4 SYSTEM-LEVEL SENSITIVITY STUDIES

This chapter describes the sensitivity and uncertainty analysis techniques used in conjunction with results of the TPA Version 3.2 code system-level calculations. In general, a sensitive parameter is defined as one that provides a relatively large change in the output variable for a unit change in an input parameter. The goal of the sensitivity analyses presented in this report is to determine the parameters to which peak dose or the TPI shows the most sensitivity. The goal of the uncertainty analyses is to determine the parameters that are driving uncertainty (i.e., variation) in peak dose output. The analyses were conducted primarily for the basecase and to a limited extent for the igneous activity and faulting disruptive events. The analyses conducted herein rely on the models and assumptions used in the TPA Version 3.2 code.[7] For a more detailed description of these models and assumptions, the reader is referred to the TPA Version 3.2 code "User's Guide" (Mohanty and McCartin, 1998). Conclusions based on these analyses may be updated as the models or assumptions are updated, and certain parameters or processes may become more or less influential.

The sensitivity analyses in this report use peak dose as the output variable for each realization because this result is most likely to demonstrate sensitivity relationships among the independent and dependent variables. The performance measure in the draft version of the YM implementing regulation 10 CFR Part 63 (Nuclear Regulatory Commission, 1999a) is stipulated to be the peak of the average dose history within the 10,000-yr TPI. Although there is an important distinction between these two measures of performance, the use of the peak dose for each realization would not significantly alter the sensitivity analysis conclusions since approximately 90 percent of the realizations have their peak dose at 10,000 yr, and for those realizations with earlier peak doses, the peak dose does not significantly differ from the dose at 10,000 yr.

4.1 SENSITIVITY ANALYSIS TECHNIQUES

Most techniques used herein rely on the Monte Carlo method for probabilistically determining system performance. As mentioned in the previous chapters, the performance measure of the system in the NRC YM repository PA exercises is the peak dose in the TPI to an average member of a receptor group located 20 km (12.4 mi) from the repository. Many of the input parameters are not precisely known and are spatially variable, so their values are described by probability distributions (Figure 4-1). The Monte Carlo technique makes repeated calculations (called realizations) of the possible states for the system, choosing values for the input parameters from their probability distributions. Although 246 input parameters[8] are sampled in the TPA Version 3.2 code, only a few of these parameters contribute significantly to the uncertainty in peak dose, because of the great sensitivity of peak dose to the parameters, the large variability of the parameters, or both.

This section describes the techniques used to determine which input parameters in the TPA Version 3.2 code most influence the results. It is noted that not all techniques described were applied to all cases. For generalization purposes, the output from the system is denoted as y. In general, y is a

[7]The specific version of the TPA code used in this Chapter is 3.2, whereas Version 3.2.3 was used in developing Chapter 3. Results from Version 3.2.3 do not affect the peak dose calculation, compared with Version 3.2, which is the performance measure used in this chapter.

[8]The actual number of parameters contributing to the variability in peak dose is fewer than 246, depending on which group of conceptual models is used in the calculation. The LHS module in the TPA Version 3.2 code samples all parameters that are not constant, regardless of their use in a specific run.

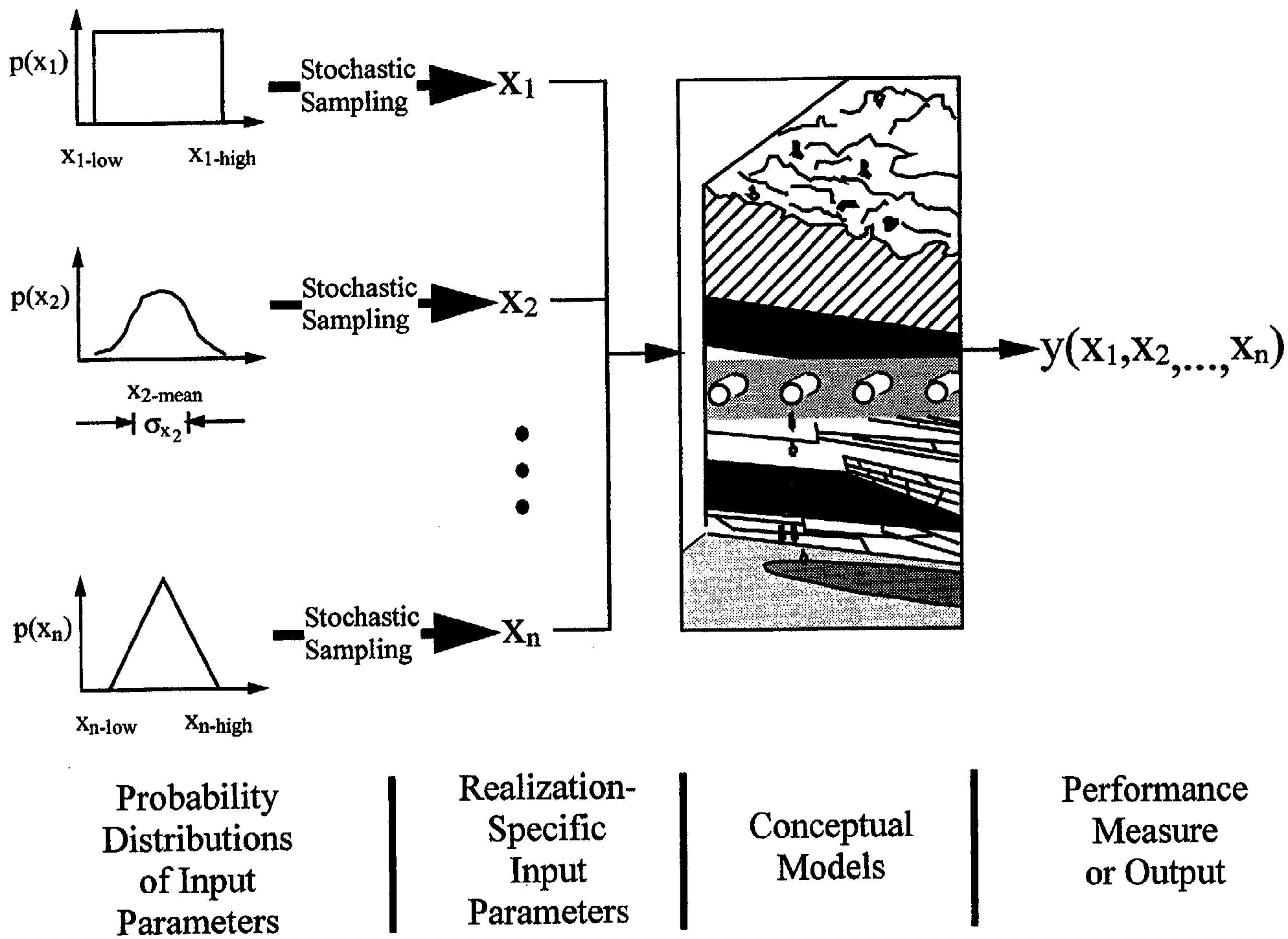

Figure 4-1. A diagram illustrating the use of the Monte Carlo method in performance assessment.

function of random parameters, x_i; deterministic parameters, d_k; and model assumptions, a_m. The system output, y, is such that

$$y_j = f(x_{1,j}, x_{2,j}, \ldots, x_{I,j}, d_k, a_m) \tag{4-1}$$

where j represents the jth realization and I is the total number of sampled parameters in the model. It is assumed that the behavior of the system is simulated by appropriately sampling the random parameters and then computing the system output, y, for each realization of parameter vector (see Figure 4-1). For the purposes of this section, which are to outline a method for analyzing simulation output, to identify important random parameters, and to develop understanding of their relationship to the output, it is assumed that the decisions about appropriate model assumptions and deterministic parameters have been made *a priori.* As a result, we do not consider the dependence of y on deterministic parameters and model assumptions any further, and focus on the dependence of y on the x_is only.

4.1.1 Regression Analyses Methods

4.1.1.1 Scatter Plot/Single Linear Regression on One Variable

To understand the nature and strength of relationships between input and output variables of a model, it is often useful to examine scatter plots in which the output variable is plotted against one input variable at a time. As shown in Figure 4-2, results of scatter plots give an initial visual indication of nonlinear effects, thresholds, and variables likely to be important to further sensitivity and uncertainty analyses. Single linear regression (i.e., regression with only the first power of one input variable and an intercept) of the output variable, with respect to each of the input parameters, can give a quantitative measure of the correlation through the coefficient of determination, R^2. This figure can be misleading, however, in cases where the dependencies are not purely of the first order with respect to the input variable. It is noted that linear here and throughout this chapter refers to the functional form of the regression and not the order to which the fitting parameters appear (although the regressions are also linear in the fitting parameters). Even when the output variable is linearly dependent on the input variable being studied, univariate linear regression of Monte Carlo results may fail to show unambiguous correlation because other sampled parameters that affect the output are varying at the same time, and the model is clearly underspecified (i.e., the results depend on more than one variable).

The coefficient of determination, R^2, is small for most variables in the current analyses, and is not necessarily a good indicator of the importance of the variables. A better indication of influence is to determine the probability that the slope of the linear regression line is significantly different from zero. This is done with a t-test or t-statistic as described in succeeding sections.

Use of the t-Statistic to Determine Significance of Regression Parameters

The t-statistic is generally used to estimate with a specified confidence level that an estimated parameter value differs from another value. A parameter, x_i, is deemed influential if there is a specified (e.g., 95 percent) confidence that the slope of its regression curve, (m_i), is different from zero (Benjamin and Cornell, 1970).

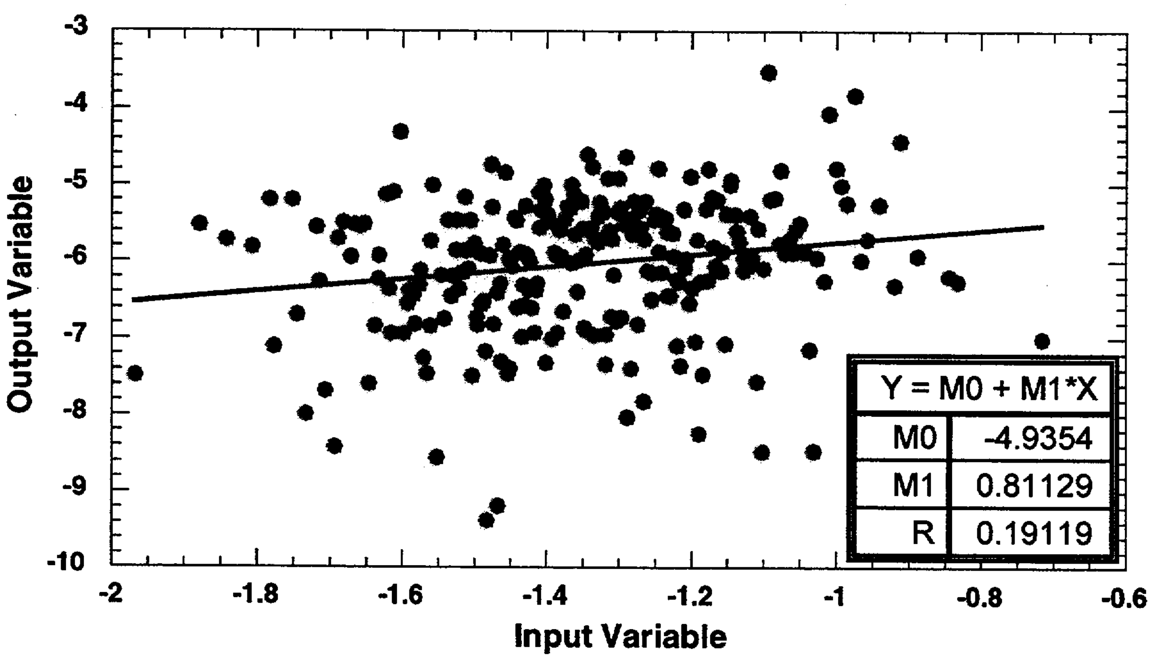

Figure 4-2. Example of a scatter plot/single linear regression.

The t-statistic of the slope of a single-variable regression line is defined as

$$t_i \quad m_i\sqrt{n\frac{S_{ix}^2}{S^2}} \tag{4-2}$$

where

t_i	ó	t-statistic for regression coefficient i;
m_i	ó	estimated value of regression coefficient i (i.e., slope of the best-fit line for dose versus the independent variable, x_i);
S	ó	estimated standard deviation of dose;
S_{ix}	ó	estimated standard deviation of independent variable, x_i; and
n	ó	number of samples.

For the analyses conducted herein, the number of realizations is greater than 250, which provides essentially an infinite number of degrees of freedom for the t-statistic. The critical value to ensure 95-percent confidence that m_i differs from zero under these conditions is 1.96 (Mason, *et al.*, 1989). Equation (4-2) is used, therefore, to determine if the absolute value of the t-statistic for each independent variable is greater than 1.96. If not, then the hypothesis that the independent variable was significant is rejected.

The t-statistic was used for the single variable regressions and multiple linear regressions as described in Eq. (4-5).

4.1.1.2 Variable Transformations and Their Attributes

The correlation between input and output variables can be enhanced by transforming the variables. This section describes variable transformations used in this study. In general, variable transformations are used to: (i) eliminate dimensionality of the variables; (ii) reduce the role of points at the tails of the distributions; and (iii) properly scale the resulting sensitivities to the variability of the input variables. Although transformations generally increase the goodness of the fit analyses, they distort the meaning of the results. For example, transformations such as rank, logarithmic, and power law frequently give unfair weight to small doses, which do not affect the mean results as much as the higher doses. Because the proposed regulations are based on mean doses, regression results based on transformed variables should be used cautiously.

Normalization

In normalization, the input variable, x_i, is transformed by dividing it by its mean value (or another baseline value such as the median, 90th percentile, and such):

$$x_i^* = \frac{x_i}{\bar{x}_i} \tag{4-3}$$

Normalized variables are dimensionless and are scalar multiples of their baseline values. Dimensionless variables allow the comparison of sensitivities to other independent variables with different dimensions. Other types of normalization can also be used and will be shown later in this chapter.

Sensitivity measures based on normalized variables describe only the relative change in the dependent variable (peak dose) to changes in the independent variables. Although this is a useful measure of sensitivity, it does not consider the ranges of the variability of the independent and dependent variables (see standardization, following).

Rank Transformation

If the distributions of input and output are far from a normal distribution, particularly if they have one or two long tails, they are liable to distortions from the effect of outliers. One way to avoid such effects is to arrange the output values according to the rank order, or the samples of each input parameter (Morgan and Henrion, 1990). Rank transformation, a dimensionless transform, replaces the value of a variable by its rank (i.e., the position in a list that has been sorted from largest to smallest values) (Iman and

Conover, 1979). Analyses with ranks tend to show a greater sensitivity than results with untransformed variables. If the distribution of doses is skewed toward the low end, which is usually the case, rank transformation gives unfair weights to lower doses.

Logarithmic Transformation

For situations in which input and output variables range over many orders of magnitude, it may be advantageous or even necessary to perform analyses on the logarithm of the variables instead of the variable values themselves. The log transformation is also valuable for creating regression equations, where the subprocesses of the model multiply each other to form the output variable, such as in a transfer function approach. For the present situation in which the dose calculation results from radionuclide releases from the waste form, transport through the geosphere, and uptake by humans, the processes are indeed largely multiplicative rather than additive. Log transforms, therefore, tend to give better fits to the Monte Carlo results than untransformed variables, but at the expense of unfair weighting of the smaller doses. The log transformation may be used in conjunction with normalization.

