QUANTIFICATION OF THE SENSITIVITY OF REPOSITORY PERFORMANCE TO SUBSYSTEM VARIABILITY

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ABSTRACT

The U.S. Nuclear Regulatory Commission (NRC) is preparing to review a possible license application for a potential Yucca Mountain nuclear waste repository in Nevada, U.S.A. Sensitivity analysis is a quantitative tool that can be used to focus regulatory activities on sensitive models and parameters for the NRC's technical evaluation of this site. The NRC has completed sensitivity analyses using a variety of techniques on results generated with the Total-system Performance Assessment (TPA) code. The TPA code is composed of a number of subsystems that simulate the performance of the waste package, fuel, near-field environment, transport pathways and doses to a potentially exposed population. The proposed standard,10 CFR Part 63,(1) uses the expected (i.e., mean) dose to a member of the critical group to demonstrate compliance. The expected dose is derived from the results of the TPA code using assumed distributions for all of the uncertain variables.

Identification of the subsystems that contribute to uncertainty in the risk metric is one task in implementing risk-informed regulation in high-level waste disposal. We used the results of the latest version of the performance assessment code, TPA 4.0, to explore the contribution of uncertainty in a single input variable, subsystem or system comparing the nominal case with the case in which the variable or group of variables are held at their mean values. We examined several possible metrics for sensitivity in comparing the output distributions: 1) Difference between the means of the output distributions, 2) Differences between the variances, 3) The Kolmogorov-Smirnov test, 4) a variation of the Kolmogorov-Smirnov test based on the area between two cumulative distributions. The last technique appears to have the best power to resolve system- and parameter-level sensitivity. Since this approach requires one or more large sets of Monte Carlo calculations for each system or variable tested, computational requirements are large.

The results from the analyses for the nominal scenario identify the possible systems that may contribute to uncertainty in estimates of risk for the proposed repository. These subsystems in order of importance are: 1) degradation of the engineered barrier system, 2) the exposure pathways (biosphere), 3) the quantity and chemistry of water contacting the waste packages and waste forms 4) radionuclide transport in the saturated zone, 5) radionuclide release and solubility limits, 6) flow paths in the saturated zone, and 7) well pumping.

INTRODUCTION

Policies governing the permanent disposal of HLW are defined by the Nuclear Waste Policy Act of 1982 (NWPA), the Nuclear Waste Policy Amendments Act (NWPAA) of 1987, and the Energy Policy Act of 1992. These acts specify that HLW will be disposed of underground, in a deep geologic repository. The NRC is one of three Federal agencies under the acts with a role in the disposal of spent fuel and other HLW. The Department of Energy (DOE) is responsible for determining the suitability of the proposed disposal site as well as developing, building, and operating the geologic repository. The U.S. Environmental Protection Agency (EPA) will develop environmental standards to evaluate the safety of the geologic repository proposed by DOE. NRC will decide whether or not to license the repository after determining whether DOE's proposed repository site and design comply with EPA's standards and with NRC's implementing regulations found in proposed 10 CFR Part 63, which is risk-informed and performance-based.

A necessary condition to the implementation of a risk-informed, performance-based approach to the regulation of high-level waste disposal is the identification and quantification of the important scenarios and components. In a traditional sense, a risk assessment is a method for addressing the risk triplet ('What can go wrong?', 'How likely is it?', and 'What are the consequences?') as it relates to the performance of a geologic repository [1]. Risk assessment involves the identification of likely outcomes, sensitivities, areas of importance, system interactions and areas of uncertainty. The objective of this paper is to provide the sensitivity of various systems and sub-systems that will allow NRC staff to make risk-informed decisions in the high-level waste project. A potential outcome would be to improve the efficiency and effectiveness of the program, a strategic goal of the agency. For the high-level waste program, the risk metric is the peak mean dose within 10,000 years (10 ka) to a critical group located 20 km from the proposed repository [2]. Sensitivity analyses are an evaluation of how the uncertainty and variability in a variable, subsystem or system influences or contributes to the variability of the risk metric. NRC's Total-system Performance Assessment code, TPA 4.0, is the quantitative tool used in the evaluations that follow [3]. The results of the analyses are conditional on the accuracy of the code in representing the key features, events, and processes (FEPs) to repository performance.

SENSITIVITY ANALYSES

Sensitivity analysis is a quantitative tool that can be used to focus regulatory activities on sensitive parameters. The NRC has completed a myriad of sensitivity analyses using various updates to the Total-system Performance Assessment code (TPA) [4]. The analyses that follow are sensitivity analyses completed with the 4.0 version of the TPA code. It is important to note that the parameters and associated ranges of the TPA code are influenced by such things as modeling approaches, assumptions, variability, and uncertainty.

