Summary of the Total System Performance Assessment for the Yucca Mountain License Application

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Abstract: The Department of Energy's 2008 Yucca Mountain Performance Assessment represents the culmination of more than two decades of analyses of post-closure repository performance in support of programmatic decision making for the proposed Yucca Mountain repository. The 2008 performance assessment summarizes the estimated long-term risks to the health and safety of the public resulting from disposal of spent nuclear fuel and high-level radioactive waste in the proposed Yucca Mountain repository. The standards at 10 CFR Part 63 request several numerical estimates quantifying performance of the repository over time. This paper summarizes the key quantitative results from the performance assessment and presents uncertainty and sensitivity analyses for these results.

Keywords: Performance assessment, radioactive waste disposal, uncertainty analysis, sensitivity analysis.

1. INTRODUCTION

The United States Department of Energy Office of Civilian Radioactive Waste Management (DOE-OCRWM) submitted a license application on 3 June 2008 to the United States Nuclear Regulatory Commission (NRC) seeking authorization to construct a repository at Yucca Mountain, Nevada, for the permanent disposal of spent nuclear fuel (SNF) and high-level radioactive waste (HLW) [1]. On 8 September 2008, the NRC accepted the DOE's application for technical review and docketed it to begin the formal regulatory process of review and hearings.

The total system performance assessment (TSPA) model developed to support the DOE's license application provides quantitative estimates of long-term performance of the repository, including estimates of future radiation doses to a hypothetical "reasonably maximally exposed individual" (RMEI) [2], and is based on more than two decades of scientific investigations. Modeling work performed for this TSPA builds on prior iterations of system-level analyses [3-8] beginning in the early 1990s and continuing through the 2002 Yucca Mountain Site Recommendation [9] and Final Environmental Impact Statement [10]. The conceptual structure of the Yucca Mountain PA, including representation of uncertainty, is outlined in Helton et al. [11, 12].

2. REGULATORY FRAMEWORK

The management of SNF and HLW is governed in the United States by the provisions of the Nuclear Waste Policy Act of 1982 (NWPA), as amended [13]. As required by the NWPA, the United States Environmental Protection Agency (EPA) has issued public health and environmental radiation protection standards for Yucca Mountain [14], and the NRC has issued final regulatory requirements [15] at 10 Code of Federal Regulations (CFR) Part 63 that establish criteria for the implementation of the EPA standards. Additional guidance relevant to evaluating compliance with the NRC regulations is provided in the *Yucca Mountain Review Plan* [16].

The EPA and NRC regulations define a performance assessment as an analysis that identifies and evaluates relevant features, events, and processes (FEPs) that could affect repository performance, and

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then estimates performance taking into account uncertainties associated with significant FEPs. In practice, this regulatory direction is implemented using numerical models for components of the repository and the geologic setting, linked into a system-level model suitable for uncertainty analysis [12, 17-21, 28] within a consistent mathematical framework for representing uncertainty [11].

In addition to defining the overall method to be used for the performance assessment, regulations also define the quantitative limits on long-term performance that are to be met for demonstrations of regulatory compliance. Specifically, 10 CFR 63.311 defines an individual protection standard that limits the mean annual dose to the RMEI during 10,000 years after disposal to 0.15 mSv (15 mrem). The rule also provides separate standards for allowable releases of radiation to groundwater (10 CFR 63.331), and a limit for mean annual doses to the RMEI following an assumed and stylized human intrusion event (10 CFR 63.321). The final EPA rule for implementing a dose standard after 10,000 years [14] extends the individual protection and human intrusion standards to 1,000,000 years, setting a limit on the mean annual dose to the RMEI of 1 mSv (100 mrem) for the period between 10,000 and 1,000,000 years.

The EPA and NRC regulations define the scope of the long-term analysis by defining screening criteria for FEPs. Specifically, performance assessments shall not consider features, events, or processes "that are estimated to have less than one chance in 100,000,000 per year of occurring." In addition, the effects of FEPs that have a higher probability of occurrence need not be evaluated if overall performance in the initial 10,000 years "would not be changed significantly" by their occurrence (10 CFR 63.342(a)). Regulatory requirements call for the use of "multiple barriers, consisting of both natural barriers and an engineered barrier system" (10 CFR 63.113(a)). Although no quantitative limits apply to the performance of components of the multiple barrier system, the DOE is required to describe the capability of barriers and to provide the technical basis for that description, consistent with the performance assessments used to demonstrate compliance with the system-level standards.

