Held potential boundary conditions were imposed along the northwest part where the potentials indicated recharge was important. Along the northeast section, which represents the areal limit of the aquifer, held potential boundary conditions were also imposed; since interpretation of the potentiometric surface indicates that this is a recharge boundary. Along the southeast section, the Colorado River was followed, and held potential boundary conditions were imposed, since this is the regional discharge boundary for the aquifer as indicated by the potentiometric surfaces. Thickness of the upper aquifer unit was determined from a cross section prepared from a surface geologic map. The unit was modeled as a 1000 ft thick uniform layer. A permeability of 100 ft/yr was used since this was the maximum observed from drill stem tests.

Parameters on the lower aquifer were compiled in order to calculate the leakage rate between the two-aquifer system through fractures. The thickness of the lower aquifer unit was taken as 500 ft and the permeability as 45 ft/yr, the average of available drill stem tests. The potential in the lower aquifer unit was determined to be 250 ft greater than the potential in the upper unit.

The bedded salt formation separating the two aquifers is 4,500 ft thick in this region. The aquifer fluids in the lower and upper systems are essentially saturated brines and their potentials were corrected to fresh water for use in this study.

The repository site was chosen near the location of a known geologic cross section. The conceptual repository was assumed to be rectangular in shape with a length of 10,428 ft and a width of 8,148 ft, and to consist of 98 disposal rooms on 78.38 ft spacings. Each room has a 20 ft x 20 ft cross section and is 10,428 ft long. The inventory of nuclear waste was assumed to be spent fuel with values derived from information prepared for DOE's generic environmental impact statement for commercial nuclear waste management. Each disposal room contains 1000 metric tons of heavy metal (MTHM), thus the repository contains a total inventory of 9800 MTHM.

FIGURE I.7. Modeled Region with Boundary Conditions and Composition Potentials

I.4 RELEASE SCENARIO

The release scenario was developed from considering a possible, but very improbable event. A seismic event was assumed to generate a fault system through the repository with an alignment parallel to the disposal rooms such that one entire room of spent fuel (1000 MTHW) was exposed. The fault fracture system was assumed to extend from the base of the lower aquifer through the bedded salt formation to the top of the upper aquifer. The length of the fault was taken to be 10 miles (approximately the same as some of the faults mapped in the area), the width of the fracture zone to be approximately 5 feet. Permeability of the fault zone was assumed to be 500 ft/yr, or approximately ten times the permeability of the lower aquifer. A simple analytical model was used to calculate a vertical flow of 19.5 gpm of water through the fracture zone.

I.5 MATHEMATICAL MODELS

I.5.1 Leach Rate Model

A leach rate model was developed to determine the length of time and rate at which the contaminants would be carried via the water flowing through the fracture and repository into the upper aquifer. The leach rate model was formulated using preliminary data on waste leach rates and the observed effects of flow rate and temperature on leach rate. These preliminary data were collected and compiled from the WISAP Waste Form Release Rate Analysis Task (TASK 2). The data from leaching experiments on crushed spent fuel indicate that the specific leach rates vary from nuclide to nuclide. The data also indicate that the specific leach rate is a function of the flushing rate for rates greater than one flush per year. At flushing rates less than one flush per year, the rates are essentially constant. The data currently available on temperature effects indicate that specific leach rate versus temperature follows an Arrhenius-type relationship. Leach rate data comparisons between solid high level wastes and crushed high level wastes indicate that although leach rate is dependent on actual surface area, the rate is not directly proportional to the surface area. This may be due to the interference between the boundary layer concentration gradients between adjacent

waste particles. The highest specific leach rate was used for all nuclides, and the entire fuel rod was assumed to leach at this rate. The fuel was assumed to be crushed. It was assumed that all of the fuel in the repository area fractured by the fault (1000 metric tons of heavy metal - MTHM) was exposed for leaching. The leach rate model was run and the output function generated was used as an input to the transport model. This function is shown in Figure I.8. Details on the leach rate model are contained in Part 2 of this report.

I.5.2 Hydrologic Modeling

Based on the conceptual model formulated from the available data, the Variable Thickness Transient (VTT) hydrologic model⁶ was chosen to simulate the upper aquifer. The VTT Model is a two-dimensional finite difference code which uses the Boussinesq approximation to reduce the ground-water equations from three dimensions to two. The hydrologic model is used to determine the water path and travel time from the repository to the discharge site (Colorado River). From the hydrologic model-calculated potential distribution throughout the area simulated, the rate and direction of water movement in the aquifer can be determined. This velocity field provides one component of the data required to run the transport code. The travel times and flow paths for water leaving the repository through the fracture system were calculated. The potential surface was analyzed by one of the VTT auxiliary programs to determine the starting locations for five equal-in-flow flow tubes that start at the juncture of the fracture and the upper aquifer.

The five flow tubes defined by the six streamlines are shown in Figure I.9. Each carries approximately 7.28 gpm. The average flow tube length, water velocity, and water travel times are shown in Table 1.2. Additional technical discussion of the hydrologic modeling is contained in Part II.

FIGURE I.8. Release Rate Curve

FIGURE I.9. Groundwater Flow Tubes and Streamlines from the Breached Repository to the Colorado River

TABLE I.2. Table of Average Velocity

	<u>Average Travel Time (years)</u>	<u>Velocity (ft/yr)</u>	<u>Average Length (ft)</u>
Flow Tube No. 1	43,700	4.26	186,188
Flow Tube No. 2	43,500	4.24	184,500
Flow Tube No. 3	43,200	4.22	182,250
Flow Tube No. 4	43,000	4.19	180,563
Flow Tube No.5	43,000	4.16	179,438

I.5.3 Transport Modeling

The data shown in Table I.2 are used for input to the radionuclide transport model. A one-dimensional version of the Multicomponent Mass Transport Model (MMT)⁷ was used to analyze the movement of the radiocontaminants down the five flow tubes. The MMT model considers simple radioactive decay, linear chain decay, branched chain decay, and retardation from soil/nuclide interactions. The method of solution is by simulating the physical phenomena causing mass transport in ground-water aquifers. Convection is simulated by attaching mass to a parcel and moving that parcel a distance calculated by the product of the local ground-water velocity and the current time step (Discrete Parcel Random Walk). Dispersion is simulated by using random numbers between -1 and 1 multiplied by a length factor and the time step.

