Ramifications of Risk Measures in Implementing Quantitative Performance Assessment for the Proposed Radioactive Waste Repository at Yucca Mountain, Nevada, USA

Sitakanta Mohanty, Center for Nuclear Waste Regulatory Analyses, Southwest Research Institute®, 6220 Culebra Road, San Antonio, TX, USA 78228, smohanty@swri.org

Richard B. Codell, U.S. Nuclear Regulatory Commission, 11544 Rockville Pike, Rockville, MD, USA 20852, rbc@nrc.gov

Received:

ABSTRACT

As part of its preparation to review a potential license application from the U.S. Department of Energy (DOE), the U.S. Nuclear Regulatory Commission (NRC) is examining the performance of the proposed Yucca Mountain nuclear waste repository. In this regard, we evaluated postclosure repository performance using Monte Carlo analyses with an NRC-developed system model that has 950 input parameters, of which 330 are sampled to represent system uncertainties. The quantitative compliance criterion for dose was established by NRC to protect inhabitants who might be exposed to any releases from the repository. The NRC criterion limits the *peak-of-the-mean* dose which in our analysis is estimated by averaging the potential exposure at any instant in time for all Monte Carlo realizations, and then determining the maximum value of the mean curve within 10,000 years, the compliance period. The NRC chose the *peak-of-the-mean* because it more correctly represents the risk to an exposed individual. Procedures for calculating risk in the expected case of slow

repository degradation differ from those for low-probability cases of disruption by external forces such as volcanism. We also explored the possibility of risk dilution (*i.e.*, lower calculated risk) that could result from arbitrarily defining wide probability distributions for certain parameters. Finally, our sensitivity analyses to identify influential parameters used two approaches: (i) the ensemble of doses from each Monte Carlo realization at the time of the peak risk (i.e., *peak-of-the-mean*) and (ii) the ensemble of peak doses calculated from each realization within 10,000 years.

1 INTRODUCTION

Performance assessment of a repository can be defined as a systematic method for studying (i) what can happen, (ii) how likely is it, and (iii) what are the consequences[(1),(2),(2),(3)]. Any performance assessment submitted to the U.S. Nuclear Regulatory Commission (NRC) by the U.S. Department of Energy (DOE) as part of a license application must calculate the projected risk and account for uncertainty in models, scenarios, and parameters. Various performance assessments of the proposed repository at Yucca Mountain have been conducted for more than a decade by the DOE[(4),(5),(6),(7),(8)], Electric Power Research Institute[(9),(10),(11),(12,)(13)], and NRC[(14),(15,)(16,)(17)]. The NRC's main areas of focus in conducting performance assessment are to evaluate the safety of the proposed repository independently and risk-inform prelicensing interactions with DOE related to modeling and data needs. The NRC implemented its independent methodology in the Total-system Performance Assessment (TPA) code[(18)].

Regulations that apply to the Yucca Mountain site have changed over time, and the performance assessments have evolved to reflect these changes. For example, performance assessments prior to about 1995 dealt with 10 CFR 60[(19)] regulations, which stipulated subsystem performance measures such as groundwater travel time to the accessible environment, containment period, and release rates from engineered barriers. Additionally, 10 CFR 60 stipulated a maximum cumulative release to the accessible environment for 10,000 years rather than a dose to individuals or a group. In 1995, the National Academy of Sciences recommended several major changes to the regulations that should apply to the proposed Yucca Mountain repository[20]. In particular, the report recommended that the subsystem requirements should be replaced by an overall performance metric for the repository related to risk to a critical group.

Bearing in mind the findings of the National Academy of Sciences report, the NRC developed regulations [(21)] for licensing the proposed high-level waste repository at Yucca Mountain. In these regulations, the NRC included technical requirements (*e.g.,* quantitative criterion on risk) that, if met by DOE, would be part of the demonstration that the proposed repository could be constructed and operated safely and will protect public health and safety after closure. This paper focuses on those parts of the NRC regulations that deal with postclosure performance assessment.

Performance assessment techniques will be used to demonstrate compliance with the individual protection requirement that limits the *peak-of-the-mean* dose (defined here as the maximum of the average dose during the simulation period) received by a reasonably maximally exposed individual (RMEI) to 15 mrem/yr in the 10,000-year period after repository closure.[(21),(22)] The NRC developed the *peak-of-the-mean* measure of estimated risk to evaluate results of the performance assessment because it represents risk to an individual most fairly.

This paper focuses on four questions encountered in the probabilistic performance assessment of the proposed repository at Yucca Mountain:

(i) How to compute peak risk for a system that has long-term, gradually evolving consequences with high probability of occurrence.

(ii) How to compute peak risk for a system that involves low-probability disruptive events of short duration in addition to the gradually evolving process in (i).

(iii) What can cause "risk dilution" that could lead to an underestimation of peak risk?

(iv) Which performance measures identify most reliably the influential parameters?

The approach for computing risk for a gradually evolving system contrasts with the approach for computing risk for a system that involves low-probability but potentially high-consequence events. The example on risk dilution will show that information selections of parameter distribution functions needed for implementing the Monte Carlo approach could lead to an under-prediction of peak risk. Sensitivity analyses[(23),(24),(25),(26)] will highlight differences as well as the complementary nature of the two performance measures.