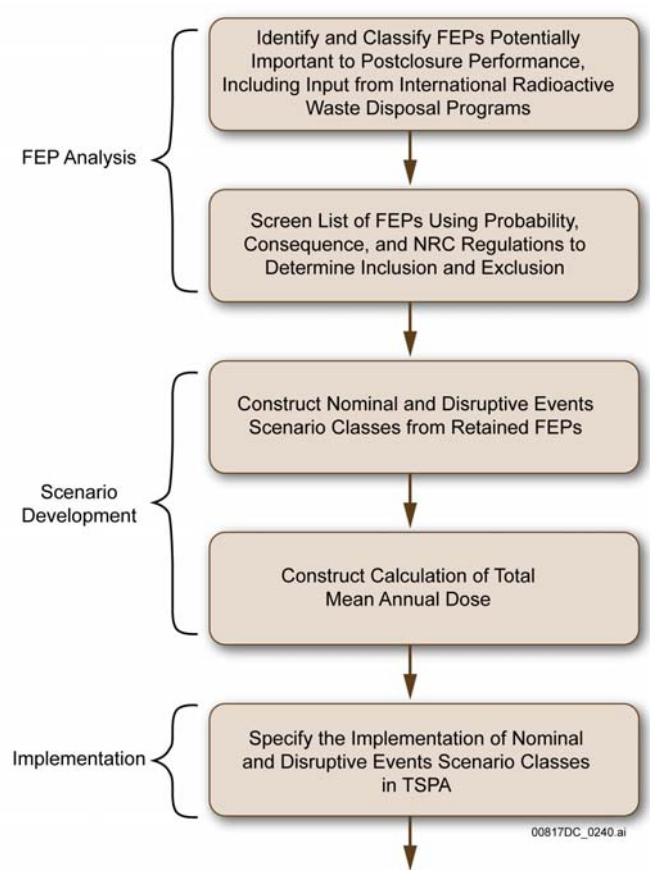
As required by 10 CFR 63 Subpart G, all scientific and engineering work that directly supports the performance assessment for the license application is performed and documented in accordance with appropriate quality assurance standards [22].

3. THE TSPA MODEL

The TSPA model is a system-level model that integrates submodels that simulate various processes that can affect repository performance, including water movement, material degradation, and radionuclide transport [17-19], computes time-varying concentrations of radionuclides in groundwater and in surficial soils, and estimates the resulting annual dose to the RMEI. The submodels comprising the TSPA model and linkages between submodels are illustrated in [Ref. 11, Fig 2]. Because of the complexity of the individual processes and the need for a large number of system-level simulations to support the uncertainty analysis, the TSPA model relies on simplifications (abstractions) of some of the submodels for major processes. As described in Ref. 2, Section 6, a number of detailed models are used to simulate specific processes, and the output of these models is represented in the TSPA model by means of a set of abstractions linked to the GoldSim software [23] that implements the TSPA calculations.

The FEPs to be represented in the TSPA model and the supporting process models were identified by means of a five-step screening analysis as shown in Figure 1. A comprehensive list of potentially relevant FEPs was identified based on input from past Yucca Mountain performance assessments and input from other international repository programs, and the FEPs were evaluated and screened according to criteria specified by the NRC, e.g., at 10 CFR 63.114 [24,25]. Of the 374 FEPs identified for evaluation, 222 were excluded from the quantitative TSPA modeling on the basis of low probability, low consequence, or incompatibility with regulatory requirements. The remaining 152 FEPs were included in one or more of the analyses for evaluating compliance with the regulatory standards.

Figure 1. FEPs Screening for the Yucca Mountain PA (from Ref. 2, Figure 6.1.1-1)



The large majority of FEPs included in the performance assessment analyses are features and processes that are relevant to essentially all possible future states of the disposal system. Some included FEPs, however, represent rare events that may or may not occur in the future. Events of similar origin or with similar effects on the repository system are grouped to define scenario classes for the analysis. Uncertainty in future events, i.e., aleatory uncertainty associated with the timing and characteristics of the events, is characterized mathematically by a probability space, separate from a second probability space that characterizes epistemic uncertainty associated with the physical properties of the disposal system [11].

The TSPA analyzes four discrete scenario classes that characterize the range of future states of the system, in addition to a stylized human intrusion scenario prescribed by regulation for evaluation under a separate standard (10 CFR 63.311) [15,16]. The four scenario classes include: an early failure scenario class, in which one or more waste packages or overlying drip shields fails prematurely due to undetected manufacturing or emplacement defects; an igneous disruption scenario class in which a volcanic event causes magma to intersect the emplacement region, with or without an accompanying eruption; a seismic disruption scenario class, in which ground motion or fault displacement damages waste packages and drip shields; and a nominal scenario class in which none of these three types of events occurs.

4. COMPUTATIONAL PROCESS

For computational purposes, each of the event-based scenario classes is further subdivided into separate modeling cases that simulate consequences of specific events within each scenario class that have different effects on the repository system: early drip shield and waste package failure cases; an igneous intrusion case (without eruption) and a volcanic eruption case; and seismic ground motion and

fault displacement damage cases. A single nominal modeling case is also defined; however, for analyses of 1,000,000-year performance, the seismic ground motion and nominal modeling cases are combined into a single modeling case because the effects on the repository system of seismic ground motion events depend on the effects of nominal processes (e.g., general corrosion of the engineered features).