Equal-in-flow flow tubes for waste moving from the repository were determined from the hydrologic model. Each of these flow tubes have different velocities and path lengths to the Colorado River. A one-dimensional transport solution was obtained for each of these flow tubes. The results obtained from these simulations were ground-water contaminant concentrations entering the Colorado River versus time or, in the case of the transuranic elements, the location and concentration in the flow tube between the repository and the river. The various output forms are as follows:

- as a plot of the nuclide concentration ($\mu\text{Ci/ml}$) in the ground water (which enters the river) versus time for each flow tube,

- as a plot of maximum nuclide concentration ($\mu\text{Ci/ml}$) in the ground water (which enters the river) versus time,
- as a plot of concentration in the ground and ground water versus distance for the actinides which have not reached the river in two million years.

Only those radioisotopes remaining in significant amounts after 10,000 years were selected for study since the travel times to the river for water alone were greater than 4×10^4 years. Isotopes that are not involved in chain decay schemes can be followed one by one through the flow system. These isotopes include the fission products and the activation products. The actinides, however, were followed in four decay chains, some of which are linear and some of which may include branches.

Figures I.10 through I.16 are examples of the model output. Figures I.10 through I.14 are the graphs of concentrations ($\mu\text{Ci/ml}$) for a specific nuclide (Iodine-129, in this case) in the ground water entering the river, plotted against time. Each plot is for an individual flowtube. Figure I.15 shows the maximum concentration (composite of all flow tubes) plotted against time. Figure I.16 is an example graph of a nuclide (Radium-226, in this case) that has not reached the river in two million years. Total concentration in the soil column (both in the ground water and sorbed on the media) is plotted versus the fractional distance to the river at time equal two million years.

Model Results

Figures I.17 through I.19 show the maximum concentrations in the ground water at the Colorado River boundary (composite of the five flow tubes) for the three fission products that arrived at the River in concentrations exceeding $10^{-10} \mu\text{Ci/ml}$ (0.01 of the most restrictive concentration guide for uncontrolled drinking water use).⁸ Figure I.17 shows that arrival of Technetium-99 (Tc-99) at the river boundary begins about 2.80×10^6 years after repository breach and rises to a maximum concentration of $1.66 \times 10^{-10} \mu\text{Ci/ml}$ at 2.92×10^6 years after breach. Technetium concentration is further reduced upon entry to the Colorado River. Mean flow rate of the river is about 7000 cubic feet per second (ft^3/sec). The contaminated ground water enters the river at a flow rate of about $0.081 \text{ ft}^3/\text{sec}$;

FIGURE I.10. I-129 Concentration Versus Time for Flow Tube 1

FIGURE I.11. I-129 Concentration Versus Time for Flow Tube 2

FIGURE I.12. I-129 Concentration Versus Time for Flow Tube 3

FIGURE I.13. I-129 Concentration Versus Time for Flow Tube 4

FIGURE I.14. I-129 Concentration Versus Time for Flow Tube 5

KD= 0.50 ML/G HALF-LIFE=1.5900E+07 YEARS BETA= 35.0 G/ML

ISOTOPE I-129

CONCENTRATION VS TIME

FIGURE I.15. Maximum I-129 Concentration Versus Time at Discharge

FIGURE I.16. Ra-226 Concentration in the Ground

FIGURE I.17. Maximum Tc-99 Concentration Versus Time at Discharge

therefore, the ground water dilution ratio is $0.81/7000$ or 1.16×10^{-5} , resulting in a concentration of Tc-99 in the river of $1.92 \times 10^{-15} \mu\text{Ci/ml}$. The concentration guide for Tc-99 in drinking water is $3 \times 10^{-4} \mu\text{Ci/ml}$.⁹

Figure I.18 shows that arrival of Iodine-129 at the river boundary begins about 7.7×10^5 years after repository breach and rises to a maximum concentration of $1.84 \times 10^{-8} \mu\text{Ci/ml}$ in the ground water at 8.0×10^5 years. The resultant concentration of I-129 in the river is $2.13 \times 10^{-13} \mu\text{Ci/ml}$. The concentration guide for I-129 in drinking water is $6 \times 10^{-8} \mu\text{Ci/ml}$.

Figure I.19 shows that arrival of Cesium-135 at the river boundary begins about 1.503×10^6 years after repository breach and rises to a maximum concentration of $5.3 \times 10^{-8} \mu\text{Ci/ml}$ in the ground water at 1.552×10^6 years. The resultant concentration of Cs-135 in the river is $6.15 \times 10^{-13} \mu\text{Ci/ml}$. The concentration guide for Cs-135 in drinking water is $1.0 \times 10^{-4} \mu\text{Ci/ml}$.

None of the transuranic nuclides were discharged to the Colorado River in a model run time of two million years. These radionuclides were contained in the ground water and sorbed on the geologic media at varying distances between the repository and the river. Figures A.1 through A.11 in Appendix A show graphs of the transuranic nuclide concentration in the ground water plotted against fractional distance from the repository to the discharge site at 2×10^6 years after repository breach. The figures also show the total inventory of the nuclides sorbed on the geologic media (soil) and total inventory in the ground water.

As an example, Figure A.1 shows the plot for Radium-226 (the only transuranic nuclide that appears in significant concentration). The peak Ra-226 ground-water concentration of $1.02 \times 10^{-7} \mu\text{Ci/ml}$ appears at 0.456 of the distance between the repository and the river. The maximum permissible concentration (MPC) of Ra-226 in drinking water (uncontrolled use) is $3 \times 10^{-8} \mu\text{Ci/ml}$;⁹ thus the modeled concentration is 3.4 times MPC. However, the ground water is a concentrated brine and could not be used for potable water supply. Figure A.1 also shows the total nuclide inventory in the ground water ($1.2395 \times 10^1 \text{ Ci}$) and sorbed on the soil ($3.0368 \times 10^2 \text{ Ci}$).

FIGURE I.18. Maximum I-129 Concentration Versus Time at Discharge

FIGURE I.19. Maximum Cs-135 Concentration Versus Time at Discharge

I.6 ADDITIONAL STUDIES

The results presented in this study are applicable only for the one particular set of parameters selected. A complete sensitivity analysis, testing several values for the hydrologic and transport model parameters, will be performed to evaluate the range of effects that might result from the release of contaminants from a breached repository, and to demonstrate and document the procedure for performing a site specific sensitivity analysis.

