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Uncertainties In Performance Assessments For The Yucca Mountain Site And The "Edge-of-Compliance"

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ABSTRACT

Numerical performance assessments of deep geologic disposal systems of long-lived radioactive wastes serve as the primary tool for quantitatively assessing projected performance and for making regulatory compliance decisions, both in the U.S. and disposal programs abroad. However there is a significant body of opinion, expressed in the international literature, that the confidence that can be placed on such assessments decreases significantly as the analysis time frames increase into the many hundreds of thousands of years. With the inclusion of highly corrosion resistant metals in the planned waste package designs for the Yucca Mountain (YM) system commercial spent fuel and defense-generated high-level radioactive waste disposal, published projections for the site show doses to the receptor at times extending into the many hundreds of thousands of years. The question of relative confidence in dose projections becomes more important at very long time frames, particularly when the time frame for significant doses increases dramatically reflecting the effects of using highly corrosion resistant materials.

To examine uncertainties in performance assessments of the YM disposal system over very long time frames, a site model developed by the U.S. Department of Energy to assess sensitivities in peak dose performance was modified and used to examine the propagation of uncertainties for a hypothetical disposal system. These analyses start with a hypothetical disposal system at the "edge-of-compliance" at 10,000 years, reflecting the generic repository standard in 40 CFR Part 191. The hypothetical system was poised to give a mean dose of 0.15 millisievert/year (15 mrem/yr.) at 10,000 years, by allowing a fixed number of waste packages to "fail" within the first 5,000 years after closure. By maintaining the number failed waste packages constant over time, the spread in dose estimates over the time to peak dose was calculated for this system perched at the "edge-of-compliance" at 10,000 years. This hypothetical construct removes waste package performance from the analyses and allows the site model to explore the effects of uncertainties in the natural barrier and site conditions on the dose projections out to the time of peak dose. The sensitivities of these projections to various "driver" parameters were examined, including infiltration rates, solubility constraints, water chemistry and roof collapse assumptions.

Overall, the initial construct showed a one and one-half order of magnitude spread between the 5th and 95th percentiles at 10,000 years, the initial state for the analyses. This spread increased to approximately three and one-half orders of magnitude at peak dose, reflecting the effects of transport and retardation mechanisms on the fixed source term. The model eliminated portions of the transport path from the repository where relatively little retardation would be expected.

Travel times were therefore significantly reduced thereby eliminating radioactive decay as an important mechanism in reducing projected doses. Solubility controls appear to be a major source of uncertainties in the dose projections for the model used. These results support the general international consensus that confidence in dose projections over very long time frames does decrease, and illustrates that this conclusion also applies to assessments of the YM projected performance as well.

INTRODUCTION

To assess potential health and safety impacts of a candidate disposal system for used nuclear fuel and high-level radioactive waste, numerical performance assessments are the only available quantitative tool available to analyze the complex processes involved in the post-closure performance period. These assessments will be a prime focus of the regulatory process. The issue of uncertainty propagation in repository performance assessments is an important component in making compliance decisions and also in structuring national standards, particularly tiered standards. The "sharpness" of the performance assessment tool determines how well alternate conceptualizations of the disposal system can be distinguished from each other, and has a direct bearing on the implementability of standards, particularly for tiered standards. To gain some insight on these issues, a site-specific modeling effort was performed to examine the propagation of uncertainties for the Yucca Mountain commercial spent fuel and defense-generated high-level radioactive waste (defense waste) disposal system over extended time periods.

STANDARD SETTING CHALLENGE

National standards for the acceptable performance of a deep geologic repository have been in place since 1985, as contained in Code of Federal Regulations, Title 40, Part 191 (40 CFR Part 191). The Energy Policy Act of 1992 however directed that the National Academy of Sciences (NAS) to prepare recommendations for the U.S. Environmental Protection Agency (EPA) at the development of site-specific standards for the safe management and disposal of used nuclear fuel and high-level radioactive waste at the Yucca Mountain (YM) site. The most important finding by the NAS [1] was to state that they "believe that there is no scientific basis for limiting the time period of the individual- risk standard to 10,000 years or any other value" [1, pg 55]. They then recommended individual protection standards be developed for the period when risks were highest whenever it occurs, within a period of geologic stability for the site, which could be on "the order of one million years". The credibility of dose projections made for such extremely long time periods raises the question of how much confidence can be placed in the projections as reasonable forecasts of repository performance.

MODELING APPROACH

The model used for the assessments presented here was developed by the U.S. Department of Energy ((DOE) for the purpose of doing sensitivity studies for the most important parameters contributing to peak dose projections for the YM site [2], referred to here as the DOE Peak Dose Model (PDM). It differs from the Total System Performance Assessment (TSPA) models used for more detailed assessments, being less detailed, but was built by the same extraction process as the various TSPA models. Parameter values for the approximately 100 variables in the model were developed from numerous reports documenting the results of site characterization studies at the site for many years, as documented in the report cited above and within the DOE-PDM. No changes were made to this extensive data base to preserve the integrity of the DOE_PDM site-specific data base. Both models operate under the GoldSim probabilistic simulation software (version 8.02) with the Contaminant Transport Module.