A Latin hypercube sample (LHS) of size 300 is generated consistent with the probability space for epistemic uncertainty which comprises 392 epistemically uncertain variables. For each element of the LHS, the expected (expectation over aleatory uncertainty) value of annual dose to the RMEI is computed for each modeling case for both 10,000 years and 1,000,000 years post-closure using either quadrature or Monte Carlo integration methods (Ref. 2, App. J). For each time period, the results are summed over all modeling cases to obtain a distribution of total expected (expectation over aleatory uncertainty) annual dose to the RMEI. The expectation over aleatory uncertainty accounts for the probability of occurrence of the events represented by each modeling case.

5. BARRIER CAPABILITY

Consistent with the requirements of 10 CFR 63.113(a), the DOE has identified three barriers that are important to waste isolation at Yucca Mountain: an upper natural barrier that limits the amount of water reaching the repository drifts (tunnels); the engineered barrier system that both limits water flow and restricts radionuclide migration from the waste; and the lower natural barrier that significantly delays radionuclides during groundwater transport away from the repository. Each of these barriers is composed of multiple features that contribute to the overall capability of the system.

The upper natural barrier includes the surficial soils and topography that limit the amount of precipitation that infiltrates into the bedrock, the 200 to 400 meters of unsaturated rock that dampen the episodic effects of weather-related infiltration, and the capillary barrier provided by the drift walls that tends to divert water flow around the emplacement drifts. The overall effect of the upper natural barrier is to reduce water flow (percolation flux) in the mountain to a small fraction (5 to 7 percent) of the mean annual precipitation above the repository, and to further reduce mean seepage (the amount of water that enters a drift) to a small fraction of percolation flux (2-11%) in uncollapsed drifts (Ref. 2, Section 8.3.3.1.1[a]).

The engineered barrier system includes: the drift environment; the titanium drip shield; the waste package, including the Alloy 22 (a nickel-chromium alloy) outer corrosion barrier and the inner stainless steel container; the waste forms and associated shipping containers; the emplacement pallet; and the invert material that forms the floor of the drift. Two types of waste packages are modeled: codisposal waste packages which contain both spent fuel and high-level waste glass from defense-related activities in the DOE complex; and commercial spent nuclear fuel (SNF) waste packages. The drip shield contributes to barrier performance by providing a robust barrier to the flow of water: modeled failures of the drip shield due to corrosion occur between 270,000 and 340,000 years after closure, and the drip shield effectively prevents flowing water from reaching the waste until then (Ref. 2, Section 8.3.3.2[a]). Earlier failures of the drip shield may occur due to emplacement errors, igneous disruption, fault displacement, or extreme ground motion events, but all are anticipated to occur at very low probabilities. Similarly, the Alloy 22 outer corrosion barrier of the waste packages provides a very effective barrier to both water flow and radionuclide transport. Under nominal conditions (without ground motion damage), cracks in the closure welds of waste package, which would allow diffusive transport of radionuclides, are modeled to occur only rarely before approximately 170,000 years after closure.

Taking ground motion damage into account, stress corrosion cracks can occur earlier in the repository history, but releases are still anticipated to occur by diffusion only. Larger penetrations of the waste package outer barrier due to general corrosion of the Alloy 22, which would allow advective transport of radionuclides in flowing water, rarely occur in the model before about 560,000 years. By 1,000,000 years, approximately 9 percent of the waste packages have penetrations due to general corrosion,

regardless of damage due to seismic ground motion. Seismic damage that could result in advective transport of radionuclides is accounted for in the model, but rarely occurs (Ref. 2, Section 8.3.3.2 [a]).

The lower natural barrier contains 250 to 380 meters of unsaturated rocks (estimated to be up to 120 meters less during wetter future climates) between the repository and the water table, and approximately 18 km of saturated rocks laterally along the potential transport pathway from the repository to the location of the RMEI. Processes that will delay radionuclide transport through the lower natural barrier include the slow rate of water flow, diffusion of dissolved-phase radionuclides from rock fractures into the rock matrix where water moves more slowly, adsorption of dissolved species in the rock matrix, and reversible filtration of colloidal species. Estimated transport times through the unsaturated portion of the lower natural barrier vary considerably, depending on the degree of sorption and the extent to which transport occurs in fractures or in matrix porosity. For nonsorbing radionuclides (e.g., ^{99}Tc), median transport times through the unsaturated zone range from tens of years (for cases in which transport is largely in fractures) to many thousands of years (for cases in which transport is largely in matrix porosity) (Ref. 26., Figure 6.6.2-8[b]). Transport times for sorbing species are longer. Similar ranges of transport times are estimated for the saturated zone. For nonsorbing radionuclides (e.g., ^{99}Tc), median transport times range from 100 years to 22,000 years, and strongly sorbing species (e.g., ^{226}Ra) show median transport times from 18,000 years to more than 1,000,000 years (Ref. 27, section 6.7.1[a]). Overall, the lower natural barrier effectively delays transport of many radionuclides sufficiently that radioactive decay greatly reduces their concentrations by the time they reach the location of the RMEI.