2 CALCULATING PEAK RISK

We present procedures for calculating peak risk for two cases: the nominal case and the disruptive event case. The nominal case[(27)] involves slow degradation of repository systems leading to groundwater release and transport of radionuclides to the dose receptor; i.e., the RMEI) located 18 km from the repository as defined in the regulations[(21)]. The alternative case involves events such as volcanism[(28)] that could disrupt repository systems and lead to a relatively larger dose to the receptor from earlier and more rapid airborne releases and transport of radionuclides; however, risk, in this case, could be tempered by low-event probability.

2.1 Nominal Case

For the nominal case, mean dose rate $\overline{D(t)}$ at time t to the receptor individual can be expressed as

$$\overline{D(t)} = \sum_{r=1}^{N} D_r(t) p_r \tag{1}$$

where

$D_r(t)$—dose rate (e.g. dose/year) as a function of time for the r^{th} realization and

p_r —probability of $D_r(t)$; $\sum p_r = 1$.

Each Monte Carlo output result is assumed to have an equal probability of occurrence, *1/N*, thus Eq. (1) reduces to representing an arithmetic mean $1/N \sum_{r=1}^{N} \overline{D_r(t)}$. This expression is a direct measure of risk; that is, it takes into account both the consequence (e.g., dose) to which the RMEI could be exposed and the probability of the exposure. Because each of the dose rate curves, $D_r(t)$, for the nominal case is a slowly varying function of time and is expected to occur in every realization, the mean dose rate $\overline{D(t)}$ converges relatively quickly; i.e., with a small number of realizations.

2.2 Disruptive Event Scenario

Although the standard Monte Carlo approach is suitable for the nominal case that has long-term, gradually evolving consequences and high probability of occurrence, this method is not well suited to the incorporation of effects of the disruptive events, which may be of short duration and have low probability of occurrence (*e.g.*, a recurrence rate of ~ 10^{-8} to 10^{-6}/yr). For a typical nominal case evaluation of Yucca Mountain repository performance using NRC's TPA code,(18) the number of Monte Carlo samples must be greater than the number of sampled parameters, and is generally 350 or more when Latin Hypercube Sampling is used in order to generate a relatively stable mean dose curve. On the other hand, simulations involving disruptive events have been shown to require an impractically large number of realizations to generate a stable risk curve. An event like extrusive volcanism[1] that has a low recurrence rate (10^{-7}/yr in this analysis) through the repository, could require on the order of 10^4-10^5 realizations in 10,000 years to produce a single occurrence. Furthermore, the low-probability events can occur anytime within the 10,000-year time period of interest and do not evolve slowly and more or less predictably by deterioration of the waste material and engineered components as in the nominal case. Finally, the duration of the disruptive events is generally short (years to hundreds of years) compared to that of the nominal case. Many thousands of events would have to occur to produce a stable mean dose curve. Monte Carlo simulation with such a large number of realizations would be impractical because each realization typically takes several minutes to compute using the TPA code. Scenario-based approaches such as those suggested by Helton (1993b)[(27)] are not suitable when the performance measure is the *peak-of-the-mean* dose.

The NRC staff approach to calculating $\overline{D(t)}$ for low-probability events is to convolute the conditional mean dose curves generated, assuming the event has taken place at a time t_e after repository closure. A person living at time t' will only be at risk from events taking place prior to t'. For the volcanism scenario, the average annual dose, $\overline{D(t)}$ to a person living at time t' given that a volcanic event occurs at time $t_e \le t'$ would be

$$\overline{D}(t'|t_e) = a f_1(t_e) f_2(t' - t_e) \qquad (2)$$

[1]Two types of igneous events occur, either (i) a volcanic eruption, which intersects the repository, breaches waste packages, and ejects waste into the atmosphere or (ii) an igneous intrusion that disrupts waste packages but does not directly release waste to the atmosphere. A volcanic event is always associated with a subsurface igneous intrusion, however, an intrusive event does not require formation of a volcano at the ground surface (Mohanty *et al.*, 2002b).

where

$\overline{D}(t'|t_e)$ —conditional dose at time t' given a volcanic event at t_e.

a —peak amplitude of the dose if the event happened at t = 0,

f_1 —peak dose correction factor to account for radioactive decay of the initially buried waste up to the time of the event t_e, and

f_2 —fall-off of dose by radioactive decay and other natural attenuation processes to the person living at t' from an event at time t_e.

Considering that extrusive volcanism has a constant probability of occurring in any year, the risk to a person living at t' is the convolution of all possible prior volcanic events multiplied by the annual event probability, p:

$$\overline{D}(t') = \int_{t_{min}}^{t'} p\, a\, f_1(\tau) f_2(t' - \tau)\, d\tau \qquad (3)$$

t_{min} —the earliest time when volcanism is considered (*e.g.*, 100 years after repository closure).

Because there are relatively few sampled parameters that describe the extrusive volcanism case, each new calculation of $\overline{D}(t')$ for a fixed t_e requires only a modest number of realizations, typically several hundred.

3 Results

Results from the implementation of the methods presented in the previous section for calculating peak risk for the nominal case and the volcanic disruptive case are discussed in this section. Results of additional calculations highlight the effects of risk dilution and idiosyncrasies of sensitivity results applied to the *peak-of-the-mean* risk.

Calculations were performed using Version 4.1 of the TPA code(18). Although doses for disruptive events are calculated for two scenario classes (faulting and extrusive igneous activity), faulting does not have a significant impact on the risk relative to extrusive volcanism for the models and parameters used. The effects of the seismic disruptive event class are included in the nominal case because of their high frequency of occurrence. The probabilities of the two scenario classes, along with the nominal case, are assumed to sum to unity. This implies that other scenario classes are either too improbable (*i.e.*, smaller than 10^{-8}/yr) or have consequences too small to affect significantly the overall risk.