Scaled-Power Transformation

The scaled power transformation is similar to the logarithmic transformation, but often allows a closer approach to normality. For a variable, v, and power, p (p not equal to 0), the scaled power transformation is (Cook and Weisberg, 1994):

$$v^{(p)} = \frac{\left(v^{p} - 1\right)}{p} \tag{4-4}$$

For $p = 0$, it can be demonstrated that the scaled power transformation reduces to the logarithmic transformation.

The algorithm steps through a range of values of the exponent, p, in small increments and compares the shape of the resultant scaled distribution to the shape of a normal distribution. The staff employed the Lilliefors test for normality (Bowen and Bennett, 1988). The exponent yielding the best fit to the normal distribution is then chosen to scale the variable under consideration. This procedure is used for the independent variables and the dependent variable (peak dose).

The scaled power transformation can be shown graphically for an example of the peak dose for 10,000 yr. Figure 4-3 shows a normal probability plot of dose for 10,000 yr in the 1000-vector basecase, demonstrating that it is highly skewed. Using Eq. (4-4) with an exponent, $p = 0.1$, transforms the data to a close fit to the normal distribution, as shown in Figure 4-4. As with the logarithmic transformation, the improved fit is at the expense of an overemphasis on the smaller dose.

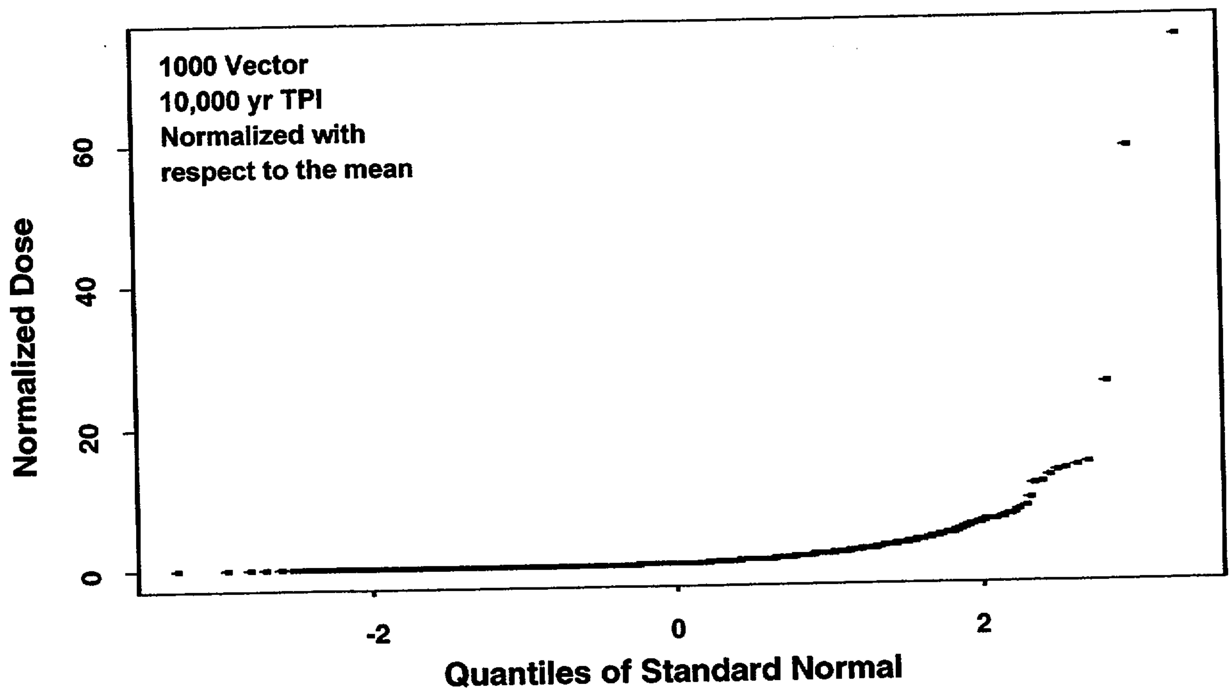

Figure 4-3. Normal probability plot of dose for 10,000 yr in the 1000-vector basecase.

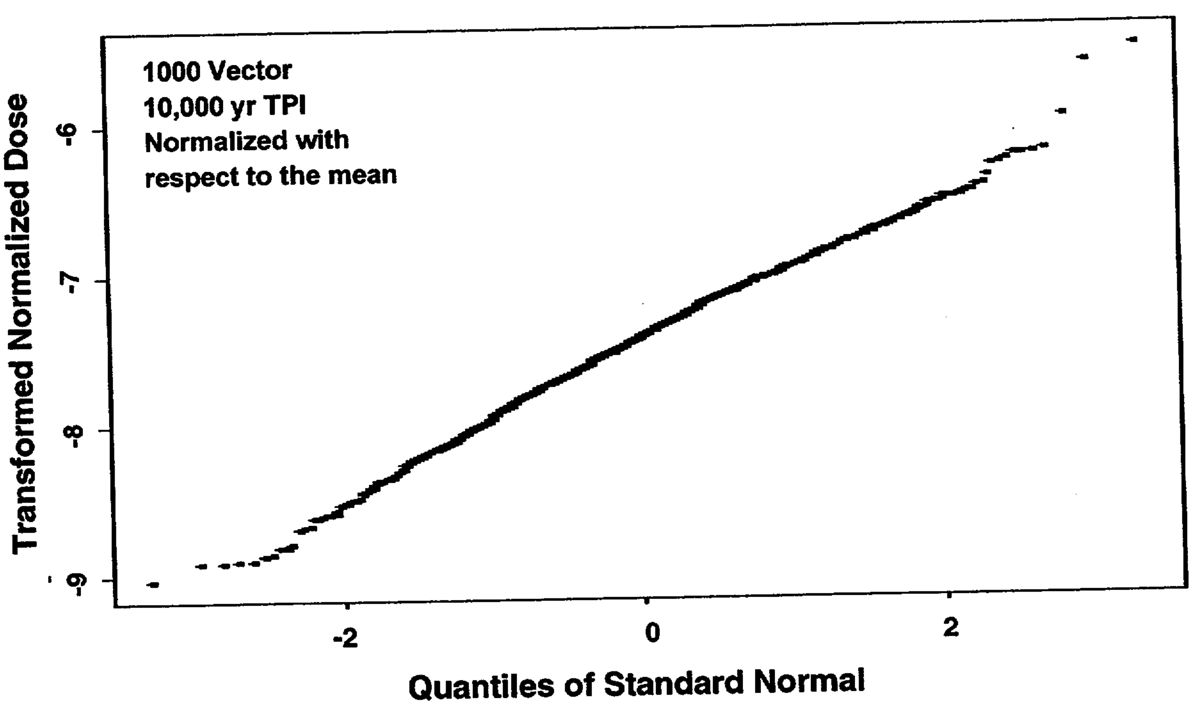

Figure 4-4. Figure showing a close fit to normal distribution after using p = 0.1 transforms.

Standardization

The independent and dependent variables can be standardized by subtracting the mean and dividing by the standard deviation

$$x_i^* = \frac{x_i - \bar{x}}{\sigma_x} \tag{4-5}$$

Sensitivity measures based on standardized variables (standardized sensitivities) have the advantage of taking into account the uncertainty (in the standard deviation) of the independent variable. Furthermore, the standardized sensitivities preserve the absolute values of peak dose because the derivatives are divided by the standard deviation for the entire set of calculations, rather than the mean peak dose at the evaluation point. Therefore, the absolute value of changes in mean peak dose is preserved with standardized sensitivities.

Standardized variables can be greater or less than zero, hence they cannot be used directly in the regression analyses using the log-transformed variables. Instead, the standardized sensitivities can be derived from sensitivities based on logs of the normalized variables:

$$\frac{\partial y^*}{\partial x^*} = \frac{\sigma_{x_i}}{\sigma_y}\left(\frac{\partial y}{\partial x_i}\frac{x_i}{y}\right)\frac{y}{x_i} \tag{4-6}$$

where y^* and x^* are the standardized dependent and independent variables as defined by Eq. (4-5). The quantity in parentheses is the sensitivity derived from regression analysis with the logs of the normalized variables. Note that since Eq. (4-6) requires the normalized sensitivities, it necessarily suffers from some of the same disadvantages as normalized sensitivities. Direct linear regression with standardized variables gives the proper weight to all doses.

A modified form of the standardized sensitivities approach was also used in the differential analysis described in Section 4.1.2. In this case, only seven points were defined for the parameter space, so the independent variables were standardized by the same standard deviations used in the regression analyses (i.e., the standard deviation based on 250 samples generated in the Monte Carlo analyses). Peak dose did not need to be standardized to show the relative sensitivities to the standardized independent variable. Therefore, those sensitivities have units of dose.

4.1.1.3 Stepwise Multiple Linear Regression

Stepwise multiple linear regression (stepwise regression) determines the most influential input parameters according to how much each input parameter reduces the residual sum of squares (RSS) (Helton, 1991). The form of the regression equation is

$$y = m_1 x_1 + m_2 x_2 + \ldots + m_n x_n + b \tag{4-7}$$

where

y — dependent variable;
x_i — independent variables;
m_i — regression coefficients (also known as partial correlation coefficients); and
b — intercept.

The regression coefficients, m_i, are measures of linear sensitivity of y to input x_i (Draper and Smith, 1981). The variables may be the raw variables, transformed variables, or ranks. The stepwise algorithm calculates the reduction in RSS for the independent variables in the order that gives the greatest reduction first. In the implementation of the procedure, a multiple linear regression model is fitted to the data in an iterative fashion. The procedure starts with the variable, x_i, which explains most of the variations in the model output, y. Then it adds additional variables (one at a time) to maximize the improvement in fit of the model according to the R^2 value. In the regression model, R^2, the coefficient of determination indicates the fraction of variability in the data explained by all the variability in the model. The sequence in which the inputs are selected is a useful measure of their uncertainty importance, as is the increment in R^2 they produce. Iman and Conover (1979) also suggested the use of partial correlation coefficients, which are measures of the contribution of each uncertain input to the output uncertainty, after removing the effects attributable to other inputs. These coefficients are useful when there are significant correlations between the inputs (Morgan and Henrion, 1990).

The regression coefficients, m_i ,are the partial derivatives of the dependent variable with respect to each of the independent variables. The correlation coefficient reflects the fractions of the variability explained by the individual variables (Zimmerman, *et al.*, 1991). The form of the linear regression equation that gave the best fit used the log of the normalized peak dose and the log of the normalized independent variables, x_n:

$$\log\left(\frac{y}{\overline{y}}\right) = b + m_1 \log\frac{x_1}{\overline{x_1}} + m_2 \log\frac{x_2}{\overline{x_2}} + \ldots + m_i \log\frac{x_i}{\overline{x_i}} + \ldots + m_n \log\frac{x_n}{\overline{x_n}} \tag{4-8}$$

where

b — intercept; and
m_i — coefficient of the regression

and the overbars denote the value of the quantities used for normalization (generally the mean value).

When the antilog of both sides of Eq. (4-8) is taken, then the resulting equation becomes

$$\frac{y}{\overline{y}} = 10^b \left(\frac{x_1}{\overline{x_1}}\right)^{m_1} \left(\frac{x_2}{\overline{x_2}}\right)^{m_2} \cdots \left(\frac{x_n}{\overline{x_n}}\right)^{m_n} \tag{4-9}$$

After taking the partial derivative of both sides of Eq. (4-9) with respect to the independent variables and rearranging, it reduces to

$$\frac{x_i}{y}\frac{\partial y}{\partial x_i} = m_i \tag{4-10}$$

Therefore, the normalized sensitivities are exactly the coefficients of the regression equation using the logs of the normalized peak dose and independent variables. The form of the sensitivities given by Eq. (4-10) is the same measure calculated by the differential method of Eq. (4-12) in Section 4.1.2.

4.1.1.4 Application of the Kolmogorov-Smirnov and Sign Tests for Determining Important Parameters

The K-S and Sign tests differ from regression in that they are nonparametric; that is, these tests do not require fitting the data to prespecified functional forms.

The Kolmogorov-Smirnov Test

The K-S test determines if a set of samples was drawn from a given distribution (Bowen and Bennett, 1988). It is used to determine if an independent variable is influential by comparing the distribution of a subset of the independent variables composed of the values from the highest 10 percent of the peak dose realizations to the theoretical distribution of that variable. If the two distributions are equivalent, then peak dose is not sensitive to the variable in question. Conversely, if the distributions are different, then the variable in question does have an effect on peak dose. For the present study, there are 1000 vectors in the entire set, and the subset consists of the 100 vectors corresponding to the top 10 percent of the peak doses. The distribution of the variable in the 1000-vector set is taken as the theoretical distribution, although it would also be possible to get the theoretical distribution directly from the generating function specified in the LHS routine. The significance of the K-S test was determined at the 95-percent confidence level.

The Sign Test

The Sign test is another nonparametric test used to determine if a set of data corresponds to a given theoretical distribution (Bowen and Bennett, 1988). It is used in a manner similar to the K-S test. In the Sign test, each observation of the input variable is represented by either a plus sign (+) or a minus sign (−), depending on if it is greater than or less than the median value estimated by the theoretical distribution. The subset of the input parameter values corresponds to the highest 10 percent of the calculated peak doses. The subset is compared with the theoretical distribution, which, in this case, is assumed represented by the entire set of 1000 vectors. The significance of the Sign test was determined at the 90 percent confidence level.

4.1.2 Differential Analysis Technique

Regression analysis on the Monte Carlo results can only determine the most influential parameters when those parameters also have large enough correlation coefficients that they are distinguishable from the confounding effects of the simultaneous sampling of all other independent variables. Differential analysis determines sensitivity unambiguously because it deals with changes in only one independent variable at a time. Differential analysis determines sensitivity of parameters only at local points in parameter space and does not consider the wide range of parameter variations, as does the Monte Carlo method. This section describes the results of a differential analysis conducted to determine the most influential parameters with respect to peak dose.

Differential analysis tests were conducted through multiple deterministic runs in which a single input parameter was changed by a known amount compared to its initial baseline value, and all other input parameters were held at a baseline value. The baseline value for the purposes of this report is a sampled value for the input parameter. The sensitivity of a performance measure (in this case peak dose for the TPI) to a parameter is estimated as the first derivative of the performance measure with respect to that parameter

$$\frac{\delta y}{\delta x_i} = \frac{y(x_i + \Delta x_i) - y(x_i)}{\Delta x_i} \tag{4-11}$$

Usually Δx_i is relatively small (e.g., 10 percent of the parameter value). These estimates of sensitivity are local (i.e., the value of the derivative may change at different points in the sample space). To partially alleviate this concern, the derivative may be evaluated at several points in the sample space. In the analyses presented herein, the derivative is transformed in one of two ways to allow for comparison of sensitivity coefficients between parameters whose units may differ. The first transformation is described by

$$S_i = \frac{\delta y}{\delta x_i} \frac{\overline{x_i}}{\overline{y}} \tag{4-12}$$

where S_i is the dimensionless normalized sensitivity coefficient. These normalized sensitivity coefficients are in the same form as the sensitivities defined by the regression analyses with the log of the normalized variables. Because S_i does not account for the range of the input parameter, a second transformation of the derivative is also performed where the derivative is multiplied by the standard deviation of the input parameter distribution. This transformation is described by

$$S_\sigma = \frac{\delta y}{\delta x_i} \sigma_{x_i} \tag{4-13}$$

Baseline cases were run with input parameter values set at seven random points within each parameter distribution range selected using the LHS technique. Seven points may not cover the whole space, but this limitation was imposed for expediency purposes.