In the sensitivity study, the base case will be defined as the values of the parameters selected for use in the initial VTT and MMT model runs as discussed above. The base case provided a starting point from which sensitivity comparisons could be made. In the sensitivity analysis, each parameter will be allowed to vary over a range of practical values while holding all other parameters constant at their base case values.

The following parameters will be considered in the sensitivity analysis:

VTT Hydrologic Model

- 1) Porosity of the upper aquifer
- 2) Permeability of the upper aquifer
- 3) Boundary Recharge Rate
- 4) Fracture Flow Rate

MMT Transport Model

- 1) Retardation Factor
- 2) Dispersion Length
- 3) Porosity
- 4) Ground-water Velocity
- 5) Waste Leach Rate

These parameters will be selected because of the uncertainties in field data (i.e., they may not be determined accurately in the field). The remaining parameters (e.g., geologic structure, repository site location, etc.) will not be considered because they can either be accurately measured, will be defined by the final design and location of the repository, or will have little impact on the results.

PART II. TECHNICAL DISCUSSION

II.1 HYDROLOGIC MODELS

A simple analytical model was used to calculate the flow through a unit length of fracture. Figure II.1 shows a diagram of the system. Accounting for the loss or gain in head in each unit we have:

$$H_{total} = H_u + H_\ell + H_b \quad (1)$$

where the H_i ($i = u, \ell, b$) are given by Darcy's law for flux, Q , as:

$$Q = 2 L T_u K_u \frac{H_u}{D_u} \text{ or } H_u = \frac{Q D_u}{2 L T_u K_u} \quad (2)$$

$$Q = K_b W_b \frac{H_b}{T_b} L \text{ or } H_b = \frac{Q T_b}{W_b L K_b} \quad (3)$$

$$Q = 2 L T_\ell K_\ell \frac{H_\ell}{D_\ell} \text{ or } H_\ell = \frac{Q D_\ell}{2 L T_\ell K_\ell} \quad (4)$$

Thus, substituting the above expressions for H_i into the expression for H_{total} and solving for Q/L (flow per unit length of fracture) we obtain:

$$Q/L = \frac{2 H_{total}}{\frac{D_u}{T_u K_u} + \frac{D_\ell}{T_\ell K_\ell} + \frac{2 T_b}{W_b K_b}} \quad (5)$$

Assuming a radius of influence of 10,000 ft for the upper aquifer and 2500 ft for the lower aquifer, we obtain a Q/L of 1.87×10^{-3} gpm/ft. The total flow through the length of the repository fracture would thus be 19.47 gpm and the total flow between aquifers over the entire 52,500 ft of fracture would be 98.18 gpm.

H_{total} = total head differential between aquifer units prior to fracture

K = permeability of unit (feet/year)

Subscripts u = upper aquifer

b = salt bed fracture

l = lower aquifer

H = head increase or decrease (feet)

T = thickness of unit (feet)

D = distance to essentially no influence due to fracture leakage (feet)

W_b = width of fracture zone (feet)

FIGURE II.1. System Diagram for Fracture Flow Calculation

The flow computed in this fashion served as the only source (or sink) term for the analysis of flow in the upper aquifer. All other flow into or out of the aquifer arises from the held potential boundary conditions.

The VTT (Variable Thickness Transient) model was chosen for simulating the flow in the upper aquifer. The VTT model is a two-dimensional finite difference code which uses the Boussinesq approximation to reduce the groundwater equations from three dimensions to two. The formulation solved by VTT is shown in Equation (6).

$$\nabla \cdot (K\{h_T - h_b\}\nabla h) = S \frac{\partial h}{\partial t} - Q \quad (6)$$

where:

∇ = the two-dimensional (x,y) gradient operator;

K = the hydraulic conductivity;

h = the free-surface potential or potentiometric water elevation;

h_T = the aquifer top if confined or h for a water table;

h_b = the aquifer bottom;

S = the storage coefficient; and

Q = the source or sink term.

The hydrologic model is used to determine the water path and travel time from the repository to the discharge site (Colorado River). From the calculated potential distribution, the rate and direction of water movement throughout the aquifer can be determined. This velocity field provides the data necessary to run the transport code.

The input required by the VTT model consists of:

- Interpreted Potentiometric Distribution
- Boundary Conditions
- Hydraulic Conductivity Distribution
- Thickness Distribution or Elevation of Base and Elevation of Top of Aquifer Unit
- Distribution of Sources and Sinks

The VTT model was set up using a 7,500-foot node spacing over the region modeled. This resulted in a finite difference grid with 54 nodes in the east-west direction and 73 nodes in the north-south direction. In order to model waste pathways from the repository, VTT was used to analyze a subregion extending from the repository to the discharge site. This subregion was defined over columns (east-west) 20-32 and lines (north-south) 8-38 of the large region. The resulting small region grid had 59 nodes in the east-west direction and 151 nodes in the north-south direction and a 1500-ft node spacing. The travel times and flow paths for water leaving the repository from the fracture were calculated using this small region. The small-region potential surface was analyzed by one of the VTT auxiliary programs to determine the starting locations for the equal-in-flow spaced flow tubes that originate at the repository fracture.

II.2 TRANSPORT MODEL

The transport model used for the simulation was the one-dimensional MTT (Multicomponent Mass Transport) model which has been modified to handle simple decay, linear chain decay, as well as branch chain decay. The transport equation which considers the retardation resulting from soil-nuclide-water interactions has the form shown in Equation (7).

$$K_1 \frac{\partial N_1}{\partial t} = D \frac{\partial^2 N_1}{\partial x^2} - V \frac{\partial N_1}{\partial x} - \lambda_1 K_1 N_1 \quad (7)$$

where:

K_1 = retardation coefficient for nuclide 1 (water velocity/
nuclide velocity);

N_1 = activity concentration of nuclide 1, Ci/ml;

λ_1 = decay rate of nuclide 1, year⁻¹;

V = ground-water velocity, ft/yr;

D = dispersion coefficient, ft²/yr;

x = distance in x-direction, ft;

t = time, yr.

