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U.S. Nuclear Regulatory Commission
ATTN: Mrs. Deborah A. DeMarco
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Subject: Programmatic review of paper for Waste Management 2002 conference titled "An Approach to Implementing Quantitative Performance Assessment for the Proposed Radioactive Waste Repository at Yucca Mountain, Nevada, USA"

Dear Mrs. DeMarco:

Attached is the subject paper which will be submitted for publication in the proceedings volume of the Waste Management 2002 conference (Tucson, Arizona, February 24–28, 2002). The version of the paper that was orally presented at the conference was previously approved by J. Firth in an email to you dated February 26, 2002. The paper describes NRC approach for computing peak expected dose for the most likely scenario and the disruptive event scenarios. The paper also presents an example showing the effect of risk dilution on peak expected dose and argues that the use of peak dose from each Monte Carlo realization may be more robust compared to doses corresponding to the peak expected dose in sensitivity analyses.

Please advise me of the results of your programmatic review. Your cooperation in this matter is appreciated. Please contact Sitakanta Mohanty at (210) 522-5185 if you have any questions regarding this paper.

Sincerely yours,

Budhi Sagar
Technical Director

Enclosure

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An Approach to Implementing Quantitative Performance Assessment for the Proposed Radioactive Waste Repository at Yucca Mountain, Nevada, USA

by
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ABSTRACT

Technical approaches for implementation of regulatory criteria applicable to post-closure performance assessment for the proposed Yucca Mountain nuclear waste repository are discussed and investigated. Recommended approaches are supported by quantitative performance assessment calculations. Formulations are presented for calculating risk for the most likely scenario as well as a scenario in which the probability of occurrence is expected to be low. The calculated risk value includes both the consequence of the scenario and its associated low probability. Overall performance is evaluated using Monte Carlo analyses to develop a risk curve of repository behavior (i.e., the variation of the mean or average risk over time). To identify influential parameters, sensitivity analysis can be performed using the peak dose or risk value from each realization of the Monte Carlo analysis or the contribution to dose or risk from each realization to the overall peak dose or risk. The magnitude of sensitivity measures indicate the use of peak dose or risk from each realization may be more discriminatory than the use of dose or risk values from each realization corresponding to the overall peak dose or risk. Finally, the risk dilution that could impact peak expected dose is demonstrated.

1 INTRODUCTION

The NRC has developed regulations (NRC, 2001) for licensing the proposed High-level nuclear waste repository at Yucca Mountain, Nevada. In these regulations, the NRC has included technical requirements that, if met by the DOE, would help to demonstrate the proposed repository could be constructed and operated safely, and provide long-term confinement of the waste from the environment. Requirements relate to site description, performance assessment for pre-closure and post-closure time periods, schedules for waste acceptance and disposal, plans for site security, radioactive material control, records, emergency plans, and access restrictions. The focus of this paper is on the post-closure performance assessment.

Performance assessment can be defined as a systematic method for studying (i) what can happen at a repository, (ii) how likely it is to happen, and (iii) what can result. Performance assessment techniques will be used to demonstrate compliance with the individual protection requirement that limits the peak risk to the reasonably maximally exposed individual (RMEI) to 15 mrem/yr in the 10,000 year period after repository closure. A performance assessment submitted with a license application must calculate the mean of projected risk and account for uncertainty in models, scenarios and parameters. Parameter uncertainty is usually taken into account through the use of probabilistic methods where parameters are sampled from distributions to produce a distribution of the performance measure(s). Monte Carlo analysis propagates the uncertainty in model parameter inputs through the conceptual models. The output of the Monte Carlo analysis is a set of results such as dose versus time, for each of the randomly chosen input sets. Each possible future behavior of the repository system is represented by a curve describing the annual risk to the RMEI as a function of time. Consequently, overall performance is based on numerous model runs developed in Monte Carlo simulations. In this approach, the risk is averaged over all realizations at each instant in time, and the highest value over the compliance period represents the peak risk.