4.1.3 Morris Method Technique

The Morris method (Morris, 1991) considers $\partial y/\partial x_i$ [9] as a random variable and uses the mean and standard deviation of the random variable to determine the sensitivity of y to x_i. A large value of mean of $\partial y/\partial x_i$ implies that x_i has a large overall influence on y. A large value of standard deviation implies that either x_i has significant interactions with other input parameters (i.e., x_k, $k = 1, 2, \ldots, I$, $k \neq i$) or its influence is highly nonlinear. Therefore, both the mean and standard deviations of $\partial y/\partial x_i$ are used to rank the influence of input parameters.

In the Morris method, the random variable, $\partial y/\partial x_i$, is evaluated using the current and the previous values of y:

$$\frac{\partial y}{\partial x_i} = \frac{y(x_1 + \Delta x_1, x_2 + \Delta x_2, \ldots, x_i + \Delta x_i, \ldots, x_I)}{\Delta x_i} - \frac{y(x_1 + \Delta x_1, x_2 + \Delta x_2, \ldots, x_i, \ldots, x_I)}{\Delta x_i} \tag{4-14}$$

This is in contrast to the differential analysis method in which $\partial y/\partial x_i$ is evaluated using the current and baseline values of y, as presented in Eq. (4-11).

To compute $\partial y/\partial x_i$, a design matrix is constructed using input variables as shown:

$$\left[\begin{matrix}
x_1 & x_2 & \cdots & x_{i-1} & x_i & x_{i+1} & \cdots & x_I \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
x_1+\Delta_1 & x_2+\Delta_2 & \cdots & x_{i-1}+\Delta_{i-1} & x_i & x_{i+1} & \cdots & x_I \\
x_1+\Delta_1 & x_2+\Delta_2 & \cdots & x_{i-1}+\Delta_{i-1} & x_i+\Delta_i & x_{i+1} & \cdots & x_I \\
x_1+\Delta_1 & x_2+\Delta_2 & \cdots & x_{i-1}+\Delta_{i-1} & x_i+\Delta_i & x_{i+1}+\Delta_{i+1} & \cdots & x_I \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
x_1+\Delta_1 & x_2+\Delta_2 & \cdots & x_{i-1}+\Delta_{i-1} & x_i+\Delta_i & x_{i+1}+\Delta_{i+1} & \cdots & x_I+\Delta_I
\end{matrix}\right]
\begin{matrix} 1 \\ \\ i \\ i+1 \\ i+2 \\ \\ I \end{matrix}$$

where $\Delta_i = \Delta x_i$. To construct this matrix, the range of each variable is subdivided into (p-1) intervals using (p-1) equally spaced points. Then x_i values are randomly sampled from these p intervals. It should be noted that each interval represents the left-most value in the original distribution. The increment Δ is now represented by $\Delta_i = p/2(p-1)$.

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[9]Strictly speaking, $\partial y/\partial x_i$ should be denoted as $\Delta y / \Delta x_i$ because Δx_i is not necessarily a small value, as in the case of differential analysis. Here the notation is maintained to simplify the comparison with the differential analysis method.

To implement the Morris method, the input variables are first normalized using the following transformation such that the transformed input parameters, x_i^*, range from 0 to 1.

$$x_i^* = \frac{x_i - x_{i\min}}{x_{i\max} - x_{i\min}}, i = 1,2,i...,I \tag{4-15}$$

To minimize the influence of the baseline sampling on the parameter sensitivity, seven samples are collected for each random variable $\partial y/\partial x_i$. The steps necessary to obtain the design matrix, which includes these samples, are presented in Appendix A. This was accomplished by sampling seven baseline realizations, using LHS, from which seven different design matrices were constructed.

4.1.4 Fourier Amplitude Sensitivity Test Method

Both the differential analysis and the Morris method handle one input parameter at a time. For a nonlinear computational model, input parameters are likely to have strong interactions. It would be desirable therefore to have a sensitivity analysis method that would investigate the influence of all input parameters at the same time. The Fourier Amplitude Sensitivity Test (FAST) method (Cukier, *et al.*, 1973) does this. It first applies trigonometric transforms to the input parameters:

$$x_i = g_i(\sin \omega_i s), i = 1,2,...,I \tag{4-16}$$

The trigonometric transforms relate each input parameter, x_i, to a unique integer frequency, w_i. All transforms have a common parameter s, where $0 \le s \le 2\pi$. As s varies from 0 to 2π, all the input parameters vary through their ranges simultaneously at different rates controlled by the integer frequencies assigned to them through Eq. (4-16). Equally spaced values of s between 0 and 2π are chosen to generate values of x_i in Eq. (4-16). Because trigonometric transforms and integer frequencies are used in Eq. (4-16), the output, y, becomes periodic in s, and the discrete Fourier analysis can be used to obtain the Fourier coefficients of y with respect to each integer frequency (Appendix B). The sensitivity of y to x_i is measured by the magnitudes of the Fourier coefficients with respect to ω_i, and y is considered sensitive to the input parameters with larger magnitudes of Fourier coefficients.

The use of integer frequencies causes some errors because of aliasing among Fourier coefficients. The integer frequencies in Eq. (4-16) were chosen to minimize interactions among Fourier coefficients to ensure, as much as possible, that the particular coefficient, A_i (Appendix B), through the particular integer frequency, w_i, represents only the influence of the corresponding input parameter, x_i. Appendix B explains how the integer frequencies are selected and how the FAST method is implemented. Assuming $0 \le x_i \le 1$, the trigonometric transformation functions used here were

$$x_i = \frac{1}{2} + \frac{1}{\pi} \arcsin\left[\sin(\omega_i s + r_i)\right], i = 1,2,...,I \tag{4-17}$$

where r_i, and i = 1, 2, ..., I are random numbers. If the range of variation of a parameter is different from [0, 1], Eq. (4-17) can be modified easily.

Currently, implementation of the FAST method is limited to 50 input parameters. According to Cukier, *et al.*, (1975), as many as 43,606 realizations are needed to perform a satisfactory analysis on 50 input parameters, to avoid aliasing among any four Fourier amplitudes.

4.1.5 Parameter Tree Method

The parameter tree method examines total system output relative sensitivity and correlations of output to subgroups of input parameters. The parameter trees appear similar to event trees but are different because no specific initiating event is associated with parameter trees. In this technique, the Monte Carlo (or LHS) method is used to examine the possible outcomes of a combination of parameter sets. Bins of realizations are examined where the bins are determined by a commonality of their input parameter states (e.g., all sampled input parameters above their median value).

To analyze the outputs, y_i, in Eq. (4-1), to determine the sensitivity and correlations of output, y, to subgroups of the input parameters, x_n, $n = 1, 2, ..., N$, where $N<I$, a tree structure is developed. The parameter tree partitions input parameter space into bins, each bin forming a branch of the tree based on a partitioning (or branching) criterion, as done in an event tree. The simplest branching criterion is a classification based on parameter magnitude, which treats sampled input values as either $a+$ or $a-$ depending on whether the sampled value is greater or less than the branching criterion value. The event tree analogy is appropriate if $a+$ is considered a parameter failure and $a-$ is considered a parameter success, or vice-versa. Figure 4-5 depicts a general parameter tree. To explain Figure 4-5 using a system model, a number of realizations are generated for a given scenario class. Next, the realizations are partitioned into two subsets determined by whether the first influential parameter, x_i, is greater than or less than a specified level. Realizations with a high value are all treated as $a+$ and low as $a-$, regardless of their position within the subset. Let the number of realizations associated with the two branches be N_{1+} and N_{1-}. Next, the output variable, - 1, is examined for realization associated with each branch of the tree. The number of realizations with y greater than a criterion (e.g., mean) are counted for both the branches. Let these numbers be L_{1+} ($L_{1+} \leq N_{1+}$) and L_{1-} ($L_{1-} \leq N_{1-}$). The difference between L_{1+} / N_{1+} and L_{1-} / N_{1-} is a measure of sensitivity of y to x_1. The procedure is repeated in each of these two subsets with the next influential parameter to be considered and so on until each of the influential parameters is considered. This procedure determines 2^M bins of realizations where M is the number of influential parameters. Note that not every sampled parameter in the system model need be considered if a subset of the sampled parameters satisfactorily explains system behavior of interest. Sensitivity measures similar to those over explained for one parameter are developed for a set of parameters.

Another measure of influence of a subset of parameters may be defined through the contribution that realizations in a bin make to specific statistics of the output. For example, one can compute the expected value of y for realizations associated with each branch of the tree and compare these means to the overall mean of y. Statistics other than the mean can be used or probability distributions can be developed for each branch and compared with the overall probability distribution of y. If, for example, the probability of y exceeding a certain limiting value (perhaps specified by regulations) is of interest, one could find the value of such exceedance probability for each branch and estimate (in a relative sense) the contribution that each parameter set makes to such a probability. Formally then, if T is a statistic (e.g., mean, mode, median, exceedance probability) of interest, for the second level of the tree, the ratios of $T_{1^+2^+}, T_{1^+2^-}, T_{1^-2^+}, T_{1^-2^-}$ to T or y as a whole provide measures of relative sensitivity.

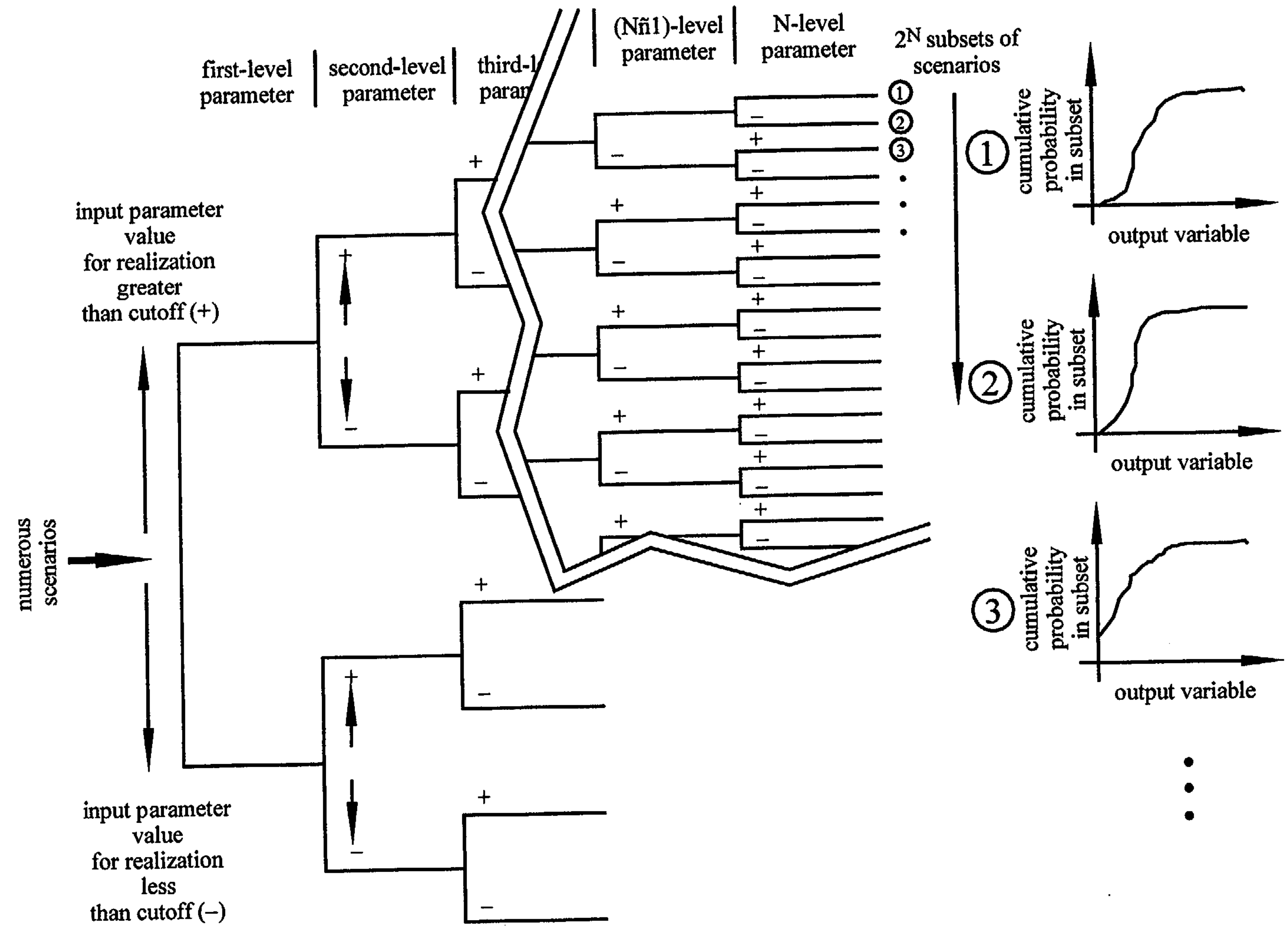

Figure 4-5. General parameter tree.

The branching criterion can be something other than the magnitude of a parameter. One of the more useful possibilities is to assume the system is made up of several components in series such that the output from one component becomes an input to the second and so on. With this conceptualization, the branching criterion can be stated as the magnitude of the output of a component. In this case, each branch of the tree would represent the contribution of a component or a set of components to overall system performance. Relative sensitivity measures could then be defined in exactly the same manner as explained previously.

4.2 ANALYSIS OF SENSITIVITY FROM MONTE CARLO RUNS

This section presents the sensitivity and uncertainty analyses results generated using methods described in the previous section. Statistical results of the 1000-vector Monte Carlo runs, treated separately from the differential analysis, Morris method, and FAST method will be covered first in this section. Comparison of the results among methods will be presented in subsequent sections.

4.2.1 Procedure for Screening Monte Carlo Sensitivity Results

The Monte Carlo simulation results were screened to estimate which variables were likely to be significantly influential and provide an estimate of the sensitivity coefficients. The sequence by which these procedures were employed is described next.

Preliminary screening analyses—This stage of the analyses used a variety of techniques to determine in gross terms whether an independent variable was possibly related to dose. All variables that passed any of the screening tests are included in the subsequent analyses. For all analyses, zero values of dose were eliminated from the data sets because these were inadmissible for logarithmic and power law transformations. For each TPI (10,000 or 50,000 yr), the following procedures were employed:

- Visual inspection of scatter plots

- t-statistic test for single linear regression of dose versus each variable
  — Normalized variables
  — Log of normalized variables

- Stepwise linear regression
  — Normalized variables
  — Log of normalized variables
  — Scaled-power transformed variables
  — Ranks of variables

- Nonparametric tests
  — K-S test
  — Sign test

Linear models—For each TPI, the list of independent variables from any of the preliminary screening analyses was used to construct a linear model, to be fitted by regression to the data, using Eq. (4-7). This was also performed on the logarithmically transformed variables.

Refined screening—The regression coefficients resulting from the linear models were then screened for significance using the t-test. The hypothesis that an independent variable is significant was rejected if the absolute value of t was less than 1.96, corresponding to a 95^{th} percentile confidence limit, for either the normalized or logarithmically transformed variables. Note that the t-test performed on the single-variable regressions in the first step frequently accepted variables that were later screened by the refined analysis.

Transform sensitivity of the variables resulting from refined screening to standardized form—Use Eq. (4-5) to transform the normalized sensitivities resulting from regression of the logarithmically transformed variables to the standardized form.