The initial and boundary conditions used include:

$N_1(x,0) = 0$ (initial)

$N_1(L,t) = \text{finite}$ (boundary)

$N_1(0,t) = \text{function of leach model and nuclide decay (source)}.$

Accounting for decay chains yields a system of partial differential equations:

$$K_2 \frac{\partial N_2}{\partial t} = D \frac{\partial^2 N_2}{\partial x^2} - V \frac{\partial N_2}{\partial x} - \lambda_2 K_2 N_2 + \lambda_2 K_1 N_1 \quad (8)$$

$$K_n \frac{\partial N_n}{\partial t} = D \frac{\partial^2 N_n}{\partial x^2} - V \frac{\partial N_n}{\partial x} - \lambda_n K_n N_n + \lambda_n K_{n-1} N_{n-1} \quad (9)$$

Branched chains are taken care of similarly; only the subscripts for the parent of the nuclide change.

The solution is obtained by simulating the physical mass transport phenomena in ground-water aquifers. Convection is simulated by attaching mass to a parcel and moving that parcel a distance equal to the product of the local ground-water velocity and the current time step. Dispersion is simulated by using random numbers between -1 and 1 multiplied by a length factor and divided by the time step.

The model used for these simulations requires the following input data:

- retardation coefficient
- dispersion
- half-life branch nuclides
- initial inventory
- a mapping illustrating the parent-daughter relationships
- path length
- ground-water velocity
- flow tube size
- time after repository closure when the breach occurs
- leach information to control entry of waste into the ground-water system

The retardation coefficient, K , is calculated from the soil-to-solution ratio (β) and the distribution coefficient, K_d (ml/g), by:

$$1 + \beta K_d = K \quad (10)$$

The soil-to-solution ratio (g/ml) is calculated from the porosity and bulk density of the media. The path length and ground-water velocity were obtained from the hydrologic model.

This one-dimensional model was used for pseudo-two-dimensional simulations. Equal-in-flow flow tubes were determined from the hydrologic model. Each of these flow tubes has a different velocity and path length to the Colorado River. A one-dimensional solution was obtained for each of these

flow tubes. The results of these simulations are: 1) the contaminant concentration in the ground water at any point in time as a function of position in the flow tube; or 2) the concentration in the ground water entering the river versus time.

Only the isotopes which would have measurable inventory after 10,000 years need be simulated since the travel times to the river were greater than 4×10^4 years for water alone. Table II.1 shows the radionuclides, half lives, inventory, K_d , and drinking water standard which were used as an input to the transport code.

Isotopes not involved in chain decay schemes can be followed one by one through the flow system. These isotopes include the fission products and the activation products. The actinides, however, are involved in essentially four decay chains, some of which are much longer than the lists shown in Table II.1, but the short half lives of the intermediate members allow them to be ignored for the transport problem. Table II.2 shows the full chain 1 actinides, as well as the reduced chain used for simulation purposes. Activity levels for the intermediate actinides not modeled are essentially equivalent to the activity of the parent, since the daughters can only disintegrate at the rate at which they are produced by the parent. Table II.3 shows the three other reduced chains modeled.

II.3 LEACH RATE MODEL

A leach rate model was developed to determine the length of time and the rate at which the contaminants would be carried, via the aquifer water, through the fractured salt and repository and into the upper aquifer system. The leach rate model was formulated using preliminary data on waste leach rates and the observed effects of flow rate and temperature on leach rate. The data from leaching experiments on crushed spent fuel (3 cm^2 of surface area/gram of fuel with a density of 10.2 g/cm^3) indicate that the specific leach rates (g-leached/cm^2 of surface area/day) vary from nuclide to nuclide as shown in Table II.4. The data also indicate that for rates greater than one flush per year the specific leach rate is a function of the flushing rate. At less than one flush per year, the rates are essentially constant.

TABLE II.1. Radionuclides Modeled by the Transport Code

	ISOTOPE	HALF LIFE (YEARS)	K_d (mL/g)	UNCONTROLLED WATER RADIATION STANDARD (μ Ci/mL)	10 YEAR INVENTORY (CURIES/MTHM)
ACTIVATION AND FISSION PRODUCTS	NI-59	8.0E+4	50.	2.0E-4	3.03
	SE-79	6.5E+4	2.	3.0E-4	3.5E-1
	RB-87	4.7E+10	1.0	1.0E-4	1.7E-5
	MO-93	3.0E+3	15.	2.0E-4	7.3E-3
	NB-94	2.0E+4	80.	1.0E-4	1.0E-4
	ZR-93	9.5E+5	80.	8.0E-4	1.79
	TC-99	2.13E+5	1.9	3.0E-4	13.007
	PD-107	6.5E+6	38.	9.0E-5	9.9E-2
	SN-126	1.0E+5	80.	2.0E-5	.48
	I-129	1.59E+7	.5	6.0E-8	.033
ACTINIDE CHAIN 1	CS-135	2.3E+6	1.0	1.0E-4	.27
	PU-240	6540.	80.	5E-6	452.5
	U-236	2.3E+7	2.9	3E-5	.22
ACTINIDE CHAIN 2	TH-232	1.4E+10	80.	2E-6	1.1E-10
	CM-245	8.5E+3	1120.	4E-6	.18
	PU-241	15.	80.	2E-4	6.9E+4
	Am-241	433.	1130.	4E-6	1600.
	NP-237	2.14E6	23.	3E-6	.32
	U-233	1.58E5	2.9	3E-5	3.8E-5
ACTINIDE CHAIN 3	TH-229	7340.	80.	7E-6	2.8E-8
	CM-246	4760.	1120.	4E-6	3.5E-2
	PU-242	3.87E5	80.	5E-6	1.6
	U-238	4.47E9	2.9	4E-4	.32
	U-234	2.44E5	2.9	3E-5	.804
	TH-230	7.7E4	80.	2E-6	4.1E-6
ACTINIDE CHAIN 4	RA-226	1600.	.7	3E-8	7.4E-9
	AM-243	7.37E3	1130.	4E-6	14.7
	PU-239	2.439E4	80.	5E-6	290.
	U-235	7.04E8	2.9	3E-5	.016
	PA-231	3.25E4	100.	9E-7	5.35E-6

TABLE II.2. Complete Actinide Chain No. 1

COMPLETE ACTINIDE CHAIN NO. 1

(UNDERLINED ISOTOPES
REPRESENT THE ONES MODELED)

TABLE II.3. Modeled Actinide Chains 2, 3 and 4

MODELED ACTINIDE CHAINS 2, 3, AND 4

Cm-245	8.5E+3 Y
↓	
Pu-241	15.0 Y
↓	
Am-241	433.0 Y
↓	
Np-237	2.14E+6 Y
↓	
U-233	1.58E+5 Y
↓	
Th-229	7340.0 Y