An approach for calculating the peak risk using a Monte Carlo style total system performance assessment calculation is documented and analyzed to illustrate its usefulness for demonstrating safety at a proposed repository. Sensitivity analyses on the results of the calculations are conducted using different performance measures to demonstrate the most effective approach to identifying important input parameters in the post-closure performance assessment calculations.

2 APPROACH FOR CALCULATING PEAK RISK

Formulas for calculating peak risk for two types of scenarios are presented in the following subsections. The most likely scenario (i.e., the nominal case) is based on expected behavior of repository systems over the period of compliance. This scenario involves slow degradation of repository systems over time leading to groundwater release and transport of radionuclides to the dose receptor location defined in the regulations. A disruptive event scenario includes consideration of much less likely events that could disrupt repository systems more rapidly leading to earlier and more rapid releases of radionuclides to the receptor location. Because risk is defined as the product of consequence and probability, the consequences of the disruptive scenarios are tempered by the low probability of the disruptive events when a risk value is calculated.

2.1 Most Likely Scenario

For the most likely scenario, expected dose rate $\overline{D}\big|_t$ at time t to the receptor individual can be expressed as:

$$\overline{D}\big|_t = \left[\sum_{r=1}^{N} D_r p_r\right]_t \tag{1}$$

where D_r = dose rate as a function of time for the rth realization and p_r = probability associated with the dose curve for the rth realization. Most commonly, each Monte Carlo output result has equal probability 1/N, thus Eq. (1) reduces to representing an arithmetic mean $\left[\frac{1}{N}\sum_{r=1}^{N} D_r\right]_t$. The analysis does not explicitly include conceptual model uncertainty, other than that captured by changes in the input parameters. This performance measure is a direct measure of risk; i.e., it takes into account both the hazard of the dose to which the affected person or group was exposed, and the probability of being exposed.

2.2 Disruptive Event Scenario

Unlikely events, such as a volcanic eruption through the repository block (i.e., volcanism), are generally of short duration. While the standard Monte Carlo approach is suitable for the nominal case scenario that has long-term, gradually evolving consequences, and high probability of occurrence, the method is not well suited to the incorporation of the effects of the disruptive events. For a typical nominal case scenario evaluation of Yucca Mountain repository performance using NRC's Total System Performance Assessment (TPA) code (Mohanty and McCartin, 2001), approximately 350 runs are needed to generate a stable risk curve. On the other hand, Monte Carlo simulation of disruptive events will require a very large number of realizations because of its low likelihood of occurrence. In general, the number of Monte Carlo realizations would be inversely proportional to the probability of occurrence if the time for the event to occur was a sampled parameter. For example, if the annual probability of occurrence of a disruptive event is 1.0E-7, nearly 10,000,000 Monte Carlo realizations may be needed to obtain a stable expected risk curve. Monte Carlo simulation with such a large number of realizations would be prohibitively expensive because each consequence calculation for each realization could take several minutes in the NRC model.

The current NRC staff's approach to generate the risk curve for low probability events is to convolute the conditional dose curves generated assuming that the event has taken place at a random time after repository closure, t_e. A person living at time t' will only be at risk from all events taking place prior to t'. For the volcanism scenario, the average dose D per year to a person living at time t' who is exposed to a volcano occurring at time t_e would be:

$$D = af_1(t_e)\, f_2(t'-t_e) \qquad (2)$$

where a = the peak amplitude of the dose if the event happened at time=0, f_1 = the peak dose correction factor to account for radioactive decay at time t_e, and f_2 = the falloff of dose to the person living at t' from an event at time t_e. Considering a volcano has a fixed probability of occurring in any year, the risk per year to a person living at t' is the convolution of all possible prior volcanic events multiplied by the annual probability p:

$$\overline{D}(t') = \int_{t_e=0}^{t'-t_{\min}} paf_1(\tau)\, f_2(t'-\tau)d\tau$$

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

In practice, the function $f_1 f_2$ within the integrand is generated by calculating the average risk curve for fixed values of t_e using a limited number of realizations in the TPA code (e.g., 350 for the example shown), and then using linear interpolation to generalize to any value of t_e.

