DOCUMENTATION OF ANALYSES IN SUPPORT OF THE NRC STAFF'S TECHNICAL EVALUATION OF DOE'S TOTAL SYSTEM PERFORMANCE ASSESSMENT (TSPA) CALCULATIONS

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Editors: T. McCartin and J. Winterle

Authors and Contributors: T. Ahn, H. Basagaoglu, J. Bradbury, T. Cao, K. Compton, R. Fedors, H. Gonzalez, A. Gray, J. Gwo, B. Hill, R. Janetzke, P. LaPlante, J. Mancillas, C. Manepally, C. Markley, T. McCartin, J. McMurry, J. Myers, S. Painter, Y. Pan, O. Pensado, D. Pickett, S. Self, L. Tipton, and J. Winterle

ACRONYMS AND ABBREVIATIONS

BDCF	biosphere dose conversion factors
CDSP	codisposal (vitrified high level waste and DOE spent nuclear fuel)
CSNF	commercial spent nuclear fuel
DOE	U.S. Department of Energy
EBS	engineered barrier system
MOX	mixed oxide spent nuclear fuel
NRC	U.S. Nuclear Regulatory Commission
RAI	request for additional information
RMEI	reasonably maximally exposed individual
SAR	Safety Analysis Report
TER	Technical Evaluation Report
TSPA	Total System Performance Assessment
WPFR	waste package failure rate

1 INTRODUCTION

After docketing the U.S. Department of Energy (DOE) license application seeking a construction authorization for the proposed repository at Yucca Mountain, Nevada, the U.S. Nuclear Regulatory Commission (NRC) staff began documenting its review in a Safety Evaluation Report. On March 3, 2010, DOE filed a motion with the Atomic Safety and Licensing Board seeking to withdraw its license application to develop a repository at Yucca Mountain, Nevada. In June 2010, the Board denied the DOE motion. To date, petitions asking the Commission to reverse or uphold this decision are pending before the Commission.

On October 1, 2010, began orderly closure of its Yucca Mountain activities. As part of orderly closure, the NRC staff prepared a technical evaluation report (TER), a knowledge management document. The TER document (NRC, 2011aa) captures the NRC staff's technical assessment of information presented in DOE's Safety Analysis Report (SAR), dated June 3, 2008, as amended, and supporting information. The TER describes the NRC staff's technical evaluation of the SAR and, in particular, the TER Postclosure Volume provides technical insights on the application of performance assessment in the context of geologic disposal. The TER was developed using the regulations at 10 CFR Part 63 and guidance in the Yucca Mountain Review Plan (YMRP). The TER does not, however, include conclusions as to whether or not DOE satisfies the Commission's regulations.

The U.S. Nuclear Regulatory Commission (NRC) staff performed independent analyses in support of its review of the U.S. Department of Energy's (DOE's) Total System Performance Assessment (TSPA) as part of DOE's Safety Analysis Report (SAR) for the disposal of high-level radioactive waste in a geologic repository at Yucca Mountain. DOE's TSPA computer model evaluates the behavior of the high-level nuclear waste repository in terms of an annual dose due to potential releases from the repository. The performance assessment provides a method to evaluate the range of features (e.g., geologic rock types, waste package materials), events (e.g., earthquakes, igneous activity), and processes (e.g., corrosion of metal waste packages, sorption of radionuclides onto rock surfaces) that are relevant to the behavior of a potential repository at Yucca Mountain. This document describes the NRC staff's independent analyses in support of its review of DOE's TSPA.

The NRC staff's independent analyses primarily focused on a confirmatory calculation of DOE's TSPA results with respect to the estimated dose. As described in Sections 2 (Confirmatory Calculation for the Groundwater Pathway) and 3 [Confirmatory Calculation for an Eruptive (Volcanic) Igneous Event], the NRC staff developed a "simplified" calculation to assist its confirmation of the results of DOE's TSPA. The simplified calculation provides a means to understand how significant processes for estimating release and transport of radionuclides affect the dose. The simplified calculation is not to be considered a replacement for the TSPA; in fact, the simplified calculation was made possible due to the review of the TSPA and its results. The simplified confirmatory calculation provides a quantitative approach for explaining the staff understanding of the TSPA results. Sections 4 and 5 provide further analyses of the DOE's TSPA that support assumptions and approaches used in the NRC staff's confirmatory calculation, and in some cases provide additional insights and understanding of DOE's TSPA. Section 4 (TSPA Diffusional Release Results) provides information on the significance of diffusional releases relative to advective releases from the engineered barrier system (EBS). Section 5 (Corrosion Product Factor Technical Support) provides information supporting the selection of values for estimating the effectiveness of the corrosion product factor in limiting

concentrations of radionuclides of water inside the waste package. Section 6 (Observations) discusses how the results of the confirmatory calculation support the NRC staff's understanding of DOE's TSPA and implications for the review of DOE's SAR.

2 CONFIRMATORY CALCULATION FOR THE GROUNDWATER PATHWAY

A confirmatory calculation by NRC staff of the radiological dose determined by DOE's Total System Performance Assessment (TSPA) is based on intermediate results and parameters from the TSPA. A dose estimate is obtained for releases of radionuclides through the groundwater pathway by obtaining estimates for

- Amount of water reaching the repository
- Timing and extent of failure of the waste packages
- Amount of seepage water that flows through the waste packages
- Release rate of radionuclides out of the waste package
- Transport through the unsaturated and saturated zones
- Concentration of radionuclides in groundwater used by an individual
- Biosphere dose conversion factors (BDCFs)

2.1 Amount of Water Reaching the Repository

The amount of water entering the drift as seepage is characterized by an average seepage value over the repository footprint and a percentage of the footprint where the seepage occurs. This percentage is known as the seepage fraction—that portion of the drifts where dripping occurs—and is also called the seeping environment.

Table 2-1 summarizes information regarding the mean values for the seepage rates and seepage fractions (mean values determined over the five percolation subregions of the repository footprint) for specific modeling cases and time frames associated with DOE's Total System Performance Assessment (TSPA). Some of the values in Table 2-1 are numbers taken directly from tables in DOE's Safety Analysis Report (SAR) [2009av] and, where applicable, references to the specific SAR tables are provided in Table 2-1. The values of 100% for the seepage fractions for the igneous intrusive modeling case for the period of time from 2,000 to 10,000 years and for the post 10,000 year period are based on DOE's assumption that igneous intrusion affects all emplacements drifts and waste packages (DOE 2009ct, Enclosure 8, p. 13; and SAR Volume 2, pp. 2.4-42 and 2.4-69). The mean values for seepage rates for the igneous intrusion modeling case are set equal to DOE's mean value for percolation in the host rock overlying the repository because DOE assumes in the TSPA that the seepage water flux into a magma-intruded drift is equal to the percolation flux in the overlying host rock (SAR p. 2.4-69). Thus, the seepage rate in Table 2-1 for the igneous intrusion modeling case for the period of time from 2,000 to 10,000 years is DOE's mean value for percolation in the host rock overlying the repository for the glacial transition climate and for the post 10,000 year time period is DOE's mean value for percolation for the post 10,000 year period (DOE. 2010ai, Enclosure 1, Table 4).

The remaining values in Table 2-1, where a reference is not provided, represent values where a minor calculation, using DOE information, was necessary to produce the values in the table.

The calculated seepage rates are not an average for the seeping environment, but rather an average for the entire repository footprint, which includes both seeping and non-seeping environments. The following calculations were used to generate those remaining values in Table 2-1:

Period of time from 2,000 to 10,000 years

- The seepage rate for the nominal and early failure modeling cases for the period of time from 2,000 to 10,000 years is determined by dividing DOE's mean value for volumetric flow per waste package for the glacial-transition climate of 0.056 m^3/yr [1.98 ft^3/yr] [DOE. 2010ai. Enclosure 1, Table 5.] by the cross-sectional area of a drift segment for one waste package, which is 28.05 m^2 [301.9 ft^2]. The cross-sectional area is determined from the dimensions for a drift segment of 5.1 m [16.7 ft] long by 5.5 m [18.0 ft] wide as provided in SAR Section 2.1.2.1.6.2, p. 2.1-29.

- The seepage rate for the seismic ground motion modeling case for the period of time from 2,000 to 10,000 years is determined by dividing DOE's mean value for volumetric flow per waste package for the glacial-transition climate of 0.064 m^3/yr [2.26 ft^3/yr] [DOE. 2010ai. Enclosure 1, Table 8.] by the cross-sectional area of a drift segment for one waste package, which is 28.05 m^2 [301.9 ft^2]. The cross-sectional area is determined from the dimensions for a drift segment of 5.1 m [16.7 ft] long by 5.5 m [18.0 ft] wide as provided in SAR Section 2.1.2.1.6.2, p. 2.1-29.

Post-10,000-year period

- The seepage rate for the nominal and early failure modeling cases for the post-10,000-year period is determined by dividing DOE's mean value for volumetric flow per waste package for the post-10,000-year period of 0.095 m^3/yr [3.36 ft^3/yr] [DOE. 2010ai. Enclosure 1, Table 5.] by the cross-sectional area of a drift segment for one waste package, which is 28.05 m^2 [301.9 ft^2]. The cross-sectional area is determined from the dimensions for a drift segment of 5.1 m [16.7 ft] long by 5.5 m [18.0 ft] wide as provided in SAR Section 2.1.2.1.6.2, p. 2.1-29.

- The seepage rate for the seismic ground motion modeling case for the post-10,000-year period is determined by dividing DOE's mean value for volumetric flow per waste package for the post-10,000-year period of 0.434 m^3/yr [15.3 ft^3/yr] [DOE. 2010ai. Enclosure 1, Table 8.] by the cross-sectional area of a drift segment for one waste package, which is 28.05 m^2 [301.9 ft^2]. The cross-sectional area is determined from the dimensions for a drift segment of 5.1 m [16.7 ft] long by 5.5 m [18.0 ft] wide as provided in SAR Section 2.1.2.1.6.2, p. 2.1-29.

Table 2-1. Repository Average Seepage Rates and Seepage Fractions			
Performance Aspect	**Nominal/Early Failure**	**Seismic Ground Motion**	**Igneous Intrusive**
Seepage into drifts from 2,000 to 10,000 years (mm/yr)	2.0	2.3	21.7
Seepage fraction from 2,000 to 10,000 years	31% (SAR Table 2.1-6)	31% (SAR Table 2.1-8)	100%
Seepage into drifts after 10,000 years (mm/yr)	3.4	15.5	31.7
Seepage fraction after 10,000 years	40% (SAR Table 2.1-7)	69% (SAR Table 2.1-9)	100%

2.2 Timing and Extent of Waste Package Breaches

The timing and extent of waste package failure depends, in part, on the probability of occurrence of disruptive events. In TSPA, the disruptive events that result in the largest number of waste package failures are associated with the seismic ground motion modeling case (including the effects of general corrosion and stress corrosion cracking) and the igneous intrusive modeling case (i.e., all waste packages are assumed to fail in the year that the event occurs).

2.2.1 Timing of Waste Package Breaches

DOE's TSPA results for the fraction of failed waste packages in the seismic ground motion modeling case include the probability for the seismic events to occur; however, there is no comparable result for the igneous intrusive modeling case. Given DOE has assumed all waste packages fail when the igneous intrusive event occurs, the fraction of waste packages failed at a given time, which includes the probability of the event occurring, is determined by multiplying the fraction of failed packages (i.e., 1.0) by the annual probability for an igneous intrusive event [i.e., 1.7×10^{-8}; Safety Analysis Report (SAR), DOE, 2009av, p. 2.3.11-12] and the period of elapsed time since repository closure. The fraction of Commercial Spent Nuclear Fuel (CSNF) and Codisposal (CDSP) waste package failures provided in Table 2-2 is based on information in DOE's SAR and responses to requests for additional information (RAIs), as indicated in the table. NRC used the information in Table 2-2 to calculate the number of failed waste packages and the waste package failure rates.

The number of breached or failed waste packages is determined simply by multiplying the fraction of failed waste packages in Table 2-2 by the total number of waste packages [i.e., 8,213 commercial spent nuclear fuel (CSNF) waste packages and 3,416 codisposal (CDSP) waste packages – SAR p. 2.1-71]. The number of breached waste packages is provided in Table 2-3. The number of breached waste packages represents a cumulative number of failed waste packages (i.e., the total number of waste packages breached up to the given times in the table). Waste package failure rates, determined using the values in Table 2-3, are provided in

Table 2-4. The failure rates represent the annual rate based on the number of breached waste packages that have been breached over the time interval for the time periods in the table (i.e., 0 to 10,000 years; 10,000 to 100,000 years; 100,000 to 400,000 years; and 400,000 to 800,000 years).

Table 2-2. Cumulative Fraction of Breached Waste Packages

Process	10,000 Years	100,000 Years	400,000 Years	800,000 Years
Seismic* all failure types	CSNF 2×10^{-4} CDSP 0.01	CSNF 2.5×10^{-3} CDSP 0.30	CSNF 0.09 CDSP 0.40	CSNF 0.43 CDSP 0.60
Seismic† ruptures and punctures (patches)	CSNF 0 CDSP 1×10^{-4}	CSNF 0 CDSP 2.0×10^{-4}	CSNF 3.0×10^{-3} CDSP 4.0×10^{-3}	CSNF 0.01 CDSP 0.01
Seismic† general corrosion (patches)	CSNF 0 CDSP 0	CSNF 0 CDSP 0	CSNF 4.0×10^{-5} CDSP 1.0×10^{-3}	CSNF 0.04 CDSP 0.07
Igneous Intrusion‡ patch failures	CSNF 1.7×10^{-4} CDSP 1.7×10^{-4}	CSNF 1.7×10^{-3} CDSP 1.7×10^{-3}	CSNF 6.8×10^{-3} CDSP 6.8×10^{-3}	CSNF 0.0136 CDSP 0.0136

*Values approximated from SAR Figure 2.1-12 a and c.

†Values approximated from Figures 1-14 [DOE. 2009bj. Enclosure 1.]

‡Values determined by multiplying failure fraction of 1.0 (all waste packages failed) by the annual probability (1.7×10^{-8}) and the specific time (i.e., 10,000; 100,000; 400,000; and 800,000 years).