The EPA modified this model as necessary to perform its analyses. The modified model will be referred to here as the EPA Uncertainty Model (EPA-UM). A detailed description of these modifications relative to the DOE-PDM capabilities is described elsewhere [3]. To establish the base case reference system, iodine (I) and technetium (Tc) had to be added to the radionuclides already in the DOE-PDM, since we were interested in performance within 10,000 years. We also added the consideration of climate variation within 10,000 years, using the timing for various climate states given in the DOE-PDM documentation (2). In addition, the EPA-UM was modified to allow selection of parameter values at fixed levels (mean values for example) so that sensitivity studies could be performed. The relatively simple EPA-UM is used here for several reasons. It can make 1,000 realizations in the course less than two hours, as opposed to the more elaborate TSPA models which would take weeks to perform the same number of realizations. We do not have the resources or time to work with the more complex TSPA codes. We were interested in looking at the most important "driver" parameters in terms of their effects on peak dose projections. These are contained in the DOE-PDM without the complicating effects of parameters that have less impact on dose projections, which would make the results more difficult to interpret.

To examine the propagation of uncertainty over very long time frames, a base case reference provides a fixed point for contrast with the forward modeling. Without a fixed base case for reference, it is difficult to understand what drives the long-term modeling since all the parameters can vary. We were interested in examining the performance of the natural barrier system at the site rather than the engineered barrier system (EBS) components and our approach takes much of the EBS out of the assessments. The base case consists of a hypothetical disposal system with a predetermined number of failed waste packages, set so that the mean dose to the receptor is 0.15 millisievert per year (mSv/yr) (15 millirem/yr.) at 10,000 years. This hypothetical disposal system is then poised at the "edge-of-compliance" for the 10,000 year standard. The modeling then addresses the question, "what would the dose variations be in the very long-term for a disposal system that performs at the 10,000 year limit". Since the calculations are done stochastically, there is a spread of dose estimates at 10,000 years as part of the initial conditions for the reference case. This spread is taken as the difference in dose values between the 5th and 95th percentiles of the dose distribution. The spread is limited to this range to eliminate extreme high or low values that might arise from statistically low-probability parameter values. The number of failed waste packages necessary was determined iteratively with the EPA-UM, beginning with failure of all the packages and working backward to derive a mean dose of 0.15 mSv/yr. (15 mrem/yr.), from 1,000 realizations with all the parameters varying stochastically as in the *base case* presented in the DOE-PDM documentation [2]. One thousand realizations were used in the analyses presented her to preserve consistency with the DOE-PDM analyses. The number of failed packages needed to make the reference case was found to be 520 (divided into 362 commercial spent fuel packages and 158 defense waste packages in proportion to the planned repository loading). The packages were allowed to fail uniformly over the first 5,000 years of the simulations. This was done because the travel times through the ground water travel path is on the order of 5-6000 years [4]. We also examined the effect of allowing all the packages to fail at 5,000 years, but the results were not markedly different.

MODELING RESULTS - EPA-UM BASE CASE

The dose projections for the EPA-UM base case ("edge-of-compliance" disposal system) are shown on Fig. 1, for runs consisting of 1,000 realizations, with all parameters varying stochastically and a fixed number of failed waste packages. For the 10,000 - year time line, the dose estimates vary approximately one and one-half orders of magnitude (difference between the 5th and 95th percentiles of the distribution) around the mean value of 0.15mSv/yr. (15 mrem/yr.). As the dose projections proceed out to the peak dose, the distribution widens to approximately three and one-half orders of magnitude surrounding the mean value of 3.42 mSv/yr. (342 mrem/yr.). This illustrates an important point that the uncertainties in projecting the doses at longer time frames increase, and gives an indication of the range of potential doses that would occur if the disposal system were functioning at the edge of compliance at 10,000 years. The dose projections did not stay in the range of tenths of a mSv/yr. (tens of mrem/yr.) at longer time frames and did not go into the range of many mSv/yr, (hundreds to thousands of mrem/yr.), illustrating that the operative portions of the disposal system functioned to keep doses relatively constrained. These results should not be interpreted to suggest that the actual Yucca Mountain disposal system would yield a closely similar dose history profile. For the actual repository, waste packages would continue to fail over time contributing to the inventory of radionuclides in the repository available for removal by infiltrating ground waters and subsequent migration from the repository.

SENSITIVITY STUDIES WITH THE EPA-UNCERTAINTY MODEL

To examine the effect of various choices in executing modeling runs, these calculations were repeated for differing numbers of realizations since a decision was made initially to retain the 1,000 realizations per model run for consistency with the DOE-PDM analyses [2]. Results with higher numbers of realizations gave higher mean values at peak dose but were within the 95% confidence interval of the 1,000 realization run. These results further illustrate the uncertainty in projecting long-term performance even when the initial conditions of the disposal system are tightly constrained, i.e., the failed waste packages are fixed in number.

