RISK INSIGHTS DERIVED FROM ANALYSES OF MODEL UPDATES IN THE TOTAL-SYSTEM PERFORMANCE ASSESSMENT VERSION 5.1 CODE

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ABSTRACT

The U.S. Nuclear Regulatory Commission (NRC), with assistance from the Center for Nuclear Waste Regulatory Analyses, has been developing risk insights. The risk insights serve as a common reference for staff to use in risk-informing the NRC High-Level Waste Program (NRC, 2005). The risk insights are based on the contribution to, or effect on, the waste isolation capabilities of the repository system. The risk significance of an aspect of the repository is categorized as high, medium, or low depending on the (i) effect on the integrity of waste packages, (ii) effect on the release of radionuclides from the waste form and waste package, and (iii) effect on the transport of radionuclides through the geosphere and biosphere. This report updates previously documented risk insights (NRC, 2005). The update was undertaken in response to model revisions in the Total-system Performance Assessment (TPA) Version 5.1 code. Modifications to the TPA code include updates to models for (i) dosimetry, (ii) longer simulation periods, (iii) drip shield and waste package damage from drift degradation and seismicity, (iv) the amount of water contacting waste forms, (v) colloidal-assisted radionuclide transport, and (vi) tephra redistribution following extrusive igneous events. These modifications were developed in response to a need for more detailed consideration of the aforementioned processes. Stylized calculations using the TPA code and observations of relative changes to release rates and dose estimates led to changing risk significance ranking from high to medium for (i) chemistry of seepage water, (ii) number of waste packages affected by an eruption, (iii) inhalation of resuspended volcanic ash, and (iv) probability of igneous activity. Note that these analyses are not intended to represent nor should they be interpreted as either predictions or determinations of potential repository compliance with performance objectives. Also, this report is not a comprehensive analysis of all repository aspects, and is focused on areas related to major updates in the TPA code.

Reference

NRC. NUREG–1762, "Integrated Issue Resolution Status Report." Vol. 2. Rev. 1. Appendix D—Risk Insights Baseline Report. Washington, DC: NRC. April 2005.

CONTENTS

FIGURES

Figure Page

TABLES

Table | Page

ACKNOWLEDGMENTS

This report was prepared to document work performed by the Center for Nuclear Waste Regulatory Analyses (CNWRA) for the U.S. Nuclear Regulatory Commission (NRC) under Contract No. NRC–02–07–006. The activities reported here were performed on behalf of the NRC Office of Nuclear Material Safety and Safeguards, Division of High-Level Waste Repository Safety. This report is an independent product of the CNWRA and does not necessarily reflect the view or regulatory position of the NRC. The NRC staff views expressed herein are preliminary and do not constitute a final judgment or determination of the matters addressed or of the acceptability of a license application for a potential geologic repository at Yucca Mountain.

This report was prepared by Osvaldo Pensado, James Winterle, Sitakanta Mohanty, and Robert W. Rice (consultant) and summarizes multiple discussions with staffs of the NRC and CNWRA. In particular, the feedback by Timothy McCartin, Roland Benke, Bret Leslie, Britt Hill, and James Durham is recognized, as well as efforts by Chris Markley and Bret Leslie to coordinate discussions. The technical review by Budhi Sagar, programmatic review by Gordon Wittmeyer, the editorial review by Lauren Mulverhill, and the secretarial assistance by Beverly Street are appreciated.

QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: Data in this report were generated using the TPA Code Version 5.1b (CNWRA and NRC, 2007). Modifications to the input parameters are discussed in the chapters. The input and relevant output files of the TPA runs were electronically archived as part of the CNWRA Scientific Notebook 355.

ANALYSES AND CODES: The TPA Code Version 5.1b is CNWRA-controlled software that has been validated (CNWRA, 2007) according to CNWRA quality assurance procedures. Scripts to read TPA output files and compute statistics were programmed in Mathematica® 5.1 (Wolfram Research, Inc., 2004). The Mathematica 5.1 notebooks were electronically archived as part of the CNWRA Scientific Notebook 355.

References

CNWRA. "Total-system Performance Assessment (TPA) Version 5.1 Code (Software Validation Report)." San Antonio, Texas: CNWRA. 2007.

CNWRA and NRC. "Total-system Performance Assessment (TPA) Version 5.1 Code." San Antonio, Texas: CNWRA. 2007.

Wolfram Research, Inc. "Mathematica® 5.1." Champaign, Illinois: Wolfram Research, Inc. 2004.

1 INTRODUCTION

In 2005, staff from the U.S. Nuclear Regulatory Commission (NRC) High-Level Waste Program published the Risk Insights Baseline Report as part of an effort to better support a risk-informed regulatory program (NRC, 2005). The Risk Insights Baseline Report has served as a common reference for staff to use in risk informing the NRC High-Level Waste Program staff prelicensing regulatory activities and in preparatory activities to review a U.S. Department of Energy (DOE) license application for a potential high-level waste repository at Yucca Mountain, Nevada. The risk insights were originally drawn from the staff experience gained through (i) the development and exercise of the TPA computer code, (ii) detailed process-level technical analyses, (iii) other analyses staff conducted to support prelicensing interactions with DOE and (iv) analyses DOE, and others had conducted. The Risk Insights Baseline Report focused on understanding the repository system following permanent closure through a 10,000-year period (NRC, 2005).

In the Risk Insights Baseline Report, (NRC, 2005), the staff documented risk insights to address important components (i.e., features, events, and processes, both natural and engineered) of the repository system, and to communicate how these components relate to waste isolation capability and to estimates of postclosure risk. Each risk insight in the Risk Insights Baseline Report (NRC, 2005) is defined in the context of a scenario (i.e., a particular set of features, events, and processes that might exist or occur during the regulatory period of interest) considering both beneficial and adverse effects on the waste isolation capabilities of the repository system. In the Risk Insights Baseline Report the risk insights were grouped into three categories (high, medium, and low) based on the relative contribution to, or effect on, the waste isolation capabilities of the repository system (NRC, 2005). Significance was evaluated relative to the waste isolation capabilities of the repository system considering three criteria:

- Effect on the integrity of waste packages
- Effect on the release of radionuclides from the waste form and waste package
- Effect on the transport of radionuclides through the geosphere and biosphere

In general, high significance is associated with features, events, and processes that could (i) affect a large number of waste packages, (ii) significantly affect the release of radionuclides, or (iii) significantly affect the transport of radionuclides through the geosphere or biosphere. Medium significance is associated with a lesser effect on waste packages, radionuclide releases, or radionuclide transport, and low significance is associated with no or negligible effect.

The TPA code has been recently updated (CNWRA and NRC, 2007). The objective of this report is to revisit some of the insights presented in the Risk Insights Baseline Report (NRC, 2005) in light of the recent modifications reflected in TPA Version 5.1 compared to the previous validated Version 4.1j. These modifications include

- Updates to dose coefficients consistent with the International Commission on Radiological Protection Publication 72 (ICRP, 1996)

- Capability to assess consequences for periods longer than 10,000 years

- A new abstracted model for drift degradation processes and associated effects of rubble accumulation, including a potential damage mechanism for drip shields and waste packages under rock loads enhanced by seismic activity

- A flexible approach to assess processes influencing water flow rates potentially contacting and mobilizing waste forms

- Colloidal-assisted radionuclide transport

- A tephra redistribution model for the igneous extrusive scenario that accounts for variable wind fields

- Updated models for localized corrosion of the waste package accounting for different corrosion susceptibility of welded areas

The complete set of changes is described in detail in the TPA Version 5.1 User Guide (Leslie, et al., 2007) and in the Validation Testing Report for TPA Version 5.1 (CNWRA, 2007).

Risk insights considered in this report are limited to results obtained from exercising the TPA Version 5.1 code and evaluating the extent to which insights into the relative importance of abstracted processes may be improved. In contrast with the previous Risk Insights Baseline Report (NRC, 2005), no attempts were made to revise risk insights from (i) detailed process-level technical analyses, (ii) other analyses staff conducted to support prelicensing interactions with DOE, and (iii) analyses DOE and others conducted. However, information from these sources was used in developing revisions to the TPA code from Version 4.1j to 5.1.

This report is organized in the following six chapters to present insights obtained from analyses related to (i) updated dose conversion factors in the biosphere model; (ii) consideration of a 1-million year simulation period; (iii) revised conceptualization of drift degradation under normal and seismic events; (iv) revised conceptualization of the amount of water contacting waste forms and number of failed waste packages; (v) effects of colloidal-facilitated radionuclide transport; and (vi) revised models for volcanic disruptive processes. Each chapter in this report includes three sections that (i) summarize the model and describe the analyses conducted; (ii) present results; and (iii) update the risk insights ranking.

Note that the analyses presented in this report represent stylized calculations designed to evaluate potential effects of parameters and abstracted processes. These analyses are not intended to represent nor should they be interpreted as either predictions or determinations of potential repository compliance with performance objectives. Accordingly, where results of analyses are presented in terms of dose, only the relative changes in dose estimates are shown and quantitative units for the dose estimates are not given. Such results can be interpreted as expected system response for some arbitrary unit release. In this context, the system response to changes in parameters or processes considered can be understood in terms of proportional changes in calculated dose estimates.

2 INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION DOSE CONVERSION FACTORS

2.1 Model Description

The reference case dosimetry model in the TPA Version 5.1 code (CNWRA and NRC, 2007) for individual protection calculations was revised to reflect ingestion and inhalation dose coefficients from the International Commission on Radiological Protection (ICRP)[1] Publication 72 (ICRP, 1996). Values from Federal Guidance Report No. 11 (EPA, 1988) were used in the previous version of the TPA code (Mohanty, et al., 2002). This set of dose coefficients represents the most recent update of ICRP dosimetry recommendations.

For ingestion dose coefficients, the ICRP Publication 72 values for neptunium, technetium, iodine, americium, and plutonium are based on updated biokinetic information regarding fractional absorption into the gastrointestinal tract. The values for all radionuclides are the same as given in ICRP Publication 30 (ICRP, 1979). Selection of inhalation dose coefficients from ICRP Publication 72 is based on consideration of airborne particle size distribution and the rate of absorption from the respiratory tract to body fluids. TPA Version 5.1 includes the option to use dose coefficients based on ICRP Publication 72 or those published in Federal Guidance Report No. 11 (EPA, 1988). A complete description of the dosimetry model in TPA Version 5.1 is provided in Leslie, et al. (2007).

2.2 Results

Table 2-1 compares the ICRP Publication 72 and Federal Guidance Report No. 11 dose conversion factors for the ingestion and inhalation dose pathways for the 22 radionuclides considered in TPA Version 5.1. Table 2-1 shows the differences between the ICRP Publication 72 and Federal Guidance Report No. 11 dose coefficients as a percent change. Replacement of dose coefficient values from Federal Guidance Report No. 11 with ICRP Publication 72 values decreased dose coefficients for 15 out of the 22 radionuclides for the ingestion pathway and increased dose coefficients for the remaining 7. In comparison, the dose coefficients for the inhalation pathway decreased for all radionuclides.

Figures 2-1 and 2-2 graphically show the effect of the revised dose coefficients on the expected doses from groundwater and the direct surface releases for the disruptive seismic and igneous scenarios, respectively. The net effect of the ICRP Publication 72 ingestion dose coefficients is a decrease in the expected groundwater dose beyond 6,000 years by a factor of 2 to 5 (Figure 2-1). Note that the expected dose scales linearly with the dose coefficients. In spite of the fact that the new dose coefficients exceeded the previous dose coefficients for seven radionuclides, the groundwater expected dose at longer times was smaller by as much as a factor of 5. This drop is primarily because of the tenfold decrease in the dose coefficient in ICRP Publication 72 for Np-237, which is a dominant radionuclide at later times. The early groundwater dose (up to 6,000 years) is dominated by Tc-99. The Tc-99 ingestion dose coefficient is 62 percent greater in ICRP Publication 72 compared to its value in Federal Guidance Report No. 11. This resulted in a slight increase in the expected dose prior to 6,000 years.