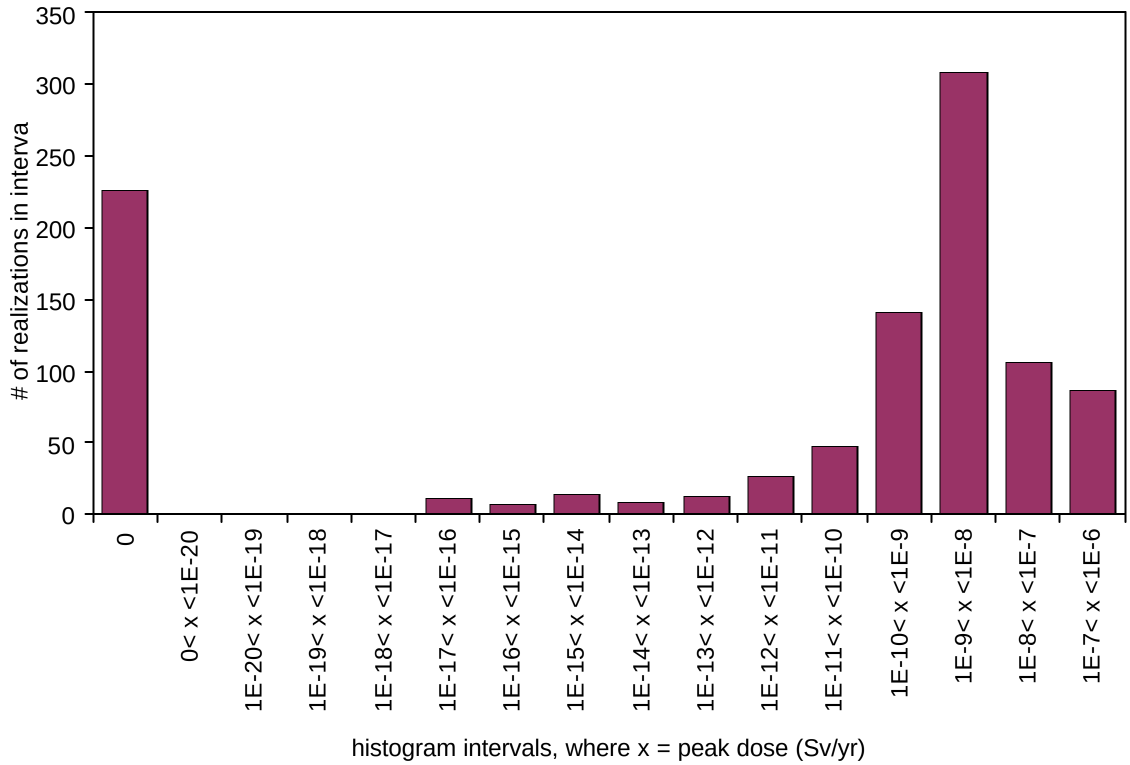
The proposed high-level waste standard, 10 CFR Part 63, identifies the use of the expected annual dose (i.e., mean) to the average member of the critical group. Calculation of the mean dose requires Monte Carlo analysis to generate a large number of random realizations of the possible repository performance. Figure 1(a) is an example of a histogram of peak dose values for the 10,000 year compliance period calculated for the Yucca Mountain site. For the problem being evaluated, roughly 800 to 1000 realizations were needed for the desired stability in the resulting sensitivities.

We used the results of the TPA code to explore the contribution of uncertainty in a single input variable or system by comparing the nominal case to the case in which the variable or group of variables are held at their mean values. Since the expected dose is derived from the complete probability distribution function representing the model outputs, we need a method to compare the output distributions among cases. We examined several possible methods to compare statistics of the output distributions from Monte Carlo runs of the altered and nominal cases: 1) Difference between the means, 2) Differences between the variances, 3) The Kolmogorov-Smirnov metric, which is the maximum separation between two cumulative distributions, and 4) a variation of the Kolmogorov-Smirnov metric, based on the area between two cumulative distributions. For more information on the Kolmogorov-Smirnov test see Bowen and Bennett (1988) [5]. Of the four methods tried, the last gave the most consistent results. This method was able to reproduce results consistently irrespective of the choice of the seed for the random number generator. The other three methods gave usable, but less-reproducible results when the random number sequences changed.