Sensitivity analyses were also performed to examine the effects of fixed vs. random waste package failure times, fixed versus variable parameter variations and Monte Carlo vs. Latin hypercube sampling for the parameter distributions. These variations are simply modeling choices for the analysis of the reference base case scenario and do not measure the effects of the site parameters, which are the main point of interest for the sensitivity analyses. Rather, they reflect the effects of fundamental aspects of performance assessment in a broader sense. The results of these exercises are given in Table I. Mean doses varied from a low of 1.62 mSv/yr. (162 mrem/yr.) to a high of 4.08 mSv/yr. (408 mrem/yr.). The low-end value corresponds to a single dose projection within the reference base case (d in Table I). The timing of waste package failures made essentially no difference in the mean dose projections (c and d in Table I), indicating that the site parameter variations are acting in a similar way in both alternatives.

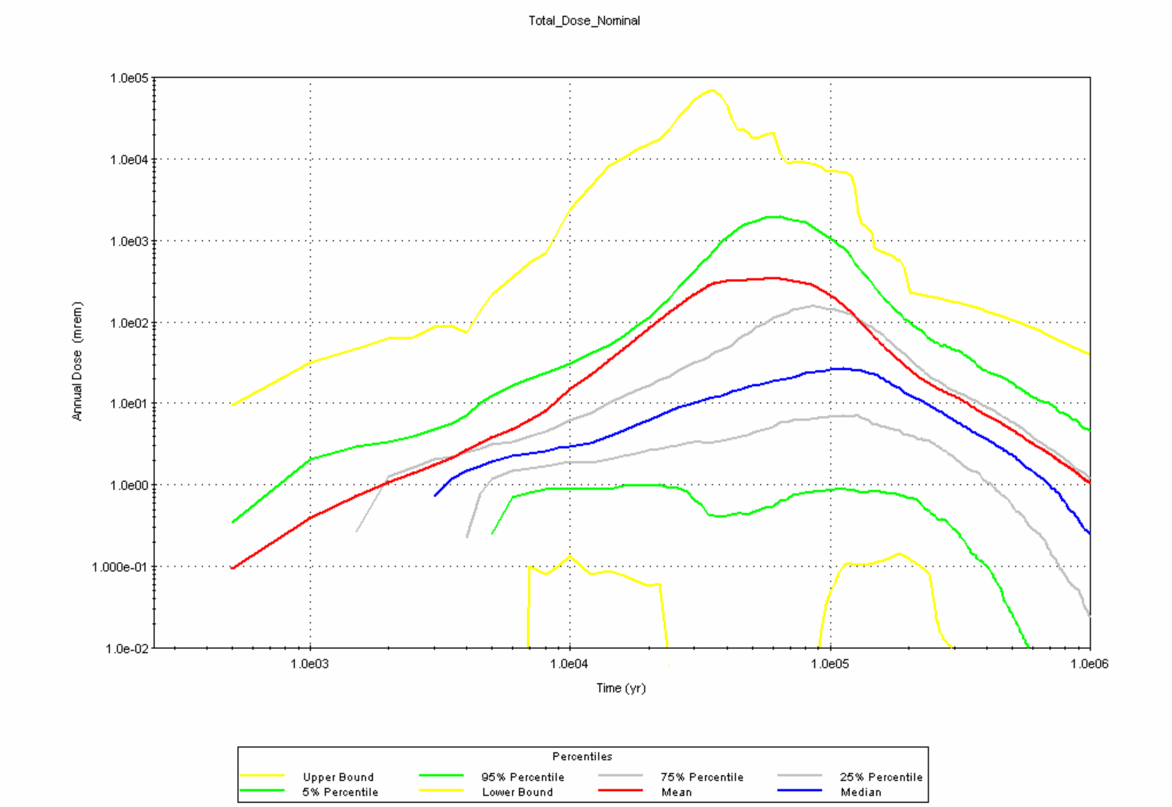

Fig. 1. Total Annual Dose, Mean and Selected Percentiles of 1,000 Realizations for EPA Uncertainty Model

Sensitivity studies with the EPA-UM were also performed to examine the effects of variations in infiltration, seepage (the amounts of water actually entering the emplacement drifts), and solubility variations (varied by allowing pH and pCO_2 to vary). These sensitivity runs were done by setting the stochastic parameters to fixed values and allowing the parameters for the individual processes under consideration to vary across their allowable range in the data base. To interpret these results, the mean value of dose at 10,000 years was noted along with the spread of the 5th and 95th percentiles for these analyses. These values are different than the reference base case since the reference case was calculated allowing all the parameters to vary stochastically whereas for the sensitivity studies most parameters were fixed (see below). Results of these analyses are summarized in Table II. The calculated mean, and median values are shown, along with the values for the 5th and 95th percentiles to illustrate the variations observed. Table II also shows the results for variations of all the parameters to illustrate the variations observed for the reference base case with the EPA-UM.

For infiltration sensitivity, the infiltration rate was varied from highest to lowest rather than the blended treatment used to develop the reference base case. Results showed, not unexpectedly, that higher infiltration caused the peak dose to occur earlier in time than in the base case. The lowest infiltration produced a mean peak dose of only 0.2 mSv/yr. (20 mrem/yr.). Higher variations in dose were calculated with the EPA-UM in contrast to sensitivity runs presented by DOE for the DOE-PDM results [2], probably due to the addition of I and Tc to the EPA-UM. and the fact that these radionuclides are quickly removed from the waste packages in the EPA-UM reference base case scenario.