[1]International Commission on Radiological Protection is used frequently throughout this chapter; therefore, the acronym ICRP will be used.

Table 2-1. Ingestion and Inhalation Dose Conversion Factors From TPA Version 5.1* and Dose Conversion Factors From TPA Version 4.1†						
	Dose Conversion Factors (Sv/Bq)‡					
	Ingestion			Inhalation		
Radionuclide	**(TPA 5.1)***	**(TPA 4.1)†**	**Percent Change**	**(TPA 5.1)***	**(TPA 4.1)†**	**Percent Change**
Am-241	2.00×10^{-7}	9.84×10^{-7}	-80%	1.90×10^{-5}	1.20×10^{-4}	-84%
Am-243	2.00×10^{-7}	9.79×10^{-7}	-80%	1.90×10^{-5}	1.19×10^{-4}	-84%
Cl-36	9.30×10^{-10}	8.18×10^{-10}	**+14%**	3.10×10^{-9}	5.93×10^{-9}	-48%
Cm-245	2.10×10^{-7}	1.01×10^{-6}	-79%	1.90×10^{-5}	1.23×10^{-4}	-85%
Cm-246	2.10×10^{-7}	1.00×10^{-6}	-79%	1.90×10^{-5}	1.22×10^{-4}	-84%
Cs-135	2.00×10^{-9}	1.91×10^{-9}	**+5%**	8.90×10^{-10}	1.23×10^{-9}	-28%
I-129	1.10×10^{-7}	7.46×10^{-8}	**+47%**	4.60×10^{-8}	4.69×10^{-8}	-2%
Nb-94	1.70×10^{-9}	1.93×10^{-9}	-12%	4.70×10^{-9}	1.12×10^{-7}	-96%
Ni-59	6.30×10^{-11}	5.67×10^{-11}	**+11%**	6.90×10^{-11}	7.31×10^{-10}	-91%
Np-237	1.10×10^{-7}	1.20×10^{-6}	-91%	1.00×10^{-5}	1.46×10^{-4}	-93%
Pb-210	6.90×10^{-7}	1.45×10^{-6}	-52%	5.20×10^{-7}	3.67×10^{-6}	-86%
Pu-239	2.50×10^{-7}	9.56×10^{-7}	-74%	2.30×10^{-5}	1.16×10^{-4}	-80%
Pu-240	2.50×10^{-7}	9.56×10^{-7}	-74%	2.30×10^{-5}	1.16×10^{-4}	-80%
Pu-242	2.40×10^{-7}	9.08×10^{-7}	-74%	2.20×10^{-5}	1.11×10^{-4}	-80%
Ra-226	2.80×10^{-7}	3.58×10^{-7}	-22%	1.60×10^{-6}	2.32×10^{-6}	-31%
Se-79	2.90×10^{-9}	2.35×10^{-9}	**+23%**	1.40×10^{-9}	2.66×10^{-9}	-47%
Tc-99	6.40×10^{-10}	3.95×10^{-10}	**+62%**	1.90×10^{-9}	2.25×10^{-9}	-16%
Th-229	4.90×10^{-7}	9.54×10^{-7}	-49%	3.20×10^{-5}	5.80×10^{-4}	-94%
Th-230	2.10×10^{-7}	1.48×10^{-7}	**+42%**	4.40×10^{-6}	8.80×10^{-5}	-95%
U-234	4.90×10^{-8}	7.66×10^{-8}	-36%	1.60×10^{-6}	3.58×10^{-5}	-96%
U-233	5.10×10^{-8}	7.81×10^{-8}	-35%	1.70×10^{-6}	3.66×10^{-5}	-95%
U-238	4.50×10^{-8}	6.88×10^{-8}	-35%	1.30×10^{-6}	3.20×10^{-5}	-96%

*ICRP. "Age-Dependent Doses to Members of the Public From Intake of Radionuclides, Part 5: Compilation of Ingestion and Inhalation Dose Coefficients." ICRP 72. Annals of the ICRP. Tarrytown, New York: Elsevier Science, Inc. 1996.
†EPA. "Limiting Values of Radionuclide Intakes and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion." Federal Guidance Report No. 11. EPA–520/1–88–020. Washington, DC: EPA. 1988.
‡Dose coefficient per unit uptake from TPA 5.1b code data file *gnewdf.dat*

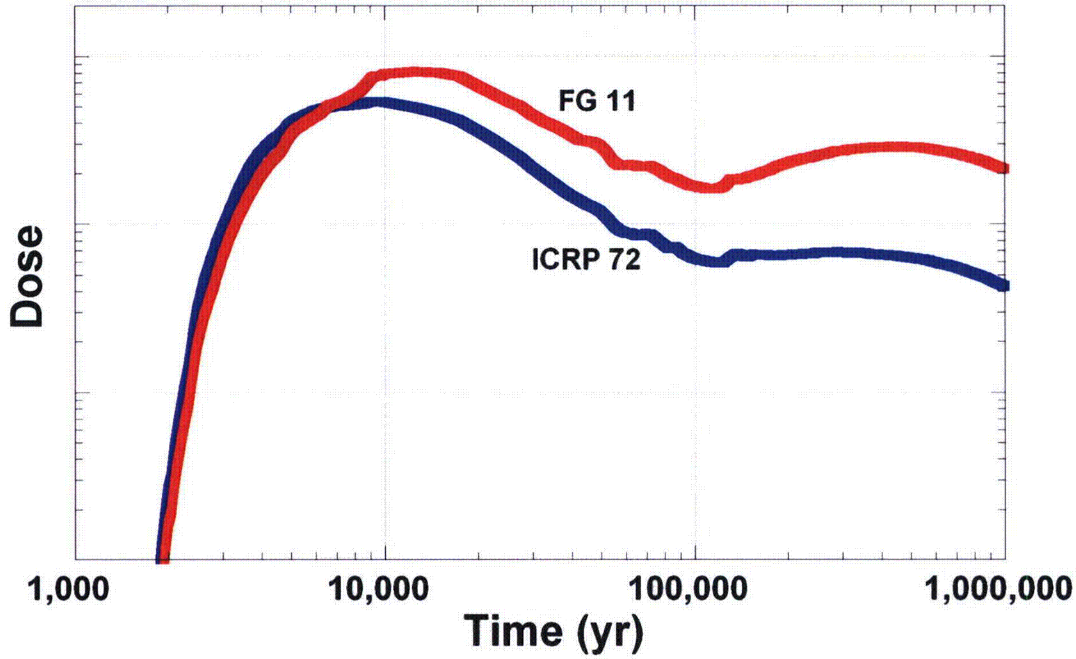


Figure 2-1. Expected Groundwater Dose for the Disruptive Seismic Scenario, Considering ICRP Publication 72 and Federal Guidance Report No. 11 Dose Coefficients. The Averages Were Computed From 500-Realization Runs of the TPA Version 5.1.

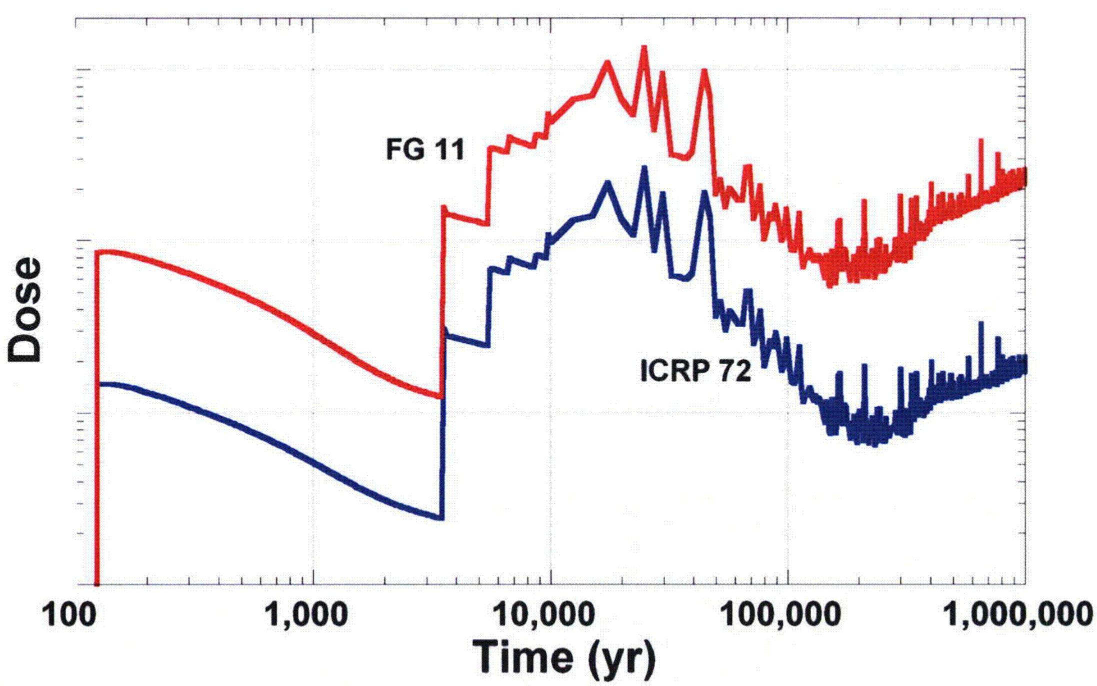


Figure 2-2. Conditional Ground Surface Dose Using TPA Version 5.1, Considering ICRP Publication 72 and Federal Guidance Report No. 11 Dose Coefficients. One Igneous Event Per Realization Was Assumed To Occur Between 100 and 1 MillionYears; Averages Were Determined From 500 Realizations.

All ICRP Publication 72 inhalation dose coefficients are smaller than Federal Guidance Report No. 11 inhalation dose coefficients. The net effect of the ICRP Publication 72 inhalation dose coefficients is a lowering of the expected ground surface dose over the entire simulation period of 1 million years by up to a factor of 10 (Figure 2-2). The decrease in the expected dose is a result of the decrease in the relative contribution of individual radionuclides throughout the 1-million-year simulation period.

2.3 Conclusions

The previous risk ranking for Biosphere Characteristics, which includes dosimetry, was low significance (NRC, 2005, Table 2). This low ranking was attributable to the fact that the dose coefficients are established by internationally accepted methods and practices, leaving little uncertainty in determining appropriate dose coefficient values to use in performance assessment analyses. Thus, although the preceding analyses demonstrate that the update from Federal Guidance Report No. 11 to ICRP Publication 72 dose coefficients results in moderate decreases in estimated total doses (by up to a factor of 5 in the disruptive seismic scenario and up to 10 in the disruptive igneous scenario), the present analyses do not affect any of the existing risk insights (in particular, Biosphere Characteristics).

3 ONE-MILLION-YEAR RESULTS

3.1 Model Description

To estimate repository performance over an extended period, the maximum simulation period of 100,000 years in the TPA Version 4.1j code (Mohanty, et al., 2002) was extended to 1 million years in the TPA Version 5.1 code. The 1-million year simulation period allows a more complete evaluation of the effects related to waste package degradation, rockfall, waste form degradation, climate, and unsaturated and saturated zone transport over a longer period than was considered in the previous risk insights baseline report. The following paragraphs summarize relevant model updates implemented in the TPA Version 5.1 code.

Waste Package Degradation: Localized-corrosion degradation of waste packages occurs in the simulations before 3,000 years, the earliest time at which seepage water contacts the waste package during the thermal period.

Rockfall: In the revised model, rubble accumulates on the drip shield over time as a result of thermally induced drift degradation or seismic events, and eventually causes the collapse of the drip shield. The rock loads transferred to the waste package after drip shield collapse (loads transferred through structural components of the drip shield such as bulkheads or stiffeners and concentrated on small areas of the waster package) could be amplified by seismic events, causing damage to the waste packages. After the drip shield is fully corroded, it is assumed that rock loads are redistributed on the waste package surface. As a result of that redistribution, it is assumed that further seismic damage to the waste package cannot take place. The time of complete degradation by corrosion of the drip shield is assumed to be less than 750,000 years. Therefore, loads amplified by seismic events are assumed to damage the waste package only up to 750,000 years. Past 30,000 years, seismically damaged waste packages are the main contributors to radionuclide release (see Chapter 5).