3.1 Peak Risk for the Yucca Mountain Nominal Case

For the nominal case, TPA calculations were performed with 350 Latin Hypercube Sampling realizations out to 10,000 years. Results of the nominal case dose are provided in Figure 2. The mean annual dose (solid line) and the 75th and 95th percentile dose curves (broken lines) are superimposed on the individual conditional dose versus time curves from all 350 realizations. Table 1 and Figure 2 show the peak risk from the nominal case is 0.021 mrem/yr, and the peak occurs at about 10,000 years. Note that the mean dose curve exceeds the 95th percentile curve at times less than approximately 6,000 years and the 75th percentile throughout the 10,000-year period, indicating the mean dose curve is skewed by a few realizations with relatively large doses. Thus, the *peak-of-the-mean* dose appears to be a robust measure of risk; i.e, not overly sensitive to unimportant details.

3.2 Peak Risk for the Yucca Mountain Disruptive Case

Equation 3 was applied to obtain a mean dose curve from the extrusive volcanism case. The function, $f_1 f_2$, (the fall-off of dose as a function of time after burial and elapsed time since the eruptive event) was approximated by a linear interpolation of the mean dose curves generated at a manageably large number of volcanic event times (12 events times used for calculations reported in this paper) between 100 and 10,000 years.

Risk from the extrusive igneous case as a function of time is shown in Figure 3 for an annual probability of 10^{-7}/yr. For comparison, the figure also shows the risk curve for the nominal case. As shown in Table 1 and in Figure 3, the peak risk for the extrusive igneous case is 0.35 mrem/yr occurring at 245 years. The time when the peak occurs in the disruptive case is much earlier than in the nominal case because dose consequences are largest for events that may occur soon after repository closure, when the relatively short-lived but high-activity radionuclides such as Am-241 (half-life 423 years) are still present in significant quantities. The risk curve reaches a maximum at 245 years, rather than immediately after the event because of the accumulation of risk from probabilistically weighted earlier events.

3.3 Risk Dilution

The term "risk dilution" connotes that the estimated peak risk would be reduced unknowingly by an inappropriate choice of parameter ranges. For example, the choice of wide distributions that go beyond the available data may lower the *peak-of-the-mean* dose even though greater uncertainty is being taken into account. To illustrate this effect, the range of a single sampled parameter in the TPA code, drip-shield failure time, was increased while the mean of all other sampled parameters remained unchanged. We specified the parameter range for the original distribution of drip shield failure time as 4,000–6,000 years and 0–10,000 years for the modified distribution (Figure 4). Both distributions had identical means of 5,000 years, however, the variance of the modified distribution was much larger. Peak mean doses for these cases were then obtained for the 10,000-year simulation period using 100 Monte Carlo realizations each. Because sampling of all other parameters was identical, these results reflected only the differences caused by the different ranges of the drip-shield failure time.

For the narrower range, the peak risk of 5.1×10^{-2} mrem/yr occurs at 6,407 years whereas the wider range results in a peak risk of 4×10^{-2} mrem/yr, at 10,000 years. Although the change is small in this example case, it is unmistakable. The difference in the peak risks is caused by two factors: (i) the wider distribution delays some releases past 10,000 years and (ii) the wider distribution results in spreading the peak doses for each of the realizations, which reduces the superposition of peaks that would occur more frequently using the narrower distribution. This calculation illustrates that risk dilution can occur if large ranges unsupported by data are used, especially for those parameters that affect the timing of the peak dose for each realization. Therefore, distributions of at least those parameters that influence timing of the release should be carefully estimated for performance assessment.

3.4 Peak Risk in the Context of Sensitivity Analysis

The performance assessment model has a large number of input parameters that are described by distribution functions representing uncertainties and variability. Of the 330 input parameters in the most current NRC performance assessment model, there are at most a few tens of parameters that influence the results significantly. We performed a parametric sensitivity analysis of the Monte Carlo performance assessment results to determine changes in the response caused by changes in the input parameters for the given ranges. Knowledge of the most influential input parameters is important. Among other things, it can improve understanding of the system and allow us to concentrate on the most important models and parameters.

Compliance with the quantitative postclosure risk limits will be based on the *peak-of-the-mean* dose. However, parameters sensitivity analysis is based on dose responses caused by changes in input parameters. Two possible ways to measure the dose response are Method 1—evaluate the dose from each vector at a fixed time (*i.e.*, the time at which the *peak-of-the-mean* dose occurs) and Method 2—evaluate the peak dose from each vector regardless of time (as long as it occurs within the time period of interest, such as 10,000 years). Figure 5 illustrates peak doses from each realization of a Monte Carlo set (filled circles) and doses corresponding to the time of the peak mean dose (empty circles). The mean dose curve is shown by the dotted line. There are advantages and disadvantages of each approach. Using Method 1 maximizes the relevance of the parameters and models to the regulatory criterion. Method 2 has the advantage of working with larger doses; i.e., the peak dose from each realization. This method, therefore, has potentially greater discriminatory power in the statistical sense because it is able to distinguish more readily an actual response within the background of computation "noise" created by the Monte Carlo technique. There are some differences, however, in results interpreted from the two methods. Sensitivities of parameters that determine the timing of the releases from the repository (*e.g.*, drip shield failure time) are higher in Method 2 for the same reason that explains the risk dilution result (*i.e.*, spreading the individual peak doses leads to a diminished *peak-of-the-mean* dose). The fact that the dose values used in Method 2 are equal to or greater than the dose values used in Method 1 is evident in Figure 5. In this figure, the dose values for all three realizations at the time of the *peak-of-mean* dose are lower than the peak doses from each of these realizations.