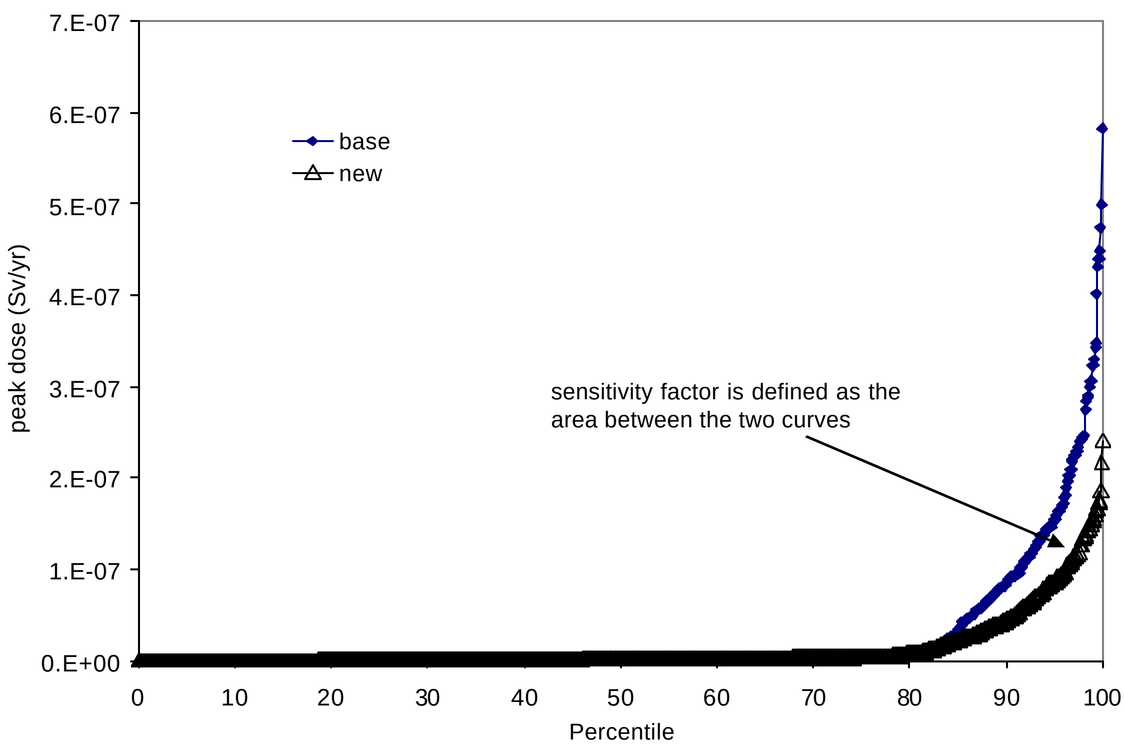
The base-case or nominal problem gave a distribution of peak dose responses similar to that presented as a histogram in Figure 1(a). The alternative analyses of the variable, system or subsystem under study were then set up by changing the corresponding model parameter or parameters to their mean values. Rather than change parameter distributions to constants, however, we kept them defined as very narrow distributions centered around the mean. For example, if a parameter representing retardation of iodine in alluvial materials had an original distribution that was uniform and had a range of [1, 5], the new distribution would be uniform and have a range of [2.999, 3.001]. The reason for this was to preserve the order of the random number sequences used in the Monte Carlo analyses, so that the results could be compared vector-for-vector in the subsequent analyses. The new dose response was then compared to the original dose response, as shown in Figure 1(b). We define a sensitivity factor, SF:

$$SF = \left(\frac{\sum_{i=1,n} \left\{ ABS\left(\left[D_{base,i} \right] - \left[D_{new,i} \right] \right) \right\}}{\sum_{i=1,n} \left[D_{base,i} \right]} \right) * 100 \qquad \text{(Eq. 1)}$$

where n is the number of realizations, ABS is the absolute value, $D_{base,i}$ is the peak dose for realization i of the base case, and $D_{new,i}$ is the peak dose for realization i of the altered problem. Whereas the Kolmogorov-Smirnov test uses the maximum distance between the two curves shown in Figure 1(b), the above equation essentially calculates the area between the two curves. When a parameter or subsystems exhibits little sensitivity, the curves will be similar or identical. For the example presented, significant sensitivity can be attributed to the parameter, subsystem, or system. The analyses are computationally intensive, consequently we have concentrated most of our efforts at the system- and subsystem-level.



(a)



(b)

Fig.1 (a) Peak dose output data from the TPA 4.0 code. (b) Base case sorted peak dose data from (a) and new sorted peak dose data from a sensitive parameter or subsystem. Note that the base case is only relevant to this analyses, it is not the NRC TPA 4.0 base case.

DESCRIPTION OF REPOSITORY SYSTEM

Repository system performance is best described as the interaction of the physical features and processes represented the natural and engineered systems with the driving forces of the repository environment. The grouping of these features, events, and processes (FEPs) into manageable subsystems is not unique, i.e. there are many potential ways to complete this categorization. Presented below is the division of the repository into subsystems considered in this paper. The repository as a whole is divided into engineered, natural, biosphere, and disruptive systems. The disruptive system considered, eruptive igneous activity, is really an event that operates on the engineered, natural, and biosphere systems. However to simplify terminology, we referred to it as a system in this analyses. Each system is further subdivided into subsystems. These subsystems are essentially consistent with the architecture of TPA 4.0. Most of the parameters of the subsytems are uncertain, and are defined as probability distributions that are sampled in Monte Carlo fashion to conduct uncertainty and sensitivity analyses. The reader is referred to the TPA 4.0 User's Guide for a complete description of each subsystem [2]. The discussion that follows is cursory and is only intended to provide enough background to allow interpretation of the sensitivity analyses results.

- <u>Engineered barrier system (EBS) degradation</u> - The engineered barrier system is essentially composed of a titanium drip shield and a dual canister waste package. For the Engineered Design Alternative-II (EDA-II) design, the waste package is comprised of an outer barrier of nickel-based alloy 22 and an inner barrier of stainless steel [6]. We represent the degradation of the waste package by humid-air corrosion, dry-air oxidation, and aqueous corrosion, both uniform and localized. The degradation processes consider the pH, temperature, chloride ion concentration, oxygen partial pressure, and relative humidity of the potential exposure environment. We represent the degradation of the drip shield by a failure-time distribution that can take into account any potential exposure environment and degradation process.