Table I Mean and Median Annual Dose Forecasts at 10,000 Years and at Year of Peak Mean Dose in mSv/yr. (mrem/yr)

	Forecast of Annual Dose at 10,000 Years		**Forecast of Peak Annual Dose(1)**	
Model Specification	**Mean**	**Median**	**Mean**	**Median**
a) Fixed Parameters with fixed WP failure time (n=1)	0.05 (4.83)	0.05 (4.83)	1.63 (162.83) @100,000 yr	1.63 (162.83) @100,000 yr
b) Fixed Parameters with Random WP failure times (n=1000)	0.05 (4.79)	0.05 (4.78)	1.63 (162.65) @100,000 yr	1.63 (162.83) @100,000 yr
c) Random Parameters with Fixed WP failure time (n=1000)	0.15 (14.7)	0.03 (3.03)	3.41 (341.24) @60,000 yr	0.27 (26.78) @112,000 yr
d) Random Parameters with Random WP failure times (n=1000)	0.15{0.09,0.22} (15.0,{8.5, 21.6})(2)	0.03 (2.98)	3.42{2.69, 4.15} (342.20, {269, 415})(1) @60,000 yr	0.27 (26.59) @112,000 yr
e) All Random Parameters with no LHS Sampling (n=1000)	0.20 (19.7)	0.03 (3.17)	4.08 (408.14) @52,000 yr	0.31 (31.12) @116,000 yr

(1) The model uses 2,000-year time steps from 10,000 to 52,000 years and 4,000-year time steps from 52,000 to 1,000,000 years.

(2) An approximate 95% confidence interval for the estimated mean is shown in parentheses for n = 1,000 realizations.

For seepage sensitivity studies, four parameters are varied to handle the variation in seepage rates in the site database while the other stochastic parameters are held constant. Results showed that seepage has, not unexpectedly also, a strong influence on peak dose projections. As more ground water enters the drifts, higher amounts of radionucides would migrate out into the natural barrier. In addition to the seepage variation runs, an additional run was performed utilizing the model's capability to simulate collapsed and non-collapsed drifts [2]. For the case where the drifts are not collapsed, there is a marked decrease in peak dose, with the peak doses of less than one tenth of a mSv/yr (only a few mrem/yr.). Some realizations for this scenario show no releases within one million years.

For solubility sensitivity runs, the pH and pCO_2 in the model data base were varied. The model assumes solubility of the radionuclides (with the exception of I and Tc) are controlled by the appropriate thermodynamically stable phases for the repository ground water chemistry. For the actinides, these are carbonate and hydroxycarbonate phases. Solubility variations produced the largest variations in peak dose projections, but not dramatically different than the seepage variations.

Table II Statistics Measuring Uncertainty in Various Sensitivity Cases
[Doses in mSv/yr. (mrem/yr.)]

Statistic		Vary Solubility	Vary Seepage	Vary Seepage, Solubility, and Infiltration Rate	Vary All Parameters
5th percentile	Peak Dose	0.14(13.7)	0.07(6.5)	0.02(2.4)	0.01(1.0)
	Year of Peak Dose	96,000	144,000	144,000	22,000
Mean	Peak Dose	4.42(442)	1.83(183)	4.91(491)	3.42(342)
	Year of Peak Dose	92,000	92,000	80,000	60,000
Median	Peak Dose	1.61(161)	1.60(160)	0.87(87.1)	0.27(26.6)
	Year of Peak Dose	100,000	104,000	112,000	112,000
95th percentile	Peak Dose	22.82(2,288)	4.85(485)	30.89(3,089)	19.72(1,972)
	Year of Peak Dose	84,000	84,000	80,000	64,000
5th percentile. (At year of peak of 95th percentile)		12.6	3.0	1.3	0.6
Range Ratio (95th/5th)		181	162	2,387	3,049
Orders of Magnitude Spread in Range Ratio [a]		2.3	2.2	3.4	3.5

a - log base 10 of range ratio

The case where seepage parameters, solubility parameters, and infiltration rates are allowed to vary (Column 4) versus the case where all parameters are allowed to vary (Column 5) shows a slightly lower Range Ratio for the former. However, the 5th percentile, mean, and 95th percentile are lower for the case where all parameters are allowed to vary. The fact that the two cases have similar range ratios indicates that most of the uncertainty is captured by these three groups of parameters. It must be remembered that, with the EPA Uncertainty Model, uncertainties associated with waste package and drip shield behavior are eliminated.

By comparing the range ratio (95th/5th) data at the time of the peak dose from Table II with the equivalent range ratios at 10,000 years, one can obtain an estimate of the extent that uncertainty increases with time. The following tabulation provides such a comparison:

Sensitivity Case	Range Ratio at Peak/Range Ratio at 10,000 yrs.
Vary Solubility	181/3.35 = 54.0
Vary Seepage	162/2.32 = 23.3
Vary Seepage, Solubility & Infiltration	2,387/7.52 = 317
Vary All Parameters	3,049/34.0 = 89.7

The increase in the range ratio over the period from 10,000 years to the time of the peak dose clearly demonstrates the large temporal increase in uncertainty. For the case where all parameters are varied, the increase is about two orders of magnitude from 10,000 years to the time of the peak dose. The increase in the range ratio over the period from 10,000 years to the time of the peak dose clearly demonstrates the large temporal increase in uncertainty (the approximate range shown in Fig.1).