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 event scenario are discussed in this section. Results of additional calculations highlight risk dilution effects and the effect of the peak risk approach on sensitivity analysis results.

The calculations were done using the TPA code (version 4.1k). Although doses for disruptive events are calculated for two scenario classes (faulting and igneous activity), results are shown only for the nominal case with igneous activity because faulting does not show do not significant impact on the risk. Currently, the effects of the seismic disruptive event class is included in the nominal case. The probability of the two scenario classes along with the most likely scenario (i.e., the nominal case) is assumed to sum to unity. This implies that other scenario classes are either too improbable (i.e., smaller than 1.e-8 per yr), or have consequences too small to significantly affect the overall risk.

3.1 Peak Risk for the Most Likely Scenario

For the nominal case, TPA calculations were performed with 350 Latin Hypercube Sampling (LHS) realizations. Performance calculations were carried out to 10,000 yr. Results of the nominal case risk are provided in Figure 1. The risk (dotted line in the figure), 75th percentile, and 95th percentile risk curves are superimposed on the individual risk versus time curves from all 350 realizations. Table 1 and this figure show that the peak risk is 0.021 mrem/yr and the peak occurs at 9769 yr. It should be noted that the peak mean risk exceeds the 95th percentile at early times (i.e., less than 6000 years) and the 75th percentile throughout the 10,000 yr period. With a peak mean risk value of 0.021 mrem/yr, the mean or the expected value already reflects a high degree of confidence that dose limits will not be exceeded.

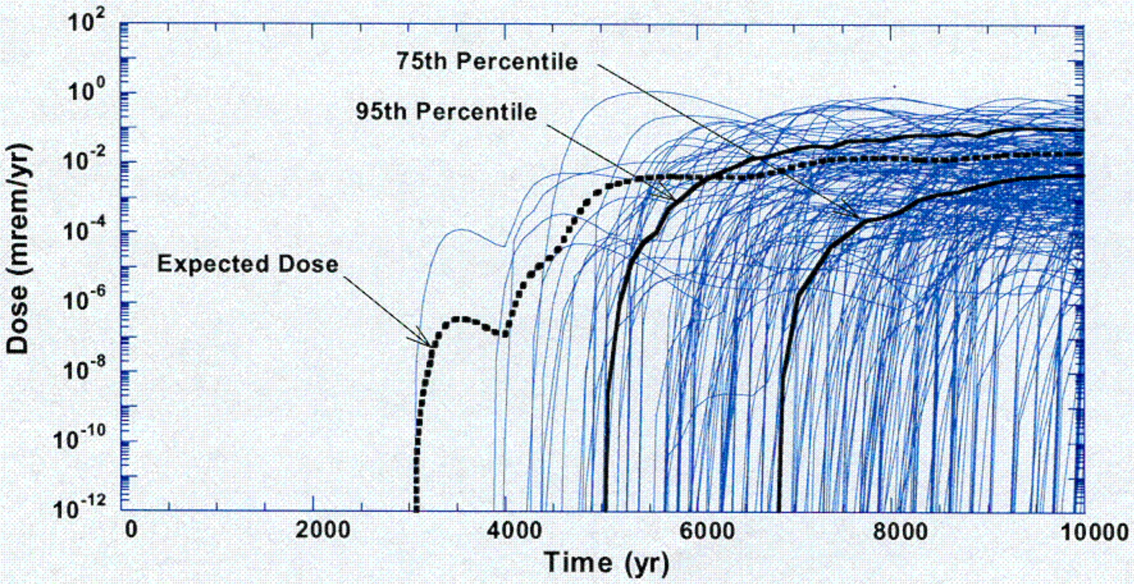

Figure 1. Dose as a function of time from 350 nominal-case realizations. Note that the expected dose exceeds 95th percentile dose at early times.