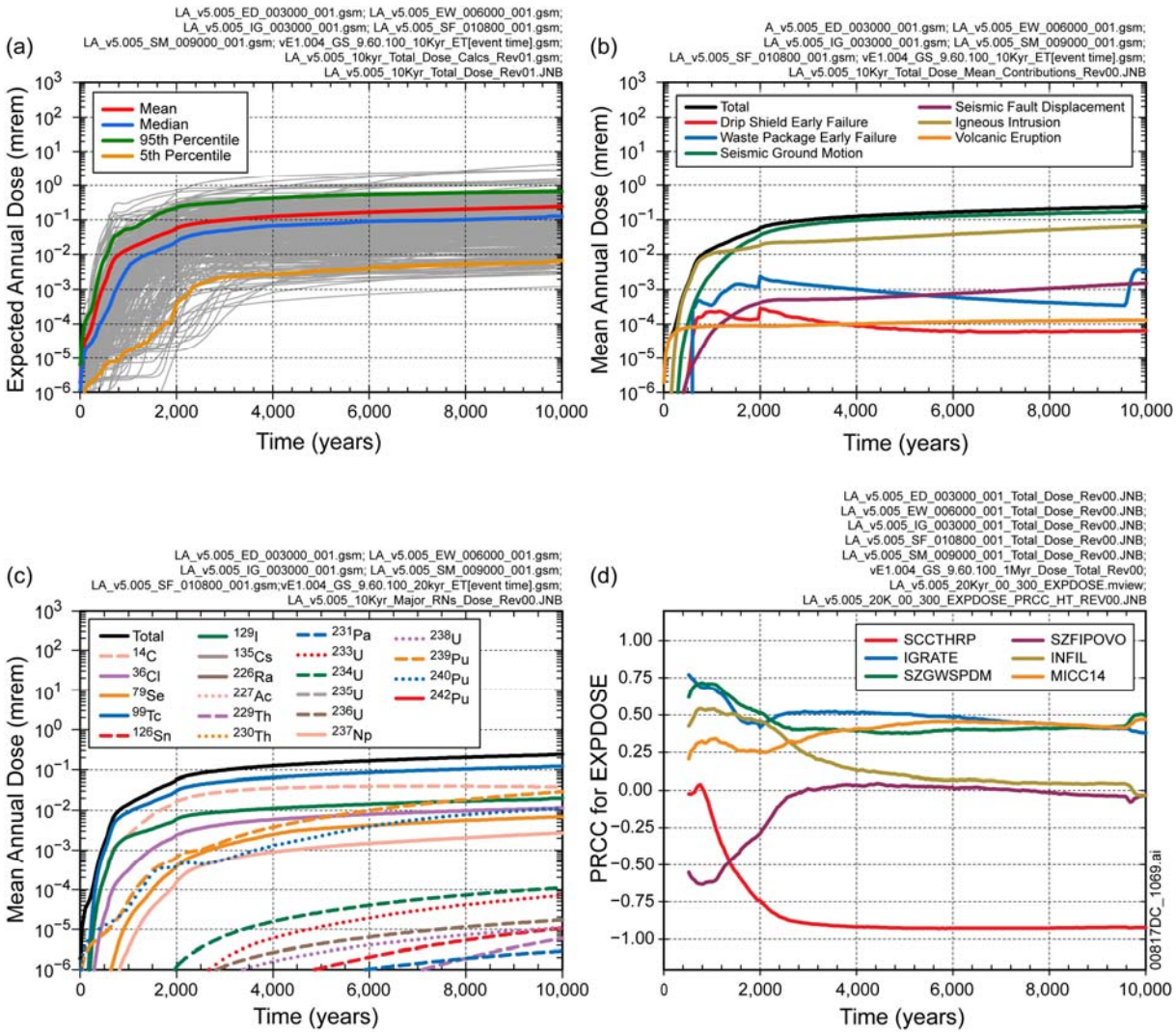
6. COMPLIANCE WITH QUANTITATIVE LONG-TERM STANDARDS

Compliance with the 10,000-year individual protection standards (10 CFR 63.311(a)(1)) is demonstrated by estimating the mean (expectation over both epistemic and aleatory uncertainty) annual dose to the RMEI considering all scenario classes. Figure 3a shows the distribution of expected (expectation over aleatory uncertainty) annual doses, summed over all scenario classes, along with statistics for this distribution; compliance with 10 CFR 63.311(a)(1) is demonstrated by comparing the maximum of the mean annual dose curve to the limit of 15 mrem. The smoothness evident in the expected dose results from the quadrature procedure used to evaluate the expectation over aleatory uncertainty for this time period (Ref. 2, App. J). Individual curves correspond to different elements in the LHS from the sample space for epistemic uncertainty and thus the spread in the curves reflects uncertainty associated with the characteristics of the physical system. CCDFs of annual dose, showing the effects of aleatory uncertainty are available (Ref. 2, App. J). Uncertainty and sensitivity analyses for each modeling case are summarized in Ref. 21.