In the EPA-UM sensitivity runs, 22 parameters were varied to assess the effects of infiltration, seepage and solubility on the dose projections. A step-wise regression analysis was performed (using the SPSS package) to determine the contribution of these parameters to the total variation seen in the results. The results of this analysis are shown in Fig. 2.

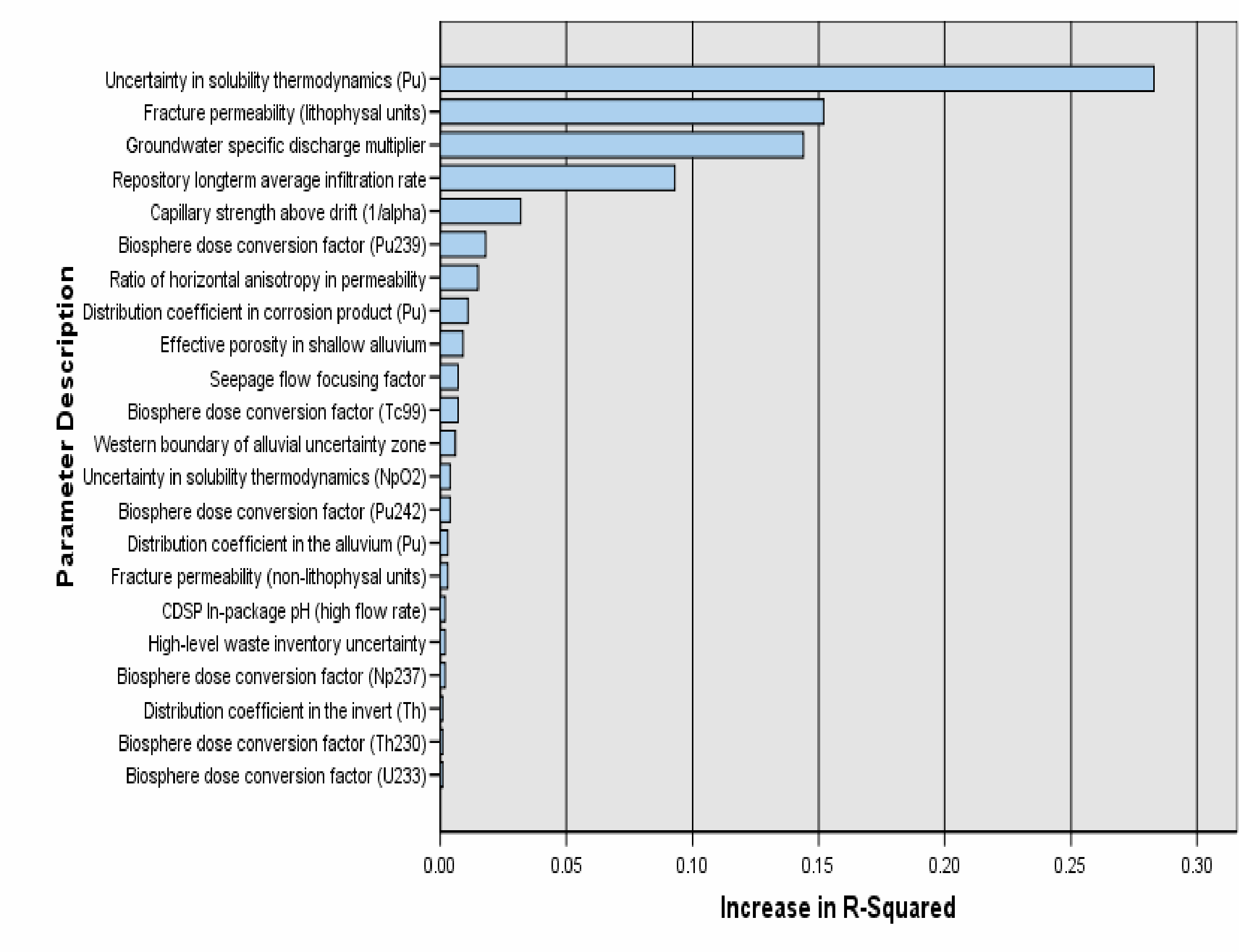

Fig. 2. Increase in R-Squared Achieved by Stepwise Addition of the 22 Selected Parameters in Regression of Annual Dose Maxima versus All 76 Stochastic Parameters Used in EPA Uncertainty Model
(N=1000 realizations, $R^2 = 0.801$)

The largest contributor to the variation is the solubility data for plutonium, followed by parameters that determine seepage into the emplacement drifts and infiltration rate [3]. These results correlate with the results of DOE's analyses of peak dose sensitivity [2], indicating that our modifications to the DOE-PDM did not alter the fundamental structure or functions contained in the model.