Table 1: Peak expected dose estimated for various scenarios using NRC's independently developed performance assessment approach

Cases	Dose (mrem/yr)	Peak occurred at (yr)
Nominal Case	0.021	9769
Igneous activity (Probability weighted)	0.34877	at 245 years
Faulting	Similar to the nominal case	Similar to the nominal case

C01

3.2 Peak Risk for the Disruptive Event Scenario

For the disruptive event case, performance calculations were done for a time period from repository closure to 10,000 years. Equation 3 was applied to obtain an overall expected dose curve from the volcanism scenario. The function $f_1 f_2$ (the fall-off of dose with time after burial and elapsed time since the eruptive event) was approximated by a linear interpolation of the mean dose curve generated at 12 assumed volcano event times. The 12 assumed volcano event times were: 100, 500, 1000, 2000, 3000, 4000, 5000, 6000, 7000, 8000, 9000, and 10,000 yr. TPA calculations were carried out for direct release and groundwater release dose consequences corresponding to each event time with 350 LHS realizations.

Risk (i.e., probability-weighted doses consequences) from the igneous activity disruptive event scenario as a function of time is shown in figure 2. For comparison purposes, the figure also shows the risk curve for the nominal case as a function of time. As shown in table 1 and in figure 2, the risk for the igneous activity disruptive event scenario is 0.348 mrem/yr with the peak occurring at 245 yr. The time when the peak mean risk occurs in the igneous activity disruptive event case is much earlier than the nominal case because dose consequences are largest for events that may occur soon after repository closure, while the relatively short-lived but high-activity radionuclides such as ^{241}Am are still present in significant quantities. Radionuclides can reach the affected population in short times (hours to days), but persist in the environment and cause lower levels of exposure long after the event (e.g., hundreds of years).

3.3 Peak Risk in the Context of Risk Dilution

The peak risk could be affected by risk dilution. Risk dilution is the effect of lowering a mean risk by inappropriately increasing input parameter uncertainties in a Monte Carlo style calculation.

To illustrate this effect, the range of a single sampled parameter in the TPA code was artificially increased while the mean of the parameter remained unchanged. For the purposes of this paper, parameter drip shield failure time was selected. For illustration, two sensitive cases are created, with identical mean drip shield failure time but different ranges. The drip shield failure time is assumed to have a normal distribution, which permits easy change of the range without altering the mean value. Parameter ranges for the two test cases are 4,000-6,000 yr and 0-10,000 yr with a mean value of 5,000 yr. Peak expected doses for these cases are then obtained for 10,000 yr simulation period using 100 Monte Carlo realizations each.

The first case (i.e., the narrow range shown in figure 3) results in a peak risk value of 5.083×10^{-2} mrem/yr occurring at 6,407 yr whereas the second case (i.e., the wider range) results in a peak risk value of 3.984×10^{-2} mrem/yr occurring at 10,000 yr. It should be noted that the two TPA runs are identical except the range has been changed. Consequently, the difference between the two values of the peak risk can be attributed solely to the difference in the range of the drip shield failure time. Although, the difference in the peak risk in the test are not substantial, the calculation nonetheless illustrates that risk dilution can occur and could be amplified if excessively large ranges were used for a number of input parameters. Caution must be exercised to avoid bias by risk dilution; e.g., inappropriately increasing a distribution in a poorly known parameter causing an inappropriate spread in the timing of the peak or magnitude of the peak mean risk.