ACTINIDE CHAIN 2

Cm-246	4760.0 Y	Am-242 M	152 Y
↓		↓	
Pu-242	3.87E+5 Y	Cm-242	0.45 Y
↓		↓	
U-238	4.47E+9 Y	Pu-238	87.8 Y

↓		↓	
U-234	2.44E+5 Y		
↓			
Th-230	7.7E+4 Y		
↓			
Ra-226	1600.0 Y		

ACTINIDE CHAIN 3

Cm-247	1.54E+7 Y		
↓			
Am-243	7.37E+3 Y	Cm-243	28 Y
↓		↓	
Pu-239	2.439E+4 Y		
↓			
U-235	7.04E+8 Y		
↓			
Pa-231	3.25E+4		

ACTINIDE CHAIN 4

TABLE II.4. Preliminary Specific Leach Rate^(a) Values

Isotope	Crushed Spent Fuel at 25°C, 3 cm/g, Weekly Flushing	Crushed Spent Fuel at 250°C, 3 cm/g, One Flush/Year	Crushed Spent Fuel at 25°C, 3 cm/g, One Flush/Year	Solid High-Level Waste Particles, One Flush/Year	Crushed High-Level Waste (42-60 mesh), One Flush/Year
Cs	5×10^{-6}	5×10^{-6}	5×10^{-8}	4×10^{-7}	4×10^{-9}
Pu	5×10^{-6}	5×10^{-6}	5×10^{-8}		
Sb	2×10^{-6}				
Eu	1×10^{-6}				
Cu	1×10^{-6}				
Ce	3×10^{-7}				
U	8×10^{-8}				
I	1×10^{-6}				
Tc	5×10^{-6}				

(a) Rates are in g-leached/cm² of surface area/day.

The data currently available on temperature effects indicate that specific leach rate versus temperature follows an Arrhenius-type relationship. Data currently available at $T = 25^\circ\text{C}$ and $T = 250^\circ\text{C}$ allow us to determine the constants in this relationship. Leach rate data comparisons between solid and crushed high-level wastes indicate that although leach rate depends on actual surface area, the rate is not directly proportional to the surface area.

For the initial leach rate model the highest specific leach rate was used for all nuclides. The entire fuel rod, including all drummed wastes, was assumed to leach at this rate. The fuel was assumed to be crushed, and the crushed fuel particles were modeled as spheres. Leach rate at any time was calculated as follows:

$$LR = SLR(T) \times SA(t) \times WSP \quad (11)$$

where

LR = leach rate (g/day)

t = time (days)

SLR(T) = specific leach rate (g/cm² of surface area/day) and is dependent on the temperature T

WSP = mass of one of the spherical fuel particles (g)

T = temperature of the fuel at any time t in °C

SA(t) = surface area to mass ratio for a spherical waste particle (cm²/g).

The temperature of the fuel is assumed to be proportional to the heat generation rate of the fuel, and the heat generation rate is determined from a power function fit of the table of heat generation rate (HGR) for spent fuels. Equation (12) shows the power function used for HGR as a function of time t:

$$\text{HGR}(t) = 7468 t^{-0.723} \quad (12)$$

and Table II.5 compares published and fitted heat generation rates. The temperature is calculated by assuming that at t = 10 years, the crushed fuel in the breached canister and clad will be at the design canister temperature, and at 1,000,000 years the fuel will be at a background or ambient temperature of 50°C. Temperature at any time is calculated by Equation (13).

$$T(t) = 50 + \frac{(375 - 50)}{(1414 - 0.34)} \times (7468 t^{-0.723} - 0.34). \quad (13)$$

SLR(T) is assumed to follow an Arrhenius relationship which states that $\ln(\text{SLR}[T])$ is proportional to the inverse of the absolute temperature. Now, since we have measured values for the fuel leach rate at 25°C and 250°C, we can determine the constants C1 and C2 in this relationship:

$$\ln(\text{SLR}[T]) = \ln(\text{SLR}[T_a]) - \left(C2 \left[\frac{T_a + 273}{T + 273} \right] + C1 \right). \quad (14)$$

TABLE II.5. Comparison Between Fitted and Published Heat Generation Rate and Model-Predicted Temperature

<u>Time, yr</u>	<u>Published HGR,¹⁰ W/MTHM</u>	<u>Fitted HGR, W/MTHM</u>	<u>Modeled Temperature, °C</u>
10	1,200	1,413	375
100	290	268	112
1,000	55	51	62
10,000	14	9.6	52
100,000	1.1	1.8	50.4
1,000,000	0.39	0.34	40.0

Since we are dealing with crushed spent fuel and our flushing rate is less than one flush/year, we have determined that $SLR(T_a) = SLR(25^\circ\text{C}) = 5 \times 10^{-8}$ and $SLR(250^\circ\text{C}) = 5 \times 10^{-6}$, thus $C_1 = -10.72$ and $C_2 = 10.72$ and the resulting equation for $SLR(T)$ is given by Equation (15).

$$SLR(T) = SLR_0 \times \exp \left(- \left[10.72 \left[\frac{T_a + 273}{T + 273} \right] - 10.72 \right] \right) \quad (15)$$

where

$$SLR_0 = 5 \times 10^{-8}$$

$$T_a = 25^\circ\text{C}$$

The specific surface area of the fuel or glass (SA) assuming a spherical model is given by Equation (16).

$$SA(t) = \frac{3}{R(t) \times D} \quad (16)$$

where

$$R(t) = \text{radius of a spherical particle}$$

$$D = \text{density of fuel.}$$

The weight of a spherical particle of fuel at any time t is given by Equation (17).

$$WSP = \frac{4}{3} \pi R(t)^3 \times D. \quad (17)$$

The leach rate model uses the above equations to calculate the fraction of the waste remaining in the repository at any time t by a simple rectangular integration scheme that determines the current radius of the fuel particles. At the time t_0 when the leaching begins, the fuel is assumed to be composed of equal-sized spherical particles. The values for T , SA , SLR , and WSP are calculated for time t_0 to determine the current rate, LR , at which fuel or glass is being leached from the surface of each spherical particle. This rate is assumed to hold for some time Δt , thus dissolving some weight of fuel or glass from the particle, $WD = LR \times \Delta t$. From this leached weight the decrease in radius, DR , of the fuel particle is then calculated from Equation (18).

$$DR(t) = R(t) - \sqrt[3]{R^3(t) - \left[\frac{WD(T)}{D \times \frac{4}{3} \times \pi} \right]} \quad (18)$$

$R(T_0 + \Delta t)$ is now $R(t_0) - DR(t_0)$ and the process is repeated until $R(t)/R(t_0)$ is less than 0.1, at which time all the fuel is assumed to be dissolved.