Figures 6 shows the relative sensitivity for the most influential parameters determined from the two methods. The sensitivity measure in the y-axis shows the relative influence of the parameter on the output. Most of the full parameter names are intentionally omitted (identified only by symbols) because the significance of the sensitive or influential parameters in these figures is beyond the scope of this paper, and not necessary to explain the results. Description of these abbreviated parameter names can be found in Mohanty, et al., (2002a).[17]

We present results from only one of the several sensitivity analysis techniques used[30] to illustrate similarities and difference for the two methods. Results of the two methods have many important parameters in common. A few differences provide useful insights, however. Four parameters (SFWt%I10, SFWt%I5, SFWt%I3, and SFWt FI1, which are the fractions of spent fuel wetted for initially failed waste packages in four of the repository subareas appear in the list of most important parameters using Method 1 (Figure 6a), but not in the list using Method 2 (Figure 6b). Conversely, four parameters genlvirC, (leafy vegetable irrigation rate), MPrm-PPw, (matrix permeability of the Prow Pass welded tuff), DTFFAVIF (distance traveled in saturated tuff), and Fpr_STF (frature porosity of the saturated tuff), identified by Method 2 (Figure 6b) do not appear in the list identified by Method 1 (Figure 6a). Even for those parameters identified by both methods, the rankings within the lists were frequently somewhat different. The clearest example of this is the parameter “drip-shield failure time” (DSFailTi), which appears as the third most important parameter in Method 2, but is ranked only 20th using Method 1. No change in rank was observed only for AAMAI@S and MAPM@GM, the top two parameters in both methods.

The most likely reason for the difference for the ranking between the two methods is that some parameters have an influence predominantly on the timing of the peak dose within a realization, whereas other parameters have an influence predominantly on the magnitude of the peak. The parameters, MPrm-PPw, DTFFAVIF, Fpr STF, and DSFailTi all affect the timing of the peak, and therefore have a lower influence on the peak-of-the-mean does.

4 CONCLUSIONS

Although the calculation of the peak risk for the nominal case is straightforward, calculations for the disruptive case are more complicated to produce stable mean dose curves with a reasonable number of realizations when the event probability is small, event times are random, and release rates are of relatively short duration.

It is possible to conduct sensitivity analyses using doses calculated at the time corresponding to the maximum risk or using the peak dose from each Monte Carlo realization. Quantitative comparisons suggest that using the peak dose from each realization can provide greater discriminatory power because of their larger magnitude, which makes this approach less prone to noise. However, some parameters, especially those that determine timing of the releases, should be carefully interpreted for the impact of their associated uncertainties on system performance. It is, therefore, useful to perform the analysis both ways.

Analysts must guard against risk dilution caused by inappropriately increasing the bounds of the distribution of poorly known parameters, especially if these parameters affect the timing of peak dose within a realization.

It is important to note that although the dose versus time curves vary from realization to realization, there is only one mean dose curve, and there is only one maximum of the mean dose curve. The sensitivity analyses presented in this paper are concerned mainly with the response of the dose in a realization to a change in an input parameter, and not directly to the change in the mean dose. Mohanty and Wu (2002) present an analysis for the direct sensitivity of the mean dose curve to the moments of the input parameters (e.g., mean and standard deviation).

5 ACKNOWLEDGMENTS

The authors would like to thank Timothy McCartin and Patrick LaPlante for the insights they provided during the early part of the development of this paper and Jose Menchaca for assisting with computer code executions and preparing several figures presented in this paper. The authors would also like to thank David Esh and Budhi Sagar for their technical reviews and Ruth Mantooth for her typographical assistance in the preparation of this paper. The paper was prepared to document work performed by the Center for Nuclear Waste Regulatory Analyses (CNWRA) and the U.S. Nuclear Regulatory Commission (NRC) under Contract No. NRC–02–97–009. Activities

reported here were performed on behalf of the Office of Nuclear Material Safety and Safeguards. The paper is an independent product of CNWRA and the NRC staff, and does not necessarily reflect the views or regulatory position of NRC.

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Footnotes

[1]The term “case” is used to contrast with the term “scenario”. “Case” refers to a combination of scenarios. For example, each Monte Carlo realization represents a scenario.

[1]Two types of igneous events occur, either (i) a volcanic eruption, which intersects the repository, breaches waste packages, and ejects waste form in the waste packages into the atmosphere or (ii) an igneous intrusion that disrupts waste packages but does not directly release waste form to the atmosphere. A volcanic event always is associated with a subsurface igneous intrusion, however, an intrusive event does not require formation of a volcano at the ground surface (Mohanty *et al*., 2002b).