- <u>Mechanical disruption of engineered barriers</u> - We consider potential failure of the drip shield and waste packages caused by seismically induced rockfall. Effects such as incomplete failure (displacement of drip shields, development of a stress state in the materials that can lead to stress corrosion cracking) are not included in the model.

- <u>Quantity and chemistry of water contacting the waste packages and waste forms</u> - We use this subsystem to consider the potential near-field environmental conditions to which the waste packages and waste forms may be exposed. The chemical variables are currently limited to pH and chloride ion concentration. The models implement the alteration of chemical conditions as a result of thermohydrological processes. We also represent the potential diversion of water from the waste package by potential large-scale (external to the drift) focusing/diversion, film flow at the surface of the drift, capillary diversion in the fractures near the drift, and diversion of flow due to the presence of corrosion products in corroded waste packages. The code can represent potential time-dependency of the water contact phenomena. We assume that an intact drip shield will divert all chemicals and infiltrating water from contacting the waste packages, but not water condensed from air.

- Radionuclide release rates and solubility limits - The source-term in the TPA 4.0 model represents commercial spent nuclear fuel. There are four alternative release models for spent fuel. The base case model, used in this paper, is a function of total carbonate concentration, oxygen partial pressure, the concentration of hydrogen ions, and temperature. The base case model was derived from experimental observations [7]. Mass transfer out of the waste package (WP) is by flow through the failed waste packages and diffusion and flow through the porous invert. The time-dependence of the radionuclide inventory is considered. Two models were developed to represent water contact with the source-term: bathtub and flow-thru.

- Climate and infiltration - We represent potential climate cycles in response to a glacial cycle, with a main period of roughly 100 ka, and shorter perturbations superimposed. The shallow infiltration conceptual model includes water and energy balances for a system of shallow surficial soil above a fractured impermeable bedrock.

- Flow paths in the unsaturated zone (UZ) - The hydrology of the unsaturated zone is represented as vertical flow in both porous and fractured media, considering fracture vs. matrix flow, groundwater velocity, moisture content, stratigraphic thickness, and fracture and matrix porosity and permeability. Time-varying deep percolation is derived from the climate and infiltration models and is the primary input to the unsaturated zone flow model, which considers longitudinal dispersion and matrix diffusion.

- Radionuclide transport (RT) in the unsaturated zone - We represent sorption of radionuclides in the unsaturated zone with retardation factors, the ratio of the velocity of a dissolved radionuclide to the water velocity. Distribution coefficients (as well as any variables in the code) can be correlated, if appropriate. Retardation of radionuclides in fractures, while possible with the TPA code, is not represented in the base-case. In addition, matrix diffusion is possible but is conservatively assumed to not occur for the base case.

- Flow paths in the saturated zone (SZ) - Steady-state flow is represented through a series of four one-dimensional flow tubes from the water table (at locations directly below the repository) to the receptor location. We used a two-dimensional horizontal flow model to abstract the steady-state velocity fields for the flow tubes. Geologic variability at small- and large-scales are represented, to some degree, in the model. The model considers steady-state flow through multiple sections of porous and fractured media.

- Radionuclide transport in the saturated zone – The model for transport of radionculides considers longitudinal dispersion, retardation, and matrix diffusion. Lateral dispersion is not included as well as sorption of radionuclides on fracture surfaces.

- Volcanic disruption of waste package – Volcanic disruption of waste packages represents the potential interaction of magma with waste packages and waste forms. The model is flexible and can represent variable numbers of packages damaged or failed resulting from different drift interactions. Magma that intersects a waste package is assumed to fail the waste package. If the magma reaches the earth's surface, we assume that the contents of the waste packages will be partially entrained in the magma and released to the air as volcanic ash.

- Airborne transport of radionuclides – Radionuclides released to the atmosphere will be transported downwind. The airborne transport model considers the height of the eruption column, wind speed, wind direction, and ash particulate characteristics, to determine the airborne concentration of radionuclides and their deposition on the ground.

- Dilution of radionuclides due to well pumping - Other than volcanism, all doses to the affected population will be caused by contamination of ground water. The model considers the transport of radionuclides reaching the user's well(s), and the amount of dilution at the well head. The code is capable of representing complete or partial capture of a contaminant plume. Well pumping rates can be selected based on the critical group being evaluated (residential or farming).

- Redistribution of radionuclides in soil – The redistribution of radionuclides in soil subsystem represents the time-dependent areal densities of contaminated soil surface layers subject to removal by leaching, erosion, and radioactive decay. The model also accounts for ingrowth of radionuclides.

- Exposure pathways - Time-varying release rates for each radionuclide released in groundwater and intercepted by the pumping well(s) are the inputs to the exposure pathways subsystem. Important reference biosphere and receptor group parameters (such as growing times, consumption rates, irrigation rates, etc.) can be sampled or represented as constants. The exposure pathways subsystem defines how the receptor group is exposed to potentially contaminated groundwater or ash (from extrusive igneous activity).

RESULTS

The results that follow are for the nominal case only, without volcanic or faulting disruptive events. The mean risk curve from the volcanic system requires a somewhat complicated calculation involving a convolution of a set of up to 12 Monte Carlo calculations completed at various time periods. The computational requirements would be prohibitive to use the sensitivity techniques presented here on the disruptive system. However, we expect from previous sensitivity techniques, that disruption of waste packages and redistribution of radionuclides in soil would be the most sensitive subsystems for the igneous system.