Table 2-3. Cumulative Number* of Breached Waste Packages

Process	10,000 Years	100,000 Years	400,000 Years	800,000 Years
Seismic all failure types	CSNF 1.6 CDSP 34.2	CSNF 20.5 CDSP 1,024.8	CSNF 739.2 CDSP 1,366.4	CSNF 3,531.6 CDSP 2,049.6
Seismic ruptures and punctures (patches)	CSNF 0 CDSP 0.3	CSNF 0 CDSP 0.7	CSNF 24.6 CDSP 13.7	CSNF 82.1 CDSP 34.2
Seismic general corrosion (patches)	CSNF 0 CDSP 0	CSNF 0 CDSP 0	CSNF 0.3 CDSP 4.8	CSNF 328.5 CDSP 239.1
Igneous Intrusion patch failures	CSNF 1.4 CDSP 0.6	CSNF 14 CDSP 5.8	CSNF 55.9 CDSP 23.2	CSNF 111.7 CDSP 46.5

*Number of waste packages based on fractions from Table 2-2 and the total number of 8,213 commercial spent nuclear fuel (CSNF) and 3,416 codisposal (CDSP) waste packages.

Table 2-4. Annual Waste Package Failure Rates*				
Process	**10,000 Years**	**100,000 Years**	**400,000 Years**	**800,000 Years**
Seismic all failure types	CSNF 1.6×10^{-4} CDSP 3.4×10^{-3}	CSNF 2.1×10^{-4} CDSP 0.011	CSNF 2.4×10^{-3} CDSP 1.1×10^{-3}	CSNF 7.0×10^{-3} CDSP 1.7×10^{-3}
Seismic ruptures and punctures (patches)	CSNF 0 CDSP 3.0×10^{-5}	CSNF 0 CDSP 4.4×10^{-6}	CSNF 8.2×10^{-5} CDSP 4.3×10^{-5}	CSNF 1.4×10^{-4} CDSP 5.0×10^{-5}
Seismic general corrosion patches)	CSNF 0 CDSP 0	CSNF 0 CDSP 0	CSNF 1.0×10^{-6} CDSP 1.6×10^{-5}	CSNF 8.2×10^{-4} CDSP 5.9×10^{-4}
Igneous Intrusion patch failures	CSNF 1.4×10^{-4} CDSP 6.0×10^{-5}	CSNF 1.4×10^{-4} CDSP 5.8×10^{-5}	CSNF 1.4×10^{-4} CDSP 5.8×10^{-5}	CSNF 1.4×10^{-4} CDSP 5.8×10^{-5}
*Failure rates based on the waste packages failed (Table 2-3) within a given time period (i.e., 0 to 10,000 years; 10,000 to 100,000 years; 100,000 to 400,000 years; and 400,000 to 800,000 years).				

2.2.2 Extent of Waste Package Breaches

The extent of the waste package breaches refers to the portion of the surface area of the waste package that is damaged, which is expressed as a percentage of the surface area in Table 2-5. As will be described in the next section, the area of the breach or opening is important for determining the amount of the drift seepage water that can enter the waste package breaches of sufficient size that water is assumed to flow through the waste package (i.e., patch failures due to ruptures and punctures, general corrosion, and igneous intrusion).

The extent of damage varies over time in the seismic ground motion modeling case due to such processes as the timing and magnitude of seismic events and general corrosion. In contrast, after the igneous intrusion event occurs, DOE's TSPA assumes the waste package, drip shield and repository drifts offer no protection for seepage water to contact waste (SAR p. 2.3.11-10). Once the temperatures drop below the boiling point of water, seepage is assumed to enter the magma-filled drifts at a rate consistent with the properties of the surrounding rock (SAR p. 2.3.11-12). Thus, deep percolation in the surrounding rock is assumed to be available to enter repository drifts and contact waste.

Table 2-5. Percentage of Waste Package Surface Area Breached				
Process	**10,000 Years**	**100,000 Years**	**400,000 Years**	**800,000 Years**
Seismic Ruptures and punctures* (patches)	CSNF 0% CDSP 6%	CSNF 0% CDSP 4%	CSNF 0.4% CDSP 0.6%	CSNF 0.3% CDSP 0.3%
Seismic General corrosion* (patches)	CSNF 0% CDSP 0%	CSNF 0% CDSP 0%	CSNF 0.07% CDSP 0.08%	CSNF 0.3% CDSP 0.4%
Igneous intrusion patch failures	CSNF 100% CDSP 100%	CSNF 100% CDSP 100%	CSNF 100% CDSP 100%	CSNF 100% CDSP 100%
*Values approximated from Figures 1-14 [DOE. 2009bj. Enclosure 1.]				

2.3 Amount of Seepage Water That Flows Through Waste Packages

The following assumptions are made to determine the amount of seepage water entering the waste package for the seismic ground water modeling case:

- The drip shield is assumed to be ineffective at reducing seepage after the waste packages are breached. This is a conservative approach inconsistent with the DOE's performance assessment; however, beyond approximately 200,000 years (the average lifetime for the drip shields), this assumption will be generally consistent with DOE's performance assessment.

- Seepage water is assumed to be able to flow into and through the waste package via waste package breaches from ruptures, punctures, and general corrosion (i.e., openings due to cracks are too small to allow seepage water to flow into the waste package). This is generally consistent with DOE's performance assessment.

- Volume of seepage water available for entering the waste package is determined by multiplying the seepage rate over the repository footprint times the cross-sectional area of the drift segment for one waste package {i.e., waste package length of 5.1 m [16.7 ft] times the 5.5-m [18.0 ft] width of an intact drift; SAR p. 2.1-29} and divided by the seepage fraction (the seepage rate over the repository footprint includes both seepage and non-seepage locations; thus dividing by the seepage fraction provides the value for seepage rate where seepage occurs). This is generally consistent with DOE's performance assessment; however, the use of an intact drift rather than a degraded drift does not account for drift degradation to enlarge the cross section of the drifts.

- The waste package will divert some of the seepage water from entering the waste package when less than 4 percent of the waste package surface area is breached. The fraction of seepage water that enters a waste package that has less than 4 percent of the surface area breached is determined by multiplying the volume of

available seepage water by the ratio of the percentage of the waste package surface area breached to 4 percent. This is generally consistent with DOE's performance assessment.

The following assumptions are made to determine the amount of seepage water entering the waste package for the igneous intrusion modeling case:

- The drip shield is assumed to be ineffective at reducing seepage after the waste packages are breached. This is generally consistent with DOE's performance assessment.

- Seepage water is assumed to be able to flow into and through a waste package breached due to igneous intrusion. This is generally consistent with DOE's performance assessment.

- Volume of seepage water available for entering the waste package is determined by multiplying the seepage rate over the repository footprint times the cross-sectional area of the drift segment for one waste package {i.e., waste package length of 5.1 m [16.7 ft] times the 5.5-m [18.0 ft] width of an intact drift; SAR p. 2.4-138} and divided by the seepage fraction (the seepage rate over the repository footprint includes both seepage and nonseepage locations; thus dividing by the seepage fraction provides the value for seepage rate where seepage occurs. This is generally consistent with DOE's performance assessment.

- The waste package damaged by an igneous intrusive event does not have the capability to divert seepage water from entering the waste package. The fraction of seepage water that enters a waste package is assumed equal to the entire volume of water available to enter the waste package (refer to the previous item in this list). This is generally consistent with DOE's performance assessment.

Equation 2-1: Equation for determining volume of seepage water entering a waste package

$$V = (S/F) \times A \times (B/0.04)$$

$$B = \text{minimum } (0.04, B)$$

where

V volume of seepage water entering one waste package (liters/year)

S average seepage rate over the repository footprint (mm/year)

F seepage fraction

A drift segment cross-sectional area (28.05 m^2)

B fraction of the waste package surface area that is breached (any fraction larger than 0.04 is to input as 0.04, consistent with the assumption that all seepage water enters the waste package when the percentage of breached area is 4 percent or greater)

Using Equation 2-1 and the values from Tables 2-1 and 2-5, the volume of water entering a single waste package is presented in Table 2-6 for the seismic ground motion modeling case and the igneous intrusion modeling case.

Table 2-6. Volume of Water Entering a Waste Package Breached by Patch Failure

Process	10,000 Years (liters/yr)	100,000 Years (liters/yr)	400,000 Years (liters/yr)	800,000 Years (liters/yr)
Seismic ground motion (ruptures and punctures)	CSNF 0 CDSP 208	CSNF 0 CDSP 630	CSNF 63 CDSP 94	CSNF 47 CDSP 47
Seismic ground motion (general corrosion)	CSNF 0 CDSP 0	CSNF 0 CDSP 0	CSNF 11 CDSP 13	CSNF 47 CDSP 63
Igneous intrusion	CSNF 609 CDSP 609	CSNF 889 CDSP 889	CSNF 889 CDSP 889	CSNF 889 CDSP 889

2.4 Release of Radionuclides From the Engineered Barrier System

2.4.1 Equation for Calculation of Engineered Barrier System Releases

The determination of the annual release rate from the repository engineered barrier system (EBS) is a straightforward concept in the sense that it is calculated by accounting for the failed waste packages and the release rate from the waste packages. The simplest expression of this concept would be multiplying the release rate from a single waste package by the number of failed waste packages to determine the release rate from the EBS (Equation 2-2).

Equation 2-2: Equation for EBS releases

$$EBS(t) = WPFR(t) \times t \times R(t)$$

where

t	time (years)
EBS(t)	release rate from the EBS at time t (grams/yr)
WPFR(t)	failure rate at time t for waste packages releasing radionuclides (1/yr)
R(t)	release rate from a single waste package at time t (grams/yr)

Equation 2-2 assumes the releases from the engineered barrier system (EBS) at a given time t can be determined by cumulative releases from those waste packages that have failed and are releasing radionuclides on or before time t. The number of waste packages failed on or before time t is determined in Equation 2-2 by multiplying the waste package failure rate (WPFR) by the number of years t. Equation 2-2 neglects the significance that the magnitude of the release rate (R) from a single waste package may have on the estimate of the EBS release rate at a given time. There are two potential conditions that provide insight to the significance of the waste package release rate. The first is the potential condition where the release rate is sufficiently low such that the releases from any failed package persist beyond the time period of the EBS release estimate. For this case, all the failed waste packages releasing radionuclides contribute to the EBS release rate (i.e., as packages fail over time they simply add to the releases from the packages that have failed in previous years). Equation 2-2 provides a reasonable estimate for this type of condition.

The second potential condition is where the release rate is sufficiently high that the releases from a failed waste package do not always persist over the time period of the EBS release estimate. For this case, all failed waste packages do not always contribute to EBS releases at later times (i.e., there is a limited amount of time over which an individual waste package release persists until the inventory is completely released). For this condition, Equation 2-2 has the potential to significantly overestimate the releases from the EBS (i.e., result in releases over a given time period that exceed the inventory of the waste packages). To prevent the possibility of calculating an EBS release rate that would result in releases over time to exceed the available inventory of the waste packages, a bounding rate was determined by replacing the release rate R(t) from a single waste package in Equation 2-2 with a bounding release rate for a single waste package (i.e., the inventory of the waste package divided by a period of time equal to t; see Equation 2-3. Equation 2-3 is bounding in the sense that the entire inventory is released for all waste packages that are failed on or before the time of the estimate.

Equation 2-3: Bounding equations for EBS releases based on release of the entire inventory in the waste packages

$$EBS(t) = [WPFR(t) \times t] \times INV(t)/t$$

Because t appears in the numerator and denominator, the equation can be simplified to

$$EBS(t) = WPFR(t) \times INV(t)$$

where

t	time (years)
EBS(t)	release rate from the engineered barrier system (EBS) at time t (grams/yr)
WPFR(t)	failure rate at time t for waste packages releasing radionuclides (1/yr)
INV(t)	radionuclide inventory for an individual waste package at time t (grams)

When the EBS release rate, as determined with Equation 2-2, exceeds the release rate determined with Equation 2-3, the EBS release rate calculated with Equation 2-3 is used to ensure releases do not exceed the available inventory.

The waste package failure information provided in Tables 2-2 to 2-4 include the probabilities for the disruptive events (i.e., seismic ground motion and igneous intrusive); therefore, EBS releases determined with Equations 2-2 and 2-3 using the waste package failure rate information in Table 2-4 represent a probability-weighted release.

The release rate from a single waste package depends on the inventory; solubility limits; sorption factor onto corrosion products, which can further reduce solubility limited releases; and radioactive half-life. Three radionuclides were selected for the confirmatory calculation on the basis of their significance to performance and a range of potential release and transport characteristics: Tc-99, Np-237, and Pu-242. Tc-99 (a nonsorbing radionuclide) is the largest contributor to the average annual dose in the initial 10,000 years and represents large release rates and short travel times in the geosphere. Tc-99 accounts for approximately one-third of the peak of the overall average annual dose of approximately 0.003 mSv/yr [0.3 mrem/yr] (SAR Figure 2.4-20a). After 10,000 years and up to 1 million years, the peak of the overall average annual dose occurs at 1 million years, with Pu-242 and Np-237 being the largest contributors to the peak of the overall average annual dose. Pu-242 and Np-237 account for approximately one-half of the peak of the overall average annual dose of approximately 0.02 mSv/yr [2.0 mrem/yr] (SAR Figure 2.4-20b). Np-237 release is moderately constrained by its solubility limit and transport time in the geosphere is moderately increased from sorption, whereas Pu-242 release is more strongly constrained by its solubility limit and transport time in the geosphere is significantly increased by sorption relative to Np-237.

2.4.2 Non-Solubility-Limited Releases From the Engineered Barrier System

A radionuclide such as Tc-99 (i.e., highly soluble and nonsorbing) can be expected to have somewhat high release rates with significant contributions from both advective and diffusional release from the waste package. The potential for a high concentration within the waste package for highly soluble radionuclides increases the significance for the diffusional process for highly soluble radionuclides as compared to other radionuclides that are much less soluble (e.g., Np-237 and Pu-242). Therefore, the engineered barrier system (EBS) release rate for Tc-99 was calculated using the bounding approach (Equation 2-3) where it is assumed the entire inventory is released and all waste package failure types (i.e., cracks and patches) were assumed to contribute to the EBS release rate. When both diffusional and advective releases are assumed to be significant, waste packages with crack failures (note that only diffusional releases can occur through cracks) or patch failures (patch failures have the potential for diffusional and advective releases) need to be considered in determining releases from the EBS. Additionally, the NRC staff's determination of the EBS release of Tc-99 assumes all the breached waste packages contribute to EBS release because DOE's TSPA assumes diffusion can occur in both in dripping and nondripping conditions (dripping occurs where drift seepage occurs); thus even where there is no dripping water diffusional releases can occur. Tc-99 releases from the EBS, using Equation 2-3 to bound the releases, are presented in Table 2-7.