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APPENDIX A

CONCENTRATION VERSUS DISTANCE PLOTS FOR TRANSURANIC NUCLIDES

KD= 0.70 ML/G HALF-LIFE=1.6000E+03 YEARS BETA= 35.0 G/ML
INVENTORY(CURIES) INITIAL=7.4000E-06.ON SOIL=3.0368E+02.IN THE WATER=1.2395E+01
ISOTOPE RA-226 CONCENTRATION VS DISTANCE AT 2.00E+06 YEARS

FIGURE A.1. Concentration Versus Distance Plot for Ra-229

KD= 80.00 ML/G HALF-LIFE=7.3400E+03 YEARS BETA= 35.0 G/ML
INVENTORY(CURIES) INITIAL=2.8000E-05, ON SOIL=3.7161E+02, IN THE WATER=1.3272E-01
ISOTOPE TH-229 CONCENTRATION VS DISTANCE AT 2.00E+06 YEARS

FIGURE A.2. Concentration Versus Distance Plot for Th-229

KD= 80.00 ML/G HALF-LIFE=7.7000E+04 YEARS BETA= 35.0 G/ML
INVENTORY(CURIES) INITIAL=4.1000E-03, ON SOIL=3.1703E+02, IN THE WATER=1.1323E-01
ISOTOPE TH-230 CONCENTRATION VS DISTANCE AT 2.00E+06 YEARS

FIGURE A.3. Concentration Versus Distance Plot for Th-230

KD= 100.00 ML/G HALF-LIFE=3.2500E+04 YEARS BETA= 35.0 G/ML
INVENTORY(CURIES) INITIAL=5.3500E-03, ON SOIL=2.5328E+01, IN THE WATER=7.2366E-03
ISOTOPE PA-231 CONCENTRATION VS DISTANCE AT 2.00E+06 YEARS

FIGURE A.4. Concentration Versus Distance Plot for Pa-231

KD= 80.00 ML/G HALF-LIFE=1.4000E+10 YEARS BETA= 35.0 G/ML
INVENTORY(CURIES) INITIAL=1.1000E-07.ON SOIL=3.3437E-02.IN THE WATER=1.1942E-05
ISOTOPE TH-232 CONCENTRATION VS DISTANCE AT 2.00E+06 YEARS

FIGURE A.5. Concentration Versus Distance Plot for Th-232

KD= 2.90 ML/G HALF-LIFE=1.5800E+05 YEARS BETA= 35.0 G/ML
INVENTORY(CURIES) INITIAL=3.8000E-02.ON SOIL=3.6619E+02.IN THE WATER=3.6078E+00
ISOTOPE U-233 CONCENTRATION VS DISTANCE AT 2.00E+06 YEARS

FIGURE A.6. Concentration Versus Distance Plot for U-233

KD= 2.90 ML/G HALF-LIFE=2.4400E+05 YEARS BETA= 35.0 G/ML
INVENTORY(CURIES) INITIAL=7.4000E+01.ON SOIL=3.1597E+02.IN THE WATER=3.1130E+00
ISOTOPE U-234 CONCENTRATION VS DISTANCE AT 2.00E+06 YEARS

FIGURE A.7. Concentration Versus Distance Plot for U-234

KD= 2.90 ML/G HALF-LIFE=7.0400E+08 YEARS BETA= 35.0 G/ML
INVENTORY(CURIES) INITIAL=1.6000E+01.ON SOIL=2.5870E+01.IN THE WATER=2.5488E-01
ISOTOPE U-235 CONCENTRATION VS DISTANCE AT 2.00E+06 YEARS

FIGURE A.8. Concentration Versus Distance Plot for U-235

KD= 2.90 ML/G HALF-LIFE=2.3000E+07 YEARS BETA= 35.0 G/ML
INVENTORY(CURIES) INITIAL=2.2000E+02.ON SOIL=3.2508E+02.IN THE WATER=3.2028E+00
ISOTOPE U-236 CONCENTRATION VS DISTANCE AT 2.00E+06 YEARS

FIGURE A.9. Concentration Versus Distance Plot for U-236

KD= 23.00 ML/G HALF-LIFE=2.1400E+06 YEARS BETA= 35.0 G/ML
INVENTORY(CURIES) INITIAL=6.6700E+02, ON SOIL=3.4854E+02, IN THE WATER=4.3297E-01
ISOTOPE NP-237 CONCENTRATION VS DISTANCE AT 2.00E+06 YEARS

FIGURE A.10. Concentration Versus Distance Plot for Np-237

KD= 2.90 ML/G HALF-LIFE=4.4700E+09 YEARS BETA= 35.0 G/ML
INVENTORY(CURIES) INITIAL=3.2000E+02, ON SOIL=3.1677E+02, IN THE WATER=3.1209E+00
ISOTOPE U-238 CONCENTRATION VS DISTANCE AT 2.00E+06 YEARS

FIGURE A.11. Concentration Versus Distance Plot for U-238

APPENDIX B

GLOSSARY

APPENDIX B

GLOSSARY

Actinide chain: The four decay series (uranium, actinium, thorium, neptunium) which start in the actinides and decay through various species of radioactive materials to stable lead and bismuth.

Actinide elements: The series of elements of highest numbers, beginning with actinium (at. no. 89). Sometimes restricted to the tervalent form of these elements.

Activation productions: Characteristic radionuclides formed from nuclear bombardment of some material.

Anticline: 1. Term applied to strata which dip in opposite directions from a common ridge or axis, like the roof of a house and from what is termed an "anticline" or "saddleback". 2. When beds are arched so as to incline away from each other, they form an anticline.

Aquiclude: A formation which, although porous and capable of absorbing water slowly, will not transmit it fast enough to furnish an appreciable supply for a well or spring.

Aquifer: A formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.

Arrhenius-type relationship: A relationship in which the logarithm of the leach rate is proportional to the absolute temperature.

Bedded formation (bedded salt): A formation which shows successive beds, layers or strata, due to the manner in which it was formed. A bedded deposit.