Climate: In the revised climate model, the climate is time dependent during the first 10,000 years and is constant beyond this period. It is assumed that the deep percolation rate is time invariant past 10,000 years, but exhibits spatial variability.

Unsaturated and Saturated Zone Transport: The revised models for transport in the geosphere include colloidal-facilitated transport. Retardation factors for colloids may be orders of magnitude lower than retardation factors for dissolved radionuclides, resulting in faster transport of radionuclides attached to colloids. It is assumed that isotopes of Am, Pu, and Th could be attached to colloids.

A complete description of the TPA Version 5.1 code models is provided in Leslie, et al. (2007).

3.2 Results

TPA Version 5.1 code was executed for 500 realizations of the seismic disruptive scenario. The expected groundwater doses for all radionuclides (total) and for those radionuclides with the greatest contribution to the expected groundwater dose are presented in Figure 3-1.

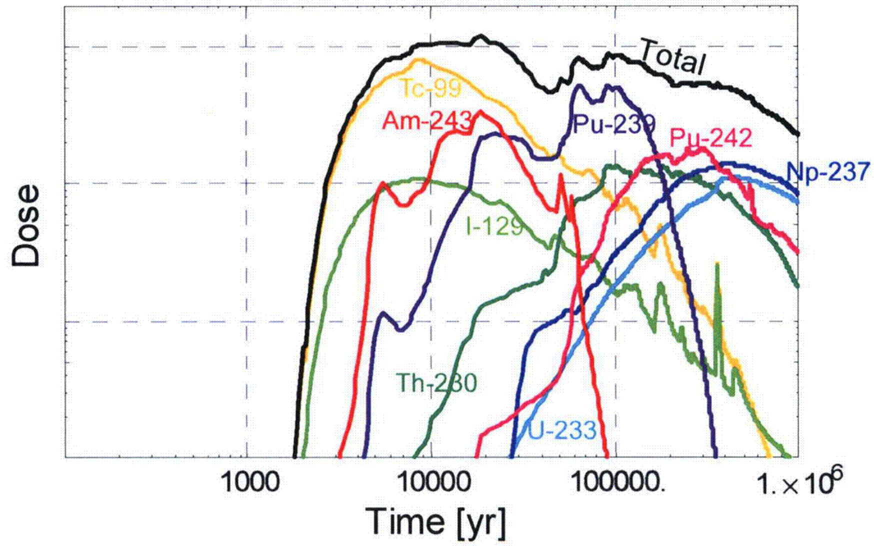


Figure 3-1. Total and Individual Radionuclide Contribution to Expected Groundwater Dose Using TPA Version 5.1, Seismic Disruptive Scenario, Averages From 500 Realizations

In the 10^4-year simulation period, Tc-99, I-129 (transported in dissolved form), and Am-243 (transported in colloidal form) are the major dose contributors. In the first 10,000 years, the dominant mechanism leading to waste package failure is localized corrosion (see Chapter 5). Tc-99 and I-129 release rates from the engineered barrier system are controlled by waste form dissolution rates. Assumed values of colloid retardation parameters for transport in the Calico Hills nonvitric unit and saturated alluvium are important to dose estimates of Am-243. These parameters are sampled over a large uncertainty range from a minimum value of 1.0 to a maximum value of 5,188.

In the 10^5-year simulation period in TPA 5.1, the major dose contributors are Pu-239 (colloidal), Th-230 (colloidal), Tc-99, and Pu-242 (colloidal). In the 10^6-year simulation period, Np-237, U-233, Pu-242 (colloidal), and Th-230 (colloidal) are the major dose contributors. The isotope U-233 was modeled as a daughter product of Np-237. In previous risk insights analyses (NRC, 2005), U-233 was disregarded because of the shorter timeframe considered in the computations (up to 10^5 years).

Contributions from different radionuclides to the expected dose vary at different times based on factors such as (i) inventory, (ii) half-life, (iii) in-growth, (iv) the presence of colloids, and (v) colloidal transport. Overall, Tc-99, Pu-242 (in colloidal form), and Np-237 dominate dose estimates during most of the simulation period (Figure 3-1). Because it is assumed that rock loads are transferred and concentrated by drip shield structural components onto the waste package, and that such rock load concentration mechanism operates until the time the drip shield is fully corroded, the general corrosion rate of the drip shield is related to the likelihood of seismic damage of the waste package. At low corrosion rates, the drip shield lasts longer, increasing the likelihood of seismic damage to the waste package. Hence, a higher general corrosion rate of the drip shield can result in slightly lower maximum dose estimates for Pu-242 and Np-237.

Figure 3-2 shows the contribution of exposure pathways to dose estimates. The two dominant pathways are drinking water and plant consumption; the latter is the highest dose contributor in

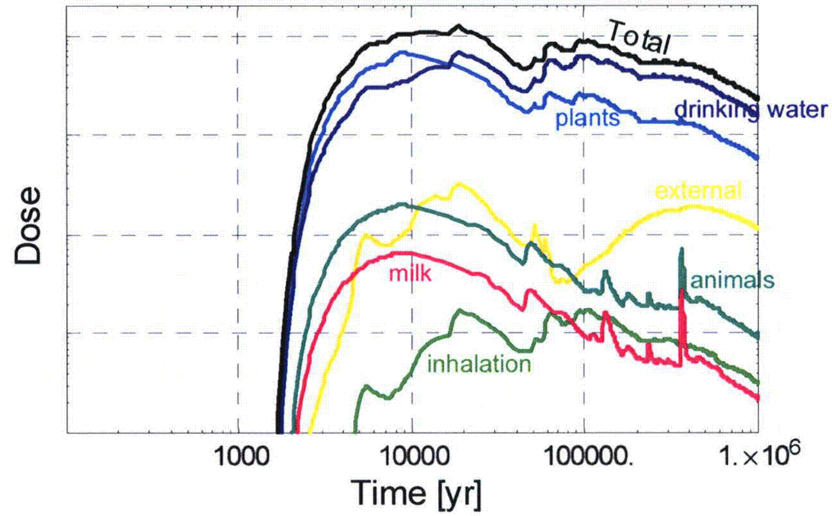


Figure 3-2. Exposure Pathway Contribution to the Total Expected Dose Seismic Disruptive Scenario Averages From 500 Realizations

the first 20,000 years. The main radionuclide in the plant consumption pathway is Tc-99. Because the distribution coefficient, K_D, for Tc in soil is highly variable, an uncertainty of up to three orders of magnitude was considered in the TPA Version 5.1, based on a generic compendium by Sheppard and Thibault (1990). High K_D values imply a significant retention of Tc in soil after irrigation (low mobility of Tc). The plant uptake factor is uncertain (a variation of two orders of magnitude was considered; Leslie, et al., 2007). Of the elements modeled in TPA Version 5.1, Tc has the highest soil-to-plant transfer factor (LaPlante and Poor, 1997; Staven, et al., 2003). The combination of the uncertainties in the uptake factor and the K_D causes significant variability in dose estimates associated with the plant consumption pathway—on average, exceeding drinking water pathway dose estimates. The K_D of Tc in soil, given the three orders of magnitude assumed variation, is identified as an important parameter by sensitivity techniques in 10^4-year dose assessments. In TPA Version 5.1, transport of dissolved Tc is assumed to be unretarded (i.e., $K_D = 0$) in the geosphere. This assumption is consistent with some experimental data of transport in geologic media (Bechtel SAIC Company, LLC, 2003, 2001) and will most likely overestimate doses compared to cases where Tc is appreciably retarded in the geosphere. Consideration of a range of uncertainty for Tc retardation in geosphere transport in TPA Version 5.1 parameter values is likely to result in lower dose estimates associated with the plant consumption pathway.

3.3 Conclusions

These results relate to the following risk insights from the Risk Insights Baseline Report (NRC, 2005, Table 2). The suggested relative risk rankings based on the foregoing analysis, as well as an indication of whether this ranking reflects a change, also are given.

- ENG1—Degradation of Engineered Barriers
  - Waste Package Failure Mode—Medium (unchanged from previous ranking)
  - Drip Shield Integrity—Medium (unchanged from previous ranking)

- ENG2—Mechanical Disruption of Engineered Barriers
  - Effects of Accumulated Rockfall on Engineered Barriers—Medium (unchanged from previous ranking)

- UZ1—Climate and Infiltration
  - Long-term Climatic Change—Medium (unchanged from previous ranking)

- UZ3—Radionuclide Transport in the Unsaturated Zone
  - Retardation in the Calico Hills Nonwelded Vitric Unit—Medium (unchanged from previous ranking)
  - Effect of Colloids on Transport in the Unsaturated Zone—Medium (unchanged from previous ranking)

- SZ2—Radionuclide Transport in the Saturated Zone
  - Retardation in the Saturated Alluvium—High (unchanged from previous ranking)
  - Effect of Colloids on Transport in the Saturated Zone—Medium (unchanged from previous ranking)

- DOSE3—Biosphere Characteristics
  - Characterization of the Biosphere—Low (unchanged from previous ranking)

4 DRIFT DEGRADATION AND SEISMIC MODEL

4.1 Model Description

Drift degradation and the resulting rubble accumulation in an emplacement drift are modeled in TPA Version 5.1 for lithophysal and nonlithophysal tuff. The model accounts for rubble accumulation in excavated drifts caused by rock stress from thermal loading and seismic activity. Drift degradation resulting from thermal loading is assumed to occur at a steady rate beginning at the time of closure. Rubble accumulation from seismic activity is episodic and is assumed to follow a linear relationship between ground motion magnitude and rubble accumulations caused by the ground motion. A complete description of the drift degradation and seismic models is provided in Leslie, et al. (2007).

The volume of rubble that fills a drift and the height of the rubble above the drip shield are determined by the rubble bulking factor and the degraded drift shape. The rubble load transferred to the drip shields is calculated at each timestep for each of 10 repository subregions. If computed loads are found to be sufficient to collapse the drip shields, TPA Version 5.1 assumes some fraction of seepage may pass through the drip shields and contact waste packages. If water contact with waste packages occurs early during the thermal period, localized corrosion may occur, depending on the chemical environment.

The rubble load on collapsed drip shields is assumed to be transferred to waste packages and may be concentrated depending on the contact area and contact angle with which the drip shield contacts the waste package. If the resulting stress is amplified by seismic acceleration, mechanical damage of the waste package may occur if the calculated stress exceeds the ultimate tensile strength of the outer waste package. The fraction of mechanically damaged waste packages that contribute to release is computed based on the probability that a pathway exists for water to enter the outer waste package barrier. Additional discussion and analysis of water contact with waste packages are provided in Chapter 5.