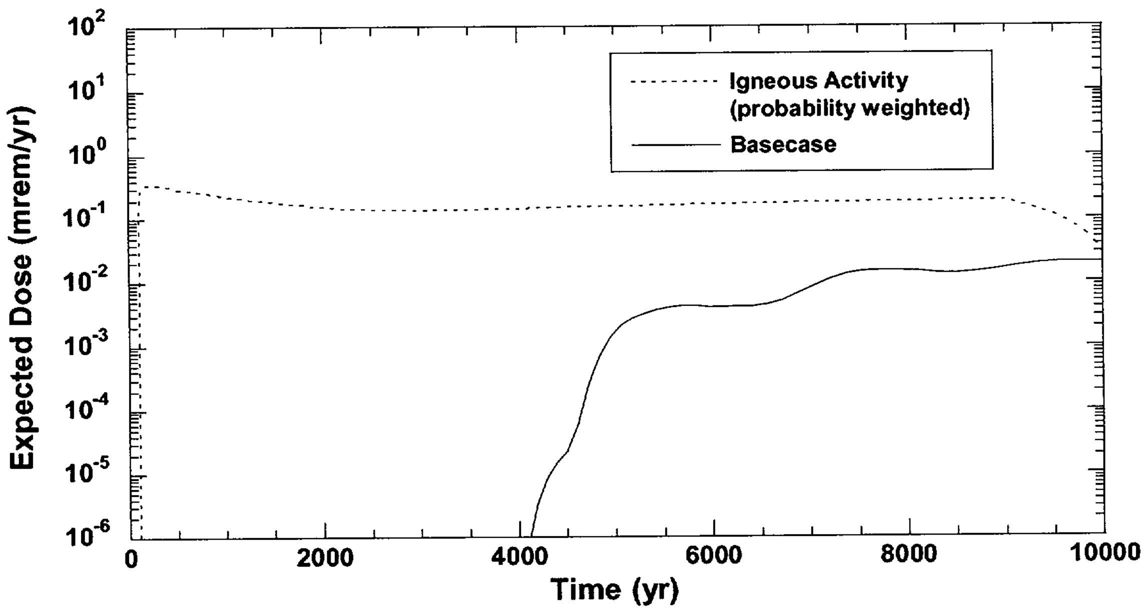

Figure 2. Expected dose as a function of time for the nominal case (i.e., most likely scenario) and the igneous activity scenario. Probability weighting of the igneous activity scenario uses a value of $1x10^{-7}$ per year.

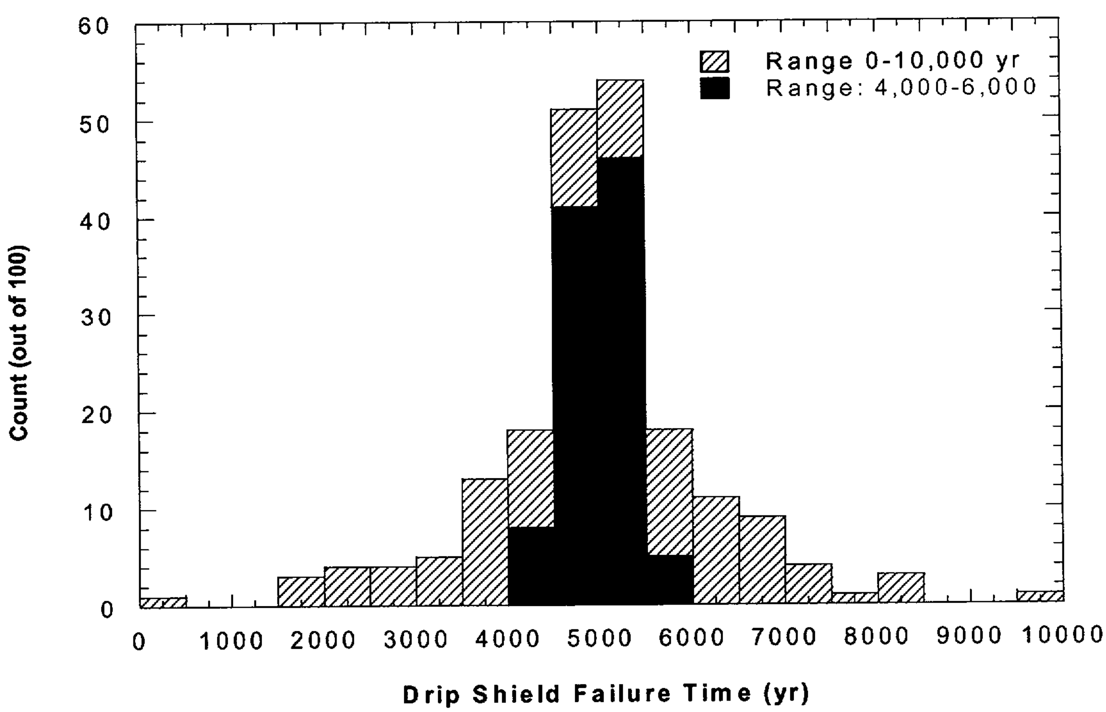

Figure 3. Histograms for the sampled values of drip shield failure time, with two different ranges but with the same mean value. The values are sampled from normal distributions with equal mean values.