Biosphere: The life zone of the earth, including the lower part of the atmosphere, the hydrosphere and soil.

Boundary layer concentration gradient: The thin layer of ground water surrounding the waste particles.

Boussinesq approximation: Assumption that the head varies gradually with the distance along the main flow, so that transversal flow components may be neglected.

Bulk density: Ratio of the mass of soil particles to the total volume of the soil.

Calcareous: Resembling, containing, or composed of calcium carbonate.

Chert: 1. (Insoluble residue) Cryptocrystalline varieties of silica regardless of color, composed mainly of petrographically microscopic chalcedony and/or quartz particles whose outlines range from easily resolvable to nonresolvable with binocular microscope at magnifications ordinarily used. Particles rarely exceed 0.5 mm in diameter. 2. In mineralogy, a compact, siliceous rock formed of chalcedonic or opaline silica, one or both, and of organic or precipitated origin. Chert occurs distributed through limestone, affording cherty limestones. Flint is a variety of chert.

Concentration gradient: The change in concentration with distance.

Conglomerate: 1. Rounded water-worn fragments of rock or pebbles, cemented together by another mineral substance, which may be of a siliceous or argillaceous nature.

Contour line: 1. A line on a map representing a contour. Note: present usage makes contour and contour line synonymous. 2. A line connecting points of equal elevation above or below a datum plane such as sea level. May be topographic or structural.

Curie: Unit of radioactive disintegration, 3.70×10^{10} disintegrations per second.

Darcy's Law: A relationship describing flow which states that the flow rate is proportional to the head loss, inversely proportional to the length of the flow path, and proportional to a coefficient related to the nature of the porous media.

Decay rate: The time rate of disintegration of radioactive material, generally accompanied by emission of particles or gamma radiation.

Deformation: Any alteration of shape or dimensions of a body caused by stresses, thermal expansion or contraction, chemical or metallurgical transformations, or shrinkage and expansions due to moisture change.

Discharge site: Location where ground water (and contaminants traveling in ground water) leaves the geosphere and enters the biosphere.

Dispersion coefficient: As fluid moves through a porous medium it gradually spreads beyond the region it would be expected to occupy based on average flow and diffusion (molecular) alone. This additional spreading is called dispersion and is characterized mathematically like diffusion. The coefficient which describes this additional spreading is the dispersion coefficient.

Distribution coefficient (K_d): a measure of the distribution of an ion species between the water or liquid phase, and the solid phase which tends to sorb the ion.

Dolomite: 1. A mineral, $\text{CaMg}(\text{CO}_3)_2$. Commonly with some Fe replacing Mg (ankerite). Hexagonal rhombohedral. A common rock-forming mineral. 2. A term applied to those rocks that approximate the mineral dolomite in composition. Also called magnesian limestone, it occurs in a great many crystalline and noncrystalline forms the same as pure limestone, and among rocks of all geological ages. When the carbonate of magnesia is not present in the above proportion the rock may still be called a magnesian limestone, but not a dolomite, strictly speaking.

Dose models: Mathematical formulations used for calculation of radiation doses to individuals and to population groups.

Drill-stem test: A test of the productive capacity of a well when still full of drilling mud. The testing tool is lowered into the hole attached to the drill pipe and placed opposite the formation to be tested. Packers are set to shut off the weight of the drilling mud, and the tool is opened to permit the flow of any formation fluid into the drill pipe, where it can be measured.

Event: A specified change of state at a defined moment of time.

Failure: Condition caused by collapse, break, or bending, so that a structure or structural element can no longer fulfill its purpose.

Fault: A fracture or fracture zone along which there has been displacement of the two sides relative to one another parallel to the fracture. The displacement may be a few inches or many miles.

Fission products: Elements or compounds resulting from fission.

Flow tube (stream tube): A division of a hydrologic flow field into representative parts in such a way that each part (flow tube) carries the same flow. Each flow tube has its own characteristic travel time. A tube of fluid bounded by a group of streamlines which enclose the flow.

Flushing rate: The rate at which water fills the void space between the contaminants in the repository or replaces that water.

Formation: 1. In Geology, any assemblage of rocks which have some character in common, whether of origin, age, or composition. 2. As defined and used by the U.S. Geological Survey, the ordinary unit of geologic mapping consisting of a large and persistent stratum of some one kind of rock.

Fracture: 1. The manner of breaking and appearance of a mineral when broken, which is distinctive for certain minerals, as conchoidal fracture. 2. Breaks in rocks due to intense folding or faulting.

Fresh water correction: Correction of the brine potential to an equivalent fresh water potential because of the density difference.

Geologic: 1. Any great period of time in the history of the earth or the material universe marked by special phases of physical conditions or organic development; an eon; as the age of mammals.

Gradient: 1. Any departure from the horizontal; a grade; a slope; frequently used in connection with the slope of streams or groundwater.

Ground water: Subsurface water occupying a saturation zone.

Half-life: The time required for one-half of a given material to undergo chemical reactions. The average time interval required for one-half of any quantity of identical radioactive atoms to undergo radioactive decay. Also known as half-value period; radioactive half-life.

Head: Pressure of a fluid upon a unit area due to the height at which the surface of the fluid stands above the point where the pressure is determined. Usually expressed as pounds per square inch, and sometimes as actual feet of head or fluid column.

Held potential boundary: A boundary in the hydrologic model at which the hydrologic model at which the hydraulic potential is held at a particular value.

Hydraulic conductivity: A measure of the ease with which ground water can move through aquifers and aquitards. More specifically, the hydraulic conductivity of a medium is defined as the volume of water that will move, in a unit period of time, under a unit hydraulic gradient (1 ft per ft) through a unit area (1 square ft).

Typical Value Range

<u>Soil</u>	<u>Hydraulic Conductivity</u>
Clay	0.007-15 ft/day
Sandstone	0.7-400
Sand	750-22,000
Sand and Gravel	1,500-37,000
Gravel	7,500-110,000

Hydraulic gradient: Represents the rate of change in the ground-water surface elevations per length. Hydraulic gradient is calculated by dividing the difference in head between two points by the distance between those two points.

Hydrologic model: Mathematical formulations to simulate natural hydrologic phenomena.

Hydrology: The science dealing with the properties, behavior and distribution of water above, on and beneath the surface of the earth.

Interbeds: Beds lying between other rock beds with different characteristics.