4.2 Results

Figure 4-1 shows expected doses for four cases: (i) nominal scenario, (ii) nominal without thermal drift degradation, (iii) disruptive seismic scenario, and (iv) disruptive seismic without thermal drift degradation. The maximum dose for Case 2 is two orders of magnitude lower than the nominal scenario, Case 1. If thermal drift degradation is considered (Cases 1 and 3 in Figure 4-1), nearly all drip shields are computed to collapse from rubble accumulation after about 1,000 years. Consequently, waste packages are contacted by seepage water during the thermal period and are thus vulnerable to localized corrosion if an aggressive chemical environment also exists. Without drift degradation and seismic events (Case 2 in Figure 4-1), drip shields fail from general corrosion starting at about 25,000 years and by 750,000 years essentially all of the drip shields are assumed fully corroded. Because of the earlier drip shield failures computed in the nominal scenario (Case 1 in Figure 4-1), approximately 13 percent of waste packages fail by localized corrosion (see also Chapter 5), whereas only a fraction of a percent of waste packages fail by localized corrosion in Case 2. Note that a damaged waste package results in a release only if it is contacted by water; thus, not all damaged waste

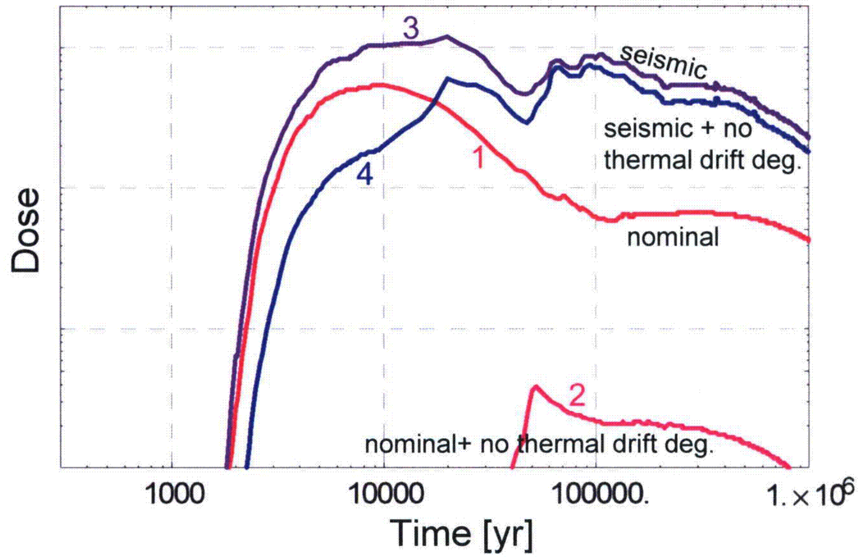


Figure 4-1. Mean Dose Estimates From 500-Realization Runs of TPA Version 5.1: (1) Nominal Scenario, (2) Nominal Scenario Without Thermal Drift Degradation, (3) Disruptive Seismic Scenario, and (4) Disruptive Seismic Scenario Without Thermal Drift Degradation

packages in these simulations contribute to release. In this report, failed waste packages are defined as packages contributing to radionuclide release. Chapter 5 provides additional discussion and analyses of water contacting waste.

From Figure 4-1, the expected doses for the seismic scenario prior to 30,000 years differ by as much as an order of magnitude with (Case 3) and without (Case 4) thermal drift degradation. This difference is attributable to the mechanical collapse of nearly all drip shields occurring due to thermal drift degradation, whereas only about 10 percent of drip shields collapse, on average, when thermal drift degradation is disregarded (Case 4 in Figure 4-1). After 30,000 years, the dose estimates from the 2 simulations (Cases 3 and 4) are nearly equal as the number of drip shields collapsed by seismic drift degradation approaches the number that collapse early by thermal drift degradation. The difference between the two curves (Cases 3 and 4) at late times is caused by earlier drip shield collapse calculated for the disruptive seismic scenario (Case 3), which results in source contributions from both localized corrosion and mechanical waste package failures. When only seismic drift degradation is considered (Case 4), source contributions are mainly from mechanical waste package failures. For Case 4, drip shield collapse is well distributed in time, while it is assumed that practically all drip shields are collapsed at around 1,000 years in Case 3. The likelihood of localized corrosion of the waste package is higher at higher temperatures, if seepage water contacts the waste package. As time elapses and temperatures drop, the likelihood of localized corrosion decreases. This is the main reason why localized corrosion is computed to occur more frequently in Case 3 compared to Case 4. In Case 4, the drip shield could collapse at later times at which localized corrosion of the waste package does not initiate even if contacted by seepage water, because of the low system temperatures.

Results in Figure 4-1 illustrate the effect on the mean dose estimate of computed waste package mechanical damage resulting from increased loads on the drip shields during seismic events. The timing of seismic events in any single realization is a stochastic variable, which causes the resulting waste package damage to be distributed among the realizations from the time after repository closure up to about 750,000 years (see Chapter 5). After 750,000 years, drip shields are corroded and are assumed to no longer concentrate rubble loads onto waste packages.

4.3 Conclusions

These results relate to the following risk insights from Table 2 of the Risk Insights Baseline Report (NRC, 2005). The suggested relative risk rankings based on the foregoing analysis, as well as an indication of whether this ranking reflects a change, also are given.

- ENG1—(Degradation of Engineered Barriers)
  - Drip Shield Integrity—Medium (unchanged from previous ranking)
- ENG2—(Mechanical Disruption of Engineered Barriers)
  - Effects of Accumulated Rockfall on Engineered Barriers—Medium (unchanged from previous ranking)
  - Effects of Seismic Loading on Engineered Barriers—Medium (unchanged from previous ranking)

5 AMOUNT OF WATER CONTACTING WASTE FORMS

5.1 Model Description

Total releases in the TPA Code Version 5.1 are computed by scaling the releases from a representative waste package. The number of waste packages releasing radionuclides is estimated by scaling the total number of waste packages in the system with factors that account for (i) the fraction of waste packages located under seeps; (ii) the probability for seepage water to contact waste packages under collapsed drip shields; (iii) the probability for water to enter mechanically damaged or ruptured waste packages; and (iv) the probability of regions forming on the waste packages where localized corrosion could initiate and propagate (e.g., wet crevices). Estimates of water flow rates contacting waste forms are required to compute radionuclide releases from the representative waste package. This water flow rate is estimated by scaling seepage water flow rates with factors that account for (i) potential diversion by rubble; (ii) extent of drip shield damage; and (iii) extent of waste package damage. A complete description of the scaling approaches is provided in the TPA User's Guide (Leslie, et al., 2007).

In the TPA Code Version 5.1, the spatial coverage of seepage water in the repository is sampled from a log-uniform distribution ranging from 0.25 to 1. On average, 54 percent of the repository is assumed located under seeps (referred to as *repository wet fraction*). The inventory of the waste packages in the complementary 46 percent (the *repository dry fraction*) is assumed immobile independently of the state of the waste package. In the repository wet fraction, seepage is assumed to contact the waste package only if the drip shield is damaged. Damaged drip shields are assumed to partially limit seepage water flow to the waste package. Water flow into the waste package depends on the waste package breaching mechanism. Accordingly, in the TPA Code Version 5.1, it is possible to have compromised or damaged waste packages (e.g., initially defective or mechanically ruptured) that would not contribute to radionuclide release if not contacted and infiltrated by seepage water (e.g., those waste packages located in the repository dry fraction). With respect to localized corrosion, in the TPA Code Version 5.1, all of the waste packages damaged by localized corrosion are assumed to contribute to radionuclide release.

Figure 5-1 illistrates the distinction between damaged waste packages and waste packages contributing to release (or failed waste packages). Figure 5-1 displays averages from 500 realizations of the seismic disruptive scenario. Line 1 represents total waste packages in the system. Line 2 is the average fraction of waste packages in the repository wet fraction. Curve 3 is the average fraction of waste packages that could be contacted by water of chemical composition capable of inducing localized corrosion. However, this water contact condition alone is not sufficient to cause localized corrosion, as explained in Leslie, et al. (2007). In other words, not all the waste packages represented by Curve 3 would necessarily exhibit localized corrosion. Curve 4 is the actual fraction of waste packages affected by localized corrosion; it represents the set of waste packages with all conditions attained to initiate and propagate localized corrosion. These conditions could include the presence of wet crevices with a water solution of high concentration of chloride and low concentrations of localized corrosion inhibitors such as nitrate. It is assumed that all of the waste packages represented by Curve 4 contribute to radionuclide release. Curve 5 is the fraction of waste packages in the repository wet fraction

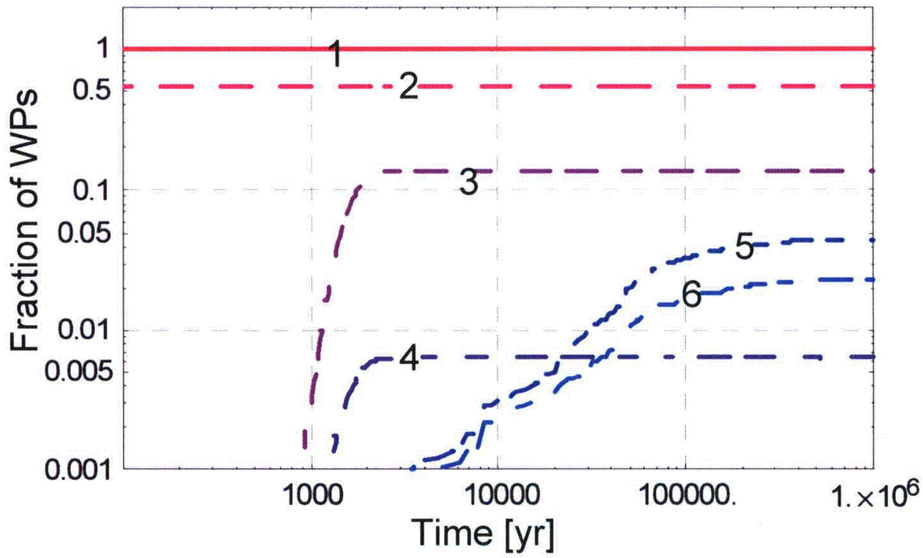


Figure 5-1. Fraction of Waste Packages in the System Undergoing Various Processes. The Curves Represent (1) Total Fraction, (2) Fraction of Waste Packages in the Wet Part of the Repository, (3) Fraction Contacted by Water Capable of Supporting Localized Corrosion (but Not Necessarily Damaged by Localized Corrosion), (4) Fraction Damaged by Localized Corrosion (and Contributing to Radionuclide Release), (5) Fraction Damaged by Seismicity and in the Wet Part of the Repository, and (6) Fraction Damaged by Seismicity With Seepage Water Contacting and Mobilizing the Waste Forms. The Curves Represent Averages From 500 Realizations of the TPA Version 5.1, Seismic Disruptive Scenario.

that are mechanically damaged. Curve 6 is the fraction of mechanically damaged waste packages with seepage water infiltrating mechanical ruptures and contacting the waste forms. It is assumed that all of the waste packages represented by Curve 6 contribute to radionuclide release.

5.2 Results

The TPA Version 5.1 code was executed for 500 realizations of the seismic disruptive scenario. Figure 5-2 shows average fractions of waste packages affected by various processes. Line 1 is the average fraction of waste packages located in the repository wet fraction (54 percent). Curve 2 is the actual fraction of waste packages with waste forms contacted by seepage water and contributing to radionuclide release. Initially, the only waste packages contributing to radionuclide release are initially defective waste packages. Two factors cause the sharp increase in Curve 2 at around 1,000 years: (i) drip shield collapse due to drift degradation in the first 1,000 years and (ii) drift wall temperatures that drop below boiling, allowing for the establishment of seepage. When conditions (i) and (ii) occur, brines could form on the waste package that could support localized corrosion. The gradual increase in Curve 2 in Figure 5-2 past 10,000 years is due to an increase in the mean number of waste packages that fail due to seismicity.