The mean dose for the time period [0, 10^4 yr] is primarily determined by the expected dose resulting from the effects of seismic ground motion, with a secondary contribution from the effects of igneous intrusion events (Fig 3b). Although an igneous intrusion results in greater consequence (i.e., release of radionuclides) than does a damaging seismic event, the probability of an igneous event is much lower than the probability of a damaging seismic event, and thus the contribution to mean dose from the igneous intrusion modeling case is less. In the seismic ground motion modeling case, vibratory ground motion causes stress-corrosion cracking damage to co-disposal waste packages at frequencies as high as 2×10^{-5} yr^{-1}; all other effects of seismic events (e.g., damage to commercial SNF waste packages, failure of drip shields) are far less likely. In contrast, igneous intrusion events occur at frequencies less than 3×10^{-8} yr^{-1}. However, radionuclides releases from the EBS following an igneous intrusion are greater than those that result from stress-corrosion cracking damage from a seismic event because an igneous intrusion is assumed to completely negate the containment function of the engineered barrier system. All other scenario classes have a marginal contribution to mean dose, either because the number of waste packages affected by the represented event is small (e.g., early waste package failure), because the event probability is small (e.g., seismic fault displacement), or both (e.g., volcanic eruption). Nominal processes did not result in annual dose during the time period [0, 10^4 yr] and thus the nominal modeling case is not shown on Fig. 3b.

Mean annual dose in the first 10,000 years after repository closure predominately results from ^{99}Tc, with lesser contributions from other radionuclides (e.g., ^{14}C, ^{239}Pu, and ^{129}I) (Fig. 3c). Radioelements comprising most of the mean annual dose fall into two broad categories: highly soluble and non-sorbing (i.e., technetium, carbon, iodine, chlorine, selenium); solubility-limited and sorbing (i.e., plutonium and neptunium). Roughly 80% of the mean annual dose from ^{99}Tc is attributable to the seismic ground motion modeling case (Ref. 2, Fig. 8.2-12[a]a). Because technetium is modeled as highly soluble and non-sorbing in the lower natural barrier, annual dose from ^{99}Tc is primarily constrained by its rate of release from the engineered barrier system by diffusion through tight, tortuous stress corrosion cracks in the waste package outer barrier. Constraints on other highly soluble, non-sorbing radionuclides are similar. In contrast, essentially the entire mean annual dose from ^{239}Pu results from the igneous intrusion modeling case (Ref. 2, Fig 8.2-10[a]a). In this modeling case, releases of plutonium (and neptunium) are constrained principally by radioelement solubility, limited water volume flowing through the waste package, and by retardation due to sorption onto degraded steels from waste package materials. Retardation due to sorption in the lower natural barrier further reduces the annual dose from plutonium and neptunium.

Figure 3. Expected annual dose to RMEI (mrem) for all radioactive species and all scenario classes for [0, 10^4 yr]: (a) expected dose (Ref. 2, Fig. 8.1-1[a]); (b) contributions to mean dose by scenario class (Ref. 2, Fig. 8.1-3[a]a); (c) contributions to mean dose by radionuclide (Ref. 2, Fig. 8.1-6[a]); and (d) associated partial rank correlation coefficients (PRCCs) (Ref. 2, Fig. K8.1-1[a]).



As shown by the spread of the results in Fig. 3a, a substantial amount of uncertainty is present in the estimation of expected annual dose from all scenario classes. The sensitivity analyses in Fig. 3d indicate the variables from the sample space for epistemic uncertainty that give rise to the uncertainty in expected annual dose. The partial rank correlation coefficients (PRCCs, see 11) in Fig. 3d indicate that, for most of the time interval [0, 10^4 yr], uncertainty in expected annual dose is dominated by the threshold yield strength for stress corrosion cracking (*SCCTHRP*) (see Table 1 for definitions of individual variables), reflecting the dominant contribution to total expected dose from the expected dose from seismic ground motion, and the importance of this variable to the expected dose from seismic ground motion. In the analysis, *SCCTHRP* essentially determines the probability that a seismic ground motion event with given horizontal peak ground velocity will cause damage to waste packages. Smaller effects are evident from the frequency of igneous events (*IGRATE*), from variables that influence movement of water (*SZGWSPDM*, *SZFIPOVO*, and *INFIL*), and from uncertainty in the biosphere dose conversion factor for ^{14}C (*MICC14*), which converts ^{14}C activity concentration in the groundwater to radioactive dose to the RMEI (the uncertainty in the biosphere dose conversion factor for ^{99}Tc has slightly less effect than the six variables identified in Fig. 3d). Stepwise regression analyses reach similar conclusions (Ref. 2, Fig. K8.1-2[a]).