SENSITIVITY ANALYSES WITH THE DOE-PDM

The EPA analyses presented here removed the containment function of the metal barriers in the EBS. To create the reference base case, a fixed number of waste packages were allowed to fail within 10,000 years, the drip shields were removed and no containment credit was taken for spent fuel cladding. The results then reflect only the effects of site parameters on the dose projections. However, the performance of the EBS components is in reality an important contributor to the disposal system performance. To examine the contribution of the waste package and drip shields, the DOE-PDM was exercised to examine this aspect. Twelve scenarios were examined using the "switches" provided in the model to activate or deactivate various components of the model. The results are shown in Table III, and Fig. 3.

Table III. Peak Mean Dose and Selected Percentiles in Year of Peak Dose for Base Case and 12 Alternative Scenarios – Doses in mSv/yr. (mrem/yr.)

ID	Scenario	Peak Dose	Year of Peak Dose	5th	25th	50th	75th	95th	Ratio 95th/ 50th	Ratio Mean /75th
0	Base Case	1.25 (125)	730,000	0	0	0.05 (5)	1.26 (126)	5.70 (570)		1.0
1	Low Infiltration Case	0.8 (84)	870,000	0	0	0.31 (31)	1.04 (1.04)	3.39 (339)	11	0.8
2	Medium Infiltration Case	1.36 (136)	690,000	0	0	0	1.24 (124)	6.39 (6.39)	-	1.1
3	High Infiltration Case	1.62 (162)	690,000	0	0	0	1.51 (151)	7.70 (770)	-	1.1
4	WP Corrosion Rate times 5	2.53 (253)	225,000	0	0	0	1.30 (130)	11.44 (1144)	-	1.9
5	Full Temperature Dependence	0.03 (3)(a)	1,000,000	0	0	0	0	0	-	-
6	DS Corrosion Rate times 5	1.51 (151)	690,000	0	0	0.07 (7)	1.56 (156)	6.64 (664)	92	1.0
7	Remove DS Functionality	1.54 (154)	690,000	0	0	0.08 (8)	1.57 (156)	6.74 (674)	80	1.0
8	2nd Phase Np Solubility Control	1.11 (1.11)	865,000	0	0	0.36 (36)	1.26 (126)	4.84 (484)	14	0.9
9	SZ Transport Length Set to 0	24.97 (2497)	775,000	0	0	2.88 (288)	27.19 (2719)	111.39 (11,139)	39	0.9
10	Non-Collapsed Drifts	0.37 (37)	860,000	0	0	0.01 (0.7)	0.28 (28)	1.83 (183)	250	1.3
11	WP & DS Corrosion Rate times 5	7.68 (768)	180,000	0	0.1	1.06 (106)	4.86 (486)	38.19 (3819)	36	1.6
12	Vary Pu242 BDCF +20%	1.38 (1.38)	730,000	0	0	0.05 (5)	1.40 (140)	6.48 (648)	133	1.0

(a) A higher peak is reached after the end of the one-million-year timeframe used in the current model.