Table 2-7. Engineered Barrier System Release Rates of Tc-99*				
	10,000 Years	**100,000 Years**	**400,000 Years**	**800,000 Years**
Tc-99 inventory† (grams per waste package)	CSNF 7,405 CDSP 1,131	CSNF 5,526 CDSP 844	CSNF 2,082 CDSP 318	CSNF 567 CDSP 86
EBS release for seismic ground motion (grams/year)	CSNF 1.2 CDSP 3.8 Total: 5.0	CSNF 1.2 CDSP 9.3 Total: 10	CSNF 5.0 CDSP 0.35 Total: 5.4	CSNF 4.0 CDSP 0.15 Total: 4.2
EBS release for igneous intrusion (grams/year)	CSNF 1.0 CDSP 0.068 Total: 1.1	CSNF 0.77 CDSP 0.049 Total: 0.82	CSNF 0.29 CDSP 0.018 Total: 0.31	CSNF 0.079 CDSP 5.0×10^{-3} Total: 0.084

*Determined using Equation 2-3 and waste package failure rates in Table 2-4.

†Inventory based on decay of Tc-99 (half-life of 213,000 years) and inventory at time of closure of 7,650 g (CSNF) and 1,168 g (CDSP) [0.017 Ci/g of Tc-99] from SAR Tables 2.3.7-5 and 2.3.10-5.

2.4.3 Solubility-Limited Releases From the Engineered Barrier System

Low release rates will generally be associated with solubility-limited releases where the more significant releases will occur primarily as a result of water flow through the waste package (see Section 4). Water flow into the waste package is associated with large “patch” failures and not small crack failures of the waste package. The release rate of a particular radionuclide dissolved in the water flowing through the waste package (termed advective release) is time dependent because the extent of the damage to the surface of the waste package, seepage into the drifts, and the inventory of each radionuclide vary with time. Equation 2-4 is used to estimate the release rate from a waste package on the basis of values for the volume of water entering the waste package, solubility limit, and a factor accounting for the effect of corrosion products on the release (i.e., sorption of specific radionuclides onto corrosion products within the waste package resulting in a reduction in the ‘effective’ solubility limit; see Section 5).

Equation 2-4: Determination of waste package release rate for solubility-limited radionuclides

$$R(t) = V(t) \times S \times SORB$$

where

R(t)	advective release rate for a single waste package at time t (grams/yr)
V(t)	annual volume of seepage water entering a waste package at time t (liters/yr)
S	solubility limit (grams/liter)
SORB	a factor, which is equal to or less than 1, accounting for reduced release (effectively reducing the solubility limit) due to sorption onto corrosion products

2.4.3.1 Np-237 Release

Although releases of Np-237 can occur via diffusion through small cracks and advection and diffusion through patch openings, larger releases of Np-237 are expected to occur via advection through patches. DOE's TSPA results show that the majority of the Np-237 releases occur via advection (see Tables 4-1 and 4-2). Therefore, the waste package release rate for Np-237 (for use in Equation 2-2) is based on advective releases through patch openings using Equation 2-4 and the characteristics of the radionuclide (i.e., solubility limit and inventory) as well as characteristics of the waste package and the seepage (i.e., amount of water that enters the waste package and corrosion products). The radionuclide-specific values and the corrosion product factor for Np-237 are provided in Table 2-8, and the values for the amount of water entering the breached waste packages are provided in Table 2-6.

The range of neptunium solubility limits, 0.3 to 6 mg/L [0.3 to 6 ppm], was developed from the range of Np_2O_5 solubility abstraction lookup values used by the applicant and presented in SNL Table 6.6-9 and Figure 6.6-2 (SNL 2007ah). The maximum and minimum values were selected (and interpolated, if necessary) from the lookup table for the range of pH and log fCO_2 applicable to the corrosion products domain. (The range does not include uncertainty terms the applicant used that can yield values higher and lower than this range.) The applicable pH range was 7.0 to 8.4, as illustrated in DOE Enclosure 3 (2009ay) and supported in DOE Enclosure 2 (2009da). The applicable range of log fCO_2 (bars) was -3 to -2, which includes the range of values for the drift the applicant's near-field chemistry and thermal-hydrologic-chemical models predicted for 10,000 years and later (SAR Figure 2.3.5-24).

Only the Np_2O_5 solubility model was used, because it is applicable at longer times when all in-package steel has been corroded. The NpO_2 model would yield a lower range of values—0.02 mg/L to 3 mg/L [0.02 to 3 ppm]—but was not used in this calculation. Although the use of the NpO_2 solubility model values at early times would reduce the lower solubility value used in the confirmatory calculation, the overall impact of this reduction on release could be offset by a lessened effect from corrosion products on the release of radionuclides. The adopted neptunium solubility range includes the TSPA long-term mean value of about 1 mg/L [1 ppm] for both the igneous intrusion and seismic ground motion cases. Note that the neptunium solubility limit ranges described here differ from the ranges discussed in the Postclosure Volume of the Technical Evaluation Report (TER) Chapter 7 (NRC, 2011aa), because those ranges incorporated values from a wider pH range.

EBS release rate for Np-237 is determined using Equation 2-2 with the waste package release rate from Equation 2-4. Because the release mode is primarily advective (this was not the case for Tc-99, as discussed in Section 2.4.2), only those waste packages with both patch failures and seepage can experience flowing water that results in advective releases. Thus the seepage fraction (Table 2-1) multiplies the waste package failure rate from Table 2-4 to provide the waste package failure rate for those failures relevant to advective releases (i.e., failures of waste package associated with ruptures and punctures, general corrosion, and igneous intrusion can result in advective releases under dripping conditions, assuming the drip shield has failed) for use in Equations 2-2 or 2-3. (Note: Equation 2-3 is used to provide an upper bound for releases from the waste package.) Tables 2-9 and 2-10 provide the EBS releases for Np-237 for the igneous intrusion and seismic ground motion modeling cases, respectively.

Table 2-8. Radionuclide-Specific Information for Np-237				
	10,000 Years	**100,000 Years**	**400,000 Years**	**800,000 Years**
Np-237 inventory* (grams per waste package)	CSNF 15,530 CDSP 504	CSNF 15,084 CDSP 490	CSNF 13,687 CDSP 444	CSNF 12,024 CDSP 390
Range for solubility (milligrams/liter)	0.3 to 6	0.3 to 6	0.3 to 6	0.3 to 6
Corrosion product factor†	0.05	0.05	0.05	0.05

*Inventory based on decay of Np-237 (half-life of 2.14 million years) of 5,380 g (CSNF) and 223 g (CDSP) at the time of closure and assumption that entire inventory of 10,200 g (CSNF) and 283 g (CDSP) of Am-241 (half-life of 432 years) present at the time of closure decays to Np-237 within a few thousand years after closure [7.05×10^{-4} Ci/g of Np-237] from SAR Tables 2.3.7-5 and 2.3.10-5.

†See Section 5 for further information on corrosion product factors.

Table 2-9. Engineered Barrier System Release Rates of Np-237 for the Igneous Intrusion Modeling Case (Assuming Advective Releases Only)				
	10,000 Years	**100,000 Years**	**400,000 Years**	**800,000 Years**
Releases from igneous intrusion failures* (grams/year)	CSNF: 0.013 to 0.26 CDSP: 5.5×10^{-3} to 0.030†	CSNF: 0.19 to 2.1† CDSP: 0.028†	CSNF: 0.75 to 1.9† CDSP: 0.026†	CSNF: 1.5 to 1.7† CDSP: 0.023†
Total igneous release (CSNF plus CDSP releases) (grams/year)	0.018 to 0.29	0.22 to 2.1	0.78 to 1.9	1.5 to 1.7

*Range of values based on high and low solubility values for Np-237 given in Table 2-8.

†Indicates bounding value from Equation 2-3.

Note: Single values, rather than a range of values, for the CSNF and CDSP release rates is due to both low and high solubility limits resulting in use of the bounding value from Equation 2-3.

Table 2-10. Engineered Barrier System Release Rates of Np-237 for the Seismic Ground Motion Modeling Case (Assuming Advective Releases Only)

	10,000 Years	100,000 Years	400,000 Years	800,000 Years
Releases from rupture and puncture failures from seismic ground motion* (grams/year)	CSNF: 0 CDSP: 2.9×10^{-4} to 4.7×10^{-3} †	CSNF: 0 CDSP: 1.5×10^{-3} †	CSNF: 0.016 to 0.32 CDSP: 0.013 †	CSNF: 0.039 to 0.79 CDSP: 0.014 †
Releases from general corrosion failures from seismic ground motion* (grams/year)	CSNF: 0 CDSP: 0	CSNF: 0 CDSP: 0	CSNF: 3.4×10^{-6} to 6.8×10^{-4} CDSP: 6.5×10^{-4} to 4.9×10^{-3} †	CSNF: 0.16 to 3.2 CDSP: 0.16 †
Total seismic release by package type (summation from ruptures and punctures and general corrosion) (grams/year)	CSNF: 0 CDSP: 2.9×10^{-4} to 4.7×10^{-3}	CSNF: 0 CDSP: 1.5×10^{-3}	CSNF: 0.016 to 0.32 CDSP: 0.014 to 0.018	CSNF: 0.20 to 4.00 CDSP 0.17
Total seismic release (CSNF plus CDSP releases) (grams/year)	2.9×10^{-4} to 4.7×10^{-3}	1.5×10^{-3}	0.030 to 0.34	0.37 to 4.2

*Range of values based on high and low solubility values for Np-237 given in Table 2-8.

†Indicates bounding value from Equation 2-3.

Note: Single values, rather than a range of values, for the CSNF and CDSP release rates is due to both low and high solubility limits resulting in use of the bounding value from Equation 2-3.

2.4.3.2 Pu-242 Release

Determination of the EBS release of Pu-242 followed the approach described for Np-237 in Section 2.4.3.1. The radionuclide-specific values and the corrosion product factor for Pu-242 are provided in Table 2-11, and the values for the amount of water entering the breached waste packages are provided in Table 2-6.

The range of plutonium solubility limits, 0.006 to 0.5 mg/L [0.006 to 0.5 ppm], was developed from the range of plutonium solubility abstraction lookup values used by DOE and presented in SNL Table 6.5-1 and Figure 6.5-7 (SNL 2007ah). These values reflect the adjusted-Eh model for hydrated and aged PuO_2. The maximum and minimum values were selected (and interpolated, if necessary) from the lookup table for the range of pH and log fCO_2 applicable to the corrosion products domain. These ranges were 7.0 to 8.4 for pH and −3 to −2 for log fCO_2. The adopted plutonium solubility range includes the TSPA long-term mean value of about 0.01 mg/L [0.01 ppm] for both the igneous intrusion and seismic ground motion cases.

Tables 2-12 and 2-13 provide the EBS releases for Pu-242 for the seismic ground motion and igneous intrusion modeling cases, respectively.

Table 2-11: Radionuclide-Specific Information for Pu-242

	10,000 Years	100,000 Years	400,000 Years	800,000 Years
Pu-242 inventory* (grams per waste package)	CSNF 5,360 CDSP 39	CSNF 4,542 CDSP 33	CSNF 2,614 CDSP 19	CSNF 1,251 CDSP 9
Range for solubility (milligrams/liter)	0.006 to 0.5	0.006 to 0.5	0.006 to 0.5	0.006 to 0.5
Corrosion product factor†	0.7	0.7	0.7	0.7

*Inventory based on decay of Pu-242 (half-life of 376,300 years) of 5,460 g (CSNF) and 40 g (CDSP) at the time of closure [3.94×10^{-3} Ci/g of Pu-242] from SAR Tables 2.3.7-5 and 2.3.10-5.

†See Section 5 for further information on corrosion product factors.

Table 2-12. Engineered Barrier System Release Rates of Pu-242 for the Seismic Ground Motion Modeling Case (Assuming Advective Releases Only)

	10,000 Years	100,000 Years	400,000 Years	800,000 Years
Releases from rupture and puncture failures from seismic ground motion* (grams/year)	CSNF: 0 CDSP: 8.1×10^{-5} to 3.6×10^{-4} †	CSNF: 0 CDSP: 1.0×10^{-4} †	CSNF: 4.5×10^{-3} to 0.15 † CDSP: 5.6×10^{-4} †	CSNF: 0.011 to 0.12 † CDSP: 3.2×10^{-4} †
Releases from general corrosion failures from seismic ground motion* (grams/year)	CSNF: 0 CDSP: 0	CSNF: 0 CDSP: 0	CSNF: 9.6×10^{-6} to 8.0×10^{-4} CDSP: 1.8×10^{-4} to 2.0×10^{-4} †	CSNF: 0.045 to 0.71 † CDSP: 3.7×10^{-3} †
Total seismic release by package type (summation from ruptures and punctures and general corrosion) (grams/year)	CSNF: 0 CDSP: 8.1×10^{-5} to 3.6×10^{-4}	CSNF: 0 CDSP: 1.0×10^{-4}	CSNF: 4.5×10^{-3} to 0.15 CDSP: 7.4×10^{-4} to 7.6×10^{-4}	CSNF: 0.056 to 0.83 CDSP: 4.0×10^{-3}
Total seismic release (CSNF plus CDSP releases) (grams/year)	8.1×10^{-5} to 3.6×10^{-4}	1.0×10^{-4}	5.2×10^{-3} to 0.15	0.060 to 0.83

*Range of values based on high and low solubility values for Pu-242 given in Table 2-11.

†Indicates bounding value from Equation 2-3.

Note: Single values, rather than a range of values, for the CSNF and CDSP release rates is due to both low and high solubility limits resulting in use of the bounding value from Equation 2-3.

Table 2-13. Engineered Barrier System Release Rates of Pu-242 for the Igneous Intrusion Modeling Case (Assuming Advective Releases Only)

	10,000 Years	100,000 Years	400,000 Years	800,000 Years
Releases from igneous intrusion failures* (grams/year)	CSNF: 3.6×10^{-3} to 0.30 CDSP: 1.5×10^{-3} to 2.3×10^{-3} †	CSNF: 0.052 to 0.64 † CDSP: 1.9×10^{-3} †	CSNF: 0.21 to 0.37 † CDSP: 1.1×10^{-3} †	CSNF: 0.18 † CDSP: 5.2×10^{-4} †
Total igneous release (grams/year)	5.1×10^{-3} to 0.30	0.054 to 0.64	0.21 to 0.37	0.18

*Range of values based on high and low solubility values for Pu-242 given in Table 2-11.

†Indicates bounding value from Equation 2-3.

Note: Single values, rather than a range of values, for the CSNF and CDSP release rates is due to both low and high solubility limits resulting in use of the bounding value from Equation 2-3.