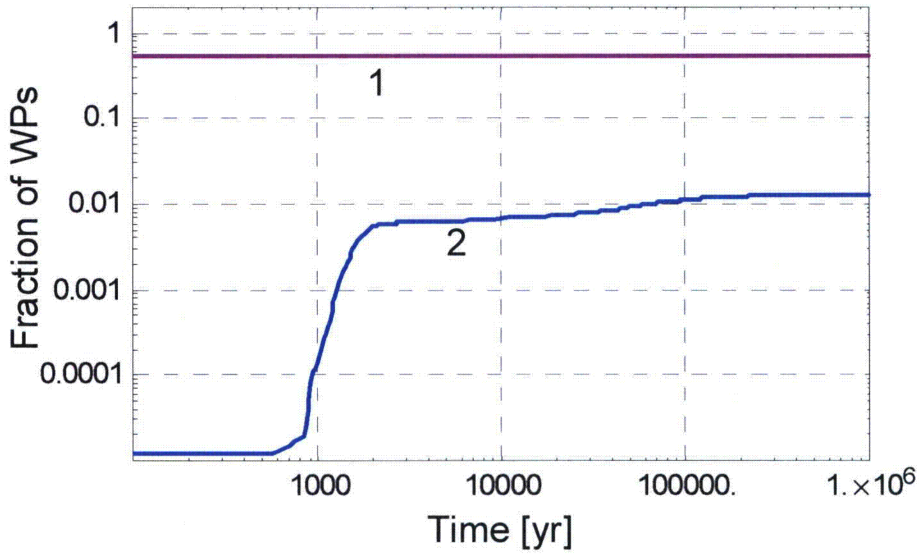


Figure 5-2. Fraction of Waste Packages in the System. (1) Waste Packages Under Water Seepage Locations (but Potentially Protected by Drip Shields) and (2) Waste Packages Contributing to Radionuclide Release. The Curves Represent Averages From 500 Realizations of the TPA Version 5.1, Seismic Disruptive Scenario.

Given the assumptions and parameters in the TPA Version 5.1 code, the average number of waste packages contributing to release is on the order of 2 percent in 10^6 years (Figure 5-2, Curve 2, end of the simulation), and the dominant waste package damage mechanism is seismic events (Figure 5-1). According to Figure 5-1, on average, 4 percent of the waste packages are estimated breached at the end of the simulation by seismic events and located in the repository wet fraction. Thus, the complementary 2 percent are waste packages that, although mechanically damaged and contacted by seepage, are not infiltrated by water. The remaining 4 percent of the waste packages breached by seismic events are located in the repository dry fraction (and assumed not to contribute to radionuclide release). Thus, from TPA Version 5.1 code simulations of the seismic disruptive scenario in 10^6 years, on average, 92 percent of the waste packages are estimated not breached by any mechanism in 10^6 years.

Figure 5-3 shows average flow rates at various locations in the system per failed waste package (averaged over all failed waste packages). The curves represent (1) deep percolation, (2) seepage water at the drift wall, (3) flow rate through the drip shield, and (4) flow rate through a damaged waste package (assumed equal to flow rate contacting waste forms). Initially, there is no seepage water at the drift wall due to elevated system temperatures (Curve 2). Eventually (at around 5,000 years), as the system temperatures decrease, the seepage water flow rate (Curve 2) is assumed to equal the deep percolation flow (Curve 1). The flow rate through the drip shield (Curve 3) equals the seepage water flow rate at times beyond 7.5×10^5 years—the time at which all drip shields are assumed fully corroded. Curve 4 never equals Curve 3 because all of the compromised waste packages (by localized corrosion or mechanical damage) are assumed to partially divert the water. Initially, Curves 3 and 4 differ by up to two orders of magnitude, and this difference decreases to one order of magnitude at later times. The decreasing difference occurs because the dominant waste package failure mechanism in the first 10,000 years, according to the TPA computations, is localized corrosion, with small damaged waste package areas allowing for limited water inflow. At later times, more waste packages are breached by mechanical processes driven by seismic events with larger ruptured areas, allowing for more water to potentially contact the waste forms.

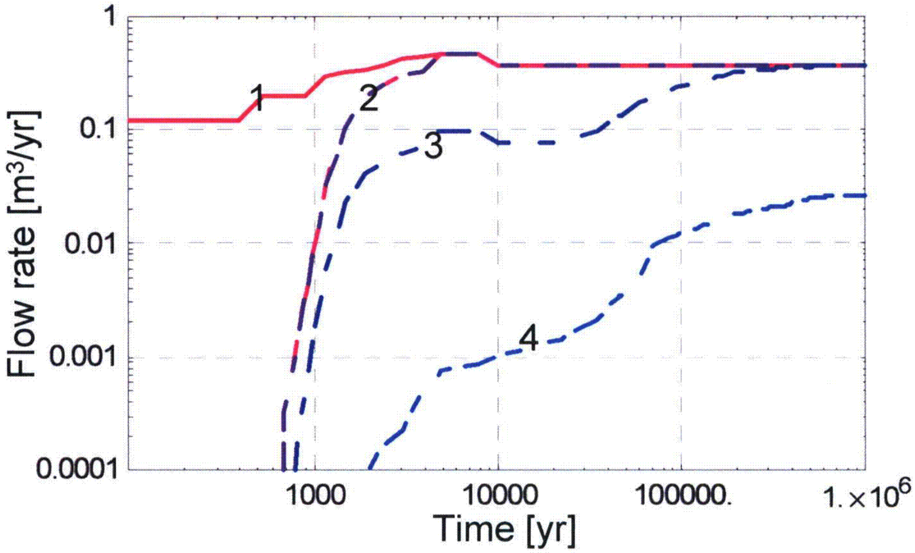


Figure 5-3. Water Flow Rate Per Waste Package. (1) Deep Percolation, (2) Seepage Water at the Drift Wall, (3) Water Flow Through the Drip Shield, and (4) Flow Rate Contacting Waste Forms. The Curves Represent Averages From 500 Realizations of the TPA Version 5.1 Seismic Disruptive Scenario.

The TPA Version 5.1 results of the seismic scenario in Figures 5-1 and 5-2, suggest that the assumed number of initially defective waste packages contributes minimally to the total release compared to the release from waste packages damaged by localized corrosion and seismically driven interactions. The dominant waste package damage mechanism in the first 10,000 years is localized corrosion, and after 20,000 years, seismic damage (Figure 5-1). Water flow rates through initially defective and localized corroded waste packages are small compared to flow rates through seismically damaged waste packages (Figure 5-3). In the first 10,000 years, doses are dominated by Tc-99 in the seismic disruptive scenario (Figure 3-1). Because Tc-99-bearing solid phases are assumed to be highly soluble and are transported relatively fast in the geosphere, in the first 10,000 years the dose is expected to be linearly related to the number of failed waste packages and a weaker function of water flow rates contacting waste forms. At later times, when other radionuclides are transported either in dissolved form or assisted by colloids, the expected dose is both a function of the number of failed waste packages and water flow rates contacting waste forms.

5.3 Conclusions

These results presented above relate to the following risk insights from the Risk Insights Baseline Report (NRC, 2005, Table 2). The suggested relative risk rankings based on the foregoing analysis, as well as an indication of whether this ranking reflects a change, also are given.

- ENG1—(Degradation of Engineered Barriers)
  - Waste Package Failure Mode—Medium (unchanged from previous ranking)
  - Drip Shield Integrity—Medium (unchanged from previous ranking)
  - Juvenile Failures of the Waste Package—Low (unchanged from previous rankings)

- ENG2—(Mechanical Disruption of Engineered Barriers)
  - Effects of Accumulated Rockfall on Engineered Barriers—Medium (unchanged from previous ranking)
  - Effects of Seismic Loading on Engineered Barriers—Medium (unchanged from previous ranking)

- ENG3—(Quantity and Chemistry of Water Contacting Engineered Barriers and Waste Forms)
  - Chemistry of Seepage Water—Medium (previously ranked High in NRC, 2005)
  - Quantity of Water Contacting Engineered Barriers and Waste Forms—Medium (unchanged from previous ranking)

- UZ2—(Flow Paths in the Unsaturated Zone)
  - Seepage—High (unchanged from previous ranking)

Based on the preceding analysis and discussion, "Chemistry of Seepage Water" should be considered of medium significance, whereas it previously was considered high significance. The reason for the revised ranking is that, based on current analyses and assumptions, it appears that the proportion of brine compositions that could support localized corrosion is relatively high (26 percent). However, additional requirements for localized corrosion in the form of crevice corrosion suggest that only a smaller fraction of waste packages might undergo crevice corrosion, even if contacted by seepage (He, et al. 2007a,b; He and Dunn, 2007). Further, if breached by localized corrosion, water flow rates potentially contacting waste forms would be limited by the size of breached regions on the waste package (He, et al., 2007a,b). Therefore, "aggressive" water chemistries alone do not imply a large number of waste packages contributing to radionuclide release nor high release rates. A medium significance ranking is based on the observation that expected doses in the first 10,000 years are a function of the number of waste packages failed by crevice corrosion, which is a function of the composition of waters contacting the waste packages.

The risk insight titled "Quantity of Water Contacting Engineered Barriers and Waste Forms" was originally considered in the Risk Insights Baseline Report (NRC, 2005) under the "Seepage" topic. In this report, "Quantity of Water Contacting Engineered Barriers and Waste Forms" refers to water contacting drip shields, waste packages, and waste forms. On the other hand, "Seepage" refers to seepage water at the drift wall and related thermal processes mobilizing water in the rock in the neighborhood of drifts. The aspect titled "Quantity of Water Contacting Engineered Barriers and Waste Forms" has a medium significance ranking, based on the observation that expected dose estimates in the disruptive seismic scenario are function of water flow rates contacting waste forms. The original discussion that supports the "Seepage" ranking as high significance (NRC, 2005) still applies, with minor updates to account for the updated scope of the seepage topic.

6 IRREVERSIBLE COLLOIDS

6.1 Model Description

Consideration of irreversible attachment of radionuclides to colloids in TPA Version 5.1 includes calculation of colloid-facilitated releases from the engineered barrier system, filtration of colloids in the unsaturated zone, and transport of colloids through groundwater pathways in the unsaturated and saturated zones. A complete description of the irreversible colloid source-term and transport models is provided in Leslie, et al. (2007).

In contrast to irreversible attachment, reversible sorption of radionuclides to colloids is conceptually equivalent to reversible sorption onto other solid phases (e.g., glass shards, clays, and zeolites). In TPA Version 5.1, the net effect of reversible sorption to colloids is to adjust the retardation factor for unsaturated and saturated zone radionuclide transport (Leslie, et al., 2007). Results obtained during validation testing of TPA Version 5.1 suggest that the effects of reversible colloid sorption are not significant; hence only the effects of irreversible sorption to colloids are evaluated in this chapter.

6.2 Results

Two simulations using TPA Version 5.1 were performed using the reference-case input data set for 500 realizations of the seismic scenario. For these two simulations, the maximum simulation time was specified at 1 million years in the *tpa.inp* file. In the first simulation, transport of both dissolved radionuclides in the aqueous phase and radionuclides irreversibly attached to colloids were modeled; in the second simulation, only aqueous-phase radionuclide transport was modeled.

In the simulation with irreversible attachment to colloids, four radionuclides contribute to approximately 95 percent of the peak expected dose: Tc-99, I-129, Am-243, and Pu-239. Note that Am-243 and Pu-239 were modeled both as aqueous species and as irreversible colloids, whereas Tc-99 and I-129 were modeled only as aqueous species.

Figure 6-1 presents the total expected (i.e., mean from 500 realizations) dose for all radionuclides and the expected doses for Tc-99, I-129, Am-243, and Pu-239 from the simulations with (colored solid lines) and without (colored dotted lines) irreversible colloids. As expected, the Tc-99 and I-129 doses are the same with and without irreversible colloids. However, the Am-243 and Pu-239 peak expected doses decrease without irreversible colloids. Additionally, the arrival times for the Am-243 and Pu-239 expected dose curves occur at approximately 2,500 years with irreversible colloids; without irreversible colloids, the arrival times for Am-243 and Pu-239 expected dose curves occur after about 100,000 years. Moreover, because the expected doses occur much later without colloid-facilitated transport, the peak expected dose is further decreased by radioactive decay of Am-243 and Pu-239 (i.e., 7,400- and 24,000-year half-lives, respectively).

To further investigate differences between expected doses with and without irreversible colloids, Pu-239 release rates from the engineered barrier system, unsaturated zone, and saturated zone were plotted for aqueous Pu-239 releases in Figure 6-2 and for irreversible colloid releases in Figure 6-3. Note that in TPA Version 5.1, Pu-239 irreversibly attached to colloids is identified as Jp-239 in these figures. Figures 6-2 and 6-3 show that the unsaturated zone results in less than an order of magnitude decrease for both aqueous Pu-239 and colloidal Pu-239 releases.