Inventory: The quantity of radioactive material contained in the repository at the time of breach.

Isopleth: A line, on a map or chart, drawn through points of equal size or abundance.

Isotopes: Elements having an identical number of protons in their nuclei but differing in the number of their neutrons. Isotopes have the same atomic number, differing atomic weights and almost but not quite the same chemical properties.

Leaching: The separation or dissolving out of soluble constituents from a solid body by percolation of water.

Leach rate model: Mathematical formulation to simulate the length of time and rate at which contaminants leach into the ground water.

Limestone: A general term for that class of rocks which contain at least 80% of the carbonates of calcium or magnesium.

Mathematical model: A mathematical technique used to analyze complex physical systems.

Maximum permissible concentration (MPC): The quantity of radioactive material in air, water, etc., per unit volume or weight, from which a human, if continuously exposed, should not (in the light of present knowledge) sustain appreciable body damage.

No-flow boundary: A boundary in the hydrologic model through which no flow occurs.

Nuclide: A species of atom characterized by the constitution of its nucleus; thus abundances of isotopes are described as abundances of various nuclides.

Outcrop: 1. The coming out of a stratum to the surface of the ground. That part of a stratum which appears at the surface. 2. To crop out; to come out to the surface of the ground.

Overburden: Rock material (consolidated or unconsolidated) overlying a mineral deposit.

Permeability: The capacity of a porous rock, soil, or sediment for transmitting a fluid without damage to the structure of the medium. Also known as perviousness.

Porosity: That portion of an aquifer's volume which consists of openings or pores; that is, the proportion of its volume not occupied by solid material. Porosity is an index of how much ground water can be stored in the saturated material and is usually expressed as a percentage of the bulk volume of the material.

Potable water: Water suitable for drinking. With regard to salt, water having salt concentration generally less than 1000 ppm.

Potential: A term applied to several different scalar quantities, the measure of each of which involves energy as a function of position or of condition. Examples are gravitational potential, electric potential, magnetic potential.

Pumping stresses: Quantities of water removed from an aquifer by pumping from wells.

Radius of influence: The area or radius around a point that is affected by stresses occurring at that point. The area beyond this radius is unaffected.

Random number: A number that is determined by chance.

Random walk: A process consisting of a sequence of steps, each of whose characteristics are determined by chance.

Recharge: The addition of water to the zone of saturation. Infiltration of precipitation and its movement to the water table is one form of natural recharge; injection of water into an aquifer through wells is one form of artificial recharge.

Recharge boundary: A boundary in the hydrologic model along which a specific amount of recharge to the model region is specified.

Release consequences analysis: Analysis of the radiological consequences of a breach in a nuclear waste repository. This includes analysis of the transport of radionuclides from the repository proximity to the biosphere and computation of the individual and population doses resultant from the biosphere entry.

Release scenario: Any hypothetical event, single or combination of events and/or processes (natural or man-caused) that results in a breach of the repository, thereby exposing the contents to some type of transport phenomena.

Repository: A location containing wastes in isolation.

Retardation: The delay resulting from the interactions between soil particles and nuclides.

Retardation coefficient or factor: The number which describes how many times slower than water that an isotope or ion moves through a porous media system.

Sandstone: A cemented or otherwise compacted detrital sediment composed predominantly of quartz grains, the grades of the latter being those of sand.

Saturated brine: Water containing its solubility limit of salt at a given temperature.

Sediment: Fragmental or clastic mineral particles derived from soil, alluvial, and rock materials by processes of erosion, and transported by water, wind, ice, and gravity. A special kind of sediment is generated by precipitation of solids from solution (i.e., calcium carbonate, iron oxides). Excluded from the definition are vegetation, wood, bacterial and algal slimes, extraneous light-weight artificially made substances such as trash, plastics, flue ash, dye and semisolids.

Seismic event: A term applied to any definite phase change or amplitude difference on a seismic record; it may be a reflection, a refraction, a diffraction, or a random signal.

Shale: Rock that is hardened and compacted clays and muds.

Siltstone: A very fine-grained consolidated clastic rock composed predominantly of particles of silt grade.

Sink: A point where water leaves the ground-water system.

Soil-to-solution ratio (B): The ratio of bulk density to porosity.

Soil-nuclide-water interactions: Sorption/desorption phenomena acting between the soil particles and the nuclides transported in the ground water.

Source: A point where water enters the ground-water system.

Spent fuel: Nuclear reactor fuel that has been used to the extent that it can no longer be used in a nuclear power plant. Spent fuel has been irradiated to the extent that it can no longer effectively sustain a chain reaction because its fissionable isotopes have been partially consumed and fission-product poisons have accumulated in it.

Stratigraphic: Pertaining to the discrimination, character, thickness, sequence, age and correlation of the rocks in the earth's crust.

Streamline: A line which is every where parallel to the direction of fluid flow at a given instant.

Storage coefficient = Coefficient of storage: The volume of water released from storage in each vertical column of the aquifer having a base of 1 ft square when the water table or other piezometric surface declines 1 ft. This is approximately equal to the specific yield for nonartesian aquifers.

Tectonic: Of, pertaining to, or designating the rock structure and external forms resulting from the deformation of the earth's crust. As applied to earthquakes, it is used to describe shocks not due to volcanic action or to collapse of caverns or landslides.

Transport model: Mathematical formulation to simulate transport processes.

Transuranic elements: Elements with atomic numbers greater than that of uranium, 92.

Velocity Field: Distribution of flow vectors over the region of interest.

APPENDIX C

CONVERSION TABLE FROM ENGLISH UNITS TO METRIC UNITS

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CONVERSION TABLE FROM ENGLISH UNITS TO METRIC UNITS

<u>To Convert from:</u> (English Unit)	<u>To obtain:</u> (Metric Unit)	<u>Multiply by:</u>
Feet (ft)	Meters (m)	0.3048
Gallons (gal)	Liters (ℓ)	3.785306
Feet/year (ft/yr)	Meters/second (m/sec)	9.665145E-9
Feet/year (ft/yr)	Meters/yr (m/yr)	0.3048
Miles	Kilometer (km)	1.609344
Cubic feet/second (ft ³ /sec)	Cubic meters/second (m ³ /sec)	0.0283169
Gallons/minute (gpm)	Cubic meters/minute (m ³ /min)	0.0037854118

1 Metric ton = 1000 kilograms

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