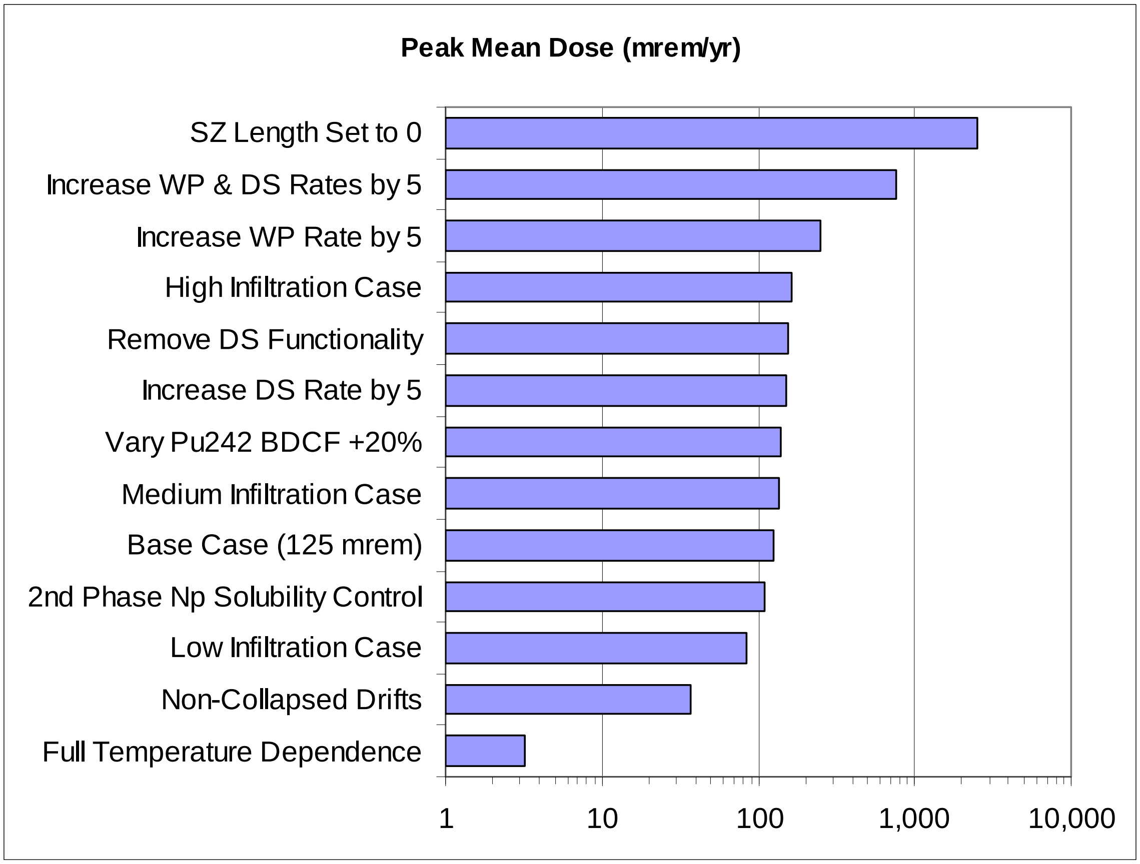

Fig. 3. Comparison of 12 Peak Dose Model Sensitivity Scenarios with DOE-PDM Base Case (#0, Table III)

The results of particular interest are scenarios # 4, 5 & 6 (Table III), which involve differing assumptions about the performance of the waste package metal and drip shields. For the case where very low corrosion rates are assumed (# 5), which track the thermal profile of the repository over time, failure of a large portion of the waste packages is delayed past one million years. For the base case scenario (#0), where higher corrosion rates are assumed, the peak dose occurs in the range of 700,000 - 800,000 years. These results illustrate the overwhelming influence of the corrosion resistance of the waste packages to total system performance.

Corrosion rates are measured by laboratory testing of relatively short duration in comparison with the in-service performance period for the repository, stretching into the hundreds of thousands of years. The extrapolation of the laboratory data to such extremely long time frames is at best optimistic and assumes that all possible corrosion mechanisms and their rates under changing repository conditions can be quantified confidently. Confirming these assumptions, as well as confirming the performance of the waste package metals in their full-size waste package configurations, is not possible in any real sense because of the extremely long time frames involved. Experience in the industrial sector on the long-term performance of the corrosion resistant alloy used in the waste packages is also not available. If a more skeptical approach is adopted toward such extrapolations, it may be within reason to ask what the performance might be if higher corrosion rates then those used in the base case and full-temperature dependence scenarios, were assumed. This possibility is examined in scenarios # 4, 6 and 11, and shown in Fig. 4.

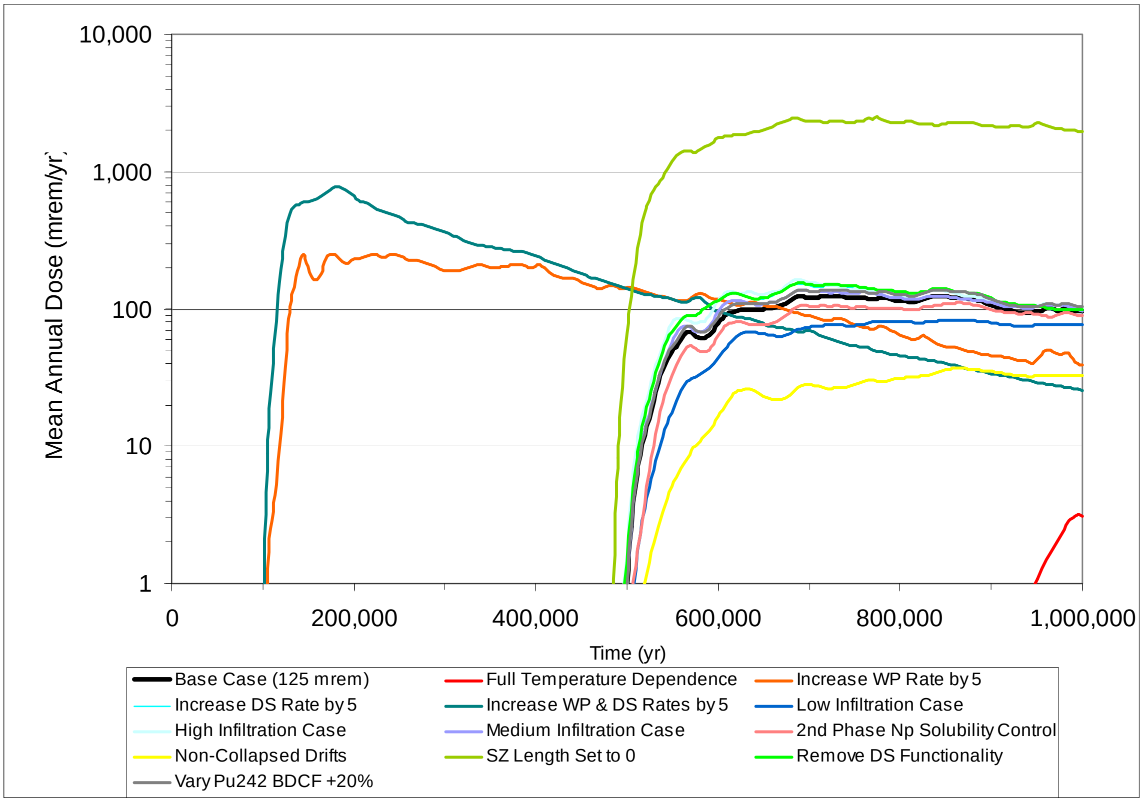

Figure 4. Mean Annual Dose, Base Case and 12 Alternative Sensitivity Scenarios

The striking shift of the peak dose forward in time from 700,000-800,000years to under 200,000 years illustrates the significance of this variable. The peak dose also increases from the base case level of 1.25 mSv/yr (125mrem/yr.) to almost 8.00 mSv/yr. (800mrem/yr.).