Figure 2 shows the sensitivity factors calculated for the nominal scenario for both 10 and 50 ka time periods, using the method previously described. Although not part of the regulation, we evaluated repository performance at 50 ka to evaluate the consistency of the 10 ka results with our understanding of the repository system (the 50 ka results include all events and processes that may have occurred during the first 10 ka, as well as what has occurred from 10 ka to 50 ka). To put the results in perspective, Figure 2 is showing the sensitivity of the risk metric to a given subsystem compared to the nominal performance. All of the results are consistent with the physical understanding of the system. At the parameter-level the technique appears to be capable of resolving not just sensitivity, but relative sensitivity compared to other parameters with some degree of certainty. At the parameter-level, the sensitivity factors were stable for 1000 realizations. The farther up in the hierarchy of the problem, the lower the accuracy of the

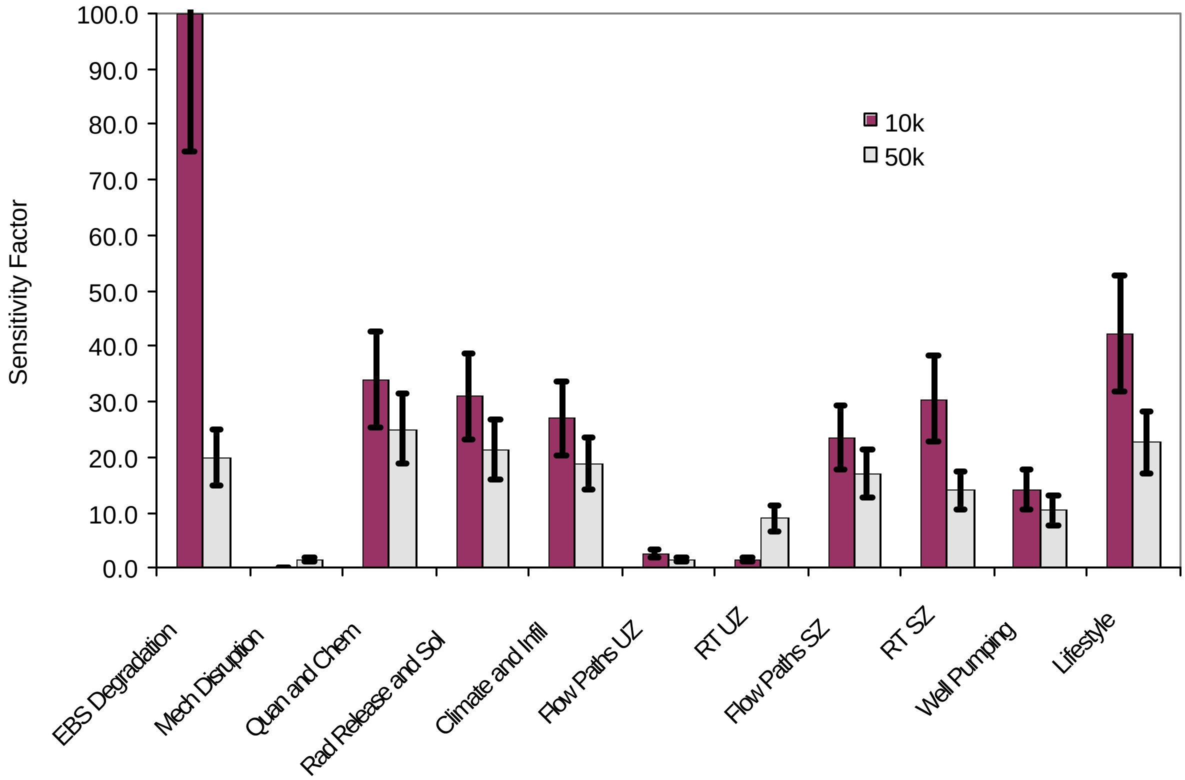


Fig. 2 Sensitivity factors of the nominal scenario subsystems

analyses, possibly because of the effect of couplings or the propagation of uncertainty. The results that follow were tested by replicating the problem starting with different random number seeds. The error bars on Figure 2 are the expected range of the sensitivity factors determined from three sets of 1000 realizations with different random number seeds for each set, demonstrating qualitatively that the mean is stable. Because of the high computational demand of running many sets of 1000 realizations each, it was not practical to generate statistical confidence limits on the sensitivity factors presented here.

- EBS degradation - The degradation of the EBS results in the largest sensitivity factor for the 10 ka time period. Waste package lifetime is a key component of the repository performance. While large uncertainties are not typical in the corrosion parameters (i.e. large driving moments), dose is related to the number of initial failures in the 10 ka time period and the number and timing of waste package failures in the 50 ka time period. Sensitivity decreases in the 50 ka time period (relative to 10 ka) because most waste packages fail in less than 50 ka.

- Mechanical disruption of engineered barriers - Mechanical disruption minimally contributes to the variability in the outcome because the EDA-II design limits mechanical disruption of the waste package or drip shield. No other mechanical effects are represented in the model that could contribute to sensitivity.