2.5 Radionuclide Transport in the Unsaturated and Saturated Zones

2.5.1 Unsaturated Zone Characteristics

Assuming that movement of water is primarily downward in the unsaturated zone below the repository horizon, transport of radionuclides in the unsaturated zone depends to some extent on the location from which they are released. In the northern area of the repository, water is expected to move principally within fractures. Average travel times for nonsorbing radionuclides from the repository to the saturated zone from the northern area of the repository are on the order of 5 to 100 years for an infiltration rate of 12 mm/yr [0.47 in/yr] (SAR Figure 2.3.8-36). Conversely, in the southern repository area, the Calico Hills nonwelded tuff unit has higher matrix permeability that can accommodate flow almost entirely within the rock matrix (porous flow). Average travel times for nonsorbing solutes from the southern repository area to the saturated zone are on the order of 500 to 5,000 years for an average infiltration rate of 12 mm/yr [0.47 in/yr] (SAR Figure 2.3.8-36). For sorbing radionuclides, travel times depend on the radionuclide-specific sorption coefficient. More strongly sorbing aqueous species, such as Pu-242, have transport times on the order of hundreds of thousands of years and longer in the southern area (see Table 2-14).

Table 2-14 shows how the combined processes affect flow of different radionuclides through the unsaturated zone by providing representative transport times for nonsorbing Tc-99, moderately sorbing Np-237, and strongly sorbing Pu-242 based on the indicated breakthrough curves that DOE provided in its SAR.

Table 2-14. Radionuclide Transport Times in the Unsaturated Zone for the Northern and Southern Repository Areas From DOE Breakthrough Curves

	Transport Time* for Release in Northern Repository Area	Transport Time* for Release in Southern Repository Area
Tc-99	~10 years	~1,000 years
Np-237	~10 years	~10,000 years
Pu-242	~30 years	>1 million years

*Transport times reflect approximate arrival for 50 percent of peak concentration for a model case with point releases at representative locations in northern and southern model areas, representative parameter values, and glacial transition 10th percentile infiltration map. See SAR Figures 2.3.8-43 for Tc-99, 2.3.8-44(b) for Np-237, and 2.3.8-47(a) for Pu-242 for complete breakthrough curves for all radionuclides.

2.5.2 Saturated Zone Characteristics

Radionuclides released from a Yucca Mountain repository would eventually enter the saturated zone within the fractured volcanic tuffs of the Crater Flat group. Transport away from the repository area would occur through permeable flowing fracture networks in the volcanic aquifer system for more than 10 km [6.2 mi] and transition to a valley fill alluvial flow system for the last few kilometers [1.5 miles] before reaching the boundary of the accessible environment at approximately 18 km [11.2 mi] from the southern boundary of the repository footprint. The exact location of the volcanic rock–alluvium contact is uncertain and is treated stochastically in the saturated zone transport abstraction model using an alluvium uncertainty zone. The fracture flow path for the volcanic tuff is conceptualized as being relatively fast because the effective porosity is relatively small [average estimated value of 0.001 (SAR Table 2.3.9-4)]. Flow in the alluvial portion of the flow system is conceptualized as relatively slow because the effective flow porosity is relatively high [average estimated value of 0.18 (SAR Table 2.3.9-4)]. Overall, the transport time for nonsorbing radionuclides ranges from about 10 years to several thousand years (SAR p. 2.3.9-9). Sorbing radionuclides can be significantly delayed by sorption to alluvium mineral grains, in which case transport times for strongly sorbing radionuclides generally exceed 10,000 years (SAR p. 2.3.9-9). Table 2-15 provides transport times for select radionuclides representing a range of sorption behavior. [Note: Use of transport times for plutonium based solely on the transport times for reversible colloids will be conservative (i.e., result in shorter transport times) when used for dissolved plutonium, which would be expected to have a longer transport time. The majority of plutonium releases are expected to occur as either dissolved or reversible colloids.]

Table 2-15. Summary of DOE Simulated Transport Times in the Saturated Zone Under Glacial-Transition Climate State*		
Species	**Range of Median Transport Times (years)**	**Median Transport Time Among All Realizations**
Tc-99 (aqueous, nonsorbing)	10 to 22,190	230
Neptunium (moderately sorbing)	100 to 455,300	3,700
Reversible colloids: plutonium	3,000 to >1 million	95,000
*BSC Table 6-10[a] (2005ak)		

2.5.3 Equation for Unsaturated and Saturated Zone Radionuclide Transport

As part of the NRC's staff confirmatory calculation, multiplicative factors are used to account for the effect of transport in the unsaturated and saturated zones to reduce releases to the biosphere (see Equation 2-5).

Equation 2-5: Transport of radionuclides in the unsaturated and saturated zones

$$REL(t) = EBS(t) \times UZF(t) \times SZF(t)$$

where

REL(t) release rate to the biosphere at time t (grams/yr)

EBS(t) release rate from the EBS at time t (grams/yr)

UZF(t) reduction factor due to transport through the unsaturated zone at time t

SZF(t) reduction factor due to transport through the saturated zone at time t

The effectiveness of the "reduction factors" in Equation 2-5 due to the travel times in the geosphere is related to the time at which the annual dose occurs. For example, a delay of thousands years is not expected to significantly affect annual dose at hundreds of thousands of years but would affect annual dose at 10,000 years.

Tc-99

Tc-99, a nonsorbing radionuclide with a radioactive half-life of 213,000 years, has a range of travel times in DOE's TSPA; however, the vast majority of the travel times are less than 5,000 years for the unsaturated and saturated zones [SAR Figure 2.3.8-43; BSC Figure 6-6(a) (2005ak)]. Releases are expected to be reduced very little; therefore, the reduction factors for Tc-99 for the confirmatory calculation were set to 1.0 (i.e., no reduction in releases).

Np-237

Np-237, a moderately sorbing radionuclide with a radioactive half-life of 2.14 million years, exhibits sufficient delay such that releases can be expected to be reduced by transport in the unsaturated and saturated zones. The reduction factors for transport in the unsaturated and saturated zones account for travel times that have the potential to significantly delay releases relative to the time period of the calculation. Specifically, this approach considers travel time delays of at least half of the time period of the calculation for the unsaturated and saturated zones (e.g., transport time delays of at least 5,000 years for the unsaturated zone and 5,000 years for the saturated zone were considered in determining reduction factors for the 10,000-year time period of the confirmatory calculation).

In the unsaturated zone, the southern area of the repository has travel times sufficient to affect the arrival of radionuclides over initial time periods of the NRC staff's confirmatory calculation (i.e., 10,000 and 100,000 years). The cumulative breakthrough curve for Np-237 (SAR Figure 2.3.8-44) was used to determine the unsaturated zone reduction factor (i.e., reduction factor assigned to the portion of the cumulative breakthrough of Np-237 that occurs beyond half of the time period). Releases for the northern area of the repository (assumed to be half of the releases) have much shorter travel times and were assigned no reduction. Thus, the largest combined reduction factor for the unsaturated zone, both southern and northern areas, is 0.5 (i.e., the northern releases have no reduction and all of the southern releases are delayed beyond the time period). Reduction due to transport in the saturated zone releases followed a similar approach; however, median transport times for 200 realizations in BSC Figure 6-11(a) (2005ak) were used to determine the fraction of travel times that exceeded half of the time period of the confirmatory calculation (additionally, there is no bifurcation of northern and southern areas in the saturated zone as was done in the unsaturated zone). The reduction factors for the effect of travel times of Np-237 in the unsaturated and saturated zones are provided in Table 2-16.

Table 2-16. Reduction Factors Due to Transport of Np-237 in the Unsaturated and Saturated Zones*

	10,000 Years	100,000 Years	400,000 Years	800,000 Years
Unsaturated zone	0.55	0.95	1.0	1.0
Saturated zone	0.6	0.9	0.95	1.0

*A reduction factor of 1.0 results in no reduction, and a reduction factor of 0.0 results in 100 percent reduction or zero release.

Pu-242

Pu-242, a strongly sorbing radionuclide with a radioactive half-life of 376,300 years, exhibits significant delays, such that releases can be expected to be reduced even for longer time periods than were estimated for Np-237. Reduction factors for Pu-242 transport in the unsaturated and saturated zones were determined using the same approach as for Np-237. The information for Pu-242 transport was obtained from the cumulative breakthrough curve in SAR Figure 2.3.47 for the unsaturated zone and from the median transport times for 200 realizations in BSC Figure 6-9(a) (2005ak) for the saturated zone. The transport of radionuclides in these figures reflects the transport of Pu-242 both dissolved in water and attached to reversible colloids. The reduction factors for the effect of travel times of Pu-242 in the unsaturated and saturated zones are provided in Table 2-17. (Note: A small quantity of Pu-242 is associated with irreversible colloids that would not be reduced by sorption; however, this amount is small in DOE's TSPA analysis, as explained in TER Section 2.2.1.4.1.3.3.1.1.4, and is not considered in the NRC staff's confirmatory calculation.)

Table 2-17. Reduction Factors Due to Transport of Pu-242 in the Unsaturated and Saturated Zones*

	10,000 Years	100,000 Years	400,000 Years	800,000 Years
Unsaturated zone	0.50	0.50	0.50	0.50
Saturated zone	0.03	0.4	0.65	0.75

*A reduction factor of 1.0 results in no reduction, and a reduction factor of 0.0 results in 100 percent reduction or zero release.

2.5.4 Releases From the Saturated Zone

Repository releases from the saturated zone to the biosphere were estimated with Equation 2-5 using the previous values for repository releases (Table 2-7 for Tc-99, Tables 2-10 and 2-11 for Np-237, and Tables 2-13 and 2-14 for Pu-242) and the unsaturated and saturated zone reduction factors (Tables 2-16 and 2-17). Radionuclide releases from the saturated zone for the seismic ground motion and igneous intrusion modeling cases are presented in Table 2-18.

Table 2-18. Radionuclide Release Rates to the Biosphere*				
	10,000 Years	**100,000 Years**	**400,000 Years**	**800,000 Years**
Tc-99 releases (g/yr)	Seismic: 5.0 Igneous: 1.1	Seismic: 10 Igneous: 0.82	Seismic: 5.4 Igneous: 0.31	Seismic: 4.2 Igneous: 0.084
Np-237 releases (g/yr)	Seismic: 9.6×10^{-5} to 1.6×10^{-3} Igneous: 5.9×10^{-3} to 0.096	Seismic: 1.3×10^{-3} Igneous: 0.19 to 1.8	Seismic: 0.028 to 0.32 Igneous: 0.74 to 1.8	Seismic: 0.37 to 4.2 Igneous: 1.5 to 1.7
Pu-242 releases (g/yr)	Seismic: 1.2×10^{-6} to 5.4×10^{-6} Igneous: 7.6×10^{-5} to 4.5×10^{-3}	Seismic: 2.0×10^{-5} Igneous: 0.011 to 0.13	Seismic: 1.7×10^{-3} to 0.049 Igneous: 0.068 to 0.12	Seismic: 0.022 to 0.31 Igneous: 0.068

*Range of values for Np-237 and Pu-242 based on high and low solubility values.

Note: Single values, rather than a range of values, for the release rates is due to both low and high solubility limits resulting in the same EBS release rate.

2.6 Annual Dose

Following EBS release and groundwater radionuclide transport, the DOE TSPA model executes the biosphere model abstraction to calculate biosphere radionuclide transport and the annual dose to the reasonably maximally exposed individual (RMEI). Exposure pathways in the DOE biosphere model are based on assumptions about residential and agricultural uses of the water and indoor and outdoor activities. These pathways include ingestion, inhalation, and direct exposure to radionuclides deposited to soil from irrigation (SAR Section 2.3.10.1). Ingestion pathways include drinking contaminated water, eating crops irrigated with contaminated water, eating food products produced from livestock raised on contaminated feed and water, eating farmed fish raised in contaminated water, and inadvertently ingesting soil. Inhalation pathways

include breathing resuspended soil, aerosols from evaporative coolers, and radon gas and its decay products.

DOE biosphere model results are quantified by the Biosphere Dose Conversion Factors (BDCFs). The BDCF is the calculated annual dose to the RMEI from all potential exposure pathways as a result of a unit concentration of a radionuclide in groundwater or surface soil mixed with volcanic ash (SAR Section 2.3.10.1). Mean groundwater exposure scenario BDCFs and primary exposure pathways (from SAR Tables 2.3.10-11 and 2.3.10-12) for the radionuclides used in NRC's confirmatory calculations are provided in Table 2-19. (Note: The volcanic ash exposure scenario for the igneous eruptive modeling case is discussed in Section 3.)

Table 2-19. DOE Groundwater Biosphere Dose Conversions Factors

Radionuclide	Mean BDCFs Sv/yr per Bq/m^3 [mrem/yr per pCi/L]	Primary Pathways
Tc-99	1.1×10^{-9} [4.1×10^{-3}]	42% drinking water 37% animal product 17% crop
Np-237	2.7×10^{-7} [1.0]	56% inhalation 29% drinking water
Pu-242	9.1×10^{-7} [3.4]	75% inhalation 19% drinking water

The average annual doses in DOE's Total System Performance Assessment (TSPA) are largest for the seismic ground motion and igneous intrusive modeling cases (generally a factor of 10 or more larger than the other modeling cases; see SAR Figure 2.4-18). Also in DOE's TSPA, Tc-99 (a nonsorbing radionuclide) is the largest contributor to the average annual dose in the initial 10,000 years—accounting for approximately 0.001 mSv/yr [0.1 mrem/yr] of the peak of the overall average annual dose of approximately 0.003 mSv/yr [0.3 mrem/yr] (SAR Figure 2.4-20a). After 10,000 years and up to 1 million years, the peak of the overall average annual dose in DOE's TSPA occurs at 1 million years with Pu-242 and Np-237 being the largest contributors. Pu-242 and Np-237 account for approximately one-half of the peak of the overall average annual dose of approximately 0.02 mSv/yr [2.0 mrem/yr] (SAR Figure 2.4-20b).

Confirmatory Calculation of Annual Dose

The concentration of radionuclides from the release of radionuclides to the biosphere is determined by assuming the annual release is contained within the annual water demand of 3,000 acre-feet (3.7 million m^3). Equation 2-6 provides this calculation.

Equation 2-6: Calculation of annual dose

$$DOSE(t) = REL(t) / Usage \times BDCF$$

where

DOSE(t)	annual dose at time t (mrem/yr)
REL(t)	release rate to the biosphere at time t (pCi/yr)
Usage	annual water demand— – 3,000 acre-feet/yr (3.7 million liters/yr)
BDCF	biosphere dose conversion factor (mrem/yr/pCi/liter)

Annual doses, estimated using Equation 2-6, the release rates in Table 2-18, and the biosphere dose conversion factors (BDCFs) in Table 2-19, are presented in Tables 2-20 and 2-21 for the seismic ground motion modeling case and igneous intrusion modeling case, respectively.