4.2.1.1 Sensitivity Results from Monte Carlo Analysis

This section presents the sensitivity analyses based on the statistical analysis of a 1000-vector Monte Carlo analysis of the basecase for 10,000- and 50,000-yr TPI.[10] The screening and regression analyses are summarized in Tables 4-1 and 4-2 for the 10,000- and 50,000-yr TPIs, respectively. The column headings in Tables 4-1 and 4-2 have the following explanations:

- Variable Name—The abbreviated name of the independent variable appearing potentially sensitive in any of the screening analyses. There is a complete list of the variable names in Appendix D.
- Step Norm—Variables that appeared to be influential from stepwise regression of the normalized variables.
- Step Lnorm—Variables that appeared to be significant for stepwise regression of the log of the normalized variables.
- Step Rank—Variables that appeared to be significant from stepwise regression of the ranks of the variables.
- Step Lilli—Variables that appeared to be significant from stepwise regression of the power-law transformed variables.
- KS + Sign—Variables that passed both the K-S and Sign tests.
- t-Norm—Variables for which the t-value of a single-variable regression of the normalized variables is greater than 1.96 (95-percent confidence level).
- t-Lnorm—Variables for which the t-value of a single-variable regression of the log of the normalized variables is greater than 1.96.
- t-Lilli—Variables for which the t-value of a single-variable regression of the power-law transformed variables is greater than 1.96.

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[10]The time period of interest of 100,000 yr used in presenting the basecase results is different from that used in the sensitivity analyses (10,000 and 50,000 yr) primarily because the basecase results were also used in reviewing the U.S. Department of Energy Total System Performance Assessment-Viability Assessment results, which extended to 100,000 yr and beyond.

Table 4-1. Summary of regression and screening for basecase, 10,000-yr time period of interest

Variable Name	Step Norm	Step Lnorm	Step Rank	Step Lilli	KS + Sign	t-Norm	t-Lnorm	t-Lilli	In LM Model	t-stat Norm	t-stat Lognorm	Sens ?
AAMAI@S	—	X	X	X	X	X	X	X	X	2.86	8.03	X
MAPM@GM	—	X	X	—	X	X	X	X	X	1.61	3.16	X
MATI@GM	—	—	—	X	—	X	X	X	X	2.13	1.06	X
FOC-R	—	X	X	—	X	—	X	X	X	1.36	0.10	—
FOCTR-R	—	—	—	X	—	—	—	X	—	—	—	—
InnOvrEI	—	—	—	—	X	—	—	—	—	—	—	—
SSMO-RPR	X	—	—	—	—	—	—	—	—	—	—	—
SSMOV201	—	—	—	—	X	—	—	—	—	—	—	—
SSMOV501	X	—	—	—	—	X	—	—	X	1.96	0.15	X
Fow*	X	X	X	X	X	X	X	X	X	4.10	14.60	X
Fmult*	X	X	X	X	X	X	X	X	X	3.01	7.65	X
SbArWt%	X	X	X	X	X	X	X	X	X	32.40	15.37	X
WP-Def%	X	X	X	X	X	X	X	X	X	4.34	12.66	X
InitRSFP	X	X	X	X	—	X	X	X	X	0.09	2.27	X
SFWt%I1	—	—	—	—	X	—	—	—	—	—	—	—
SFWt%I3	X	—	—	—	X	X	—	—	X	2.28	0.91	X
SFWt%S46	X	—	—	—	X	X	—	—	X	2.43	0.37	X
MKDPPwAm	—	—	—	—	X	—	—	—	—	—	—	—
MKDCHzNp	—	—	—	—	X	—	—	—	—	—	—	—
MKDCHzNp	—	—	—	—	X	—	—	—	—	—	—	—
MKDUFZNp	—	—	—	—	X	—	—	—	—	—	—	—
MKDCHzU	—	—	—	—	X	—	—	—	—	—	—	—
MKDCHvPb	—	—	—	—	X	—	—	—	—	—	—	—
MKDBFwPb	—	—	—	—	X	—	—	—	—	—	—	—
MKDBFwSe	X	—	—	—	—	X	—	—	X	2.19	0.78	X
MPrmTSw	—	—	—	—	X	X	X	—	X	0.54	0.35	—

Table 4-1. Summary of regression and screening for basecase, 10,000-yr time period of interest (cont'd)

Variable Name	Step Norm	Step Lnorm	Step Rank	Step Lilli	KS + Sign	t-Norm	t-Lnorm	t-Lilli	In LM Model	t-stat Norm	t-stat Lognorm	Sens ?
FPrm_CHv	—	—	—	—	X	—	—	—	—	—	—	—
FPrm_BFw	X	—	—	—	—	X	—	—	X	2.28	—	X
ARDSAVAm	—	—	—	—	—	—	—	X	X	0.75	0.49	—
ARDSAVNp	—	X	X	—	X	—	X	—	X	1.43	2.91	X
ARDSAV_I	—	X	X	X	—	—	X	X	X	0.32	4.86	X
ARDSAVTc	X	X	X	X	X	X	—	X	X	2.90	5.04	X
ARDSAV_U	—	—	—	X	X	—	X	X	X	0.22	1.40	—
ARDSAVPu	—	—	—	—	X	—	X	—	—	—	—	—
APrs_SAV	—	—	—	X	—	X	X	—	X	0.09	1.95	X
WPRRG@20	X	X	X	X	X	X	X	X	—	2.90	4.72	X
NWFZnW	—	—	—	—	X	—	—	—	—	—	—	—
NELCDAmt	—	—	—	—	X	—	—	—	—	—	—	—

Table 4-2. Summary of regression and screening for basecase, 50,000-yr time period of interest

Variable Name	Step Norm	Step Lnorm	Step Rank	Step Lilli	KS + Sign	t-Norm	t-Lnorm	t-Lilli	In LM Model	t-stat Norm	t-stat Lognorm	Sens ?
AAMAI@S	—	—	—	—	X	X	X	X	—	—	—	—
MATI@GM	—	—	—	—	X	—	—	—	—	—	—	—
H2OFThK	—	—	—	X	—	—	—	—	—	—	—	—
AA_2_1	X	X	X	X	—	X	X	X	X	1.67	-31	X
OO-CofLC	X	X	X	X	X	X	X	X	—	—	—	—
SSMO-RE	—	—	—	X	—	—	—	—	—	—	—	—
SSMO-RPR	X	—	—	—	—	X	—	—	—	3.33	9.30	X
SSMO-JS5	—	—	—	—	X	—	—	—	X	-2.22	0.04	X
SSMOV206	X	—	—	—	—	—	—	—	X	0.55	2.00	X
SSMOV408	X	—	—	—	X	X	—	—	X	1.81	0.66	—
Fow*	—	—	—	—	—	—	X	X	—	—	—	—
Fmult*	—	—	—	X	—	—	—	—	X	-0.51	-2.14	X
SbArWt%	X	X	X	X	X	X	X	X	X	2.46	35.20	X
InitRSFP	X	X	X	X	X	X	X	—	X	-2.18	4.20	X
SbGFRATF	—	X	—	—	—	—	—	—	X	-1.79	-2.92	X
SFWt%C1	—	X	X	X	—	—	—	X	X	0.88	3.96	X
SFWt%C2	—	X	X	X	X	—	—	X	X	1.69	3.57	X
SFWt%C3	—	X	X	X	—	—	X	X	X	1.13	4.20	X
SFWt%C5	—	—	X	—	—	—	—	—	—	—	—	—
SFWt%C6	—	—	X	—	—	—	—	—	X	0.22	2.13	X
SFWt%C7	—	X	X	—	—	—	—	—	X	0.28	3.53	X
MKDPPwAm	—	—	—	—	X	—	—	—	—	—	—	—
MKDCHvNp	—	—	—	X	—	—	—	—	X	-0.7	-2.11	X
MPrm_TSw	—	—	—	—	X	X	X	X	—	—	—	—
MPrm_UFZ	X	—	—	—	—	X	—	—	—	—	—	—

Table 4-2. Summary of regression and screening for basecase, 50,000-yr time period of interest (cont'd)

Variable Name	Step Norm	Step Lnorm	Step Rank	Step Lilli	KS + Sign	t-Norm	t-Lnorm	t-Lilli	In LM Model	t-stat Norm	t-stat Lognorm	Sens ?
FPrs_PPw	X	—	—	—	—	—	—	—	—	—	—	—
ARDSAVAm	X	—	—	—	X	X	X	—	—	—	—	—
ARDSAVNp	X	X	X	X	X	X	X	X	X	-4.16	24.40	X
ARDSAV_I	—	X	X	X	—	—	X	X	X	-0.71	-3.16	X
ARDSAVTc	—	X	X	X	—	—	X	X	X	0.08	-4.6	X
ARDSAV_U	—	—	—	X	X	X	X	X	X	-1.12	-2.57	X
ARDSAVTh	—	—	—	—	X	—	X	X	X	-0.82	1.20	
APrs_SAV	—	X	—	X	—	—	X	X	X	-1.02	-3.29	X
WPRRG@20	X	X	X	X	X	X	X	X	X	-2.2	-9.2	X

- Include in LM Model—Variables included in linear models for multiple linear regression.

- t-stat Norm—The t-statistic for the variable in the linear model for normalized variables.

- t-stat Lognorm—The t-statistic for the variable in the linear model for log of normalized variables.

- Sens ?—The variable had a t-statistic in either the normalized or lognormalized multiple linear regression analysis that exceeded 1.96 (95 percent confidence).

Tables 4-3 and 4-4 summarize the sensitive parameters, resulting from linear regression, for the 10,000- and 50,000-yr TPIs, with using standardized variables that give a truer indication of parameter sensitivity by taking into account the standard deviations of the independent variables sampled in the Monte Carlo analyses. Figures 4-6 and 4-7 present sensitive parameters, obtained from step-wise regression analyses, using standardized input variables for 10,000 and 50,000 yr, respectively. The ranks of the standardized variables are compared with the ranks from the other sensitivity measures in Section 4.3. In these tables, $\bar{x}$ and $\bar{y}$ represent the mean of the input and output variables. Variables σ_{xi} and σ_{yi} in Tables 4-3 and 4-4 represent the standard deviations of normalized input and output variables (indicated by x^*_i and y^*_i). The headings m-norm and m-lognorm represent coefficients from regression equations using normalized variables and lognormalized.

4.2.1.2 Parameter Sensitivity at High End of Peak Doses

Doses at the high end of the calculated range, and their associated parameter sensitivities, may be of more interest than low doses. To develop this idea further, vectors from the basecase were segregated into those with doses higher than a threshold of 0.1mSv (10 millirem/yr), and those below for the 50,000-yr TPI. The higher category contained 51 vectors and the lower category contained the balance of 949 vectors.

A t-test was then conducted on means of the independent variables to determine if the means of the two populations are statistically the same at the 95-percent confidence limit. For each independent variable x_1 from the high-dose category and x_2 from the low-dose category, calculate the sample means μ_1, and μ_2, together with the variances σ_1 and σ_2 . At the 95-percent significance level, accept the hypothesis if

$$t = \frac{|\mu_1 - \mu_2|}{\sqrt{\sigma_1^2 / m_1 + \sigma_2^2 / m_2}} < 1.96 \tag{4-18}$$

where m_1 and m_2 are the number of samples in sets 1 and 2. The results of this screening are listed in Table 4-5.

Note there were several parameters left off the list because they were probably spurious and cannot have had an effect on the results. For example, the water use parameter at 10 km was sampled but not used. Several of the significant parameters were associated with properties of Am and Pu, although neither ^{241}Am nor ^{239}Pu have any doses at all. The effects of the parameters in the models are due in large part to the deliberate correlations of several of the radionuclide retardation parameters, and it is likely that these factors

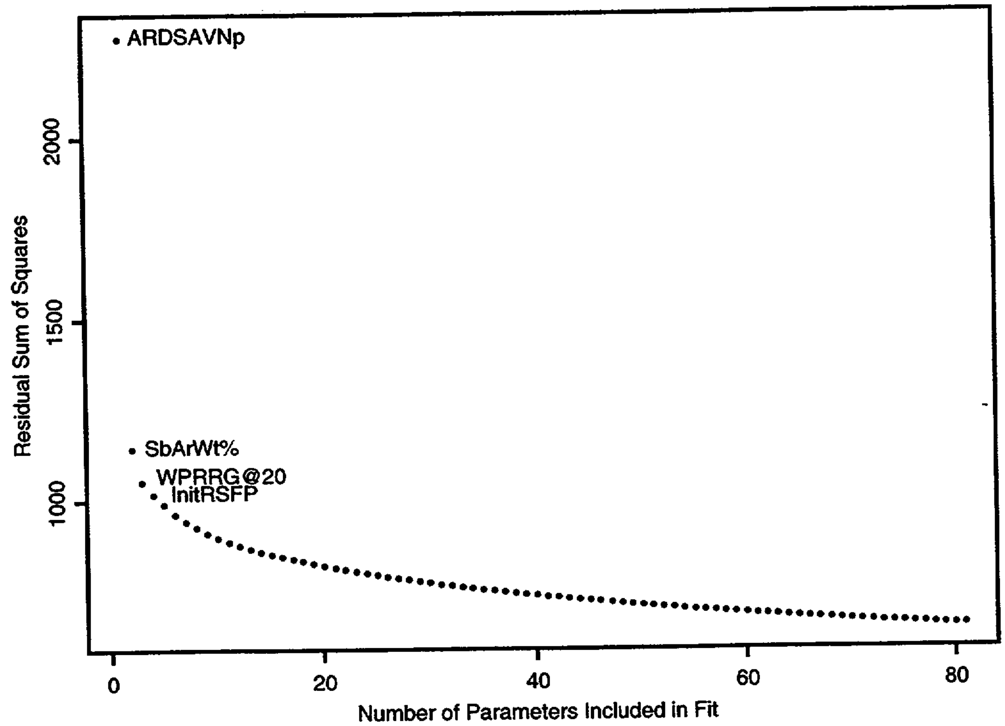


Figure 4-6. **Plot of the residual sum of squares versus number of parameters included in the fit for the basecase with a time period of interest of 10,000 yr.**

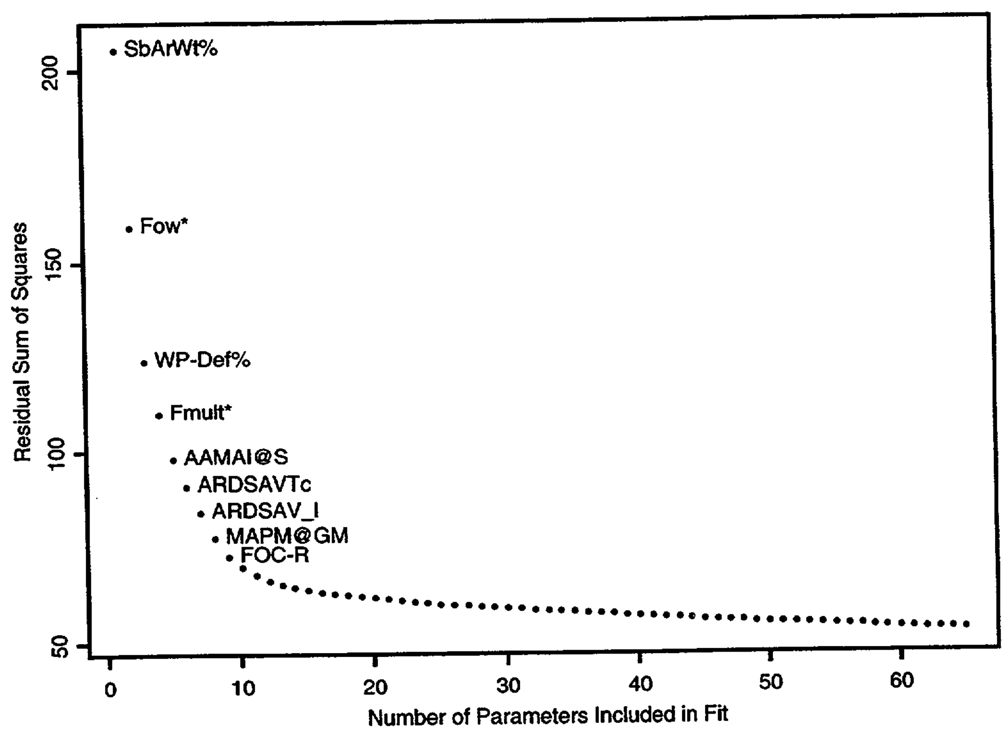


Figure 4-7. **Plot of the residual sum of squares versus number of parameters included in the fit for the basecase, with a time period of interest of 50,000 yr.**