- Quantity and chemistry of water contacting the waste packages and waste forms - The expected dose shows significant sensitivity to this subsystem in both the 10 ka and 50 ka time periods. The sensitivity is reduced for the 50 ka time period compared to the 10 ka time period because most of the sensitivity results from large uncertainty in the parameters associated with water flow. In the 10 ka time period, water flow is important to performance because it results in a delay to radionuclide release due to filling of the waste package with water. This bathtub filling time delay is typically less than 50 ka years, therefore it does not contribute directly to sensitivity in 50 ka years.

- Radionuclide release rates and solubility limits - There is significant sensitivity in the 10 ka time period due to uncertainty and variability in the dissolution rates of the spent nuclear fuel source term. The dominant contributors to dose in the 10 ka time period are ^{99}Tc and ^{129}I, both of which are not solubility limited.

- Climate and infiltration - There is sensitivity in both the 10 ka and 50 ka time periods. For the 10 ka time period, infiltration indirectly effects both the bathtub filling time, the advective release from the engineered barrier system, and transport of radionuclides through the UZ. Sensitivity in the 50 ka time period likely shows the effect of the climate-cycle.

- Flow paths in the UZ - There is no sensitivity in either the 10 ka or 50 ka time periods. Travel times are relatively fast through the UZ, dominanted by fracture flow. Soluble and unretarded species such as Tc and I are minimally influenced by transport through the UZ.

- Radionuclide transport in the UZ - There is little sensitivity in either the 10 ka or 50 ka time periods. The UZ may retard some species, such as U and Th, significantly, but those species do not transport to the critical group and therefore will not influence dose. Tc and I and are assumed to be unretarded in fractured rock. Therefore radionuclide transport in the UZ does not influence sensitivity. In the 50 ka time period, sensitivity increases somewhat due to the retardation of Np which now contributes to dose.

- Flow Paths in the SZ – There is sensitivity in both the 10 ka and 50 ka time periods. The sensitivity results from the amount of alluvium through which the radionuclides may be transported and variation to the flow-fields. Tc and I are expected to be slightly retarded in the saturated, porous alluvium and therefore variation in the flow fields (porosity, permeability, etc.) has an impact on Tc and I arrival times in 10 ka. In the 50 ka time period, variation in the flow-fields can contribute to sensitivity in dose by reducing or increasing the peak concentrations (believed to be primarily through dispersion and diffusion processes).

- RT in the SZ – There is significant sensitivity in the 10 ka year time period, but much less sensitivity in the 50 ka time period. At first this result seemed to be puzzling, but further analyses revealed the explanation. We expected significant sensitivity in the 10 ka time period. The transport of radionuclides through the alluvium can result in a substantial delay to arrival at the receptor location. Almost all (99.9%) of the dose contribution in the 10 ka time period came from slightly retarded radionuclides (^{99}Tc, ^{129}I, and ^{36}Cl). Therefore the sensitivity observed for the 10 ka time period results primarily from variability in peak arrival times of the slightly retarded species. For the 50 ka time period, ^{237}Np comprises

73.2% of the dose and the slightly retarded species (^{99}Tc, ^{129}I, and ^{36}Cl) 25.6% of the dose. The remainder of the radionuclides never reach the critical group in the 50 ka time period. Over 95% of the ^{237}Np is released prior to 50 ka (and essentially 100% of the slightly retarded species), therefore much less sensitivity is seen in 50 ka compared to 10 ka. Retardation only acts to change the arrival time of the radionclides and does not effect the peak concentrations, unless radioactive decay is important. So unless the peak arrival time distribution significantly intersects the analysis period (10 or 50 ka), little sensitivity will be observed. If the longer analysis period was shorten from 50 ka to 30 ka, it is expected that radionuclide transport in the saturated zone would show significant sensitivity.

- Well pumping - Well pumping shows moderate sensitivity for both the 10 ka and 50 ka time periods. This is expected because dose is inversely proportional to dilution. The sensitivity is recognized even with the rather narrow range of pumping values used in the base case analyses. Broader ranges for well pumping rates would result in much more sensitivity for this subsystem.

- Exposure pathways – There is strong sensitivity in the 10 ka and the 50 ka time periods. Previous versions of the TPA code used a deterministic biosphere. TPA 4.0 has been modified to allow the direct usage of GENTPA, a version of the stochastic GENII-S code [8]. While the drinking water consumption rate is fixed in the proposed rule (10 CFR Part 63), many other biosphere parameters are stochastically sampled. The probability distribution functions (lognormal) selected to represent some of the uncertain/variable parameters in the biosphere may be overestimating the maximum potential uncertainty/variability at the tails of the distributions. This highlights the importance of appropriately selecting probability distribution functions.

A concern of the analyses is whether the conclusions made above are justified based on the stability of the results. Figure 3 presents the sensitivity factors for a few select subsystems, and how they change as the number of realizations are increased. The data points in Figure 3 represent the mean of two sensitivity factors calculated at each point (from two different sets of data). It may be argued that 1000 realizations are not enough to represent the stable *absolute* value of the sensitivity factor calculated with this method. However, after 250 realizations the sensitivity factors maintain roughly the same *relative* magnitudes (to each other). The number of realizations needed to determine whether the sensitivity factors for a subsystem is stable depends on the use of the sensitivity factors. If the analyses is simply a screening, then less realizations would be acceptable. However, if the sensitivity factors are going to be used for risk-insights and issue resolution then more realizations would be needed to ensure confidence in the conclusions.