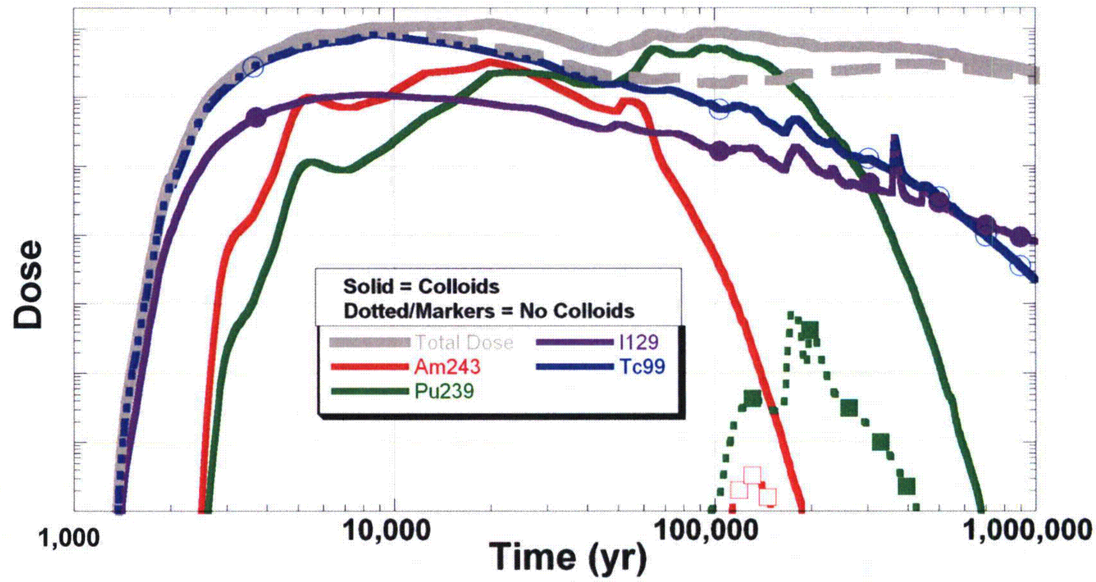


Figure 6-1. Expected Groundwater Dose, Seismic Disruptive Scenario With and Without Irreversible Colloids. Averages From 500-Realization Runs of the TPA Version 5.1.

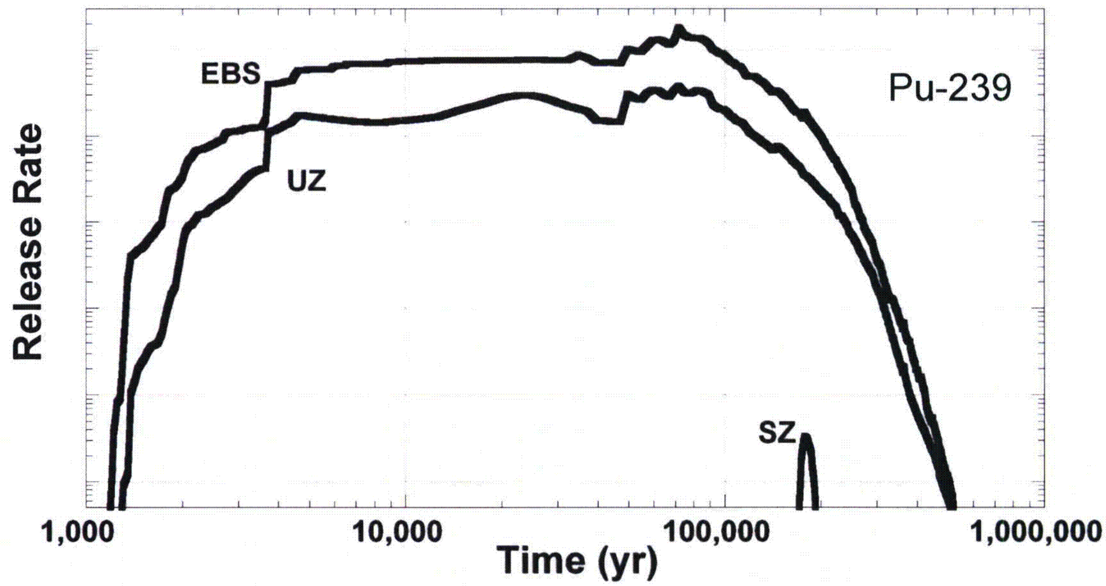


Figure 6-2. Release Rates of Dissolved Pu-239 From the Engineered Barrier System, Unsaturated Zone, and Saturated Zone. The Averages Were Computed From a 500-Realization, Disruptive Seismic Scenario Run of the TPA Version 5.1. The Vertical Scale Is the Same as in Figure 6-3.

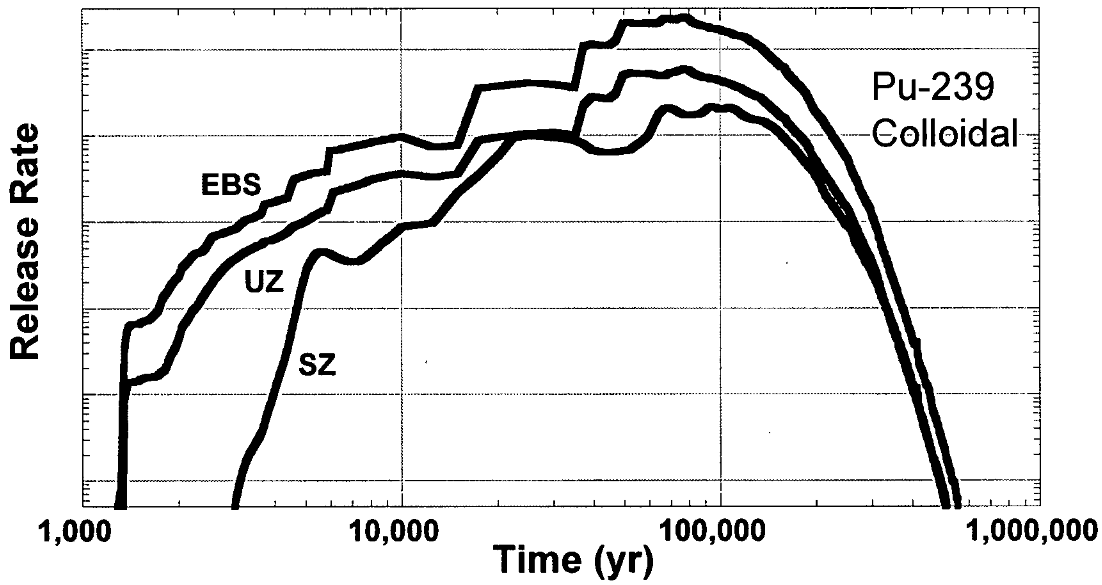


Figure 6-3. Release Rates of Pu-239 Transported in Colloids From the Engineered Barrier System, Unsaturated Zone, and Saturated Zone. The Averages Were Computed From a 500-Realization, Disruptive Seismic Scenario Run of the TPA Version 5.1. The Vertical Scale Is the Same as in Figure 6-2.

For aqueous releases shown in Figure 6-2, the relatively small degree of attenuation computed for the unsaturated zone results from the fact that TPA Version 5.1 computes fast fracture flow with no sorption in most unsaturated zone stratigraphic units and does not consider diffusion of solutes into rock matrix (matrix diffusion). However, TPA Version 5.1 does consider matrix diffusion in the saturated zone, which, combined with sorption in saturated alluvium, delays the transport of Pu-239 resulting in release rates attenuated by more than three orders of magnitude compared to release rates in the unsaturated zone.

For colloid-facilitated release of Pu-239 shown in Figure 6-3, TPA Version 5.1 also computes a relatively small degree of attenuation for the unsaturated zone. The modest reduction in colloid release in the unsaturated zone mainly results from the fraction of permanent colloid filtration specified in the reference case input. Comparison of Figures 6-2 and 6-3 shows that computed releases from the saturated zone are much less attenuated for colloid transport than for aqueous phase transport. This is attributable to the difference in the degree of retardation between the aqueous and colloid species. For example, the retardation coefficient values used in TPA Version 5.1 for aqueous Pu-239 in saturated alluvium range from about 100 to 200,000. Conversely, the colloid retardation coefficients for saturated alluvium range from about 1 to 5,000, thereby including some realizations with little or no retardation of the colloidal species.

6.3 Conclusions

These results relate to the following risk insights from the Risk Insights Baseline Report (NRC, 2005, Table 2). The suggested relative risk rankings based on the foregoing analysis, as well as an indication of whether this ranking reflects a change, also are given.

- ENG4—Radionuclide Release Rates and Solubility Limits
  - Effect of Colloids on Waste Package Releases—Medium Significance (unchanged from previous ranking)

- UZ3—Radionuclide Transport in the Unsaturated Zone
  - Effect of Colloids on Transport in the Unsaturated Zone—Medium Significance (unchanged from previous ranking)

- SZ2—Radionuclide Transport in the Saturated Zone
  - Effect of Colloids on Transport in the Saturated Zone—Medium Significance (unchanged from previous ranking)

Based on the results and discussion in Section 6.2 and considering the three evaluation criteria for risk insights significance presented in Chapter 1, the significance rankings for Effects of Colloids on Waste Package Releases should remain medium significance. Although colloids may facilitate significant releases of Pu-239 and Am-243 from waste packages, the overall contribution to expected total dose estimates is relatively small because the releases are attenuated during transport. Attenuation of colloid-facilitated releases greatly depends on transport processes, which are included in TPA Version 5.1 as permanent colloid filtration and the degree to which colloid transport velocities are retarded relative to groundwater flow velocities. Because these transport processes are uncertain, analyses show that colloid-facilitated transport in the unsaturated and saturated zones can have a moderately significant effect on effective dose estimates. Accordingly, the Effect of Colloids on Transport in the Saturated Zone and Effect of Colloids on Transport in the Unsaturated Zone are considered to be of medium significance.

7 DISRUPTIVE IGNEOUS SCENARIO

7.1 Model Description

In TPA Version 5.1, estimates of radiation exposure consequences from an igneous event account for intrusion of basaltic magma rising along a dike or conduit within the potential repository footprint and possibly erupting at the surface. Two different radionuclide release cases are considered in the TPA models. In the case referred to as *extrusive* or *direct release*, volcanic eruption carries radionuclide inventory to the surface. Wind-field variations along the height of the eruption column are considered, which affect the initial deposition of tephra, and first-order processes affecting fluvial and eolian redistribution of tephra. This variable wind-field model is a major update to the igneous event consequence model that was incorporated into TPA Version 5.1. In the case referred to as *intrusive* or *groundwater release*, the igneous event damages a number of waste packages allowing for radionuclide release in the groundwater. In this case, identical radionuclide groundwater release models are assumed as those considered in the nominal scenario models. A complete model description is provided in Leslie, et al. (2007).

7.2 Results

Two simulations of the igneous activity disruptive scenario were completed assuming that 1 event occurs in each realization between 100 years and the simulation time, T (= 10^4 or 10^6 years). The time of the event in each realization was sampled from a truncated exponential distribution with a recurrence rate equal to 10^{-7} 1/year and bounded between 100 years and the simulation time T. The probability of igneous activity (at least 1 event) in the interval from year 100 to T is

$$p = e^{-\lambda 100} - e^{-\lambda T} \tag{7-1}$$

Substituting $T = 10^4$ and $T = 10^6$ into Eq. (7-1) results in a probability of 9.9×10^{-4} and 9.5×10^{-2}, respectively. These two factors were used to compute probability-weighted dose estimates reported in this chapter. Expected doses (probability weighted) for the 10,000-year case, 500 realizations, are shown in Figure 7-1.