Table 4-3. Standardized sensitivities for basecase, 10,000-yr time period of interest

Variable Name	m-norm	$\frac{\sigma_{x_i}}{\sigma_y}\frac{\bar{y}}{\bar{x}_i}$	$\frac{\partial y^*}{\partial x_i^*}$ (norm)	m-lognorm	$\frac{\partial y^*}{\partial x_i^*}$ (lognorm)
AAMAI@s	0.659	0.134	0.088	0.934	0.125
MAPM@GM	1.208	0.042	0.051	1.463	0.061
MATI@GM	1.208	-0.05586	-0.067	0.367	-0.021
SSMOV501	0.485	0.136	0.066	-0.0174	-0.002
Fow*	0.401	0.326	0.131	1.08	0.353
Fmult*	0.64	0.1456	0.093	1.075	0.157
SbArWt%	0.612	0.161	0.099	1.054	0.17
WP-DEF%	0.847	0.164	0.139	1.079	0.177
InitRSFP	0.0492	0.0586	0.003	-0.726	-0.043
SFWt%I1	0.429	0.1684	0.072	0.062	0.01
SFWt%S46	-0.462	0.168	-0.078	-0.025	-0.004
MKDBFwSe	0.11	0.636	0.07	0.016	-0.01
FPrm_BFw	0.104	0.686	0.071	0.013	0.049
ARDSAVNp	-0.0807	0.567	-0.046	-0.148	-0.084
ARDSAV_I	-0.0872	.1149	-0.010	-0.827	-0.095
ARDSAVTc	-0.349	0.264	-0.092	-0.35	-0.092
APrs_SAV	-0.0845	0.0335	0.003	-1.141	-0.038
WPRRG@20	-1.125	0.0818	0.092	-1.08	-0.088

Table 4-4. Standardized sensitivities for basecase, 50,000-yr time period of interest

Variable Name	m-norm	$\frac{\sigma_{x_i}}{\sigma_y}\frac{\bar{y}}{\bar{x}_i}$	$\frac{\partial y^*}{\partial x_i^*}$ (norm)	m-lognorm	$\frac{\partial y^*}{\partial x_i^*}$ (lognorm)
AAMAI@s	0.9314	0.134	0.101	0.8856	0.089
SSMO-RPR	0.0154	0.0292	-0.067	-0.0154	-0.0004
SSMO-JS5	0.4284	0.0389	0.0170	0.5603	0.0.022
SSMOV206	0.5560	0.0989	0.0550	0.0700	0.0007
Fmult*	-0.0837	0.1840	-0.015	-0.135	-0.025
SbArWt%	1.0020	0.2087	0.2090	1.0810	0.2260
InitRSFP	-0.9080	0.0726	-0.066	-0.6052	-0.044
SbGFRATF	-0.7740	0.0700	-0.0540	-0.4374	-0.031
SFWt%C1	0.1448	0.2090	0.0300	0.1210	0.0250
SFWt%C2	0.2445	0.2090	0.0510	0.1080	0.0230
SFWt%C3	0.1631	0.2090	0.0340	0.1284	0.0270
SFWt%C6	0.0319	0.2090	0.0070	0.0706	0.0150
SFWt%C7	0.0403	0.2090	0.0080	0.1083	0.0290

Table 4-4. Standardized sensitivities for basecase, 50,000-yr time period of interest (cont'd)

Variable Name	m-norm	$\frac{\sigma_{x_i}}{\sigma_y}\frac{\bar{y}}{\bar{x}_i}$	$\frac{\partial y^*}{\partial x_i^*}$ (norm)	m-lognorm	$\frac{\partial y^*}{\partial x_i^*}$ (lognorm)
MKDCHvNp	-0.0164	1.2900	-0.021	-0.0338	-0.044
ARDSAVNp	-0.2	0.6930	-0.069	-0.72	-0.499
ARDSAV_I	-0.151	0.1420	-0.008	-0.242	-0.034
ARDSAVTc	-0.0083	0.3270	0.0030	-4.6	-0.047
ARDSAV_U	-0.0407	0.9280	-0.038	-0.0623	-0.058
APrs_SAV	-0.7362	0.0417	-0.031	-0.8617	-0.036
WPRRG@20	-0.6631	0.1010	0.0670	-0.945	0.0040

Table 4-5. t-test on means of high- and low-dose categories for 50,000-yr time period of interest

Variable Name	t value
AAMAI@s	3.79
OOCofLC	3.89
SSMO-RPR	3.13
SSMOV203	2
SbArWt%	7.7
WP-Def%	2.11
SFW%S37	2.15
MKDUFZAm	4.16
MKDUCFNp	3.23
MKD_CHvU	2.88
MKD_CHzU	2.82
MKD_UCFU	2.78
MKDUFZ_U	2.57
MKDTSwTh	2.93
MKDCHvTh	2.93
MKDUCFTh	2.4
MKDBFwTh	3.42
MPrm_TSw	6.14
MPrm_UFz	1.97
FPrs_CHz	2.68
FPrs_PPw	2.12
ARDSAVAm	6.72
ARDSAVNp	15.8
ARDSAVTh	3.98

show up because of the large contribution to peak dose of ^{237}Np. In the case of ^{241}Am, some dose also may be indirectly attributed to ^{241}Am decaying to ^{237}Np. Dependence of several of the parameters, particularly MKDUFZAm, MKDUFZ_U, and MPrm_UFZ, are suspicious, since these parameters were sampled but not used. It is likely that these results, and possibly others, are spurious because of the relatively small sample size of 51 samples in the high-dose category. The same also is likely to be true for U, since the contribution of ^{234}U to dose is small.

Inspection of the terms that passed this screening and of their respective t statistics indicates strong relationships between some of the parameters and relatively high doses, in particular the subarea wet fraction (SbArWt%), matrix permeability of the Topopah Springs welded tuff (MPrm_TSw), and retardation factors for Am Np, U, and Th.

4.3 ANALYSIS OF SENSITIVITY FROM NONSTATISTICAL METHODS

4.3.1 Results from Differential Analyses

Differential analyses were performed using TPA Version 3.2 code with the basecase. Cases where faulting and igneous activity were activated in the TPA code were modeled separately. A total of 223 input parameter values were perturbed for each series. The input parameters perturbed are defined by a distribution in the basecase tpa.inp input file. The parameters sampled in the tpa.inp file are the ones where a significant amount of uncertainty remains in their value or they have been shown potentially significant to estimating peak dose in the process-level sensitivity analyses.

Seven random sets of input parameters were evaluated. Perturbations to the parameters in these random sets were selected so that the parameter values were maintained in their respectively defined ranges; the first, second, fourth, fifth, and seventh random sets of input parameters were perturbed by +1 percent, whereas the third and sixth random sets of input parameters were perturbed by − 1 percent. The selection of random values yields calculations similar to one realization of a probabilistic TPA code run. The percent perturbations are with respect to the baseline (i.e., local) parameter value.

In the TPA Version 3.2 code, transport through the UZ stratigraphic units is neglected for those units where groundwater residence time is less than 10 yr, or 10 percent of the residence time for the entire UZ below the repository (Mohanty and McCartin, 1998). Differential analyses, in which UZ transport calculations are omitted because of this assumption, will result in peak dose showing no sensitivity to parameters that describe UZ properties in those stratigraphic units excluded from the transport calculations. For example, when all parameters were set at their mean values, the UZ portion of NEFTRAN was skipped for a majority of the subareas. Thus, sampled UZ flow and transport (UZFT) parameters did not show any sensitivity in these calculations. However, when the transport time in the UZ is short, it is unlikely that any of the UZ parameters would have a substantial effect on the peak dose, so this should not have a significant effect on the results of the differential analysis.

For all sets of the random parameters, the WPs did not fail from either seismicity or corrosion in the 10,000-yr TPI, but did fail from corrosion within the 50,000-yr TPI. The baseline dose values in these cases are solely from initially defective WPs.

Each set of base values was used in a TPA code run, to determine the reference value of peak dose necessary to calculate several sensitivity measures. The baseline value peak doses can be found in Appendix E.

The results of the differential analysis are shown in the following tables for TPIs of 10,000 and 50,000 yr in Appendix E: Tables E-1 and E-2 for the basecase, Tables E-3 and E-4 for the basecase plus faulting, and table E-5 for the basecase plus igneous activity. The basecase plus igneous activity was not run for the 50,000-yr TPI because the results are not expected to change after the 10,000-yr TPI when groundwater dose dominates and the primary contributors to ground-surface dose have decayed. Variables tested but indicating zero sensitivity at all baseline values are not shown in the tables for the basecase.

Tables E-1 through E-5 of Appendix E show the sensitivities calculated using four different measures:

(1) The geometric mean of the absolute value of the sensitivity coefficient S_i [see Eq. (4-12)] was calculated for the seven base values. The geometric mean is useful for emphasizing parameters that are sensitive over the entire range of base values. In cases where the sensitivity coefficient was zero (i.e., smaller than the least significant digit in code output) at a base value, the geometric mean is an upper estimate for that parameter.

(2) The arithmetic mean of the absolute values of S_i was calculated for the seven base values.

(3) The highest sensitivity of S_i is calculated at any of the seven points. This sensitivity measure is useful to determine if the parameter is sensitive at any of the seven points.

(4) An arithmetic mean of the derivative is weighted by the standard deviation of the input parameter. This sensitivity measures the response of peak dose to each of the independent variables, weighted by their standard deviation. The standard deviations are determined by the parameter range and distribution used in the Monte Carlo analyses. This measure takes into account the magnitude of the change in peak dose and the uncertainty in the independent variables. For comparison, the normalized sensitivity measure, S_i, is a relative sensitivity where the slope is scaled by the local values of dose and the independent variable. Therefore S_i does not depend on whether the baseline dose is small or large, but only on the change in dose relative to the change in the independent variable.

Measure (4) was used to sort the input parameters in descending order because it reflects both the absolute value of peak dose and the uncertainty in the independent variables. The other three sensitivity measures are also given in the tables provided in Appendix E. The lists of influential parameters are generated based on the top 10 parameters for the basecase (i.e., at 10,000- and 50,000-yr TPIs).

The tables in Appendix E provide a list of the parameters that showed nonzero sensitivity at any of the seven baseline values about which the derivatives were evaluated. Some of the sensitivities shown, however, were exceedingly small. To focus attention on the parameters to which peak dose showed the largest sensitivity for the current models on which this report is based, Tables 4-6 and 4-7 list the influential parameters for the basecase [i.e., the top 10 parameters based on the mean of S_σ as in Eq. (4-13)] for the two TPIs. Table 4-8 lists the influential parameters for the disruptive scenarios for the two TPIs. The influential parameters for the disruptive scenarios were determined by including any parameter whose sensitivity was within 1 order of magnitude of the most influential parameter from the basecase, using measure (4). For the igneous activity scenario, all sampled parameters are influential, and for the faulting scenario, three sampled parameters are influential for the 10,000-yr TPI, but no sampled parameters are influential for the 50,000-yr TPI. The reason for this difference is that the only impact of faulting on the repository is failure of the additional WPs. In the longer TPI, all the WPs fail by corrosion, and the peak dose is dominated by the WPs failed by corrosion.

4.3.2 Results from the Morris Method

The Morris method was applied to the TPA Version 3.2 code with the basecase parameter set. A total of 246 input parameters was investigated. A 1729 × 246 matrix was generated and used in sampling input parameters to the TPA code for the 1729 realizations. The 1729 realizations [(246 +1)× 7] produced seven samples for each $\partial y/\partial x_i$, which were used to calculate mean and standard deviation for each $\partial y/\partial x_i$. Seven samples were chosen to be consistent with the differential analysis method.

Figures 4-8 and 4-9 show graphs for the values of mean (abscissa) and standard deviation (ordinate) of $\partial y/\partial x_i$ values for the 10,000- and 50,000-yr TPIs. As described earlier, the greater the distance $\partial y/\partial x_i$ for parameter x_i is from zero, the more influential the parameter x_i is. Physically, a point with large values of both mean and standard deviation suggests that the corresponding input parameter has not only a strong nonlinear effect itself, but also strong interactive effects with other parameters on the output.

The top 10 most influential input parameters identified by the Morris method are listed in Table 4-6 for the 10,000-yr TPI and Table 4-7 for the 50,000-yr TPI, where each parameter was standardized according to Eq. (4-3). For the 10,000-yr TPI, the listed parameters are either related to thermal reflux or transport properties in alluvium. But for the 50,000-yr TPI, no thermal reflux-related parameters make the top 10 list of influential parameters. The parameter, WPRRG @ 20 [well pumping rate for farming receptor group located at or beyond 20 km (12.4 mi) from YM], appears in both 10,000- and 50,000-yr TPIs, as well as some parameters related to transport properties in alluvium. Several SF wet-fraction-related parameters for corrosion failure appear in Table 4-7, for the 50,000-yr TPI, but not in Table 4-6, for the 10,000-yr TPI.

The ranking of parameters using the Morris method was also examined using normalized Eq. (4-13) and log of normalized parameters. For the top 10 most influential parameters list, the normalization scheme replaced SbArWt% (subarea wet fraction) with APrs_SAV (alluvium matrix porosity) for the 10,000-yr TPI, and the list of influential parameters did not change for the 50,000-yr TPI. However, ranking among the top 10 parameters changed for several parameters for both TPIs. The log of normalized parameters replaced radionuclide parameters ARDSAV_I (AlluviumMatrixRD_SAV_I) and ARDSAV_U (AlluviumMatrixRD_SAV_U) with MAPM@GM (mean average precipitation multiplier at glacial maximum) and SbWt% (subarea wet fraction for the 10,000-yr TPI. For the 50,000-yr TPI, parameters AA_2_1 (a parameter representing the corrosion rate); SFWt%C4 (SF wet fraction for corrosion failures in subarea 4); and SFWt%C5 (SF wet fraction for corrosion failures in subarea 5) replaced ARDSAV_U (AlluviumMarixRD_SAV_U); ARDSAVTc (AlluviumMatrixRD_SAV_Tc); and MKD_CHvU (matrix Kd of U for Calico Hills). The logarithmic transformation also changed the ranking for both TPIs.