This technique has been utilized successfully to investigate parameter-level sensitivity. However, computational requirements are large, making the technique more amenable to use at the subsystem-level or higher. Executing the analyses presented in Figure 2 required ~50 hours of CPU time for each data point (on a Sun SPARC Ultra-10 with a single 333 MHz processor).

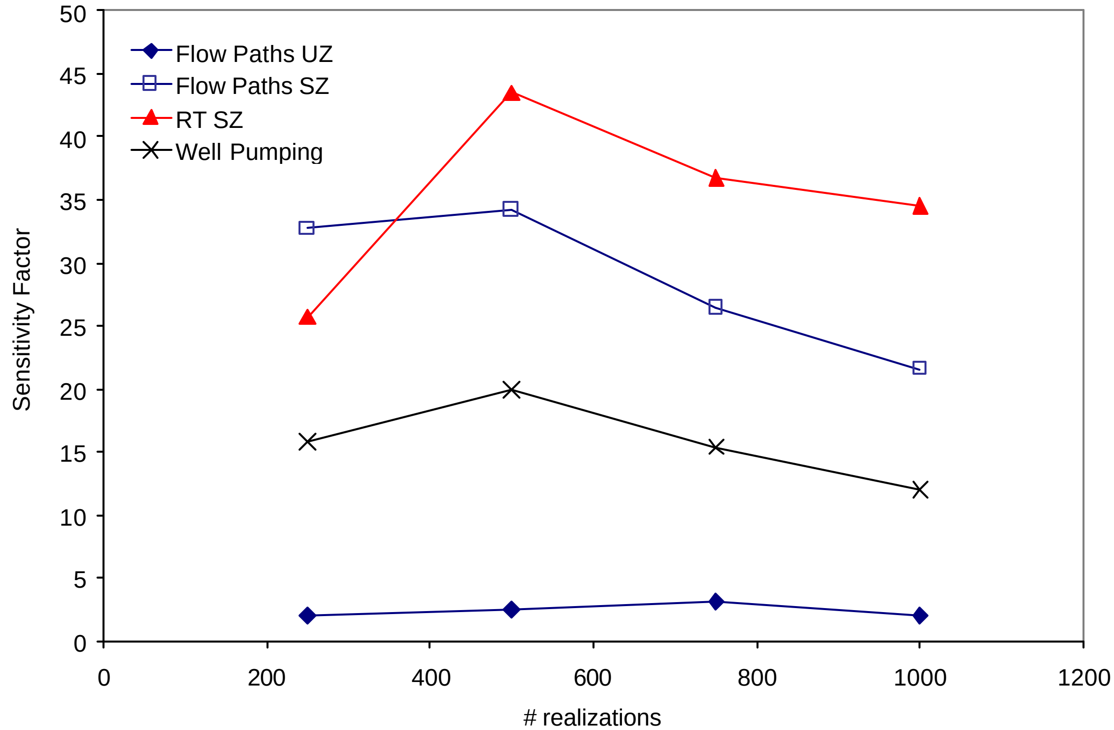


Fig. 3 Stability of the subsystem sensitivity factors

Figure 4 presents results of an analyses on single parameters. The parameters were selected in two groups; we chose the first group to include only parameters that clearly should influence uncertainty. We chose the second group to include only parameters that should have little or no influence on risk. The calculations were done with an earlier version of the TPA code (3.2) and only one subarea of the repository was represented (where there were eight in the base-case for the subsystem-level analyses). However, these results demonstrate the ability of this technique to resolve parameter-level sensitivity. Those parameters selected that would influence risk were:

- FOW – related to the amount of water that advects radionuclides from the waste package,
- $I\text{-}R_f$ – the retardation factor for iodine in alluvium,
- Pump – the expected dilution volume as a result of well pumping, and
- Defect% - the fraction of waste packages that are initially defective.

Those parameters selected that would not influence risk (and why) were:

- K_d Pb TSw – distribution coefficient for Pb in the Topopah Springs welded unit of the UZ. There is no dose from Pb in 10,000 years.
- Cl-factor - chloride concentration factor. Chloride and temperature are never high enough concurrently to initialize localized corrosion in the current model.
- Solubility Am – There is no dose from Am in 10,000 years.