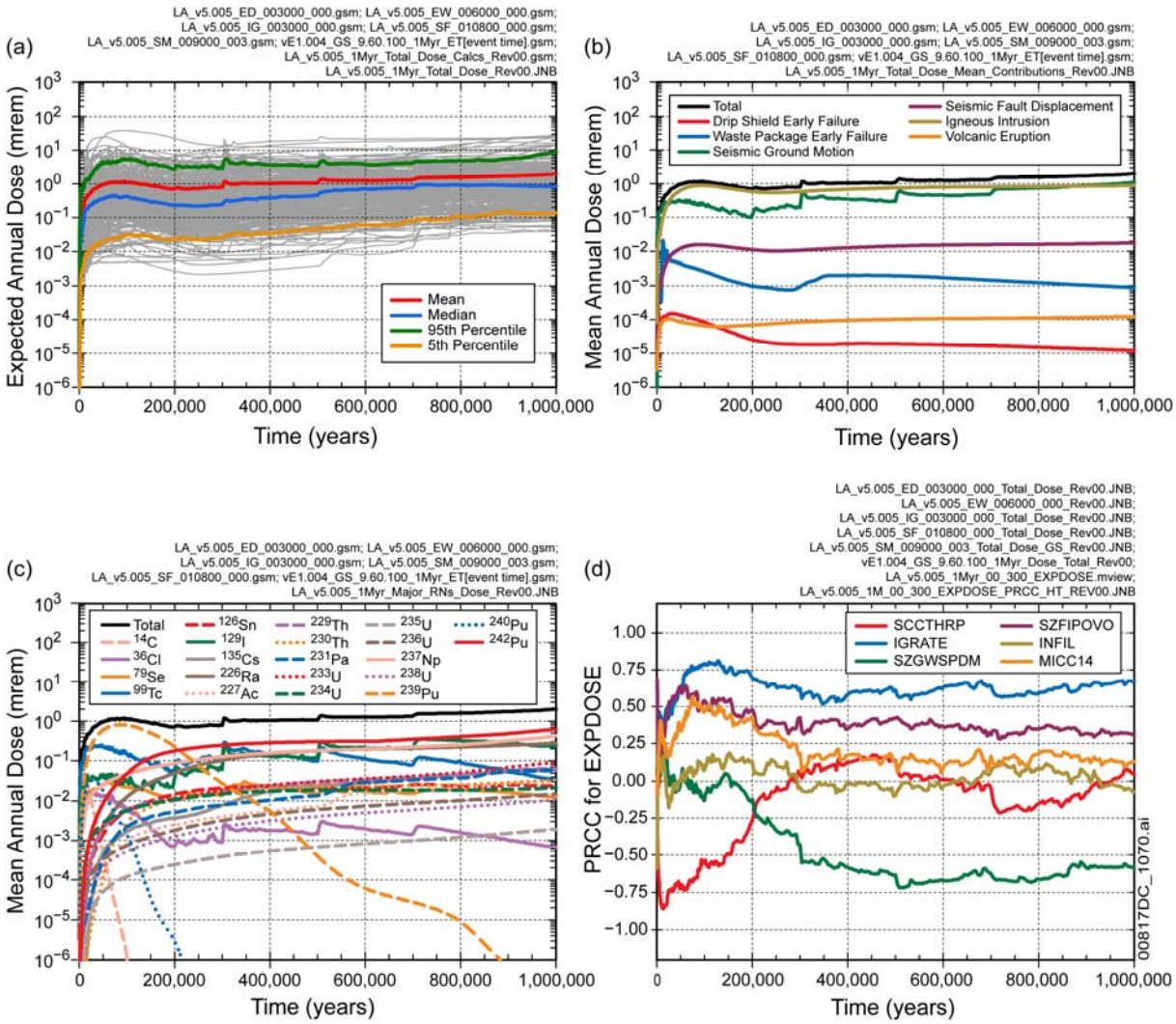
Compliance with the 1,000,000-year individual protection standards (10 CFR 63.311(a)(1)) is demonstrated in a similar manner. Figure 4a shows the distribution of expected (expectation over aleatory uncertainty) annual doses, summed over all scenario classes. The maximum of the mean of this distribution mean is compared to the regulatory limit of 100 mrem. In contrast to the results for the time period [0, 10^4 yr], the Monte Carlo procedure used to evaluate expected (expectation over aleatory uncertainty) dose from the combination of seismic ground motion and nominal corrosion processes for the time period [0, 10^6 yr] results in the spikes in total expected dose evident in Fig. 4c. Although these spikes could be smoothed by use of a larger sample size (i.e., more simulated sequences of seismic events) in the calculation, the sample sizes employed are sufficient to yield a stable estimates of the distribution of expected annual dose, and in particular, the mean (expectation over both aleatory and epistemic uncertainty), as discussed below.