Table 1. Peak mean dose estimated for various scenarios using NRC's independently developed performance assessment

Cases	Dose (mrem/yr)	Peak occurred at (years)
Nominal Case	0.021	9,769
Igneous activity (Probability weighted)	0.35	245
Faulting	Similar to the nominal case	Similar to the nominal case

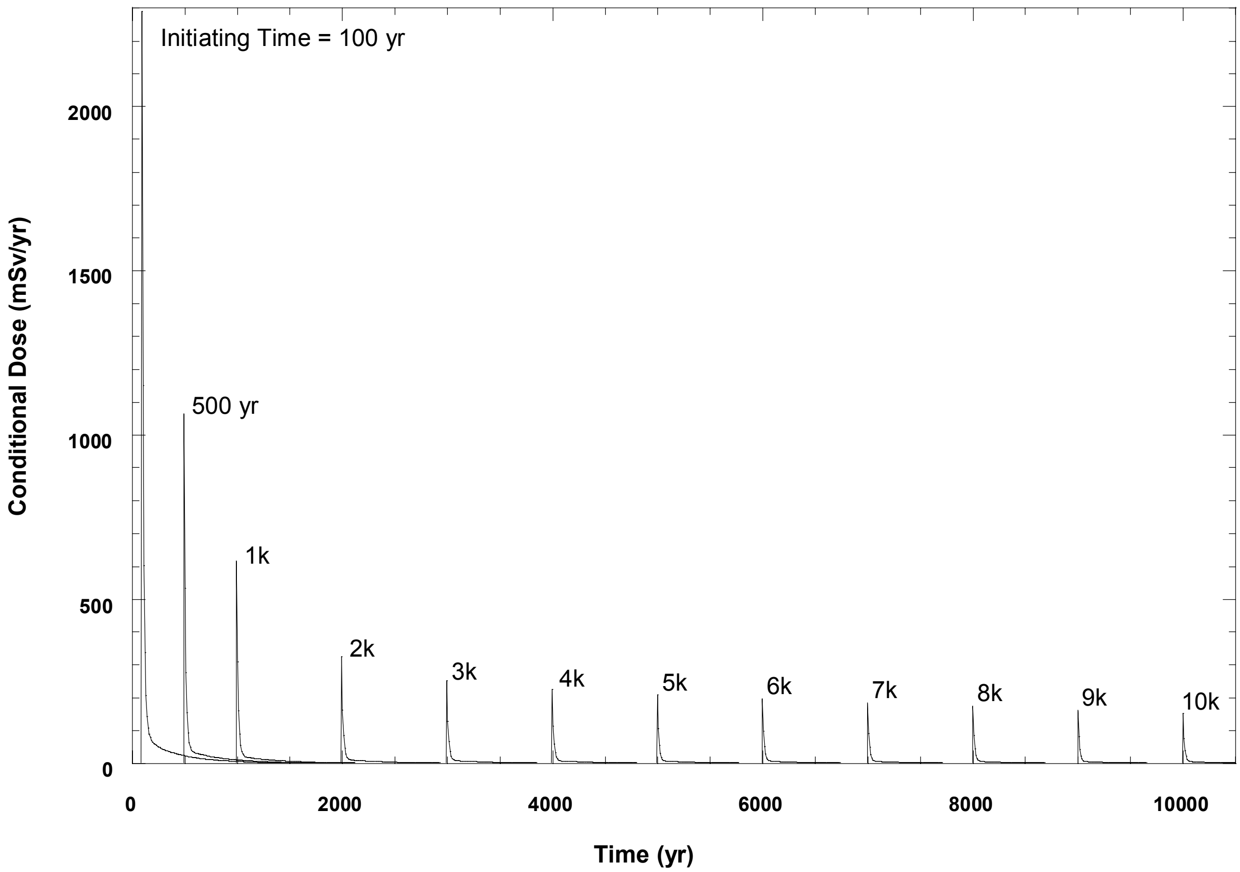

Initiating Time = 100 yr
500 yr
1k
2k
3k
4k
5k
6k
7k
8k
9k
10k
Conditional Dose (mSv/yr)
0
500
1000
1500
2000
0
2000
4000
6000
8000
10000
Time (yr)