Table 4-6. Top 10 influential parameters (standardized) from statistical and nonstatistical analyses, for 10,000-yr time period of interest

Rank	Normalized Variables	Log-Normalized Variables	Differential Analysis	Morris Method	FAST Method
1	WP-Def%	Fow*	ARDSAVTc	FOCTR-R	WPRRG@20
2	Fow*	WP-Def%	FOCTR-R	FOC-R	ARDSAV_I
3	SbArWt%	SbArWt%	Fow*	FOCTR	AAMAI@S
4	Fmult*	Fmult*	ARDSAV_I	WPRRG@20	Fow*
5	ARDSAVTc	AAMAI@S	SFWt%I3	AAMAI@S	Fmult*
6	WPRRG@20	ARDSAV_I	WP-Def%	ARDSAV_U	MKDBFwSe
7	AAMAI@S	ARDSAVTc	ARDSAVSe	Fow*	SbArWt%
8	SFWt%S46	WPRRG@20	SbArWt%	WP-Def%	ARDSAVNp
9	SFWt%I1	ARDSAVNp	Fmult*	ARDSAV_I	SFWt%I3
10	FPrm_BFw	MAPM@GM	FOC-R	SbArWt%	MATI@GM

Abbreviation	*Description*	*Abbreviation*	*Description*	*Abbreviation*	*Description*
AAMAI@S	ArealAverageMeanAnnualInfiltrationAtStart[mm/yr]	Fmult*	FmultFactor	SbArWt%	SubAreaWetFraction
ARDSAV_I	AlluviumMatrixRD_SAV_I	FOC-R	FractionOfCondensateRemoved[1/yr]	SFWt%I1	SFWettedFraction_Initial_1
ARDSAVNp	AlluviumMatrixRD_SAV_Np	FOCTR	FractionOfCondensateToward Repository[1/yr]	SFWt%I3	SFWettedFraction_Initial_3
ARDSAVSe	AlluviumMatrixRD_SAV_Se	FOCTR-R	FractionOfCondensateToward RepositoryRemoved[1/yr]	SFWt%S46	SFWettedFraction_SEISMO4_6
ARDSAVTc	AlluviumMatrixRD_SAV_Tc	Fow*	FowFactor		
ARDSAV_U	AlluviumMatrixRD_SAV_U	FPrm_BFw	FracturePermeability_BFw_[m2]	WP-Def%	DefectiveFractionOfWPs/cell
		MATI@GM	MeanAverageTemperatureIncreaseA&GlacialMaximum[degC]		
		MAPM@GM	MeanAveragePrecipitationMultiplierAtGlacialMaximum	WPRRG@20	WellPumpingRateAtReceptorGroup 20km [gal/day]
		MKDBFwSE	MatrixKD_BFw_Se[m3/kg]		

Table 4-7. Top 10 influential parameters from statistical and nonstatistical analyses, for 50,000-yr time period of interest

Rank	Normalized Variables	LogNormalized Variables	Differential Analysis	Morris Method	FAST Method
1	SbArWt%	Fow*	ARDSAVNp	ARDSAVNp	WPRRG@20
2	AAMAI@S	WP-Def%	Fow*	WPRRG@20	AA_2_1
3	WPRRG@20	SbArWt%	OO-CofLC	APrs_SAV	ARDSAV_I
4	ARDSAVNp	Fmult*	AA_2_1	MKD_CHvU	Fmult*
5	SSMO-RPR	AAMAI@S	SbArWt%	SbArWt%	SbArWt%
6	InitRSFP	ARDSAV_I	ARDSAVTc	InitRSFP	SFWt%C3
7	SSMOV206	ARDSAVTc	Fmult*	ARDSAV_U	SFWt%C1
8	SbGFRATF	WPRRG@20	WPRRG@20	SFWt%C3	ARDSAV_U
9	SFWt%C2	ARDSAVNp	APrs_SAV	ARDSAVTc	SFWt%C5
10	ARDSAV_U	MAPM@GM	ARDSAV_I	SFWt%C6	SFWt%C6

Abbreviation	*Description*	*Abbreviation*	*Description*	*Abbreviation*	*Description*
AA_2_1	AA_2_1[C/m2/yr]	Fow*	FowFactor	SFWt%C2	SFWettedFraction_Corrosion_2
AAMAI@S	ArealAverageMeanAnnualInfiltrationAtStart[mm/yr]	InitRSFP	InitialRadiusOfSFParticle[m]	SFWt%C3	SFWettedFraction_Corrosion_3
				SFWt%C5	SFWettedFraction-Corrosion_5
APrs_SAV	AlluviumMatrixPorosity_SAV	MAPM@GM	MeanAveragePrecipitation MultiplierAtGlacialMaximum	SFWt%C6	SFWettedFraction_Corrosion_6
				SSMOpRPR	RockPoissonRatioforSEISMO[]
ARDSAV_I	AlluviumMatrixRD_SAV_I	MKD_CHnv	MatrixKD_CHnv[m3/kg]	SSMOV206	VerticalExtentOfRockFall2_6[m]
ARDSAVNp	AlluviumMatrixRD_SAV_Np	OO-CofLC	CoefForLocCorrOfOuter Overpack	WP-Def%	DefectiveFractionOfWPs/cell
ARDSAVTc	AlluviumMatrixRD_SAV_Tc	SbArWt%	SubAreaWetFraction	WPRRG@20	WellPumpingRateAtReceptorGroup20km [gal/day]
ARDSAV_U	AlluviumMatrixRD_SAV_U	SbGFRATF	SubGrainFragmentRadiusAfter TransFrac[m]		
Fmult*	FmultFactor	SFWt%C1	SFWettedFraction_Corrosion_1		

Table 4-8. Most influential parameters from differential analysis for disruptive event scenarios

10,000-yr Time Period of Interest	50,000-yr Time Period of Interest
Igneous Activity Parameters	
VE-Power	VE-Power
ABMLFVDC	ABMLFVDC
VE-Dur	VE-Dur
VEROI-Tn	VEROI-Tn
VC-Dia	VC-Dia
WindSpd	WindSpd
AshMnPLD	AshMnPLD
Faulting Parameters	
FERIO-Tn	None[1]
SFWt%FO	
NEFZnW	

[1]No sensitivities greater than zero

4.3.3 Results from the FAST Method

Conducting sensitivity analyses for all 246 sampled parameters in the TPA code using the FAST method is impractical because it would take more than 40,000 realizations for the FAST method to conduct a sensitivity analysis on 50 input parameters. Such a large number of realizations is needed to avoid aliasing among Fourier coefficients (Cukier, *et al.*, 1975). Therefore, preliminary screening was necessary to reduce the number of parameters evaluated with the FAST method. In this report, the FAST method is applied to the 18 parameters identified by the statistical screening method presented in the last column of Table 4-1 for the 10,000-yr TPI, and the 20 parameters in the last column of Table 4-2 for the 50,000-yr TPI. These parameters were selected on the basis of t-statistic of the normalized or lognormalized multiple linear regression analysis that exceeded 1.96 (95-percent confidence). For the 18 parameters, only 3310 realizations are needed to avoid aliasing among any four Fourier amplitudes (Appendix B). For the 20 parameters, the number of realizations increases to 4174.To account for the range of an input parameter, each Fourier amplitude was multiplied by the standard deviation of the corresponding input parameter, as defined by Eq. (4-13). The ranking for the top 10 parameters using the FAST method is listed in Tables 4-6 and 4-7 for the 10,000- and 50,000-yr TPIs.

It should be noted that the analysis presented here is limited by the initial selection of 20 parameters from the regression analysis. Thus, some influential parameters may be identified by other nonstatistical methods, but not by the FAST method.

4.4 RESULTS FROM THE PARAMETER TREE METHOD

Several trees are presented, each using different branching criteria such as median, mean, and percentiles, for the important input parameters. A stepwise implementation of the approach is also presented. As described previously, the method used for examining system sensitivity to combinations of parameters

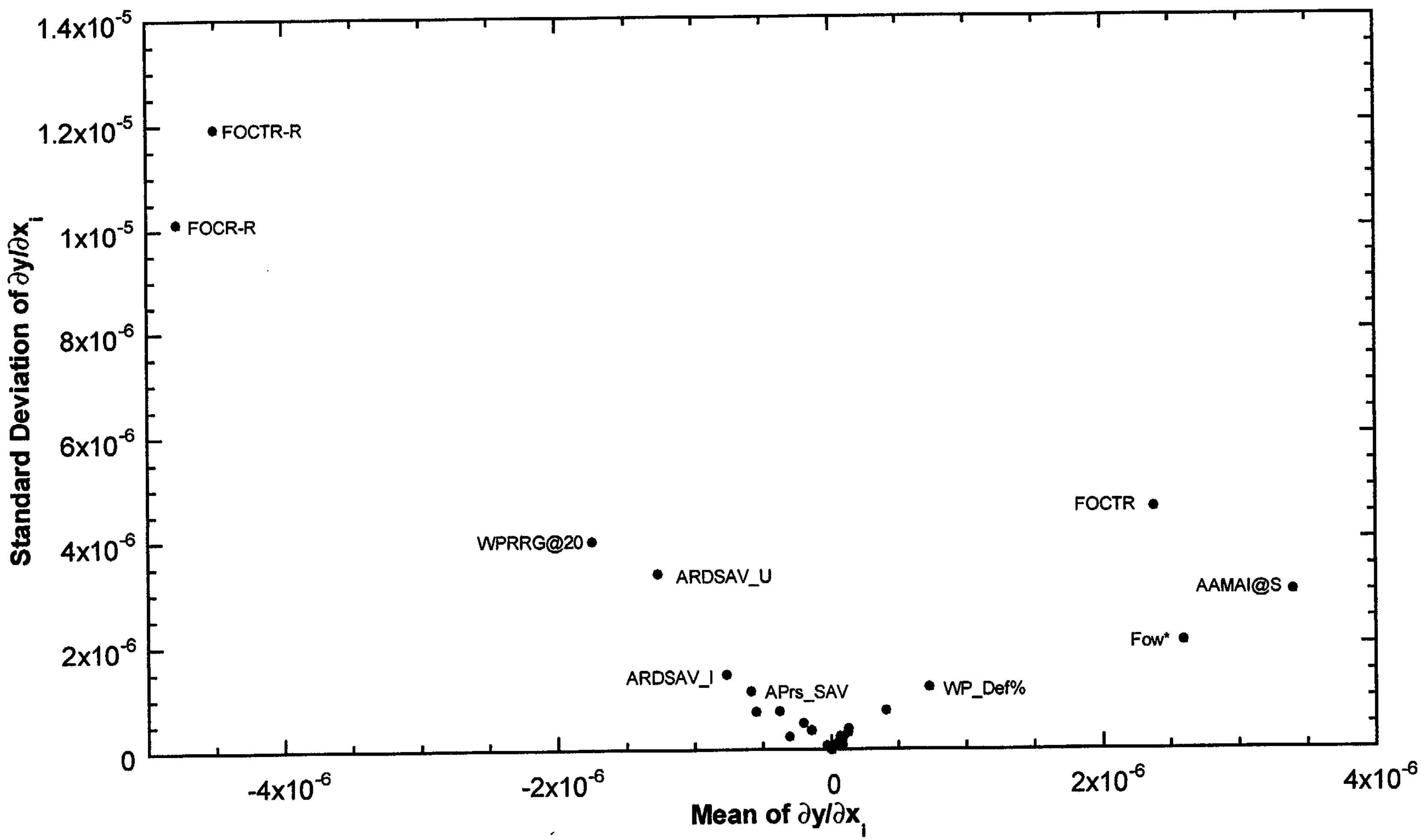


Figure 4-8. Results from the Morris method from the basecase, with a time period of interest of 10,000 yr.

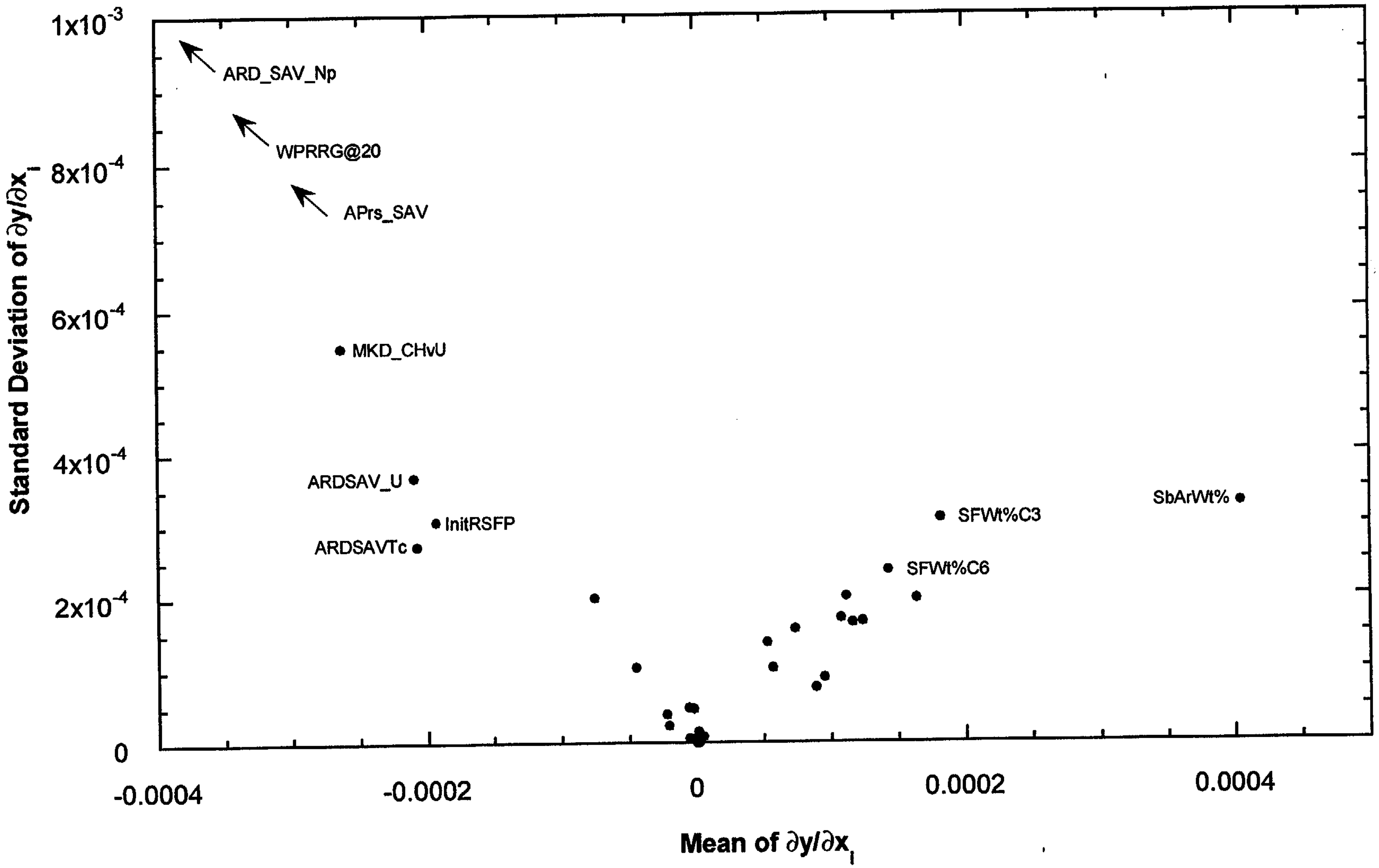


Figure 4-9. Results from the Morris method from the basecase, with a time period of interest of 50,000 yr. (Arrows indicate that the associated points lie outside the graph.)