3.4 Peak Risk in the Context of Sensitivity Analysis

Parametric sensitivity analyses are used to determine the most important parameters for performance of the repository. As noted earlier, compliance with the quantitative post closure individual protection limit will be based on the peak of the risk curve. Although it would be possible to determine the sensitivity response at a single time (i.e., the time of the peak risk) of the mean risk curve, the peak risk values of individual realizations simplify sensitivity analyses. When compared with sensitivity analysis using the risk contributions from individual realizations to the overall peak risk, the use of peak values associated with each realizations improves the capability to identify important parameters over the whole regulatory period.

Figures 4 and 5 show the relative sensitivity for the most influential variables determined two ways: (1) using the contribution of each realization to the overall peak risk (the overall peak risk will occur at a single point in time and each realization will have its own contribution to this single overall peak) and (2) using the peak risk from each realization (peak risk for a specific realization will be associated with its own specific time for it to occur). The sensitivity measure in the y-axis shows the magnitude of the influence the variability or uncertainty in the parameter has on the output variability. 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. The sensitivity measure reflects the measure presented in Morris (1991).

Results are presented from only one of the many sensitivity analysis techniques used to illustrate the difference in results based on the two risk measures, i.e., the peak risk (method 1) and peak-of-the-realization risk (method 2). Many similarities are identified in the results comparing both methods, however, a few differences provide useful insights. Four variables (SFWt%I10, SFWt%I5, SFWt%I3, and SFWFI1 in figure 5) do not appear in the sensitivity analysis of dose corresponding to the peak expected dose shown in figure 4. Four parameters (genlvirc, Morm-PPw, DTFFAVIF, and Fprs-STF in figure 4) identified by method 1 do not appear in the list identified by method 2. The rankings from the two methods were also substantially different. For example, parameter DSFailTi in figure 4, which shows up as the 3rd most important parameter in method 1, is ranked 20th using method 2 (figure 5). No change in rank was observed only for AAMAI@S and MAPM@GM (i.e., the top two parameters in both methods).

Because method 2 is based on the maximum change in risk in a realization, the sensitivity measures show larger magnitudes. In addition, the maximal change reflects the change that can occur at any time during the 10,000 yr period. The dose value corresponding to peak risk may be much lower than the realization peak. Therefore, we suggest that the peak risks from each Monte Carlo realization (i.e., method 2) should be used in sensitivity analyses. Calculations are currently underway to provide quantitative justification for this suggestion.

4 CONCLUSIONS

Available techniques can be used to calculate peak risk for nominal and disruptive events calculations conducted using a complex Monte Carlo style performance assessment code. While the calculation of the peak risk for the nominal case is straightforward, calculations for the disruptive event are more complicated because it requires numerous model runs to appropriately factor in the low event probability. While it is possible to conduct sensitivity analyses using realization risks corresponding to the overall peak risk, quantitative comparisons suggest the peak risk of each realization provides more meaningful results for such analyses. Analysts must still guard against risk dilution by inappropriately increasing a distribution in a poorly known parameter.