Figure 1

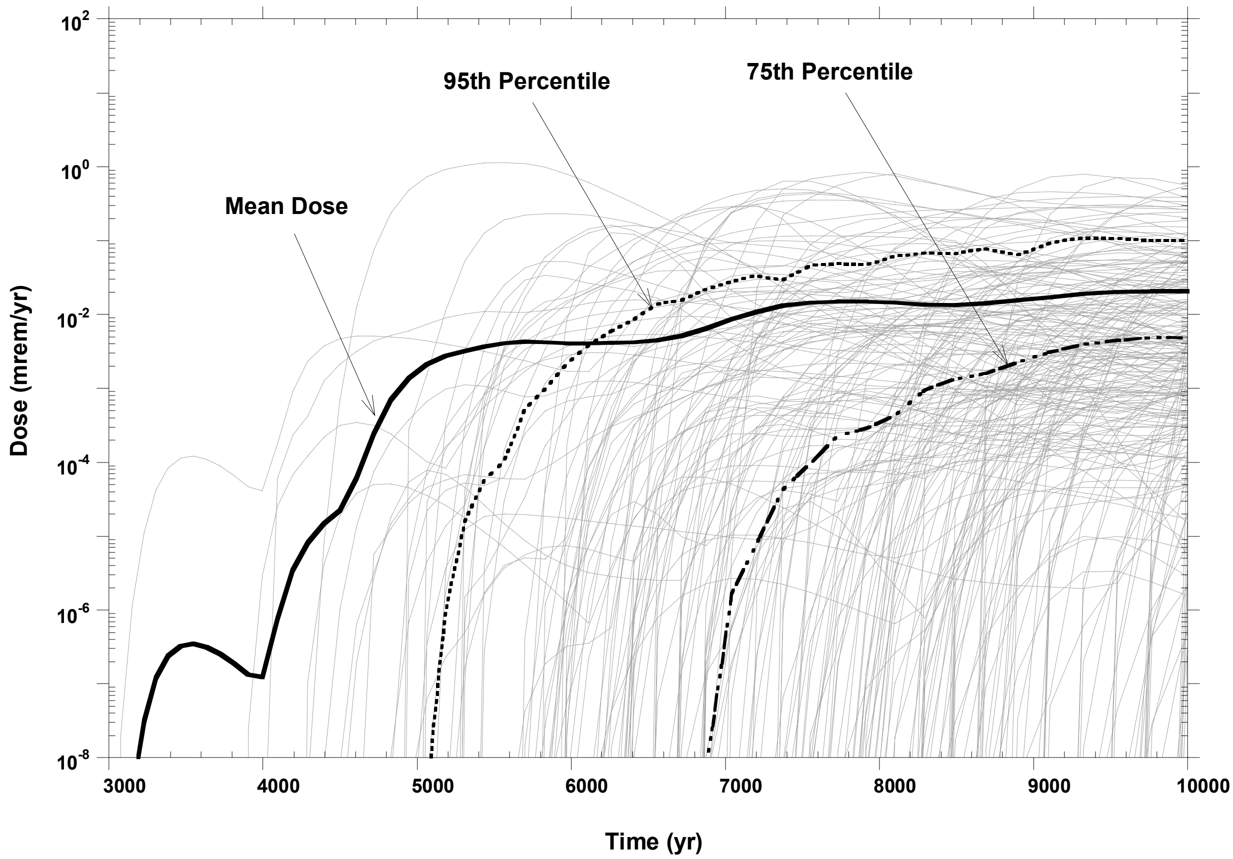