Table 2-20. Annual Dose From the Groundwater Pathway for the Seismic Ground Motion Modeling Case*

Radionuclide	Source	10,000 Years	100,000 Years	400,000 Years	800,000 Years
Tc-99 dose (mrem/yr)	NRC	0.094	0.19	0.10	0.079
	DOE	0.10	0.16	0.13	0.090
Np-237 dose (mrem/yr)	NRC	1.8×10^{-5} to 3.0×10^{-4}	2.5×10^{-4}	5.3×10^{-3} to 0.061	0.070 to 0.80
	DOE	1.5×10^{-6}	2.0×10^{-4}	2.0×10^{-3}	0.04
Pu-242 dose (mrem/yr)	NRC	4.3×10^{-6} to 2.0×10^{-5}	7.2×10^{-5}	6.2×10^{-3} to 0.18	0.080 to 1.1
	DOE	0	4×10^{-4}	0.013	0.15

*NRC values based on the confirmatory calculation; DOE values based on TSPA mean dose curves presented in SAR Figures 2.4-26 and 2.4-30.

Table 2-21. Annual Dose From the Groundwater Pathway for the Igneous Intrusion Modeling Case*

Radionuclide	Source	10,000 Years	100,000 Years	400,000 Years	800,000 Years
NRC Tc-99 dose (mrem/yr)	NRC	0.021	0.015	5.8×10^{-3}	1.6×10^{-3}
	DOE	0.017	0.013	7.0×10^{-3}	1.6×10^{-3}
NRC Np-237 dose (mrem/yr)	NRC	1.1×10^{-3} to 0.018	0.036 to 0.34	0.14 to 0.34	0.29 to 0.32
	DOE	3.0×10^{-3}	0.050	0.13	0.22
NRC Pu-242 dose (mrem/yr)	NRC	2.8×10^{-4} to 0.016	0.040 to 0.47	0.25 to 0.44	0.25
	DOE	0	0.050	0.23	0.23

*NRC values based on the confirmatory calculation; DOE values based on TSPA mean dose curves presented in SAR Figures 2.4-26 and 2.4-30.

2.7 Comparison of NRC's Groundwater Pathway Confirmatory Calculation and DOE's Total System Performance Assessment

Generally, the comparison between the confirmatory calculation and the results of DOE's Total System Performance Assessment (TSPA) is reasonable in that the comparison is best when the doses are larger {greater than 0.001 mSv/yr [0.1 mrem/yr]}. Not surprisingly, the comparison is best for Tc-99, which is a radionuclide that has limited processes affecting its release and transport (i.e., high solubility limit and nonsorbing in the unsaturated and saturated zones) and thus is more easily represented by the NRC staff's simplified confirmatory calculation. Additionally, the comparison for the other radionuclides (i.e., Np-237 and Pu-242) is best at the latest time (i.e., 800,000 years) for the confirmatory calculation, which represents the time for a larger number of waste package failures (waste package failures in the confirmatory calculation are probability weighted) and an amount of time for sorbing radionuclides like Np-237 and Pu-242 to be transported from the repository to the location of the reasonably, maximally exposed individual (RMEI). This later time period (i.e., 800,000 years) limits some of the uncertainties in the delay of radionuclide release and transport on the order of 100,000 years and longer that can significantly affect dose estimates for the earlier times (e.g., 10,000 and 100,000 years). Clearly the comparison between the NRC staff's confirmatory calculation and DOE's TSPA is not as good when the doses are very small {e.g., on the order of 1×10^{-5} mSv/yr [0.001 mrem/yr]}; however, the confirmatory calculation is intended primarily to provide insight into those performance aspects affecting the peak dose—less so for the lower valued doses.

3 CONFIRMATORY CALCULATION FOR AN ERUPTIVE (VOLCANIC) IGNEOUS EVENT

An eruptive (volcanic) event at the repository involves the intersection of ascending magma and a drift and an explosive eruption at the surface (see TER Section 2.2.1.3.10). Radioactive material entrained in tephra (including the fine-grained particles called ash) can be transported downwind and deposited on the ground surface where potential exposures can occur from (i) inhalation of radionuclides due to high-level waste entrained in ash particles, which are suspended in the air, including the breathing of radon gas and its daughter products from high-level waste entrained in the ash deposited on the ground surface and (ii) ingestion of radionuclides from locally produced crops and animal products that are assumed to be contaminated from direct (e.g., crops grown in soil containing contaminated tephra) and indirect contact with contaminated tephra (e.g., animals raised on feed that has been grown in soil containing contaminated tephra). Estimating the consequences of such an event is dependent on the concentration of radionuclides in tephra and the amount of tephra persisting at the receptor location (from both the direct deposition of tephra during the event and redistribution of tephra after the event due to water and wind action over time; see TER Section 2.2.1.3.13).

The confirmatory calculation for an eruptive event considers

1) Radionuclides of interest for an eruptive event
2) Number of waste packages entrained in the eruption
3) Concentration of radionuclides in the tephra
4) Amount and persistence of tephra present at the receptor location
5) Biosphere dose conversion factors (BCDFs)
6) Probability of the event occurring

3.1 Radionuclides of Interest for an Eruptive Event

The volcanic eruption modeling case is quite different from the groundwater pathway in that (i) if an eruptive event occurred early (hundreds to a few thousand years after closure), it could release short-lived radionuclides (e.g., half-lives on the order of hundreds of years) that might otherwise decay away inside the waste package; (ii) the eruptive event can transport tephra to the receptor location in very short time periods (minutes to hours) as compared to the thousands of years and longer for sorbing radionuclides transported to the receptor location via the groundwater pathway (see Tables 2-14 and 2-15); and (iii) the presence of radionuclides (entrained in tephra) on the ground surface has the potential for the inhalation and direct exposure pathways to be more important. Because of these differences, the radionuclides of significance for the volcanic eruption modeling case differ from the radionuclides of significance for the groundwater pathway evaluated in Section 2.

During the initial 10,000 years, the annual dose for the volcanic eruption modeling case is dominated by Pu-239, Pu-240, and Am-241 (SAR Figure 2.4-32). For these three radionuclides, the inhalation exposure accounts for more than 98 percent of the average annual dose for the volcanic eruption modeling case, as shown in SAR Table 2.3.10-15. At very early times (i.e., the initial 500 years), there is some contribution from Sr-90 and Cs-137 (primarily from external exposure). At very long times (i.e., after 100,000 years), the annual dose is dominated by Ra-226 (SAR Figure 2.4-32). These results are partially due to the half-lives for

these radionuclides. Sr-90 and Cs-137 have half-lives less than 100 years, and Am-241 has a half-life of 432 years; thus the hazard is somewhat short lived. The longer term hazard is with Pu-239 (half-life of 24,065 years); Pu-240 (half-life of 6,537 years); and Ra-226, which is a daughter product in the long-lived U-238 chain (the half-life of U-238 is 4.5 billion years, whereas the half-life of Ra-226 is 1,600 years).

The average annual dose for the volcanic eruption modeling case is less than 0.1 mSv/yr [0.001 mrem/yr] for every year in the 1-million year period (SAR Figure 2.4-18); therefore, the NRC staff's confirmatory calculation used a simplified approach for a few key radionuclides (i.e., Pu-239 and Am-241 for the inhalation pathway and Sr-90, Cs-137, and Ra-226 for the external pathway) that included effects of short-lived radionuclides including the persistence of a long-lived parent radionuclide. Additionally, the simplified calculation used assumptions that would tend to bound potential doses for this modeling case, such as assuming that waste entrained in tephra (ash) was deposited directly at the RMEI location for every volcanic event and the tephra persists unabated at that location (depositional and removal processes at the Earth's surface neither diminish nor increase the amount of waste material at the RMEI location—radioactive decay is the only process causing the decrease of radionuclides).

3.2 Number of Waste Packages Entrained in the Eruptive Event

On the basis of the expected size of a volcanic conduit, the DOE TSPA uses a range of zero to seven waste packages for the number that would be entrained in the magma (SAR Figure 2.3.11-12b and p. 2.3.11-78). Additionally, the DOE TSPA assumes that all the waste in these waste packages would be entrained in the magma. The NRC's confirmatory calculation uses an average value of four for the number of waste packages entrained in the magma, and all the waste in these packages is assumed entrained in magma.

3.3 Concentration of Radionuclides in Tephra

An average concentration of radionuclides in tephra can be determined by dividing the total amount of radionuclides entrained in the tephra by either (i) the total volume of tephra to get a concentration per cubic length or volume {e.g., per cubic meter of tephra} or (ii) the total mass of tephra to get a concentration per mass {e.g., per gram of tephra}. Although all of the waste in the waste packages is assumed to be entrained in the magma, not all the magma forms tephra. DOE TSPA uses a range of 0.10 to 0.50 to account for the fraction of magma that forms tephra (SAR p. 2.4-197); therefore 0.10 to 0.50 also represents the fraction of the waste entrained in the eruptive event that is contained in the tephra. The NRC's confirmatory calculation uses an average value of 0.30 for the fraction of waste packages that are entrained in tephra. DOE has estimated the average volume of tephra as 0.38 km^3 [0.09 mi^3], as described in DOE Enclosure 3, p. 2 (2009bj). The total volume of tephra is converted to mass simply by multiplying by the density for tephra {density of tephra is set at 1 g/cm^3 [62.4 lb/ft^3] from SAR p. 2.3.11-61}.
For the purposes of NRC staff's confirmatory calculation, it is assumed that the composite waste package comprises both Commercial Spent Nuclear Fuel (CSNF) and DOE mixed oxide spent nuclear fuel (MOX) (see SAR Table 2.3.7-5).

3.4 Amount and Persistence of Tephra on the Land Surface

For the NRC staff confirmatory calculation, it is assumed that every eruptive event results in tephra on the surface of the Earth where the reasonably, maximally exposed individual (RMEI) is assumed to live {i.e., approximately 18 km [11.2 mi] south of the potential repository location}. This assumption neglects consideration for eruptive events that could result in very limited or no tephra at the exposure location due to influences such as the eruptive power of the event and the wind direction. Once present at the exposure location, the NRC staff confirmatory calculation assumes that the tephra is present to a depth of 1 cm [0.39 in] and it persists without change over the time period of the estimated dose (i.e., only radioactive decay reduces the level of radionuclides at the exposure location after the time of the initial deposition of the tephra). Geologic evidence suggests that thin layers of tephra are often eroded away in surface environments like Yucca Mountain after a few hundred to thousands of years. As the time of dose calculation extends beyond a decade to hundreds of years and longer, the assumption of continued persistence of the tephra deposit is considered to have a more and more conservative influence on dose calculations.

3.5 Biosphere Dose Conversion Factors

Once radioactively contaminated volcanic tephra is present at the RMEI location, estimates of potential exposures can be made for specific pathways (e.g., external exposure and inhalation, which includes radon exposure). DOE's SAR provided biosphere dose conversion factors (BDCFs) for radionuclides and the relevant pathways.

Generally, the largest contribution to annual dose is from the inhalation and external exposure pathways (see SAR Table 2.3.10-15). The radionuclides Pu-239 and Am-241 are significant to the inhalation pathway, and the BDCFs are provided in Table 3-1 based on DOE's SAR. For the inhalation pathway, DOE included a short-term value (applicable only for the first year after the eruption occurs) and a long-term value (applicable to all the years after the event occurs except for the first year). The short-term inhalation factor accounts for the higher concentration of tephra or ash in the air that is expected shortly (e.g., days) after the eruption occurs. The short term inhalation factor accounts for the contribution to the dose during the year immediately following the event and does not include the contribution from events that have occurred in the previous years. Thus, the confirmatory calculation, which considers the events from previous years, only uses the long-term inhalation BDCFs. The exposure is due to the tephra particles suspended in the air, and thus the BDCFs are based on the concentration of the radionuclides in the tephra per unit mass (e.g., curies/grams).

For the other exposure pathways (i.e., external and radon from radioactive waste entrained in the tephra), BCDFs use the concentration of radioactive material on the ground surface described as an "areal concentration" (i.e., the curies per area of ground surface) to convert the areal concentration of radionuclides in tephra to a dose. As described previously, the depth of the deposit is assumed to be 1 cm [0.39 in] for all times after the event occurs. The areal concentration can be determined simply by multiplying the concentration per unit length (i.e., curies per cubic meter) by 0.01 m [0.39 in] {i.e., 1 cm [0.39 in]} to obtain the concentration in terms of curies per square meter (i.e., the areal concentration) in order to use DOE's BDCFs that are in terms of an areal concentration (Table 3-2).

Table 3-1. DOE Volcanic Eruption Modeling Case Short-Term and Long-Term Inhalation Biosphere Dose Conversion Factors (BDCFs)		
Radionuclide	**Biosphere Dose Conversion Factors Sv/yr per Bq/kg [mrem/yr per pCi/g]**	**Primary Pathways**
Pu-239	Short term: 4.0×10^{-7} [1.5] Long term: 6.1×10^{-7} [2.3]	98% of Pu-239 eruptive dose is inhalation: 39% short term 60% long term
Am-241	Short term: 3.2×10^{-7} [1.2] Long Term: 5.0×10^{-7} [1.8]	94% of Am-241 eruptive dose is inhalation: 37% short term 57% long term
Sources: SAR Table 2.3.10-14 and SNL Tables 6.12-2 and 6.12-3 (2007ac)		

Table 3-2. DOE Volcanic Eruption Modeling Case Combined Ingestion, Radon, External Biosphere Dose Conversion Factors		
Radionuclide	**Biosphere Dose Conversion Factors Sv/yr per Bq/m^2 [mrem/yr per pCi/m^2]**	**Primary Pathways**
Sr-90	1.8×10^{-9} [6.7×10^{-6}]	79% external exposure
Cs-137	7.2×10^{-9} [2.7×10^{-5}]	99% external exposure
Ra-226	3.3×10^{-8} [1.2×10^{-4}]	65% external exposure 33% radon decay products
Sources: SAR Table 2.3.10-14 and SNL Table 6.12-4 (2007ac)		

3.6 Event Probability

The annual probability for an eruptive event to disrupt waste packages is set at 1.4×10^{-9} (SAR p. 2.4-49).

3.7 Pu-239 and Am-241 Dose Estimate (Inhalation Pathway)

The confirmatory calculation for Pu-239 (radioactive half-life of 24,065 years) and Am-241 (radioactive half-life of 432 years) is associated almost entirely with the inhalation exposure pathway, which accounts for more than 90 percent of the overall dose for these 2 radionuclides (see Table 3-1). The NRC staff confirmatory calculation for the inhalation dose from exposure to Pu-239 and Am-241 in radioactive waste is based on Equation 3-1, which uses a mass concentration of radionuclides in tephra.