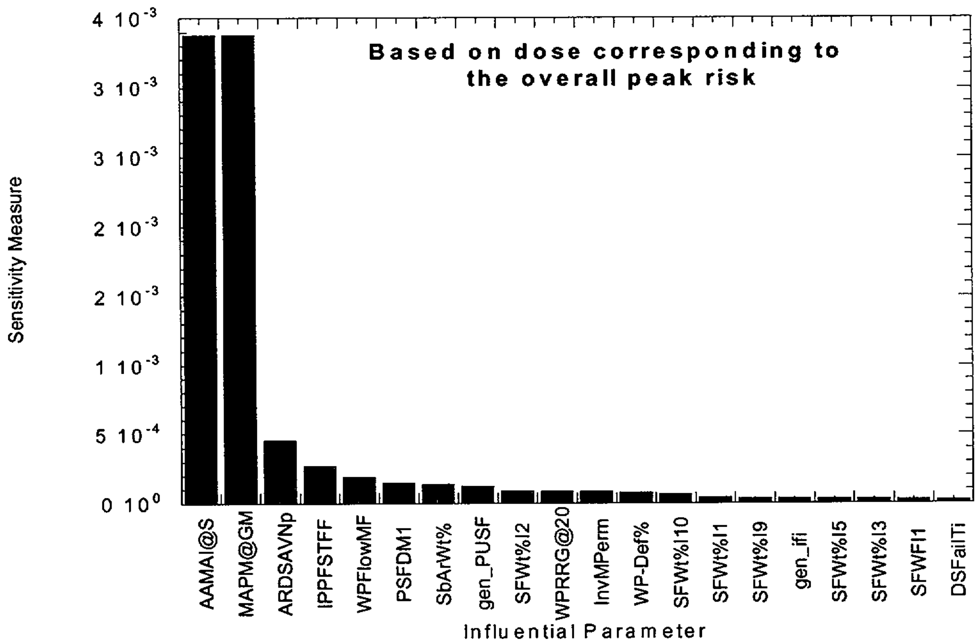

Figure 4. Identification of influential parameters using dose values from each realization corresponding to the overall peak risk

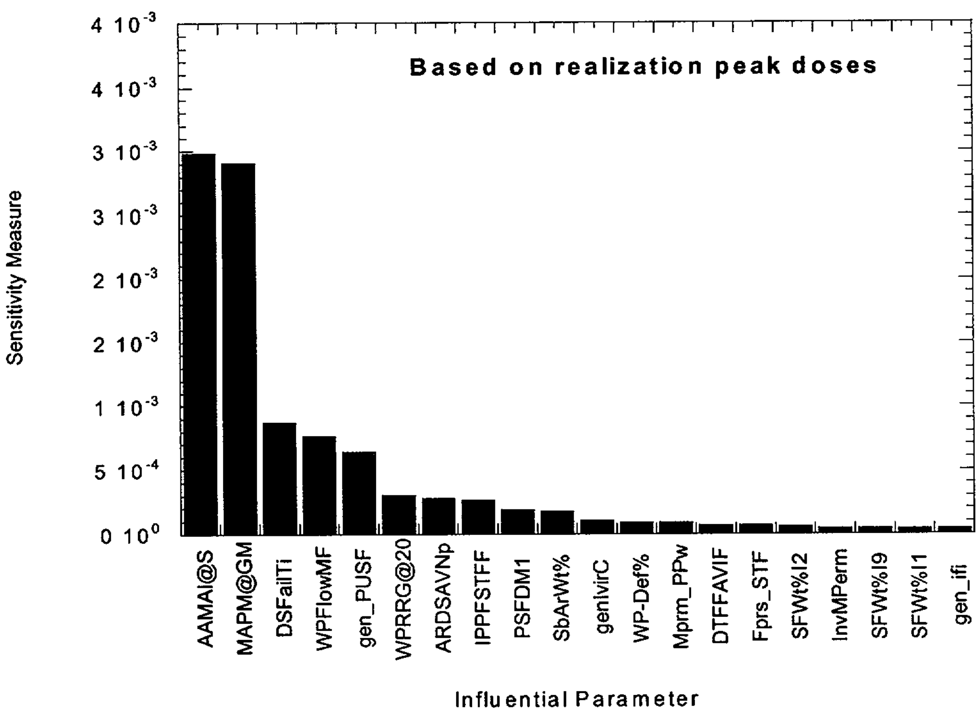

Figure 5. Identification of influential parameters using the peak doses in 10,000 yr from individual realizations

5 ACKNOWLEDGMENTS

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