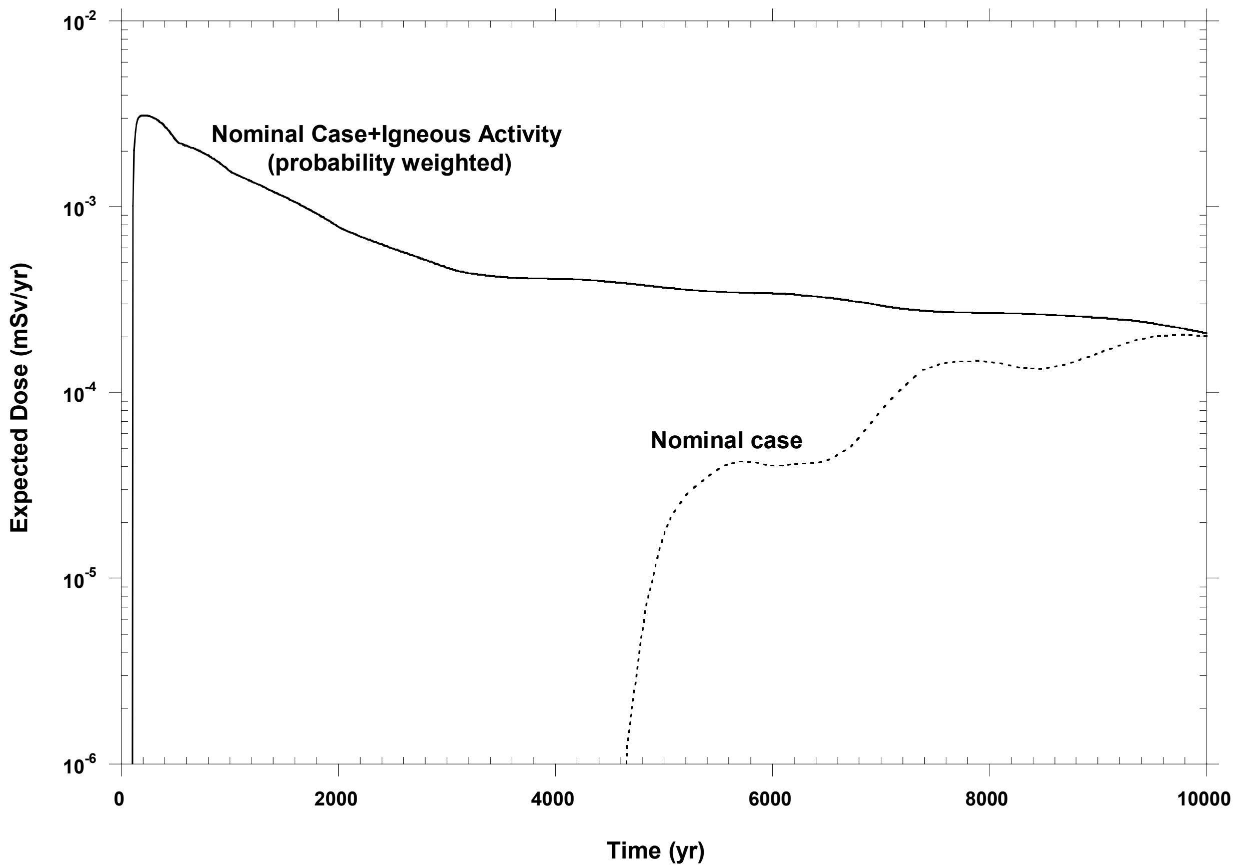
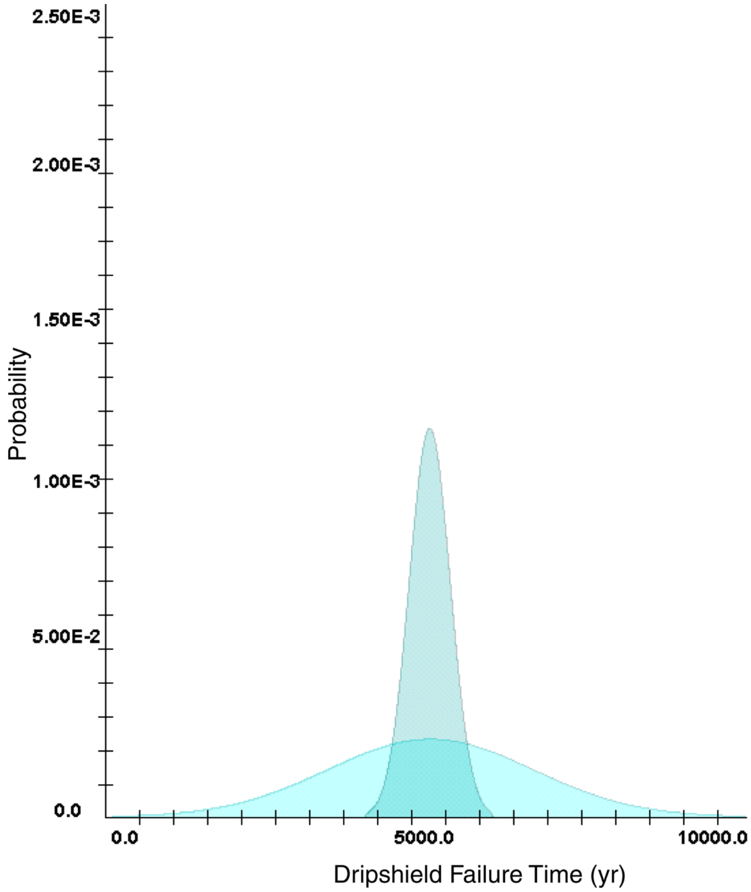