Equation 3-1: Representation of dose from the inhalation pathway

$$InhDose(t) = [(WP \times Inv(t) \times F) \div (Vol \times D)] \times MassBDCF \times P$$

where

InhDose(t)	dose from the inhalation pathway at time t (mrem/yr)
WP	number of waste packages entrained in magma
Inv(t)	inventory of 1 waste package at time t (curies)
F	fraction of waste packages entrained in tephra
Vol	total volume of tephra associated with the eruption (cubic meters)
D	density of tephra (grams per cubic meter)
MassBDCF	biosphere dose conversion factor (BCDF) based on mass concentration (mrem/yr/Ci/g)
P	probability the event has occurred on or before time t (determined by multiplying the annual probability by the time t)

The time at which to estimate the dose was selected on the basis of the half-life of each radionuclide (i.e., time periods of one and three half-lives). These times were used to provide perspective on how dose could change over time due to the probability that the event has occurred at some time in the past (i.e., this probability increases with longer times) and radioactive decay, which will decrease the concentration of radionuclides as time increases. The assumption that the tephra deposit persists over all time, but with ongoing radioactive decay, is an important assumption that is considered to increase conservatism at long times (e.g., thousands of years). Table 3-3 provides the estimates of dose and the values used to estimate the dose based on Equation 3-1.

Table 3-3. NRC Staff's Confirmatory Calculation Results for Pu-239 and Am-241 Annual Doses for the Volcanic Eruption Modeling Case (Long-Term Inhalation Pathway)

Performance Aspect	Pu-239 (Half-Life 24,065 Years)		Am-241 (Half-Life 432 Years)	
	24,065 Yrs	72,195 Yrs	432 Yrs	1,296 Yrs
Inventory per CSNF waste package (with MOX added) [Ci]	1,370	343	17,554	4,390
Number of waste packages	4	4	4	4
Fraction of waste entrained in tephra	0.3	0.3	0.3	0.3
Tephra volume (km^3)	0.038	0.038	0.038	0.038
Tephra mass concentration (pCi/g)	43	11	550	140
NRC staff's weighted annual dose (mrem/yr)	3.3×10^{-3}	2.6×10^{-3}	6.0×10^{-4}	4.6×10^{-4}
TSPA weighted average annual dose (mrem/yr) (SAR Figure 2.4-32)	8.0×10^{-5}	6.0×10^{-5}	3.0×10^{-5}	2.0×10^{-5}

Initial inventory of Pu-239 (half-life of 24,065 years) and Am-241 (half-life of 432 years) is 2,740 curies and 35,100 curies, respectively (from SAR Tables 2.3.7-5 and 2.3.10-5).

3.8 Sr-90, Cs-137, and Ra-226 Dose Estimate (External Pathway and Radon)

The radionuclides Sr-90 (radioactive half-life of 29 years), Cs-137 (radioactive half-life of 30 years), and Ra-226 (radioactive half-life of 1,600 years and its radioactive parent, U-238, has a radioactive half-life of 4.5 billion years) are associated primarily with the external exposure pathway (see Table 3-2); however, Ra-226 is included primarily because of the potential for radon exposure. In contrast to the inhalation pathway where the dose was dependent on the concentration of radionuclides in the tephra that might be inhaled via suspended particles in the air, the external pathway (including radon) is affected primarily by the amount of radionuclides present on the ground surface at the exposure location. Therefore the equation for this calculation is dependent on the areal concentration of radionuclides on the ground surface (i.e., curies per unit area). The areal concentration can be determined simply by multiplying the concentration (curies per cubic meter) by 0.01 m {i.e., 1 cm [0.39 in]} to get the concentration in terms of curies per square meter (i.e., the areal concentration). The NRC staff confirmatory calculation for the dose from exposure to Sr-90, Cs-137, and Ra-226 in radioactive waste is based on Equation 3-2 (essentially the same as Equation 3-1 except for the use of an areal concentration rather than the mass concentration, which was used in Equation 3-1).

Equation 3-2: Representation of dose from an areal concentration (primarily an external pathway)

$$ExDose(t) = [(WP \times Inv(t) \times F) \div (Vol \div Thick)] \times ArealBDCF \times P$$

where

ExDose(t)	dose primarily from the external pathway at time t (mrem/yr)
WP	number of waste packages entrained in magma
Inv(t)	inventory of 1 waste package at time t (curies)
F	fraction of waste packages entrained in tephra
Vol	total volume of tephra associated with the eruption (cubic meters)
Thick	thickness of the tephra deposit at the receptor location (meters)
ArealBDCF	biosphere dose conversion factor (BDCF) based on areal concentration (mrem/yr/Ci/m^2)
P	probability the event has occurred on or before time t (determined by multiplying the annual probability by the time t)

The time at which to estimate the dose for Sr-90 and Cs-137 was selected on the basis of the half-life of each radionuclide (i.e., time periods of one and three half-lives). These times were used to provide perspective on how dose could change over time due to the probability that the event has occurred at some time in the past (i.e., this probability increases with longer times) and radioactive decay, which will decrease the concentration of radionuclides as time increases. The assumption that the tephra deposit persists over all time, but with ongoing radioactive decay, is not nearly the conservative assumption for Sr-90 and Cs-137 as was the case for Pu-239 because of the relatively very short half-lives associated with Sr-90 and Cs-137. Table 3-4 provides the estimates of dose for Sr-90 and Cs-137 and the values used to estimate the dose based on Equation 3-2.

Although Ra-226 has a somewhat short half-life (i.e., 1,600 years), its persistence in the tephra deposit is extremely long owing to radioactive decay of its very long-lived parent U-238 (half-life of 4.5 billion years). The NRC staff's confirmatory calculation estimated the potential dose at 1 million years for this somewhat unique situation (i.e., parent radionuclide with a radioactive half-life much greater than 1 million years), which insures consideration of the maximum time period over which an igneous event might occur. Because of the differences in the half-lives of Ra-226 and U-238, the activity of Ra-226 in radioactive waste in the tephra is assumed to mirror the activity of U-238 in radioactive waste in the tephra; therefore, the confirmatory calculation uses the activity of U-238 as the activity of Ra-226 (contributions from some other radionuclides such as U-234 would increase the Ra-226 by approximately 30 percent at 1 million years, but this increase is not considered significant for the purposes of this confirmatory calculation). The external pathway BDCF for Ra-226 also includes a significant contribution from the production of radon (and its daughter products) as a result of decay of Ra-226 from the radioactive waste on the ground surface. Table 3-5 provides the estimates of dose for Ra-226 and the values used to estimate the dose based on Equation 3-2.

Table 3-4. NRC Staff's Confirmatory Calculation of Sr-90 and Cs-137 Annual Doses for the Volcanic Eruption Modeling Case (External Pathway)				
	Sr-90 (Half-Life 29 Years)		Cs-137 (Half-Life 30 Years)	
Performance Aspect	**29 Yrs**	**87 Yrs**	**30 Yrs**	**90 Yrs**
Inventory in curies per CSNF waste package (with MOX added)	52,011	13,009	81,518	20,388
Number of waste packages	4	4	4	4
Fraction of waste entrained in ash	0.3	0.3	0.3	0.3
Tephra volume (km^3)	0.038	0.038	0.038	0.038
Ash areal concentration (pCi/m^2)	1.6×10^7	4.1×10^6	2.6×10^7	6.4×10^6
NRC staff's weighted annual dose (mrem/yr)	4.4×10^{-6}	3.4×10^{-6}	2.9×10^{-5}	2.2×10^{-5}
TSPA weighted average annual dose (mrem/yr) (SAR Figure 2.4-32)	2.0×10^{-6}	1.8×10^{-6}	2.0×10^{-5}	1.0×10^{-5}
Initial inventory of Sr-90 (half-life of 29 years) and Cs-137 (half-life of 30 years) is 1.04×10^5 curies and 1.63×10^5 curies, respectively (from SAR Tables 2.3.7-5 and 2.3.10-5).				

Table 3-5. NRC Staff's Confirmatory Calculation of Ra-226 Annual Dose for the Volcanic Eruption Modeling Case (External Pathway Including Radon)	
	Ra-226 (Half-Life 1,600 Years) [U-238 (Half-Life 4.5×10^9 Years)]
Performance Aspect	**1 Million Years**
U-238 inventory in curies per CSNF waste package (with MOX added)	2.65
Number of waste packages	4
Fraction of waste entrained in ash	0.3
Tephra volume (km^3)	0.038
Ash areal concentration (pCi/m^2)	840
NRC staff's weighted annual dose (mrem/yr)	1.4×10^{-4}
TSPA weighted average annual dose (mrem/yr) (SAR Figure 2.4-32)	5.0×10^{-5}
Ra-226 activity assumed equal to its long-lived parent radionuclide U-238; initial inventory of U-238 is 2.65 curies; U-238 half-life of 4.5×10^9 years and Ra-226 half-life of 1,600 years (from SAR Tables 2.3.7-5 and 2.3.10-5).	

3.9 Comparison of NRC's Eruptive (Volcanic) Igneous Event Confirmatory Calculation and DOE's Total System Performance Assessment

The resulting annual doses from the confirmatory calculation are larger than the average annual doses from DOE's TSPA. This is not unexpected based on the approach for the confirmatory calculation (e.g., direct deposits persist without abatement for at least three half-lives) that was intended to bound certain assumptions. The match between the confirmatory calculation and the TSPA results is best for the radionuclides with the shortest half-lives (i.e., Sr-90 and Cs-137) partially because the persistence of the deposit is assumed to be on the order of 100 years rather than the tens of thousands of years and longer for the other radionuclides with longer half-lives. Although the confirmatory calculation intentionally overestimates the annual dose, the peak annual dose from the confirmatory calculation for the volcanic eruption modeling case is still limited to no more than 0.4 mSv/yr [0.004 mrem/yr].

4 TOTAL SYSTEM PERFORMANCE ASSESSMENT DIFFUSIONAL RELEASE RESULTS

In a response to an RAI (DOE, 2009cu), DOE provided two additional Total System Performance Assessment (TSPA) simulations. These additional TSPA simulations were submitted via GoldSim model files and included additional intermediate results. The NRC staff utilized intermediate results from these two TSPA simulations to assess the implementation of the engineered barrier system (EBS) transport mode. Specifically, the NRC staff reviewed radionuclide release rates from the EBS to assess the relative proportion of radionuclide release via advective and diffusive release mechanisms.

One TSPA simulation involved the seismic ground motion modeling case, over 1 realization of aleatory uncertainty (i.e., 1 seismic time history) and 300 realizations of epistemic uncertainty (consistent with the nominal modeling case). The seismic model file name is RTN00573_SMM_001. The second TSPA simulation involved the igneous intrusion modeling case, over 1 realization of aleatory uncertainty (i.e., 1 igneous event at 100,000 years) and 300 realizations of epistemic uncertainty (also consistent with the nominal modeling case). The igneous model file name is RTN00573_IGM_001.

To assess the relative release mechanisms, NRC staff extracted results from the TSPA elements: CSNF_Advec_RN, CSNF_Diff_RN, CDSP_Advec_RN, and CDSP_Diff_RN. These elements are located in subfolders of TSPA_Model\Results\EBS_Out_Results\Advec_Diff_Calcs in both of the previously noted models. Using a spreadsheet, NRC staff summed the advective releases for each radionuclide for each release mechanism. For example, NRC staff summed advective Tc-99 release from CSNF and CDSP. Then NRC staff summed diffusive Tc-99 release from CSNF and CDSP. This process was repeated for the additional radionuclides in both modeling cases. Release results are reported in Tables 4-1 and 4-2.

Values are reported for the maximum observed value in the time period identified for each of the mean value and the 5^{th} and 95^{th} percentile. For example, the maximum value of the mean advective release curve in the igneous intrusion modeling case for Tc-99 between 0 and 10,000 years is 4.4×10^{-22} g/yr [9.7×10^{-25} lb/yr].

As a first approximation of relative significance of release, NRC staff reviewed the ratio of advective release to diffusive release in the scenarios noted previously. These ratios are reported in Table 4-3.

Ratios greater than one indicate that advection would be the dominant release mechanism (the majority of values at 200,000; 600,000 and 1-million years in Table 4-3). Ratios between 0 and 1 indicate that diffusion would be the dominant release mechanism (nearly all the values at 10,000 years Table 4-3). However, note that most of the diffusion-dominated cells in Table 4-3 have either no release or virtually no release (see also Tables 4-1 and 4-2 for release amounts). Values below zero indicate “reverse diffusion,” or diffusion from the near field back into the EBS (primarily for Tc-99 at 600,000 and 1-million years in Table 4-3). Again, this generally occurs when the absolute transport rates are near zero. These results suggest that advective releases are the dominant radionuclide transport mechanism implemented in the TSPA.

Table 4-1. Engineered Barrier System Release Rates for Tc-99 and Np-237.

		Igneous Intrusion Modeling Case* Release Rates (g/yr)				Seismic Ground Motion Modeling Case † Release Rates (g/yr)			
		10,000 years	**200,000 years**	**600,000 years**	**1,000,000 years**	**10,000 years**	**200,000 years**	**600,000 years**	**1,000,000 years**
Tc-99 Advection	95th	0	920	4.4×10^{-10}	1.2×10^{-10}	0	720	160	25
	Mean	4.5×10^{-22}	530	1.4×10^{-10}	3.9×10^{-11}	4.5×10^{-22}	120	24	6.3
	5th	0	87	3.3×10^{-14}	9.0×10^{-15}	0	0	4.2×10^{-13}	3.9×10^{-4}
Tc-99 Diffusion	95th	0	6.5×10^{-18}	-9.0×10^{-15}	-2.4×10^{-15}	0	200	77	11
	Mean	1.0×10^{-19}	1.7×10^{-3}	-3.9×10^{-11}	-1.1×10^{-11}	1.0×10^{-19}	35	13	2.2
	5th	0	2.2×10^{-19}	-1.2×10^{-10}	-3.2×10^{-11}	0	0	0	4.1×10^{-4}
Np-237 Advection	95th	0	1,100	410	140	0	0.010	0.053	3.6
	Mean	1.8×10^{-22}	270	140	77	1.8×10^{-22}	2.5×10^{-3}	0.024	1.1
	5th	0	7.5	19	16	0	0	3.9×10^{-9}	1.5×10^{-6}
Np-237 Diffusion	95th	0	3.4	1.3	0.73	0	1.6×10^{-3}	7.7×10^{-3}	0.044
	Mean	8.7×10^{-22}	0.72	0.39	0.27	8.8×10^{-22}	3.6×10^{-4}	2.4×10^{-3}	0.012
	5th	0	0.017	0.043	0.040	0	0	7.7×10^{-10}	2.0×10^{-7}

* Values are conditional on an igneous event occurring at 100,000 years

† Ranges are for one aleatory sample (i.e., one seismic event sequence)

Table 4-2. Engineered Barrier System Release Rates for Pu-242 and Pu-242 Attached to Irreversible Colloids (IcPu-242).