Figure 7-1 includes dose estimates associated with the extrusive and intrusive cases. In simulations with TPA Version 5.1, both cases are considered to determine estimates of the expected dose. The intrusive case dose eventually exceeds the extrusive case dose (at around 4,000 years). The number of waste packages assumed breached in the groundwater release case is much larger than in the direct release case. On average, for an igneous event, approximately 30 percent of the waste packages are assumed damaged, and 15 percent would contribute to radionuclide release to the groundwater (on average, half of the damaged waste packages are assumed located under seeps; see Chapter 5). Conversely, less than 10 waste packages are assumed to release their inventory directly to the surface.

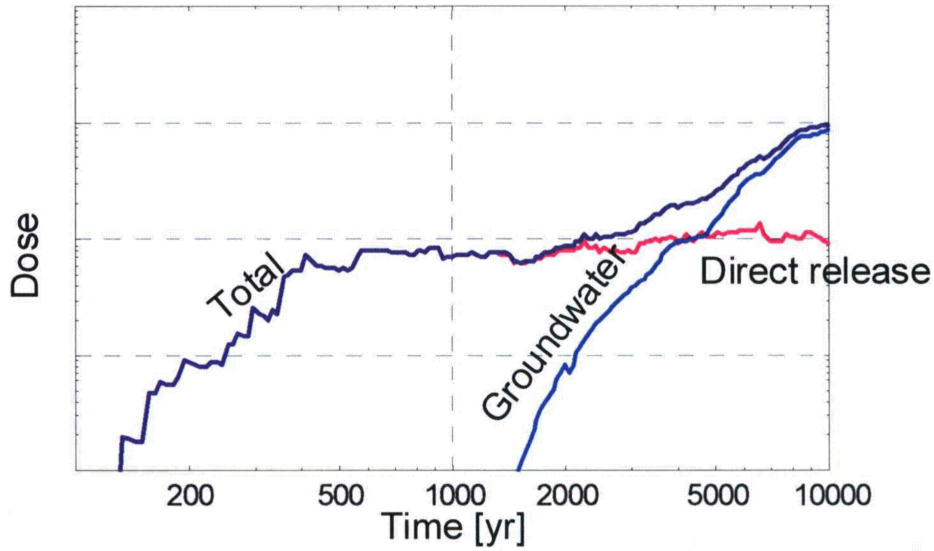
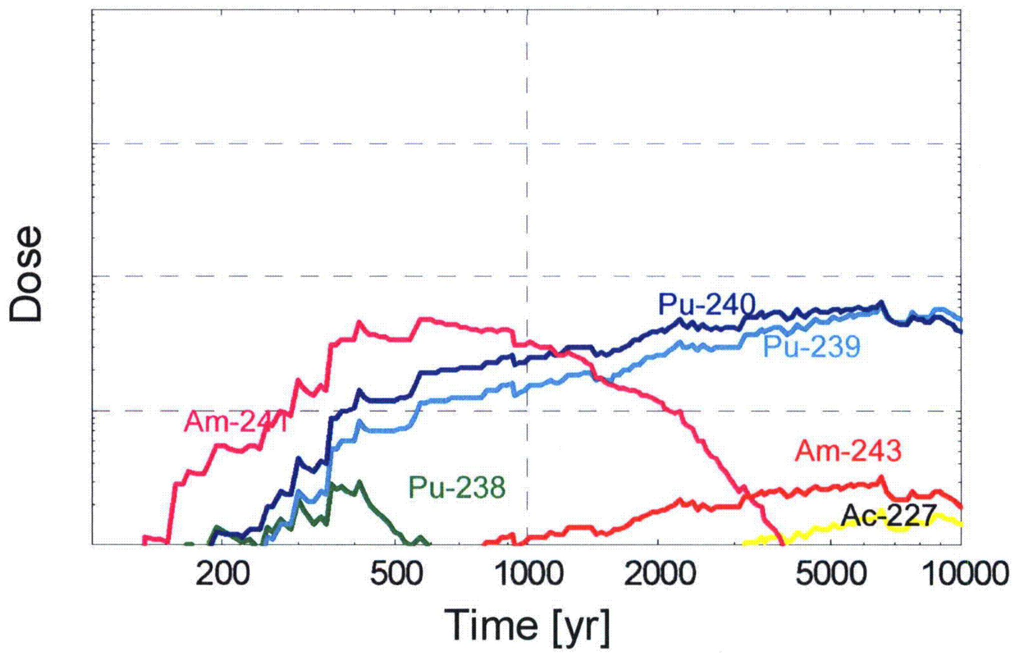


Figure 7-1. Average (From 500 Realizations), Direct Release (Extrusive Case), and Groundwater Dose (Intrusive Case) Using TPA Version 5.1, Derived Assuming an Igneous Event Occurs Within the First 10^4 Years

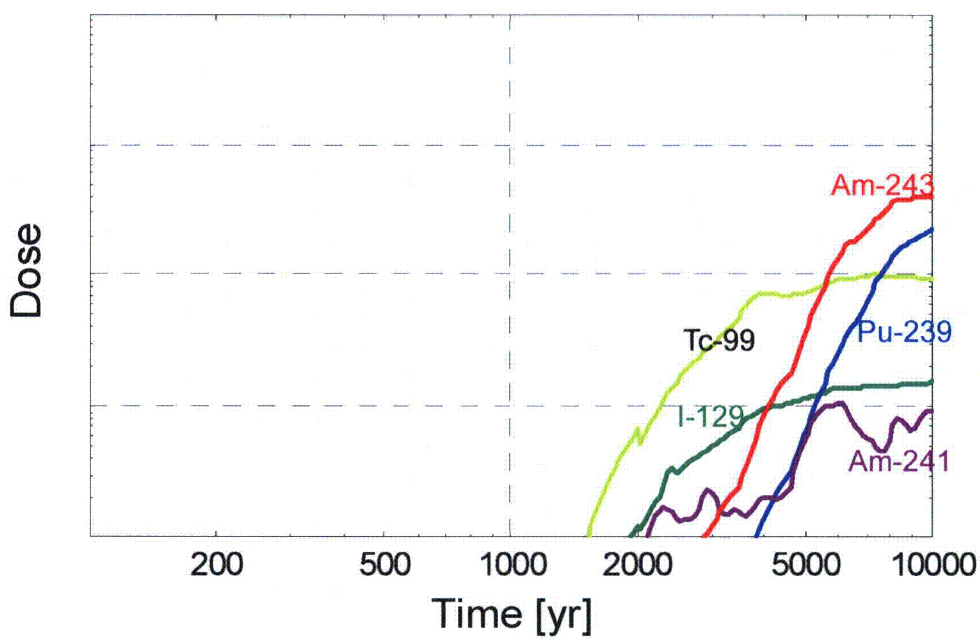
Figure 7-2 shows the dominant radionuclides contributing to expected dose associated with the direct release case: (i) Am-241, (ii) Pu-240, and (iii) Pu-239. These radionuclides are dominant given their relative inventory abundance and relatively high dose conversion factors. For the groundwater release case, the dominant radionuclides are Tc-99, I-129, Am-243, and Pu-239, consistent with results discussed in Chapter 3.

Expected doses (probability weighted) for the 10^6-year case, 500 realizations, are shown in Figure 7-3. The dominant radionuclides in the dose estimates are shown in Figure 7-4. The dominant radionuclides in the extrusive case, past 10,000 years, are Pu-240, Pu-239, Pu-242, and Th-229. In the intrusive case, the dominant radionuclides are Tc-99, I-129, Pu-239, Th-230, Pu-242, Np-237, and U-233. These latter radionuclides are consistent with those identified in Chapter 3 for the disruptive seismic scenario.

The higher expected doses associated with the intrusive case in the first 10,000 years in Figure 7-3 compared to corresponding data in Figure 7-1 is an artifact of the procedure used to conditionally sample the time of igneous events in the TPA Version 5.1 Code. In the 10,000-year computations (Figure 7-1), the igneous events per realization are temporally spaced approximately every 20 years. On the other hand, in the 10^6-year computations, the events are spaced approximately every 2,000 years. Therefore, in the 10^6-year computations, only five realizations contribute to the average in the first 10,000 years. As a consequence, the expected mean dose is in the first 10,000 years in the 10^6-year simulation (Figure 7-3) is more statistically uncertain compared to data in Figure 7-1, where all 500 realizations contribute to the computation of the expected dose at 10,000 years. Because of the statistical uncertainty, in this example, expected doses are overestimated in the first 10,000 years in the 10^6-year simulation run (Figure 7-3) compared to data in Figure 7-1. Selection of a different random seed may produce instances where the expected dose is underestimated.



(A)



(B)

Figure 7-2. Dominant Radionuclides in Estimates of the Expected Dose of the Igneous Event Scenario for (A) Extrusive Case (Direct Surface Release) and (B) Intrusive Case (Groundwater Release)