The total mean dose for the time period [0, 10^6 yr] is primarily determined by the expected dose resulting from the effects of igneous intrusion events and from the combined effects of seismic ground motion and nominal corrosion processes (Fig 4b). These two modeling cases comprise roughly equal parts of the maximum value of the mean annual dose (at 1,000,000 yr). Radionuclides contributing to mean annual dose (Fig. 4c) reflect the contributions of these two modeling cases. Contributions from solubility-limited and sorbing radioelements (i.e., plutonium and neptunium) arise primarily from the igneous intrusion modeling case; after an igneous intrusion event, advection through the EBS facilitates transport of these species. In contrast, in the seismic ground motion modeling case, even at 1,000,000 yr, waste package failures from seismic ground motion damage or from nominal corrosion processes seldom allow advection through the waste; consequently radionuclide transport out of the EBS is primarily diffusive and highly soluble and non-sorbing radioelements (i.e., iodine and technetium) dominate contributions to mean dose. The contribution to mean dose from ^{226}Ra results from transport of ^{234}U subsequent to an igneous event and decay of ^{234}U to ^{226}Ra in the groundwater.

The PRCCs in Fig. 4d identify the three most important variables with respect to the uncertainty in expected annual dose for the time interval [0, 10^6 yr]: *IGRATE*, *SCCTHRP*, and *WDGCA22*. Uncertainty in *SCCTHRP* is important only until about 200,000 yr after closure. At about this time the drip shields are estimated to fail from the combined effects of general corrosion and accumulated rockfall load. Subsequent to drip shield failure the waste packages are modeled as being surrounded by rock rubble and the probability that a seismic ground motion event causes damage to waste packages is thereby greatly reduced. Beginning at roughly 160,000 yr after closure uncertainty in *WDGCA22* (temperature dependence coefficient in model for general corrosion of Alloy 22) is of increasing importance. Before 160,000 yr failures of the waste package outer barrier from nominal corrosion processes are rare (Ref. 2, Section 8.3.3.2[a]). After 160,000 yr the outer barriers of many waste packages fail by stress corrosion cracking in the lid closure welds; this cracking initiates when the stress-relieved surface layer is sufficiently thinned by general corrosion. Smaller effects on the

uncertainty in expected annual dose are indicated for *SZGWSPDM*, *SZFIPOVO* and for uncertainty in plutonium solubility (*EP1LOWPU*).

Figure 4. Expected annual dose to RMEI (mrem) for all radioactive species and all scenario classes for [0, 10^6 yr]: (a) expected dose (Ref. 2, Fig. 8.1-2[a]); (b) contributions to mean dose by scenario class (Ref. 2, Fig. 8.1-3[a]b); (c) contributions to mean dose by radionuclide (Ref. 2, Fig. 8.1-7[a]); and (d) associated PRCCs (Ref. 2, Fig. K8.2-1[a]).