		Igneous Intrusion Modeling Case* Release Rates (g/yr)				Seismic Ground Motion Modeling Case † Release Rates (g/yr)			
		10,000 years	**200,000 years**	**600,000 years**	**1,000,000 years**	**10,000 years**	**200,000 years**	**600,000 years**	**1,000,000 Years**
Pu-242 Advection	95th	0	310	180	27	0	0.010	0.043	0.87
	Mean	1.4×10^{-24}	73	53	8.7	1.3×10^{-24}	2.5×10^{-3}	0.025	0.23
	5th	0	2.5	2.8	0.24	0	0	1.6×10^{-8}	3.9×10^{-6}
Pu-242 Diffusion	95th	0	1.5	1.3	0.24	0	7.1×10^{-4}	4.2×10^{-3}	0.017
	Mean	1.5×10^{-23}	0.40	0.32	0.067	1.5×10^{-23}	1.8×10^{-4}	1.2×10^{-3}	4.8×10^{-3}
	5th	0	0.016	0.015	1.9×10^{-3}	0	0	2.2×10^{-10}	2.1×10^{-7}
IcPu-242 Advection	95th	0	0.34	0.12	7.1×10^{-3}	0	1.8×10^{-5}	1.5×10^{-4}	0.018
	Mean	0	0.13	0.049	2.2×10^{-3}	1.1×10^{-26}	4.0×10^{-6}	6.2×10^{-4}	2.5×10^{-3}
	5th	0	0.017	6.8×10^{-3}	6.8×10^{-5}	0	0	3.4×10^{-15}	1.5×10^{-9}
IcPu-242 Diffusion	95th	0	1.1×10^{-5}	3.6×10^{-6}	1.8×10^{-8}	0	1.5×10^{-7}	7.4×10^{-7}	2.0×10^{-6}
	Mean	5.2×10^{-21}	2.5×10^{-6}	1.8×10^{-6}	2.4×10^{-7}	4.6×10^{-27}	3.0×10^{-8}	1.4×10^{-7}	3.2×10^{-7}
	5th	0	4.7×10^{-8}	-5.8×10^{-8}	-5.6×10^{-9}	0	0	5.5×10^{-18}	2.9×10^{-12}

* Values are conditional on an igneous event occurring at 100,000 years

† Ranges are for one aleatory sample (i.e., one seismic event sequence)

Table 4-3. Ratio of Advective Release to Diffusive Release.

		Igneous Intrusion Modeling Case				Seismic Ground Motion Modeling Case			
		10,000 years	**200,000 years**	**600,000 years**	**1,000,000 years**	**10,000 years**	**200,000 years**	**600,000 years**	**1,000,000 years**
Tc-99	95th	0	$1.4 \times 10^{+20}$	$-4.9 \times 10^{+4}$	$-5.0 \times 10^{+4}$	0	3.6	2.1	2.3
	Mean	4.5×10^{-3}	$3.1 \times 10^{+5}$	-3.6	-3.5	4.5×10^{-3}	3.4	1.8	2.9
	5th	0	$4.0 \times 10^{+20}$	-2.8×10^{-4}	-2.8×10^{-4}	0	0	0	0.95
Np-237	95th	0	320	320	190	0	6.3	6.9	82
	Mean	0.21	380	360	290	0.20	6.9	10	92
	5th	0	440	440	400	0	0	5.1	7.5
Pu-242	95th	0	210	140	110	0	14	10	51
	Mean	0.093	180	170	130	0.087	14	21	48
	5th	0	160	190	130	0	0	73	19
IcPu-242 (Pu-242 attached to irreversible colloids)	95th	0	$3.1 \times 10^{+4}$	$3.3 \times 10^{+4}$	$3.9 \times 10^{+5}$	0	120	200	9,000
	Mean	0	$5.2 \times 10^{+4}$	$2.7 \times 10^{+4}$	9,200	2.4	130	4,400	7,800
	5th	0	$3.6 \times 10^{+5}$	$-1.2 \times 10^{+5}$	$-1.2 \times 10^{+4}$	0	0	620	520

5 CORROSION PRODUCT FACTOR TECHNICAL SUPPORT

Staff hypothesizes, based on examination of TSPA model results, that the concentration within the waste package is controlled by the concentration in the corrosion product domain, where both precipitation and sorption to stationary corrosion products can limit the dissolved phase concentration. Either of these processes has the effect of imposing a cap on the dissolved phase concentration. If the concentration is limited by precipitation, the dissolved concentration would be at the solubility limit. If the concentration is limited by sorption, the concentration can be approximated by treating the corrosion product domain as a mixing cell. Under such an approximation, the sorption-limited concentration would be a function of the mass of contaminant in the mixing cell, the mass of sorbing media in the mixing cell, and the distribution coefficient representing the affinity of the radionuclide for sorption. In practice, the lower of the two limits would control the concentration in any given realization. When the mean is taken over many realizations, the net effect of taking an average of a function is to cause the average concentration to be lower than the average concentration computed for either of the processes individually. This allows the simple calculation to represent the reduction associated with corrosion product sorption as a factor multiplying by the mean solubility limit. However, the corrosion product factor used in the simplified calculations is a mathematical convenience that represents the average of the minimum of two random variables as a product of the solubility limit and a corrosion product factor. In other words, the simple calculation represents a process modeled by the expression ***mean(min(C_sorption,C_solubility))***, where C_solubility is the solubility limit and C_sorption is the sorption-limited concentration, by the expression ***f_Sorption*mean(C_solubility)***. In practice, this results in a scenario in which the corrosion product factor is dependent not only on sorption-related parameters (such as the mass of contaminant, mass of corrosion product, and the distribution coefficient), but also on the solubility limit. For example, in the case where the average sorption-limited concentration is higher than or comparable to the solubility limit (low solubility limit case), the minimization process will frequently select the solubility-limited concentration as the lower concentration and the factor will be relatively close to one. However, in cases where the sorption-limited concentration is relatively low compared to the solubility limit (high solubility limit case), the minimization process will more frequently select the sorption process and the net effect will be a relatively low ratio.

To examine the effect within TSPA, we can compute the ratio between the TSPA concentration and the TSPA solubility limit. The ratio of the TSPA concentrations to the TSPA solubility limits uses the mean values from the TSPA realizations, however, for certain realizations the Np-237 solubility was assigned an unlimited value and these values were not used in calculating the average solubility limit. The ratios for Np-237 and Pu-242 in the Seismic Ground Motion (GM) modeling case are shown in Figures 5-1 and 5-2, respectively. The ratios for Np-237 and Pu-242 in the Igneous Intrusion modeling case are shown in Figures 5-3 and 5-5, respectively. Figure 5-4 provides the mean value for the solubility of Np-237 in the igneous intrusion modeling case (note: Np-237 solubility values that were unlimited were not used in calculating the mean value).

Two observations are consistent with the hypothesis presented previously. First, the lower solubility limit relative to the distribution coefficient for plutonium suggests that the corrosion products would be less effective at limiting plutonium concentrations than at limiting neptunium concentrations. This is reflected by a ratio for plutonium that is consistently higher than that for neptunium. Second, the ratio for the seismic ground motion case reaches an equilibrium value

and does not change greatly once large numbers of waste packages begin failing after 500,000 years. This is consistent with a slow degradation mechanism that allows the stainless steel internals to degrade and the waste form to release most of the material into solution before it can be transported out of the waste package. Therefore, the factors controlling the sorption-limited concentration are approximately constant, and because the solubility limits are also approximately constant, the ratio of the two is relatively constant. However, in the igneous intrusion case, high releases away from the waste package can occur before the stainless steel internals have degraded, and the high release rates lower the mass of contaminant that is present in the waste package internals. The net effect would be to increase the importance of the sorption-limiting process as time increases, because the number of corrosion product sorption sites increase with time and the mass available for distribution between the sorbed and dissolved phases decreases. If the solubility limit stays relatively constant with time, the effect is to have a ratio (i.e., factor) that decreases with time.

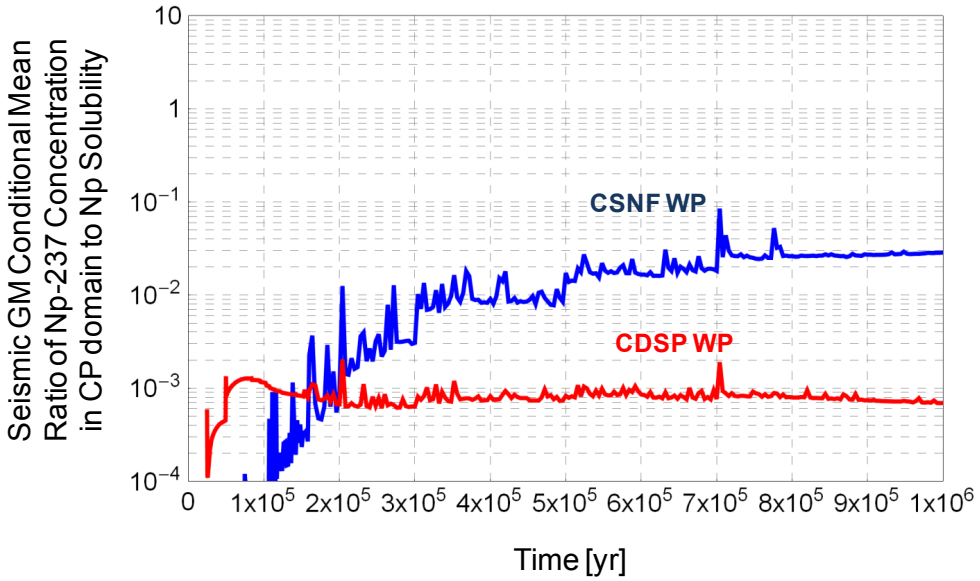

Figure 5-1: The Ratio of the Np-237 Concentration to the Np Solubility in the Corrosion Product Domain for the Seismic Ground Motion (GM) Modeling Case.

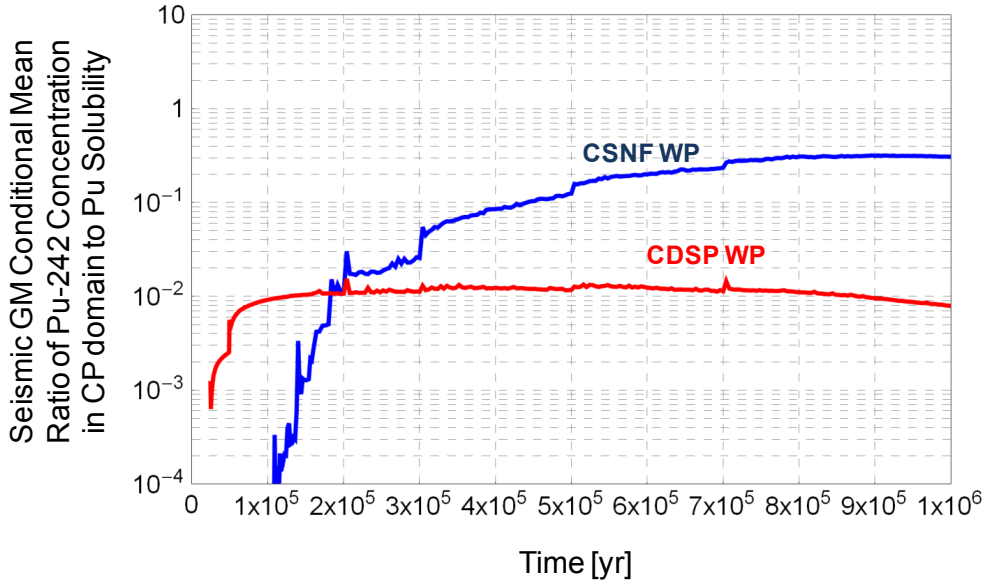

Figure 5-2: The Ratio of the Pu-242 Concentration to the Pu Solubility in the Corrosion Product Domain for Seismic Ground Motion (GM) Modeling Case.

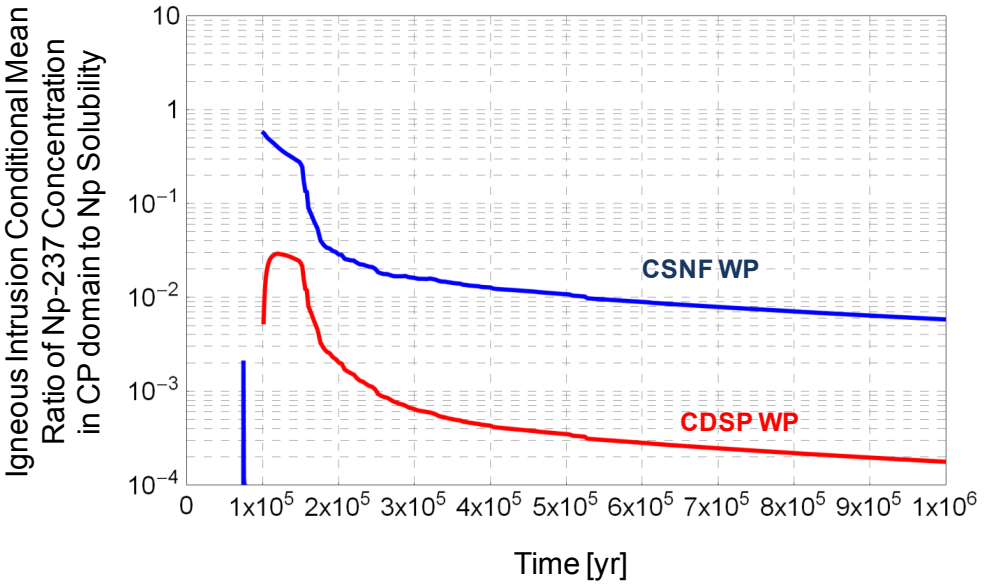

Figure 5-3: The Ratio of the Np-237 Concentration to the Np Solubility in the Corrosion Product Domain for the Igneous Intrusion Modeling Case.