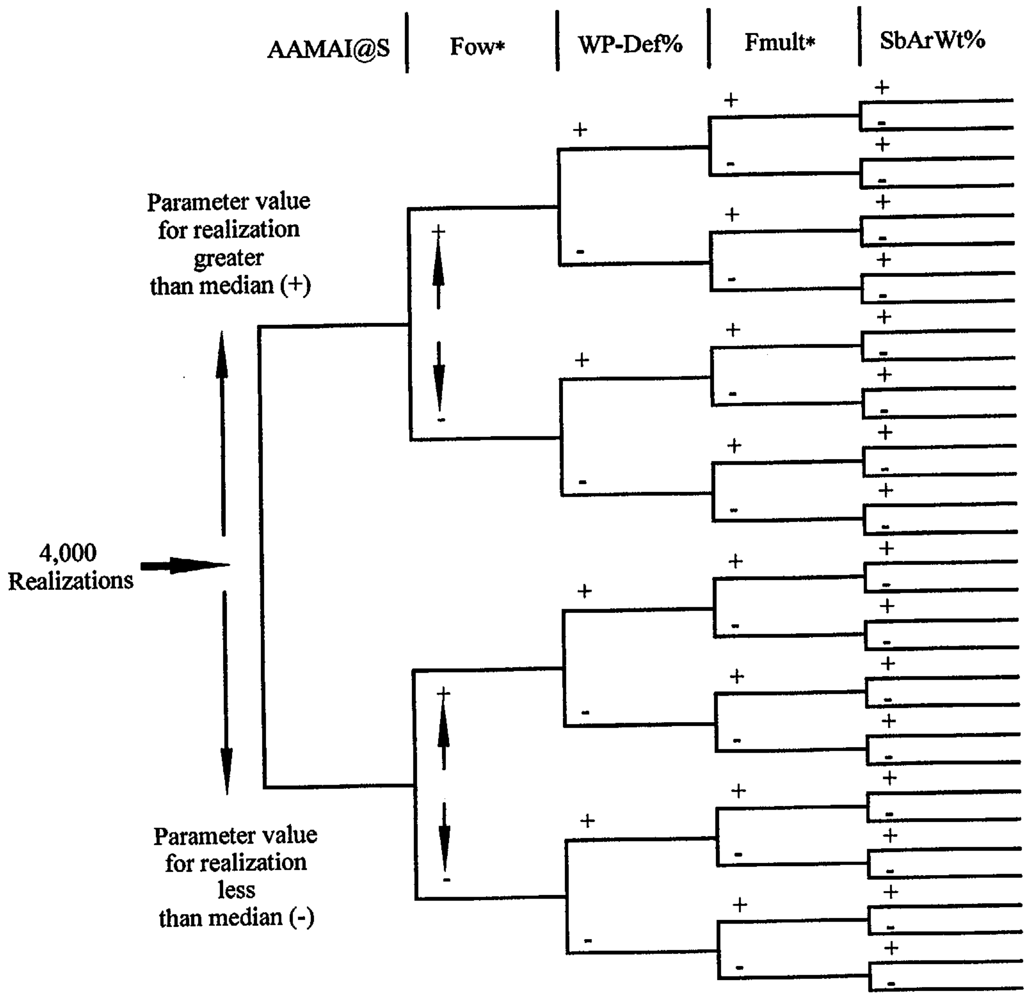
found to be most important is to treat each realization of a parameter value as either a + or a – depending on whether the realized value is greater than or less than a specified value. This is similar to the procedure followed in a Sign Test (Bowen and Bennet, 1988) as described in Section 4.1.1.4. Next, the realizations are sorted based on the commonality of their input parameters being either a + or a –. For example, realizations with all five important input parameters sampled above the median would be placed in the same bin. Similarly, all realizations where the first four parameters are a + and the last one is a – would be placed in another bin and so on.

Figure 4-10 shows the parameter tree based on median values as the branching criterion. A set of 4000 realizations of the TPA Version 3.2 code was used, and 244 input parameters were sampled for the basecase.[11] Table 4-9 shows some statistical information for the most influential parameters identified by the multiple regression analysis for use in the median-based parameter tree method and the statistics of the output variable. The table presents the median, the mean and the 90th percentile values of the parameter distribution for the identified influential input parameters and the output variable (i.e., peak dose in 10,000 yr). In Figure 4-10, Column A is the number of realizations of peak dose above the overall median value (i.e., of the 4000 realizations) in that bin. For example, row one in Column A shows that 129 out of 4,000 realizations had all 5 of the important parameters with values above the median. Of these 129 realizations, 128 had peak doses above the median value for all 4000 realizations (1.84×10^{-5} rem/yr, table 4-9). Column B shows that for these 129 realizations, the mean value of peak dose was 1.20×10^{-4} rem/yr (1.2×10^{-6} Sv/yr), and Column C shows these 129 realizations accounted for 21.07 percent of the population mean of peak doses. This analysis reinforces the notion that these are indeed influential parameters because slightly less than 3 percent of the realizations account for over 21 percent of the mean from all realizations. Column D shows an "importance factor R" which is determined as the ratio of the contribution to the overall mean from realizations in that bin to the average contribution of the same number of realizations to the overall mean, that is,

$$
\begin{aligned}
R &= \frac{\text{fractional contribution to the overall mean dose (Column C)}}{\left(\dfrac{\text{number of realizations in bin}}{\text{total number of realizations}}\right)} \\
&= \frac{\text{mean peak dose in bin (Column B)}}{\text{mean peak dose over all realizations}}
\end{aligned}
\tag{4-19}
$$

All of the data in Columns A–D serve as figures of merit for characterizing the group of realizations in a bin. Two other interesting observations can be made about Figure 4-10. First, the realizations where none or one of the input parameters is a – account for 67 percent of the mean from all realizations (includes 798 out of 4000 realizations). Second, only 8 out of 32 bins have importance factors above unity, indicating that the output variable distribution is skewed (the 8 bins include 999 out of 4000 realizations). Column 2 of Table 4-10 presents the sensitivity coefficients for the influential parameters in the median-value-based parameter tree. Symbols x_1 to x_5 for this column correspond to the five influential parameters shown in Figure 4-10. It is emphasized that these sensitivity coefficients provide only the relative sensitivities. For example, from Table 4-10, Column 2, one can infer that the system is 1.8 times (0.351/0.192) more sensitive to parameter x_1 than it is to parameter x_5. In the lower portion of Table 4-10, the system sensitivities to joint sets of parameters (see Appendix C) are presented. As can be seen in the table, the system shows relatively

[11]The data used in the parameter tree analyses are slightly different from the latest data used in implementing other methods; however, the differences do not contribute to significant changes to the output.



A	B	C	D
128/129	1.20E-04	0.2107	6.52
96/97	6.11E-05	0.0803	3.32
135/140	6.64E-05	0.1261	3.61
57/68	2.27E-05	0.0209	1.23
130/141	4.68E-05	0.0894	2.54
53/70	1.52E-05	0.0114	0.83
104/133	2.19E-05	0.0395	1.19
49/87	9.63E-06	0.0114	0.52
179/224	4.04E-05	0.1226	2.20
49/58	1.78E-05	0.0140	0.97
128/216	9.78E-06	0.0286	0.53
20/59	3.73E-06	0.0030	0.20
135/223	1.05E-05	0.0317	0.57
20/62	4.19E-06	0.0035	0.23
62/230	3.19E-06	0.0099	0.17
6/63	1.05E-06	0.0009	0.06
59/67	4.34E-05	0.0395	2.36
125/226	1.72E-05	0.0528	0.93
35/53	1.79E-05	0.0129	0.97
85/230	5.86E-06	0.0186	0.33
42/60	1.18E-05	0.0096	0.64
91/227	6.11E-06	0.0188	0.33
29/54	1.29E-05	0.0094	0.70
39/218	2.19E-06	0.0065	0.12
37/73	8.52E-06	0.0084	0.46
35/125	4.00E-06	0.0068	0.22
22/87	1.90E-06	0.0022	0.10
12/148	7.60E-07	0.0015	0.04
21/96	2.23E-06	0.0029	0.12
11/122	1.03E-06	0.0017	0.06
3/74	6.33E-07	0.0006	0.03
3/140	4.47E-07	0.0008	0.02

Figure 4-10. Median-based parameter tree describing the technique for examining system sensitivity to groups of parameters.

Table 4-9. Statistical information about the 4000 realizations

Parameter	Median Value	Mean Value	90th Percentile	Distribution Type; Minimum, Maximum Values
AAMAI@S	5.5	5.5	9.1	Uniform; 1,10
Fow*	0.173	0.264	0.566	Lognormal; 0.1, 3.0
WP-Def%$_f$	0.00505	0.00505	0.00901	Uniform; 0.0001,0.01
Fmult*	0.0447	0.0503	0.0833	Lognormal; 0.01,0.2
SbArWt%	0.5	0.5	0.9	Uniform; 0.0,1.0
Peak dose (rem/yr)	2.82×10^{-6}	1.84×10^{-5}	4.97×10^{-5}	—

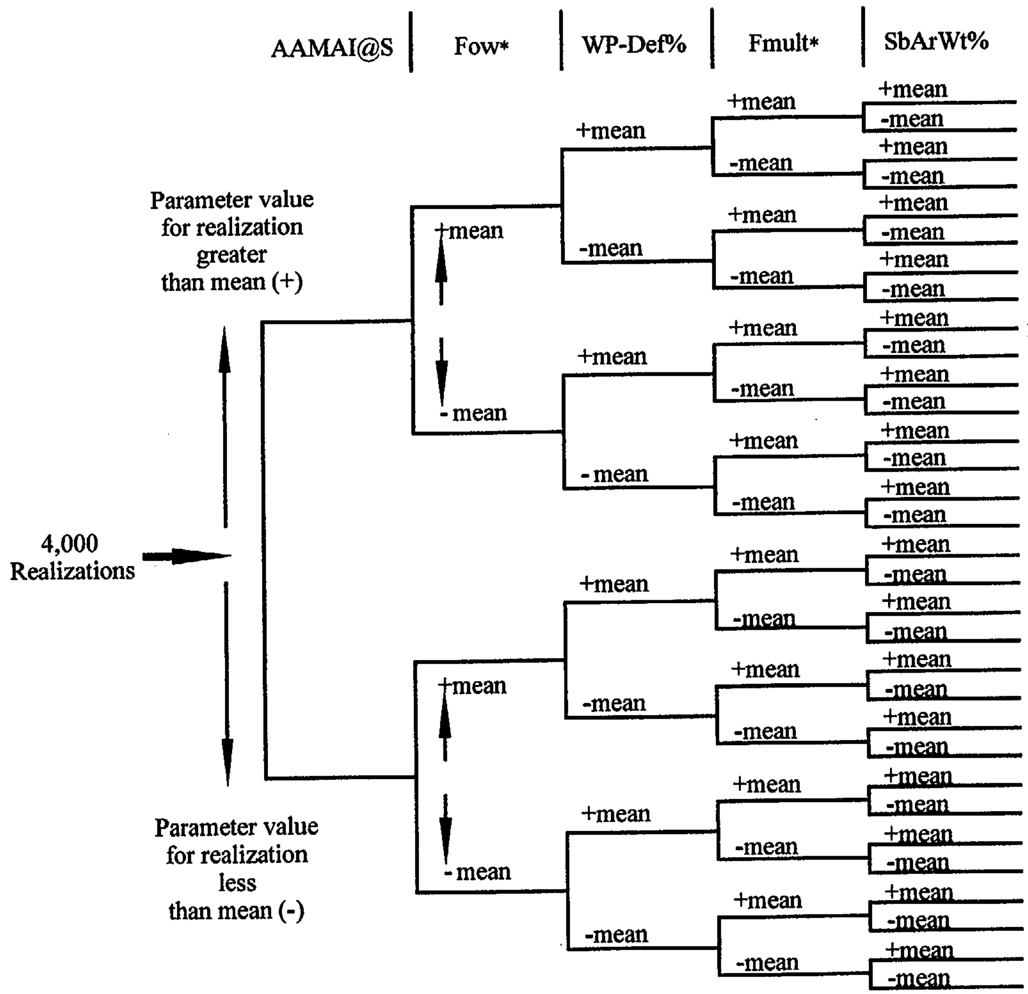
greater sensitivity to parameter sets of increasing size. Again, consider that such results are necessarily dependent on conceptual models embodied in the simulation model as well as on the many fixed value (deterministic) parameters in the TPA code. Other columns of Table 4-10 pertain to the parameter trees using other branching schemes presented in the following sections.

4.4.1 Parameter Trees Using Different Branching

Different branching criteria may be used to determine a + or a – value for a given parameter or the output variable as shown in Figures 4-11 and 4-12. The most influential parameters identified by multiple regression analysis are used in constructing the parameter tree. Figure 4-11 shows a tree where both the input parameters and the output variable have been partitioned based on their mean values. Again, the bins toward above its mean value (see Column A, Row 1, in Figure 4-11). The realizations where none or one of the input parameters is a – account for 55 percent of the mean from all realizations (includes 528 out of 4000 realizations), which is a greater fraction on a per-realizations basis than the example presented in Figure 4-10. Column 3 of Table 4-10 shows the ranking of the parameters according to sensitivity is slightly different with the mean than with the branching criterion; in this case, x_2 is the most influential parameter.

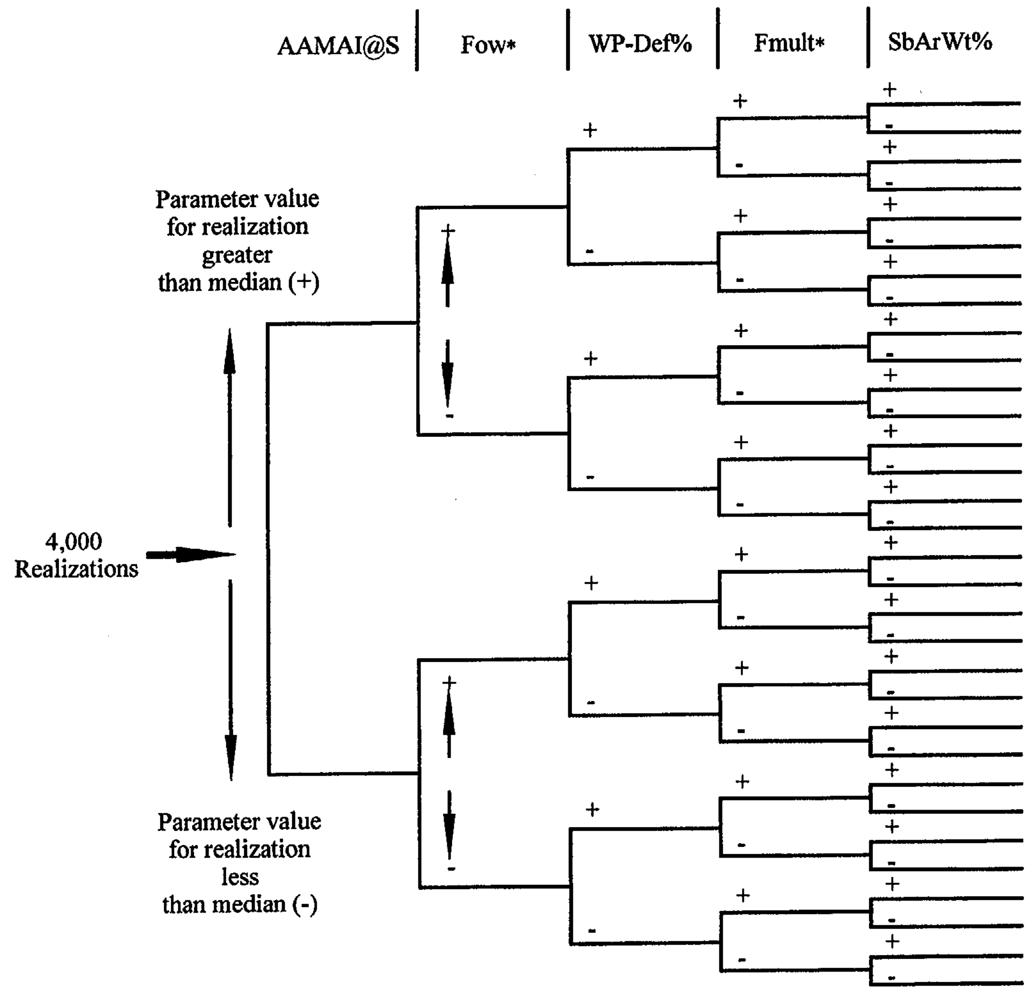
In Figure 4-12, the input parameters are partitioned based on their median values, and the output variable is partitioned based on its 90th percentile. Columns B, C, and D of this figure contain numeric entries identical to those in Figure 4-10. Row 1 of Column A, however, shows that if all five of the important parameters are sampled above their median values (129 out of 4000 realizations), the output variable is above its 90th percentile 4.97×10^{-7} Sv/yr (4.97×10^{-5} rem/yr) in 103 of these realizations. That is, only 79.8 percent of the output above its 90th percentile is provided by the set of five parameters taking on values greater than their median. Comparing to corresponding values for Cases 1 and 2, it is clear that a significant number of extreme values (i.e., above 90th percentile) of the output are produced by combinations of

Although these cases use parameter statistics as the branching criteria, other quantities could also be used. For example, total system failure could be defined as a peak dose to the hypothetical receptor greater than a predetermined limit defined by the regulation (U.S. Nuclear Regulatory Commission, 1999a). Similarly, input parameters could be partitioned based on a value that has some physical significance. For example, in the TPA Version 3.2 code, flow in fractures in the UZ begins when the infiltration exceeds the saturated matrix conductivity, currently estimated at about 3 mm/yr (0.12 inches/yr). This cutoff is important to performance of this subsystem because flow in fractures occurs more rapidly and dissolved contaminants experience much less chemical retardation than flow in the rock matrix. Hence, initiation of fracture flow in the UZ could be thought of as a transition from one performance regime to another for the UZ.