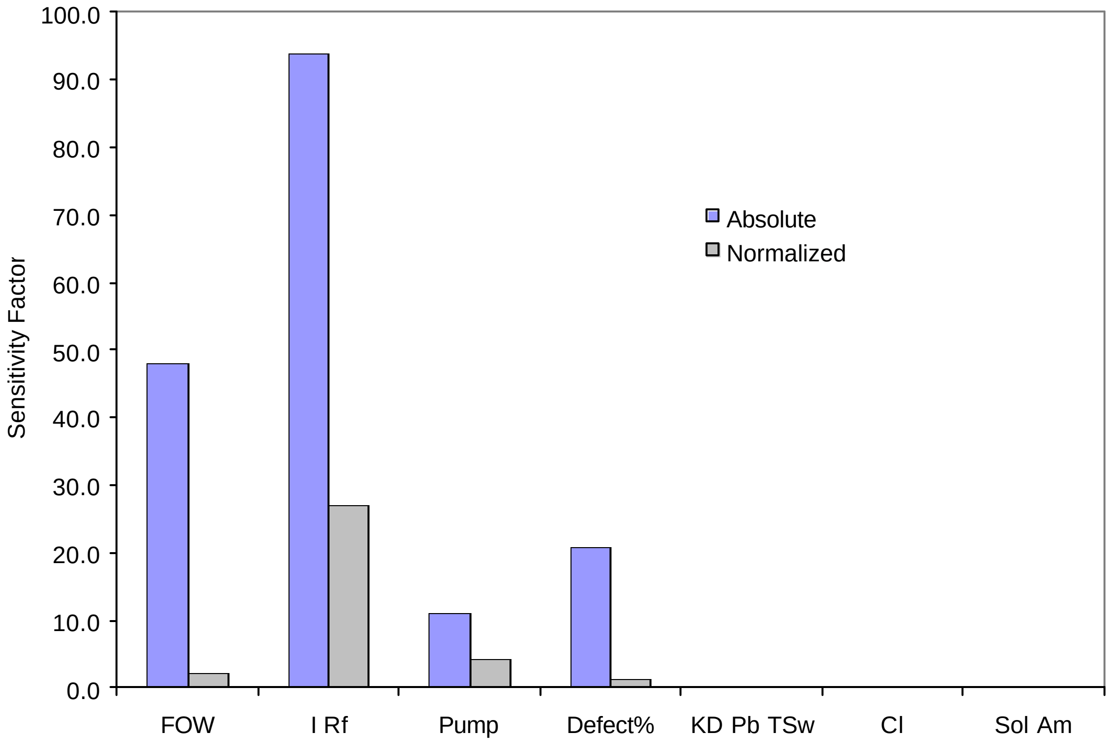


Fig. 4 Parameter-level sensitivity analyses

Figure 4 presents both the absolute sensitivity factors and the normalized sensitivity factors, determined by dividing the absolute sensitivity factors by the ratio of the 95th to 5th percentile values of the original parameter distribution. The absolute or normalized sensitivity factors convey different messages. The normalized sensitivity factors are useful in identifying which parameter distributions provide the most potential for reduction in variance of the peak dose given a unit reduction in uncertainty in the parameter distribution. The stability of the parameter-level analyses was tested by completing three sets of analyses for the FOW sensitivity factor. The results from that analyses were sensitivity factors of 48.8, 48.0, and 49.1 for 1000 realizations in each data set. At 500 realizations the results were 65.3, 57.4, and 83.8, showing considerable less stability than at 1000 realizations. It is important to not only test the stability of the performance metric (such as mean dose) but also to test the stability of importance and sensitivity analyses.

All of the uncertainty and sensitivity results demonstrated in this paper have relied on Monte Carlo analysis, in which the value of an input variable is sampled from a probability distribution. However, there is a broader range of sensitivity methods that do not rely on Monte Carlo methods explored in previous TPA analyses. These include deterministic sensitivity and Fourier Amplitude Sensitivity Tests. We have recently begun to implement factorial design methods to treat parameter-level analyses. In this method, each variable has either a high or a low value. There are 2^N combinations of all possible high or low values in a full factorial design, where N is the number of variables in the problem. Since the current TPA models have hundreds of parameters, it is unreasonable to consider all combinations for all variables. However, there is a rich literature on factorial designs that promise reasonable numbers of runs, even with for problems like TPA with hundreds of variables. Experimentation with a relatively small, artificial problem having 10 variables have been encouraging. In this experiment, a full factorial design, i.e., $2^{10} = 1024$ combinations, did significantly better in predicting the order of importance than an equivalent number of Monte Carlo runs. Furthermore, using an advanced fractional factorial method with only 32 runs did as well as the full factorial design. We have no results to report yet with larger problems like TPA.

CONCLUSIONS

Subsystem-level sensitivity analyses are a valuable tool in identifying the key drivers of uncertainty/variability in risk. Sensitivity analyses can be combined with importance analyses to quantify system components that may have the biggest impact on regulatory decision-making. The technique employed demonstrated a capability to resolve subsystem-level sensitivity

The key drivers of sensitivity in risk for the nominal scenario were: 1) engineered barrier system degradation, 2) exposure pathways, 3) radionuclide transport in the saturated zone, 4) the quantity and chemistry of water contacting the waste packages and waste forms, 5) radionuclide release rates and solubility limits, 6) climate and infiltration, 7) flow paths in the saturated zone, and 8) dilution of radionuclides due to well pumping.

We identify factorial design as a potentially useful tool for sensitivity analysis that will be developed in upcoming versions of the NRC's analyses for Yucca Mountain.

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FOOTNOTES

(1) The proposed regulations were issued for public comment in February, 1999. The analysis presented in this paper in no way pre-judged the NRC's consideration or response to public comments received on the proposed regulations the analysis in this paper would need to be revised to be consistent with the final regulations.