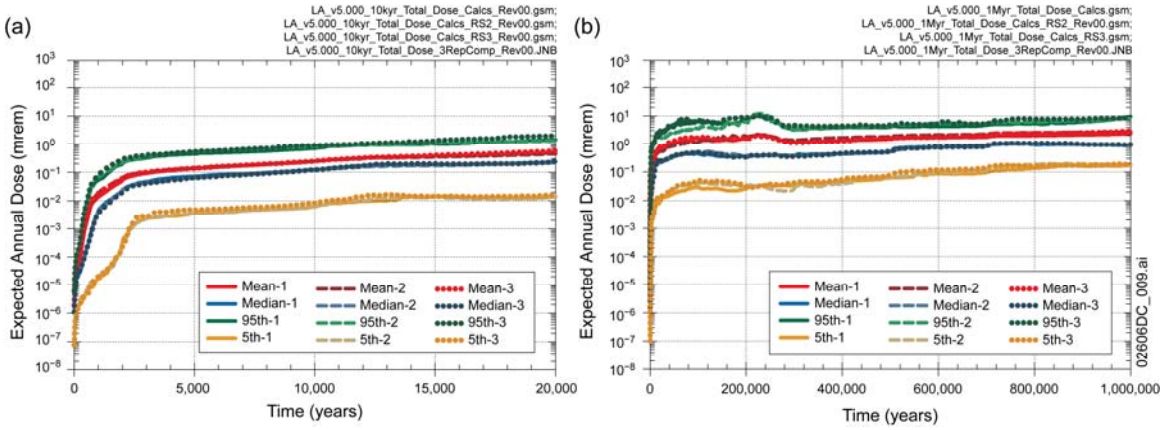


To demonstrate that the LHS sample size of 300 is sufficient to obtain stable results, the analysis was repeated three times with independently generated LHSs of size 300. As shown in Fig. 5, mean dose and quantiles for expected (expectation over aleatory uncertainty) for these three samples are similar. Thus, an LHS of size 300 is adequate to obtain stable results for the propagation of epistemic uncertainty. The reader should note that the stability results summarized in Fig. 5 are from a near-final version of the YM 2008 TSPA model, and hence are slightly different in shape and magnitude from those presented in Figs. 3 and 4. Convergence of numerical integration (to obtain expected annual dose) is also achieved (Ref. 2, Section 7.3.1[a]).

Compliance with the 10,000-year groundwater protection standards (10 CFR 63.331) is demonstrated by estimating concentrations of radionuclides in groundwater at the location of the RMEI, excluding human intrusion and unlikely natural events (i.e., igneous disruption). Specifically, the combined activity of ^{226}Ra and ^{228}Ra in ground water must be less than 5 picocuries per liter, and the total gross alpha activity, including ^{226}Ra but excluding uranium and radon, must be less than 15 picocuries per liter, with both values including natural background. The maximum mean groundwater concentration

of combined radium derived from the proposed repository is estimated to be 1.3×10^{-7} pCi/L, far below the natural background level of 0.5 pCi/L, which in turn is well below the regulatory limit. Similarly, the mean maximum gross alpha activity resulting from releases from the proposed repository is estimated to be 6.7×10^{-5} pCi/L, far below the natural background of 0.5 pCi/L, which in turn is well below the regulatory limit. Estimated mean annual doses from beta and photon emitting radionuclides in 2 liters per day of groundwater are 0.06 mrem (0.0006 mSv) for the whole body and 0.26 mrem (0.0026 mSv) for the thyroid, well below the regulatory limit of 0.04 mSv/yr (4 mrem/yr) (Ref. 2, Section 8.1.2[a]).

Figure 5. Stability of estimates of expected annual dose to the RMEI (mrem) for all radioactive species and all scenario classes: (a) [0, 2×10^4 yr] (Ref. 2, Fig. 7.3.1-15a), and (b) [0, 10^6 yr] (Ref. 4, Fig. 7.3.1-16a).



Compliance with the individual protection standard for human intrusion (10 CFR 63.321) is based on the consequences of a single penetration of a waste package by a borehole, creating a path for groundwater transport of radionuclides from the repository to the saturated zone. Borehole penetration is assumed to occur at 200,000 years after repository closure, consistent with regulatory requirements to consider intrusion at the earliest time that the waste package would be sufficiently degraded that an intrusion could occur without recognition by the drillers. Estimated maximum median annual dose resulting from a single borehole penetration is 0.00011 mSv (0.011 mrem), well below the EPA limit of 1 mSv (100 mrem/yr) for the period after 10,000 years (Ref. 2, Section 8.1.3.2[a]).

Table 1: Variables Appearing in Sensitivity Analysis Results

Variable Name	Definition
EPILOWPU	Logarithm of the scale factor used to characterize uncertainty in plutonium solubility at an ionic strength below 1 molal (dimensionless).
IGRATE	Frequency of intersection of the repository footprint by an igneous event (yr^{-1}).
INFIL	Pointer variable for determining infiltration conditions: 10th, 30th, 50th or 90th percentile infiltration scenario (dimensionless).
MICC14	Groundwater Biosphere Dose Conversion Factor (BDCF) for ^{14}C in present-day climate ((Sv/year)/(Bq/m^3)).
SCCTHRP	Residual stress threshold for SCC nucleation of Alloy 22 (as a percentage of yield strength in MPa) (dimensionless).
SZGWSPDM	Logarithm of the scale factor used to characterize uncertainty in groundwater specific discharge (dimensionless).
SZFIPOVO	Logarithm of flowing interval porosity in volcanic units (dimensionless).
WDGCA22	Temperature dependent slope term of Alloy 22 general corrosion rate (K).

7. CONCLUSIONS

The 2008 TSPA for the proposed Yucca Mountain repository provides one of the technical bases for the DOE's license application to the NRC for authorization to construct the repository. The TSPA is based on a systematic analysis of the potentially relevant features, events, and processes that may affect long-term performance of the disposal system and on detailed site characterization and process modeling. Total system modeling results, which account for uncertainty in future events, key parameters and models, indicate that the largest contributions to the estimated maximum mean annual dose come from the igneous intrusion and seismic ground motion scenario classes. Nominal corrosion processes that lead to degradation and failure of the waste packages become important release mechanisms late in the million-year postclosure period. All estimated performance measures are well below regulatory limits applicable for 10,000 years and for 1,000,000 years.

8. ACKNOWLEDGMENTS

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