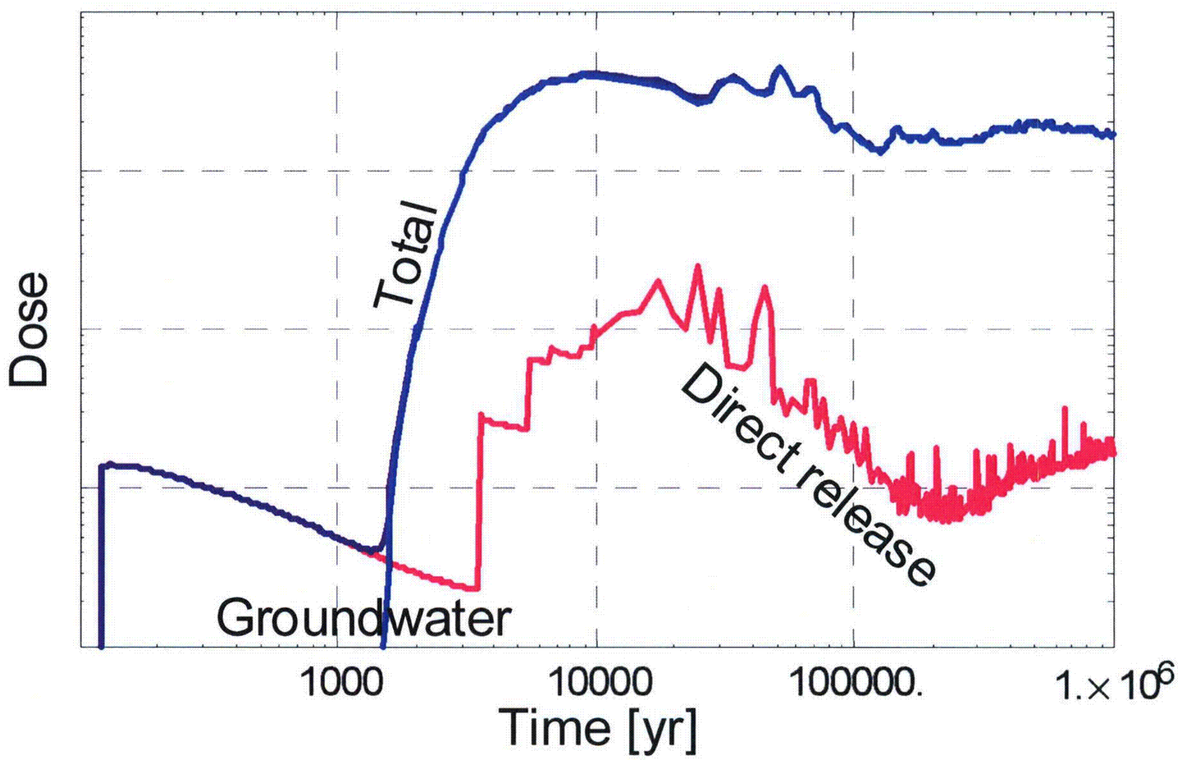
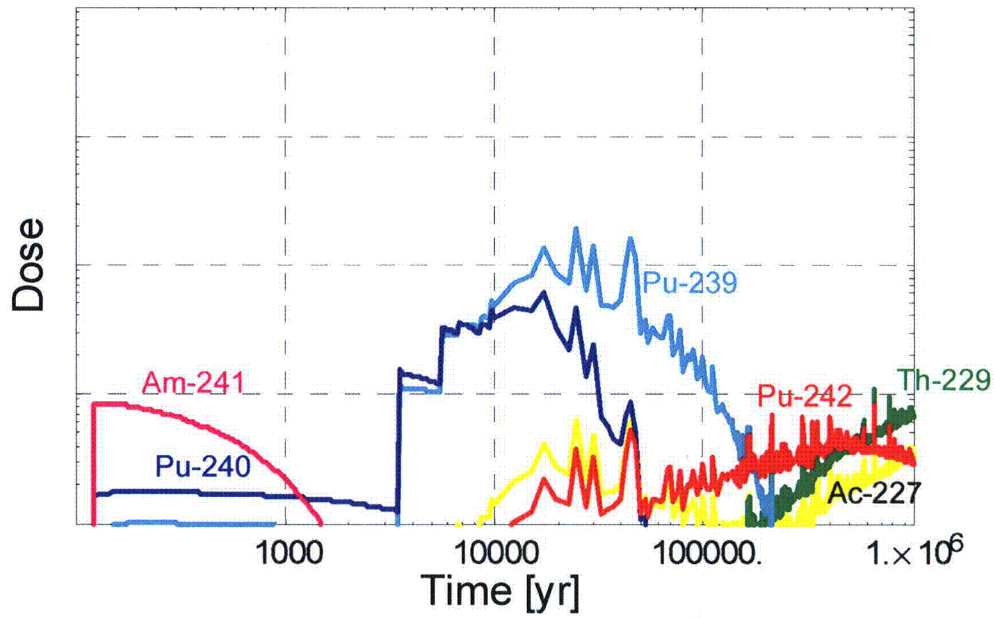
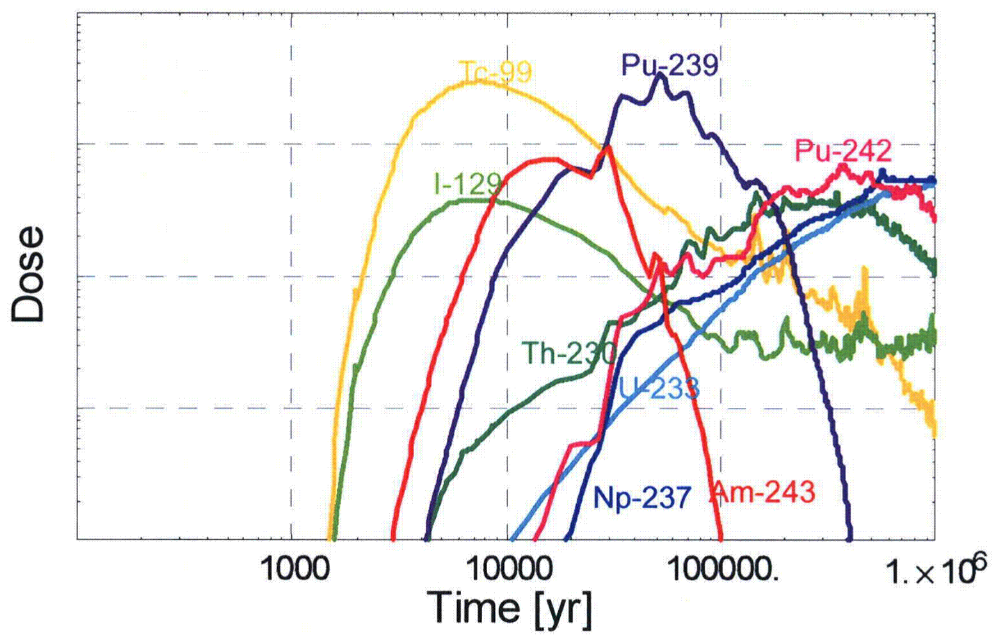


Figure 7-3. Average (From 500 Realizations), Direct Release (Extrusive Case), and Groundwater Dose (Intrusive Case) Using TPA Version 5.1, Derived Assuming an Igneous Event Occurs Within the First 10^6 Years



(A)



(B)

Figure 7-4. Dominant Radionuclides in Estimates of the Expected Dose of the Igneous Event Scenario for (A) Extrusive Case (Direct Surface Release) and (B) Intrusive Case (Groundwater Release)

7.3 Conclusions

These results relate to the following risk insights from the Risk Insights Baseline Report (NRC, 2005, Table 2). The suggested relative risk rankings based on the analysis in Section 7.2, as well as an indication of whether this rankings reflect a change are given.

- TSPAI2—Identification of Events with Probability > 10^{-8} per year
  - Probability of Igneous Activity—Medium (previously ranked High in NRC, 2005)
- DIRECT1—Volcanic Disruption of Waste Packages
  - Number of Waste Packages Affected by Eruption—Medium (previously ranked High in NRC, 2005)
  - Number of Waste Packages Damaged by Intrusion—Medium (unchanged from previous ranking)
- DIRECT2—Airborne Transport of Radionuclides
  - Volume of Ash Produced by an Eruption—Medium (unchanged from previous ranking)
  - Wind Vectors During an Eruption—Medium (unchanged from previous ranking)
- DOSE2—Redistribution of Radionuclides in Soil
  - Remobilization of Ash Deposits—Medium (unchanged from previous ranking)
- DOSE3—Biosphere Characteristics
  - Inhalation of Resuspended Volcanic Ash—Medium (previously ranked High in NRC, 2005)

The following risk insights changed from previous rankings. The "Probability of Igneous Activity" is directly related to dose estimates. The probability-weighted mean dose estimate is a fraction of the dose estimate associated with the disruptive seismic scenario (Chapter 3). Therefore, the aggregated mean dose estimate for all scenarios is only partially affected by the uncertainty in the probability, and thus the "Probability of Igneous Activity" is considered of medium significance.

"Number of Waste Packages Affected by Eruption" is considered medium significance. Previously it was considered high, when the eruption case dominated the estimated total igneous consequences (NRC, 2005). In the present updated analyses, the eruption case dominates only early dose estimates of marginal magnitude. Uncertainties exist in the number of ejected waste packages in the extrusive case that could affect dose estimates. It is unlikely that those uncertainties would affect dose estimates by more than one order of magnitude; therefore, the "Number of Waste Packages Affected by Eruption" is considered of medium significance.

Finally, the "Inhalation of Resuspended Volcanic Ash" is considered medium significance (considered high in NRC, 2005). Revised modeling approaches accounting for wind-field variations and redistribution of contaminated ash have resulted in moderate dose consequences for the airborne release scenario, compared to previous modeling approaches in TPA Version 4.1j. Reduction in the average airborne mass load following an eruption in TPA Version 5.1 is one factor contributing to lower consequence estimates. Inhalation of contaminated volcanic ash was the main pathway in dose estimates for the disruptive igneous scenario in TPA Version 4.1j, because the extrusive case dominated those estimates. In current dose estimates shown in Figures 7-1 and 7-3, the dose is dominated by the intrusive case at times when maximum doses are attained. The main pathways in the groundwater release case are drinking water and plant consumption. The inhalation pathway is the dominant exposure route for extrusive case doses and is a negligible contributor in dose estimates for the igneous intrusive case.

All of the other rankings in the Risk Insights Baseline Report (NRC, 2005, Table 2) are unchanged based on the present analysis.

8 SUMMARY

The updated significance rankings to the Risk Insights Baseline Report are summarized in Table 8-1 (NRC, 2005, Table 2). Table 8-1 incorporates a redefined scope of model abstractions for ENG3—Quantity and Chemistry of Water Contacting Engineered Barriers and Waste Forms, DIRECT1—Volcanic Disruption of Waste Packages, DIRECT2—Airborne Transport of Radionuclides, and DOSE3—Biosphere Characteristics. For example, the topic titled Remobilization of Ash Deposits is addressed under DOSE2, while in the Risk Insights Baseline Report (NRC, 2005), it was considered under DIRECT2. The topic titled Probability of Igneous Activity is covered under TSPAI2—Identification of Events with Probability > 10^{-8} per year; it was previously covered under DIRECT1 (NRC, 2005).

Based on discussions in this report, the following risk insights were updated: Chemistry of Seepage Water, Number of Waste Packages Affected by Eruption, Inhalation of Resuspended Volcanic Ash, and Probability of Igneous Activity. All were considered highly significant to waste isolation (NRC, 2005) and now are considered of medium significance. In general, the update in the rankings is the result of more detailed consideration of processes influencing dose estimates in the TPA Code Version 5.1. Discussions supporting risk insight ranking updates are available in Chapters 5 and 7.

Table 8-1. Summary of Risk Insights Rankings

Title	Significance Ranking	Considered in Chapter
ENG1—Degradation of Engineered Barriers		
Persistence of a Passive Film	High	NA
Waste Package Failure Mode	Medium	3, 5
Drip Shield Integrity	Medium	3, 4, 5
Stress Corrosion Cracking	Medium	NA
Juvenile Failures of the Waste Package	Low	5
ENG2—Mechanical Disruption of Engineered Barriers		
Effects of Accumulated Rockfall on Engineered Barriers	Medium	3, 4, 5
Dynamic Effects of Rockfall on Engineered Barriers	Low	NA
Effects of Seismic Loading on Engineered Barriers	Medium	4, 5
Effects of Faulting on Engineered Barriers	Low	NA
ENG3—Quantity and Chemistry of Water Contacting Engineered Barriers and Waste Forms		
Chemistry of Seepage Water	**Medium** (previously High)	5
Quantity of Water Contacting Engineered Barriers and Waste Forms	Medium	5
ENG4—Radionuclide Release Rates and Solubility Limits		
Waste Form Degradation Rate	Medium	NA
Cladding Degradation	Medium	NA
Solubility limits	Medium	NA
Mode of Release from Waste Package	Low	NA
Effect of Colloids on Waste Package Releases	Medium	6
Invert Flow and Transport	Low	NA
Criticality	Low	NA

Table 8-1. Summary of Risk Insights Rankings (continued)		
Title	**Significance Ranking**	**Considered in Chapter**
UZ1—Climate and Infiltration		
Present-day Net Infiltration Rate	Medium	NA
Long-term Climatic Change	Medium	3
UZ2—Flow Paths in the Unsaturated Zone		
Seepage	High	5
Hydrologic Properties of the Unsaturated Zone	Medium	NA
Transient Percolation	Low	NA
UZ3—Radionuclide Transport in the Unsaturated Zone		
Retardation in the Calico Hills Nonwelded Vitric Unit	Medium	3
Matrix Diffusion in the Unsaturated Zone	Medium	NA
Effect of Colloids on Transport in the Unsaturated Zone	Medium	3, 6
SZ1—Flow Paths in the Saturated Zone		
Saturated Alluvium Transport Distance	Medium	NA
SZ2—Radionuclide Transport in the Saturated Zone		
Retardation in the Saturated Alluvium	High	3
Matrix Diffusion in the Saturated Zone	Medium	NA
Effect of Colloids on Transport in the Saturated Zone	Medium	3, 6
DIRECT1—Volcanic Disruption of Waste Packages		
Number of Waste Packages Affected by Eruption	**Medium** (previously High)	7
Number of Waste Packages Damaged by Intrusion	Medium	7
DIRECT2—Airborne Transport of Radionuclides		
Volume of Ash Produced by an Eruption	Medium	7
Wind Vectors During an Eruption	Medium	7
DOSE1—Concentration of Radionuclides in Ground Water		
Well-Pumping Model	Low	NA
DOSE2—Redistribution of Radionuclides in Soil		
Remobilization of Ash Deposits	Medium	7
Redistribution of Radionuclides in Soil	Low	NA
DOSE3—Biosphere Characteristics		
Inhalation of Resuspended Volcanic Ash	**Medium** (previously High)	7
Characterization of the Biosphere	Low	2, 3
TSPAI2—Identification of Events with Probability > 10^{-8} Per Year		
Probability of Igneous Activity	**Medium** (previously High)	7

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