While the time to peak dose predicted by the modeling should not be taken as a realistic projection because some elements of the site system were eliminated, the relative shift in time of peak dose from over one million years to between 100,000 -200,000 years illustrates the importance of corrosion rate assumptions on long-term performance. The omission in the models of portions of the travel path from the repository to the down gradient controlled zone boundary (approx. 18 km) only contribute to the ground water travel time by amounts in the tens of thousands of years. Their inclusion in the models would not lengthen the time to peak dose back to in excess of one million years. Using corrosion resistant metals in the EBS design greatly extends the containment time for disposal system. The confidence that can be placed in very long-term dose projections is strongly tied to the level of confidence that can be placed in the extrapolation of laboratory corrosion testing results to in-service assessments for the metallic barriers in the EBS. The most recent published performance assessments for the YM site published by DOE [5] used the temperature dependent assumption for the selection of corrosion rates and calculated results were similar to those for scenario #5 in table III.

Two other significant results can be seen in the DOE-PDM analyses above. For the scenario where limited drift collapse occurs, peak doses are very low (# 10 in Table III), consistent with the results of the EPA-UM results, illustrating again that if little ground water seeps into the drifts radionuclide transport is low. Another interesting result is the major increase in peak dose for the scenario where the saturated zone (SZ) is eliminated from the model. This scenario corresponds to delivering the contaminated ground waters from directly below the floor of the repository to the receptor's drinking water well. Although this is an unrealistic scenario, it illustrates the containment and isolation contribution of the natural barrier surrounding the repository to the total system performance.

INSIGHTS RELATIVE TO STANDARD DEVELOPMENT

From the results of these modeling efforts, some insights pertinent to standard development become evident. For the highly corrosion resistant metals in the EBS design, releases within the 10,000 year period under undisturbed conditions will be extremely low because of the limited amounts of ground water able to enter the emplacement drifts (UZ setting and limited drift collapse effects) and contact the waste packages. The protection offered by drip shields and the waste package metals delays the significant release of radionuclides well past the 10,000- year time line. While the 10,000-year standard is aimed at providing protection for that time period, a peak dose limit beyond 10,000 years would extend the protection to even longer time frames. From the results of the modeling, it appears that the period of very low doses could extend from 100,000-200,000 to over a million years as a function of the corrosion rates assumed in performance assessments. Other assumptions for site parameters and processes would amplify or reduce peak dose projections for the more complex TSPA models, but the larger trends in dose projections are evident in the modeling presented here. Peak dose limits remaining in the low single digit mSv/yr. range (low hundreds of mrem/yr.) would suggest that the period of very low doses would extend easily into the time frame of many hundreds of thousands of years to potentially in excess of one million years. Establishing a peak dose standard in addition to the 10,000 year standard increases the period of very low doses to time frames well beyond that involved in 40 CFR Part 191.

The increasing uncertainties in performance assessments as time frames increase dramatically also affect the development of any form of tiered standards. The ability of the assessment tool to distinguish between alternative performance scenarios plays a significant role in framing dose limits and time frames for any form of tiered standards. Setting dose limits for performance periods ultimately is a societal decision about what exposure levels are acceptable, but the limits of the assessment tool determines the regulatory challenge for the applicant in making a credible safety case and the regulatory decision maker to come to a compliance decision.

CONCLUSIONS

Results of peak dose modeling using both the DOE-PDM and the EPA-UM provide some insights and implications for understanding the performance of the Yucca Mountain disposal system at the time of peak dose and the behavior of important uncertainties through the geologic stability period. By using a base case where some components of the disposal system are eliminated, uncertainty in projecting doses could be examined.

- Removing EBS metallic components from the EPA-UM analyses removes a major source of uncertainties and allows the uncertainties in site parameters and processes to be examined

- Modeling the disposal system with the EPA-UM showed that uncertainty increases over time relative to a fixed reference base case under the site conditions of the Yucca Mountain disposal system. These results support a general intuitive conclusion that uncertainties in projecting dose for the complex natural barrier system should increase as time frames for the projections extend into the many tens to hundreds of thousands of years.

- The most important parameters affecting dose projections are those involved with estimating ground water movement through the repository (infiltration and seepage), radionuclide mobility (release from the waste packages, solubility and ground water chemistry) and stability of the emplacement drifts to collapse after the thermal period has passed.

- Corrosion rates assumed for long-term assessments have the most dramatic effects on dose projections, both in contributing to the time frame and magnitude of peak dose estimates. Confidence in corrosion rate assumptions and dose assessments leans heavily on the extrapolation of laboratory corrosion rates over time and scale.

- Setting a peak dose limit in the range within a few mSv/yr. at most (low hundreds of mrem/yr.) would assure that the period of very low doses for the Yucca Mountain disposal system is extended in time significantly beyond the 10,000 - year period embodied in 40 CFR Part 191.

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