95th Percentile
75th Percentile
Mean Dose
Dose (mrem/yr)
10^2
10^0
10^-2
10^-4
10^-6
10^-8
3000
4000
5000
6000
7000
8000
9000
10000
Time (yr)

Figure 2



Nominal Case+Igneous Activity
(probability weighted)
Nominal case
Expected Dose (mSv/yr)
Time (yr)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0
2000
4000
6000
8000
10000

Figure 3



2.50E-3
2.00E-3
1.50E-3
1.00E-3
5.00E-2
0.0
Probability
0.0
5000.0
10000.0
Dripshield Failure Time (yr)

Figure 4

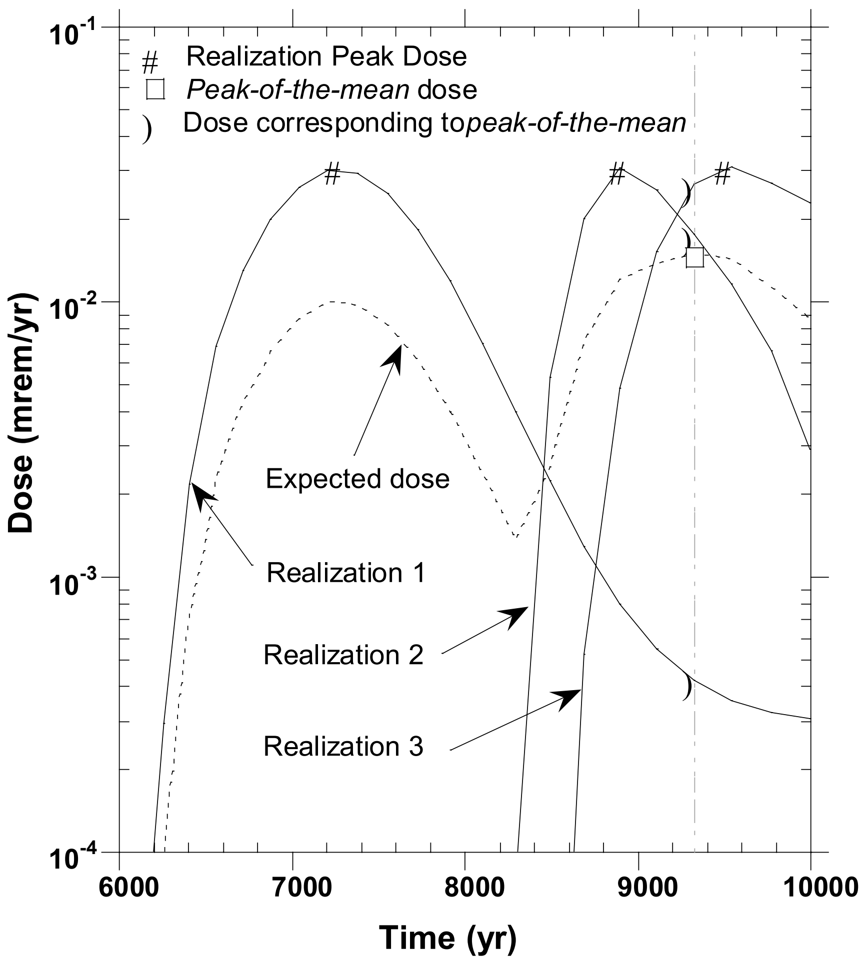
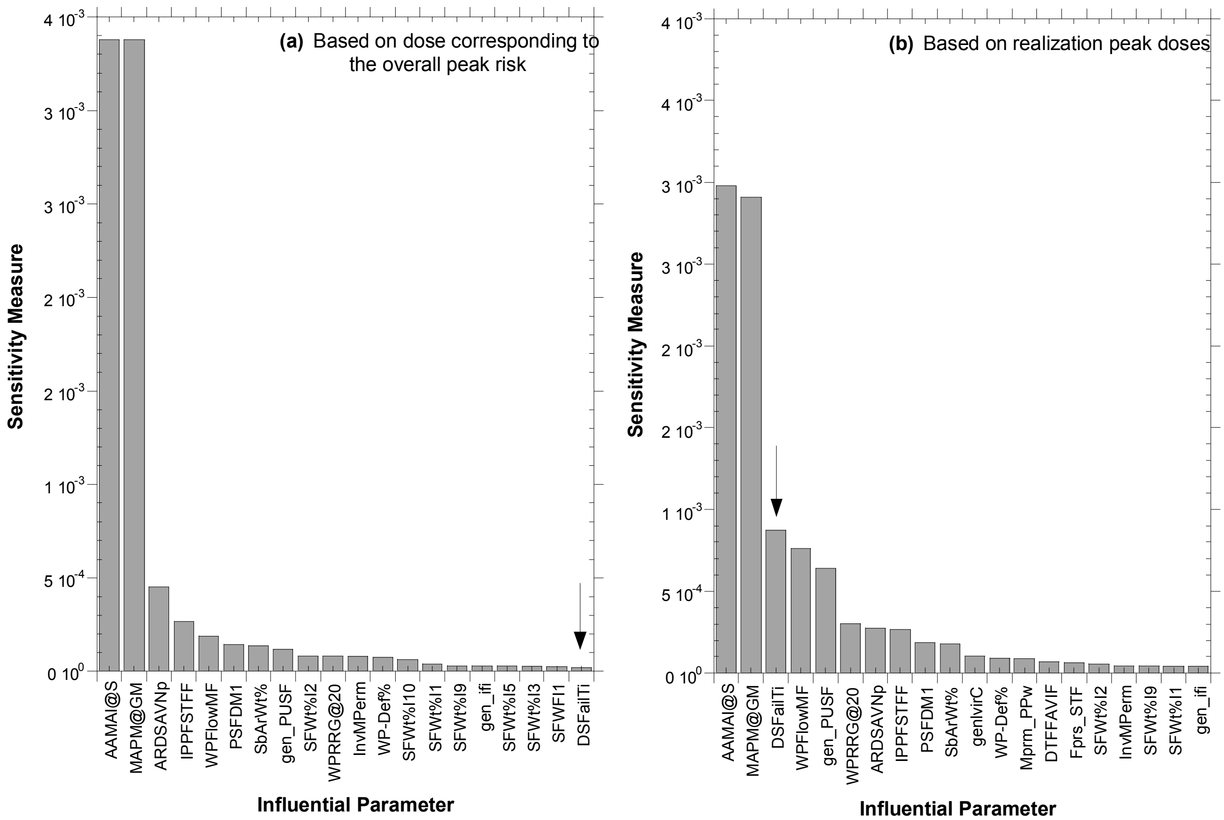


Figure 5



(a) Based on dose corresponding to the overall peak risk
Sensitivity Measure
4 10-3
3 10-3
3 10-3
2 10-3
2 10-3
1 10-3
5 10-4
0 100
AAMAI@S
MAPM@GM
ARDSAVNp
IPPFSTFF
WPFlowMF
PSFDM1
SbArWt%
gen_PUSF
SFWt%I2
WPRRG@20
InvMPerm
WP-Def%
SFWt%I10
SFWt%I1
SFWt%I9
gen_ifi
SFWt%I5
SFWt%I3
SFWFI1
DSFailTi
Influential Parameter
(b) Based on realization peak doses
Sensitivity Measure
4 10-3
4 10-3
3 10-3
3 10-3
2 10-3
2 10-3
1 10-3
5 10-4
0 100
AAMAI@S
MAPM@GM
DSFailTi
WPFlowMF
gen_PUSF
WPRRG@20
ARDSAVNp
IPPFSTFF
PSFDM1
SbArWt%
genIvirC
WP-Def%
Mprm_PPw
DTFFAVIF
Fprs_STF
SFWt%I2
InvMPerm
SFWt%I9
SFWt%I1
gen_ifi
Influential Parameter

Figure 6

Figure 1. Mean doses arising from extrusive igneous activity shown with various times for the volcanic event in 400 realizations.

Figure 2. Conditional doses, mean dose, and quantiles as a function of time from 350 nominal-case realizations. Note that the mean dose exceeds the 95th percentile dose at early times.

Figure 3. Mean dose as a function of time for the nominal case and the extrusive igneous case. Probability weighting of the igneous activity scenario uses a value of 10^{-7} per year.

Figure 4. Histograms for the sampled values of drip shield failure time, with two different ranges but with the same mean value. The values are sampled from normal distributions with equal mean values.

Figure 5. Schematic showing realization doses corresponding to the peak mean dose and peak dose for each realization. The dotted curve is the mean dose versus time.

Figure 6. Identification of influential parameters using (a) dose values from each realization corresponding to the overall peak risk and (b) using the peak doses in 10,000 years from individual realizations