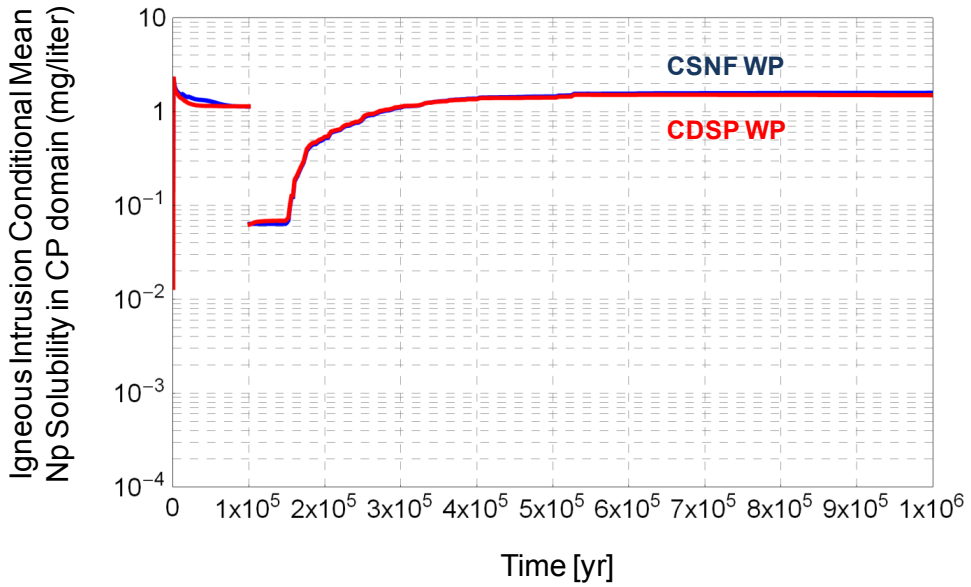

Figure 5-4: The Average Solubility for Np in the Corrosion Product Domain for the Igneous Intrusion Modeling Case. (Note: results for CSNF and CDSP waste packages are nearly identical)

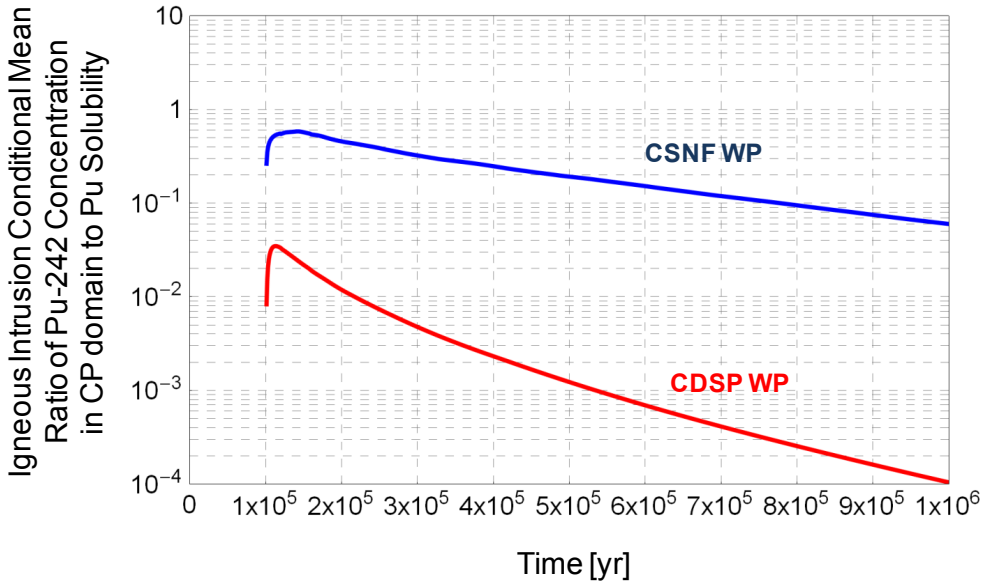

Figure 5-5: The Ratio of the Pu-242 Concentration to the Np Solubility in the Corrosion Product Domain for the Igneous Intrusion (GM) Modeling Case.

In summary, the net effect, based on examination of TSPA intermediate results and staff hypotheses, supports an approximate value for the lumped “corrosion product factor” of about 0.05 for neptunium and 0.7 for plutonium, particularly at long times.

6 OBSERVATIONS

The NRC staff conducted the confirmatory calculations to assist the review of the DOE's Total System Performance Assessment (TSPA) results. The confirmatory calculations provide both a quantitative understanding of the attributes of DOE's TSPA and an understanding of whether there is a general consistency between submodels of the TSPA and its dose results, including uncertainty (e.g., whether the timing and extent of breaching of the waste packages are consistent with the timing and magnitude of the average annual dose). The reasonableness of the individual model abstractions to capture the relevant features, events, and processes is evaluated in the NRC staff's TER.

The NRC staff's confirmatory calculation is reported herein to support the review of how the characteristics of DOE's Total System Performance Assessment (e.g., number of waste packages failed, transport of radionuclides in the geosphere, and scenario probabilities) are consistent with the performance of a potential repository at Yucca Mountain (i.e., the dose estimate). The confirmatory calculation is derived from key assumptions and model abstractions of DOE's Total System Performance Assessment (TSPA) and represents the NRC staff's understanding of those characteristics most significant to risk (i.e., probability-weighted dose) in DOE's TSPA. The NRC staff is using the confirmatory calculation to explain how the risk significant characteristics of DOE's TSPA are consistent with the TSPA estimated doses DOE reported in the SAR.

Groundwater Pathway

The confirmatory calculation considered the two modeling cases that contributed the most to groundwater releases (i.e., seismic ground motion modeling case and igneous intrusion modeling case).

Specific observations from the confirmatory calculations relevant to the groundwater pathway follow:

- **The failure of the waste package has a significant effect on dose.**

  As the initial barrier preventing release of radionuclides, it certainly is no surprise that failure of the waste package has a significant effect on dose (i.e., radionuclides must first exit the waste package and then be transported to the location of the reasonably, maximally exposed individual {RMEI} for a dose to occur). For those radionuclides that have an inventory and release rate such that the releases from the waste package persist for a very long time (e.g., on the order of 1 million years), it is expected that the largest releases from the repository will occur when the largest number of packages have failed. Releases of Np-237 and Pu-242, which are limited by solubility limits and corrosion products, can persist for long periods of time and exhibit larger releases at later times when the larger number of waste packages are failed (i.e., the largest releases of Np-237 and Pu-242 for the seismic ground motion modeling case are at the latest reported time of 800,000 years; see Tables 2-8 and 2-12). Tc-99, which is not solubility limited, has a release rate that does not persist very long compared to radionuclides such as Np-237 and Pu-242 (e.g., thousands of years for Tc-99 versus hundreds of thousands of years for Np-237). The release of Tc-99 is more sensitive to the failure rate of the waste packages than the total number of failed waste packages

primarily because the releases of Tc-99 persist for a relatively short time period and thus larger releases from the repository occur when the failure rate is highest. The total release of Tc-99 from the repository is highest for the seismic ground motion modeling case when the waste package failure rate is highest (i.e., Table 2-7 shows the total release rate highest at 100,000 years, which is the time the waste package failure rate is highest for all seismic failure types for the codisposal waste package in Table 2-4).

The results for the igneous intrusion modeling case are a little different because all the waste packages are assumed to be failed when the event occurs, and the releases estimated in the NRC staff's confirmatory calculation are weighted by the probability that the event has occurred. Although the overall characteristics of the releases of the igneous intrusion modeling case are similar to the releases of the seismic ground motion modeling case (i.e., Tc-99 shows an earlier peak release than Np-237 and Pu-242), the reasons for this behavior are different. The waste package failure rate for the igneous intrusion modeling case is uniform (see Table 2-4; note that small differences in failure rates are due to round-off errors) due to the assumption that all the waste packages fail when the event occurs. Thus, the estimated release of Tc-99 in the igneous intrusion modeling case is largest at the earliest time estimate (i.e., 10,000 years) primarily because of decrease of the inventory over time from radioactive decay. The sorbing radionuclides (i.e., Np-237 and Pu-242) in the NRC staff's calculations tend to have peak release times at later times; however, the upper value of the release range, which often is a bounding value (as indicated in Tables 2-10 and 2-13), as an upper bound is influenced by the inventory and therefore decreases in the upper value at the later times are associated with radioactive decay.

- **Releases from Engineered Barrier System (EBS) often represent a bounding value.**

  The NRC staff's confirmatory calculation used a range of values for the solubility limits of Np-237 and Pu-242. In the NRC staff's calculations, bounding Equation 2-3 was used in place of Equation 2-2 when the use of Equation 2-2 would result in a noncredible result (see Section 2.4.3). This was often the situation when the upper value of the range for the solubility limits was used (see Tables 2-9, 2-10, 2-12 and 2-13; note that asterisked values in these tables denote use of Equation 2-3). For example, the bounding Equation 2-3 was used for all time estimates after 10,000 years for the igneous intrusion modeling case and for the co-disposal (CDSP) waste packages in the seismic ground motion modeling case. In a few instances where Equation 2-3 was not used to limit the releases at the 800,000 year time (i.e., for Np-237 in the seismic ground motion modeling case for commercial spent nuclear fuel (CSNF) waste packages only) there is only a factor of three difference between the reported value and what would have been obtained if the bounding Equation 2-3 were used. The releases of Tc-99 from the EBS were determined in the NRC staff's confirmatory calculation using only bounding Equation 2-3 as described in Section 2.4.2. The use of bounding Equation 2-3 results in radionuclide releases from the EBS that would not be larger even if the volume of water entering the waste package and the solubility limits were increased and the sorption onto corrosion products were decreased.

- **Delay times due to radionuclide transport in the geosphere have a significant effect on releases to the reasonable maximally exposed individual (RMEI) location over the initial 100,000 years and to a lesser extent at times approaching 1 million years.**

  For the radionuclides (i.e., Np-237 and Pu-242) evaluated in the NRC staff's confirmatory calculation that have the potential to sorb onto mineral surfaces, the delay time can have a significant effect on releases to the reasonable maximally exposed individual (RMEI) location, especially at early times (e.g., times less than 100,000 years). The combined effects of the delay times in the unsaturated and saturated zones reduce releases from the engineered barrier system at 10,000 years by about a factor of 3 for Np-237 and almost a factor of 70 for Pu-242 (see Tables 2-16 and 2-17). At much later times (i.e., 800,000 years), the delay factor for the moderately sorbing Np-237 has no real effect on the releases to the RMEI location; however, the more strongly sorbing Pu-242 is reduced by about a factor of 3 even at 800,000 years. The nonsorbing radionuclide Tc-99 is not delayed sufficiently to have an effect on release to the RMEI location.

- **Comparison between the confirmatory calculation and the results of DOE's Total System Performance Assessment (TSPA) results is reasonable.**

  Generally, the comparison between the confirmatory calculation and the results of DOE's Total System Performance Assessment (TSPA) results is reasonable in that the comparison is best when the doses are larger {greater than 0.001 mSv/yr [0.1 mrem/yr]}. Not surprisingly, the comparison is best for Tc-99, which is a radionuclide that has limited processes affecting its release and transport (i.e., high solubility limit and nonsorbing in the unsaturated and saturated zones) and thus is more easily represented by the NRC staff's simplified confirmatory calculation. Additionally, the comparison for the other radionuclides (i.e., Np-237 and Pu-242) is best at the latest time (i.e., 800,000 years) for the confirmatory calculation, which represents the time for a larger number of waste package failures (waste package failures in the confirmatory calculation are probability weighted) and an amount of time for sorbing radionuclides like Np-237 and Pu-242 to be transported from the repository to the location of the reasonably, maximally exposed individual (RMEI). Clearly the comparison between the NRC staff's confirmatory calculation and DOE's TSPA is not as good when the doses are very small {e.g., on the order of 1×10^{-5} mSv/yr [0.001 mrem/yr]}; however, the confirmatory calculation is intended primarily to provide insight into those performance aspects affecting the peak dose—less so for the lower valued doses. Overall, the trends of dose over time are consistent between the NRC staff's confirmatory calculation and DOE's TSPA results, which suggests the NRC staff's understanding of DOE's TSPA regarding such items as waste package failure and releases, and geosphere transport is also reasonable and supported.

Air Pathway

The confirmatory calculation for the air pathway considered the volcanic eruption modeling case. Specific observations from the confirmatory calculation relevant to the air pathway follow:

- **Dose estimates for an eruptive (volcanic) igneous event are primarily impacted by assumptions regarding the persistence of tephra on the land surface.**

  The NRC staff's confirmatory calculation for the dose from an eruptive (volcanic) igneous event used a few simple assumptions to estimate the potential dose. The simple assumptions considered such things as the amount of waste entrained in the tephra, the overall tephra volume, and the depth of tephra at the reasonable maximally exposed individual (RMEI) location. The assumption regarding how long the tephra deposit remained intact on the land surface significantly influences the calculation because it affects the estimate of a probability-weighted dose directly proportional to the assumed length of time the tephra persists on the land surface. The dose estimates were performed for two time periods: an amount of time equal to the half-life of the radionuclide and an amount of time equal to three times the half-life (see Section 3.7). For certain radionuclides (e.g., Pu-239) this resulted in tens of thousands of years for the assumed persistence of the tephra (see Table 3-3). Although such a long persistence time is considered very conservative, the low dose estimates in DOE's TSPA suggested that simple, conservative assumptions would be appropriate for the air pathway.

- **Dose estimates for NRC staff's calculation are generally higher than the DOE's TSPA results; however, comparisons are far better when persistence of the tephra is shorter in the NRC staff's calculation.**

  The resulting annual doses from the confirmatory calculation are larger than the average annual doses from DOE's TSPA. This is not unexpected based on the approach for the confirmatory calculation (e.g., direct deposits persist without abatement for at least three half-lives) that was intended to bound certain assumptions. The match between the confirmatory calculation and the TSPA results is best for the radionuclides with the shortest half-lives (i.e., Sr-90 and Cs-137; half-lives of 29 and 30 years, respectively) partially because the persistence of the deposit is assumed to be on the order of 100 years for 3 half-lives rather than the tens of thousands of years and longer for the other radionuclides with longer half-lives. Although the calculation intentionally overestimates the annual dose, the annual dose from the confirmatory calculation for the volcanic eruption modeling case is still limited to no more than 0.4 mSv/yr [0.004 mrem/yr].

The observations made regarding the NRC staff's calculations and the DOE's Total System Performance Assessment (TSPA) results confirm that the results of the TSPA are consistent with the individual components of the TSPA (e.g., overall dose is consistent with the number and types of waste package failures, release processes from the EBS, and transport of radionuclides in the geosphere). Significant increases in the dose estimates could only occur by significant changes in the components of the TSPA.

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