A	B	C	D
62/62	1.48E-04	0.1244	8.04
42/52	8.31E-05	0.0586	4.52
85/96	9.94E-05	0.1294	5.40
34/53	3.66E-05	0.0263	1.99
48/61	4.94E-05	0.0408	2.68
13/35	1.86E-05	0.0088	1.01
55/94	3.29E-05	0.0420	1.79
17/78	1.21E-05	0.0128	0.66
128/229	5.42E-05	0.1683	2.95
41/72	2.31E-05	0.0226	1.26
82/322	1.51E-05	0.0659	0.82
12/105	7.50E-06	0.0107	0.41
66/220	1.95E-05	0.0581	1.06
8/73	6.11E-06	0.0060	0.33
35/352	6.20E-06	0.0296	0.34
0/96	1.95E-06	0.0025	0.11
23/28	6.30E-05	0.0239	3.42
47/138	2.14E-05	0.0401	1.16
17/39	2.44E-05	0.0129	1.33
20/185	8.05E-06	0.0202	0.44
7/27	1.45E-05	0.0053	0.79
14/120	7.58E-06	0.0123	0.41
10/41	1.73E-05	0.0096	0.94
9/185	3.35E-06	0.0084	0.18
25/90	1.77E-05	0.0217	0.96
18/157	6.69E-06	0.0142	0.36
1/123	2.71E-06	0.0045	0.15
3/249	1.52E-06	0.0051	0.08
7/96	4.34E-06	0.0056	0.24
5/159	2.30E-06	0.0050	0.13
2/120	1.23E-06	0.0020	0.07
1/243	6.47E-07	0.0021	0.04

Figure 4-11. Mean-based parameter tree describing the technique for examining system sensitivity to groups of parameters.



A	B	C	D
103/129	1.20E-04	0.2107	6.52
31/97	6.11E-05	0.0803	3.32
65/140	6.64E-05	0.1261	3.61
11/68	2.27E-05	0.0209	1.23
44/141	4.68E-05	0.0894	2.54
4/70	1.52E-05	0.0114	0.83
16/133	2.19E-05	0.0395	1.19
3/87	9.63E-06	0.0114	0.52
41/224	4.04E-05	0.1226	2.20
4/58	1.78E-05	0.0140	0.97
6/216	9.78E-06	0.0286	0.53
0/59	3.73E-06	0.0030	0.20
6/223	1.05E-05	0.0317	0.57
0/62	4.19E-06	0.0035	0.23
0/230	3.19E-06	0.0099	0.17
0/63	1.05E-06	0.0009	0.06
21/67	4.34E-05	0.0395	2.36
25/226	1.72E-05	0.0528	0.93
5/53	1.79E-05	0.0129	0.97
3/230	5.86E-06	0.0186	0.33
1/60	1.18E-05	0.0096	0.64
2/227	6.11E-06	0.0188	0.33
5/54	1.29E-05	0.0094	0.70
0/218	2.19E-06	0.0065	0.12
3/73	8.52E-06	0.0084	0.46
1/125	4.00E-06	0.0068	0.22
0/87	1.90E-06	0.0022	0.10
0/148	7.60E-07	0.0015	0.04
0/96	2.23E-06	0.0029	0.12
0/122	1.03E-06	0.0017	0.06
0/74	6.33E-07	0.0006	0.03
0/140	4.47E-07	0.0008	0.02

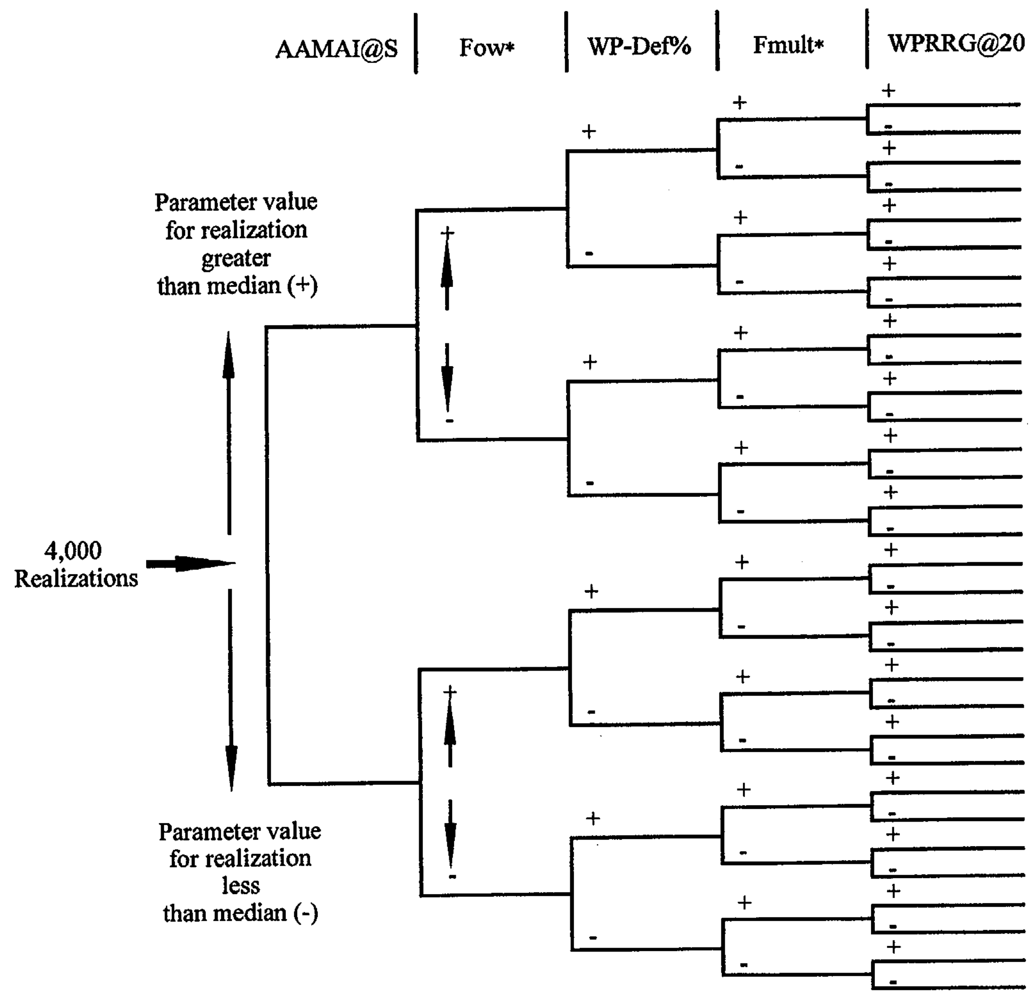
Figure 4-12. Mean-percentile-based parameter tree describing the technique for examining system sensitivity to groups of parameters; input parameters divided based on their median values, and output variable divided based on its 90th percentile value, from all 4000 realizations.

Table 4-10. Sensitivity coefficients calculated for various parameter trees

	Coefficient	Case 1 (Figure 4-10)	Case 2 (Figure 4-11)	Case 3 (Figure 4-12)	Case 4 (Figure 4-13)
Unconditional Sensitivities of Individual Parameters	S_{X_1}	0.351	0.26	0.134	0.351
	S_{X_2}	0.31	0.28	0.16	0.31
	S_{X_3}	0.202	0.173	0.119	0.202
	S_{X_4}	0.204	0.178	0.084	0.204
	S_{X_5}	0.192	0.15	0.102	0.081
Joint Sensitivities of Parameter Groups (see Appendix C)	$\dfrac{\lvert p_H - p_L \rvert}{1-\lvert p_H - p_L \rvert}$	0.541	0.351	0.155	0.541
		2.37	1.63	0.462	2.37
		6.75	4.68	0.938	6.75
		26	9.42	1.46	26
		33.5	249	3.95	26.8

4.4.2 Stepwise Implementation of the Technique

The parameter tree technique was implemented in a stepwise fashion with the importance factor (Column D of Figures 4-10 through 4-12) as the figure of merit for determining maximum polarity of the bins and the median value as the branching criterion. First, a one-parameter-depth tree was drawn for each sampled parameter. The parameter that yielded the greatest importance factor for one of the two branches was then used as the first-level parameter for the following iteration in the stepwise implementation. Next, for all remaining sampled parameters, a two-parameter-depth tree was drawn where the first-level parameter was determined as from the previous iteration. In this second iteration, the parameter that yielded the greatest importance factor on any branch of the tree was used as the second-level parameter for the third iteration. The procedure was repeated until the number of realizations in any bin dropped below 50, with the results of that iteration being discarded. This procedure resulted in a tree that was five parameters deep, as shown in Figure 4-13. The influential parameters identified by this method are compared with results from other methods in Chapter 5. It may be noted that the first four parameters appear in the same order as in the stepwise regression conducted separately; however, the fifth parameter is the well-pumping rate at the receptor location 20 km (12.4 mi) down gradient (WPRRG@20) instead of the subarea wet fraction (SbArWt%). This result is important because it shows that these parameters comprise the most important five-parameter set, which differs from the five individually most important parameters as determined by traditional methods. Also, note that WPRRG@20 is negatively correlated with the output variable (because in the TPA Version 3.2 code model, increased pumping merely increases the dilution volume and not the interception fraction of the contaminant plume by the well) and the procedure for assigning + and – was not reversed so the + + + + – bin represents the most pessimistic case in this example (i.e., the bin with the largest peak doses). In Figure 4-13, note that this group of five parameters together produces a higher value of importance factor (7.06) for one of the branches (second branch from top of the tree) as compared to that



A	B	C	D
124/124	6.59E-05	0.1109	3.58
100/102	1.30E-04	0.1801	7.06
82/90	4.31E-05	0.0526	2.37
110/118	5.90E-05	0.0944	3.20
84/102	2.81E-05	0.0389	1.53
99/109	4.39E-05	0.0649	2.38
74/109	1.44E-05	0.0213	0.78
79/111	1.96E-05	0.0295	1.06
102/137	1.86E-05	0.0345	1.01
126/145	5.19E-05	0.1021	2.82
66/134	5.51E-06	0.0100	0.30
82/141	1.13E-05	0.0216	0.61
66/135	6.78E-06	0.0124	0.37
89/150	1.12E-05	0.0228	0.61
23/145	1.71E-06	0.0034	0.09
45/148	3.73E-06	0.0075	0.20
84/153	1.55E-05	0.0321	0.84
100/140	3.17E-05	0.0601	1.72
57/145	6.93E-06	0.0136	0.38
63/138	9.55E-06	0.0179	0.52
54/133	5.69E-06	0.0103	0.31
79/154	8.67E-06	0.0181	0.47
29/148	2.97E-06	0.0060	0.16
39/124	5.92E-06	0.0100	0.32
30/95	4.11E-06	0.0053	0.22
42/103	7.10E-06	0.0099	0.39
17/115	1.23E-06	0.0019	0.67
17/120	1.13E-06	0.0018	0.06
17/111	1.53E-06	0.0023	0.08
15/107	1.60E-06	0.0023	0.09
2/124	3.23E-07	0.0005	0.02
4/90	7.70E-07	0.0009	0.04

Figure 4-13. Tree developed using a stepwise implementation of the technique, based on the importance factor.

in Figure 4-10 (6.52 for the topmost branch). In contrast, the sensitivity measures in Table 4-10 for Case 4 show that the combination of these five parameters (i.e., the last row) have a joint relative sensitivity less than that of Case 1 (26.8 versus 33.5). Thus, the nature of information provided by each sensitivity measure is somewhat different. In other words, if it had been decided to implement the stepwise procedure using the joint relative sensitivity measure, the five parameters would match exactly those of Case 1.

For all sensitivity analysis methods presented in this chapter, it should be noted that changes to the sampling ranges of the influential parameters (either expansion or contraction) should be made with greater caution than for other parameters because peak dose for the TPI shows the largest change per unit deviation in these parameters.

4.5 ALTERNATIVE CONCEPTUAL MODELS AND SCENARIO CASES STUDIED AT THE SYSTEM LEVEL

The system-level sensitivity studies cover alternative conceptual models and scenario cases. The analyses in this chapter include the full ranges of parameter variations for all modules. Two sets of results are presented. The first set of results reflects model runs that compare the basecase with alternative conceptual models. First, the basecase was evaluated with a 250-vector run. Alternative conceptual model tests were conducted with 250-vector runs, and the results were compared with the basecase. The alternative conceptual models were selected to evaluate: (i) the effect on repository performance of several repository design features currently being considered by DOE; (ii) the effect on repository performance of plausible alternate thermo-hydrologic conditions in the repository near field; and (iii) bounding engineered or natural system behavior. The second set of results reflects the effects of disruptive scenarios, including igneous activity and major faulting. Seismicity is considered part of the basecase.

For both sets of analyses, the runs were limited to 10,000 and 50,000 yr. The number of realizations was limited to 250, to keep computer resources within reasonable limits. Runs up to 50,000 yr with 4000 realizations are included in the sensitivity analyses in the previous sections of this chapter. Section 2.3.2 outlines the alternative conceptual models evaluated in this chapter.

For each alternative conceptual model, only the noted changes as described in Section 2.3.2 to the TPA input file were made, with all other input parameters set to the values used in the basecase. Results are presented as the peak of the mean dose.

Figure 4-14 shows the results for the 10,000-yr TPI, whereas Figure 4-15 is for the 50,000 yr results. The results for the NoInvert alternative were not plotted because they could not be distinguished from the basecase results.

Various observations can be made based on the calculational results shown in this chapter.

- Except for NoRet the relative effects of the alternative conceptual models (based on the peak of the mean dose) changed substantially between the 10,000- and 50,000-yr TPIs.
- The largest mean doses resulted from the NoRet assumption, demonstrating the importance of retardation in the alluvium of Pu, Am, and Th.
- The Flwthru-1 conceptual model led to a larger release in the 10,000-yr TPI, but was much less important for the 50,000-yr TPI. This probably can be attributed to the lack of a delay

time caused by the necessity to fill the WP in the bathtub model. This effect is less important for the 50,000-yr TPI.

- Fast dissolution in the case of the dissolution (Model 1) and grain-size (Grain 1) alternatives led to an increased peak dose at 10,000-yr TPI, but it was not proportional simply to the increased rate of dissolution. In some cases, the high rate of dissolution did not contribute to an overall increase of dose for the 50,000-yr TPI. This is probably an indication that the high dissolution rate of the fuel led to near-total depletion of the SF.

- Alternatives based on natural analog data (Natan) and assumptions about the behavior of radionuclides in secondary uranium minerals (Schoepite) led to much smaller peak doses.

- Protection of the fuel by cladding (Clad-M1) leads to a large reduction in peak doses.

- Matrix diffusion (Matdif) would reduce the peak of the mean dose for both the 10,000- and 50,000-yr TPI. Note, however, that the results from a single calculation, such as the mean value estimates in Chapter 3, indicate that matrix diffusion might occasionally cause an increase in dose at later times.

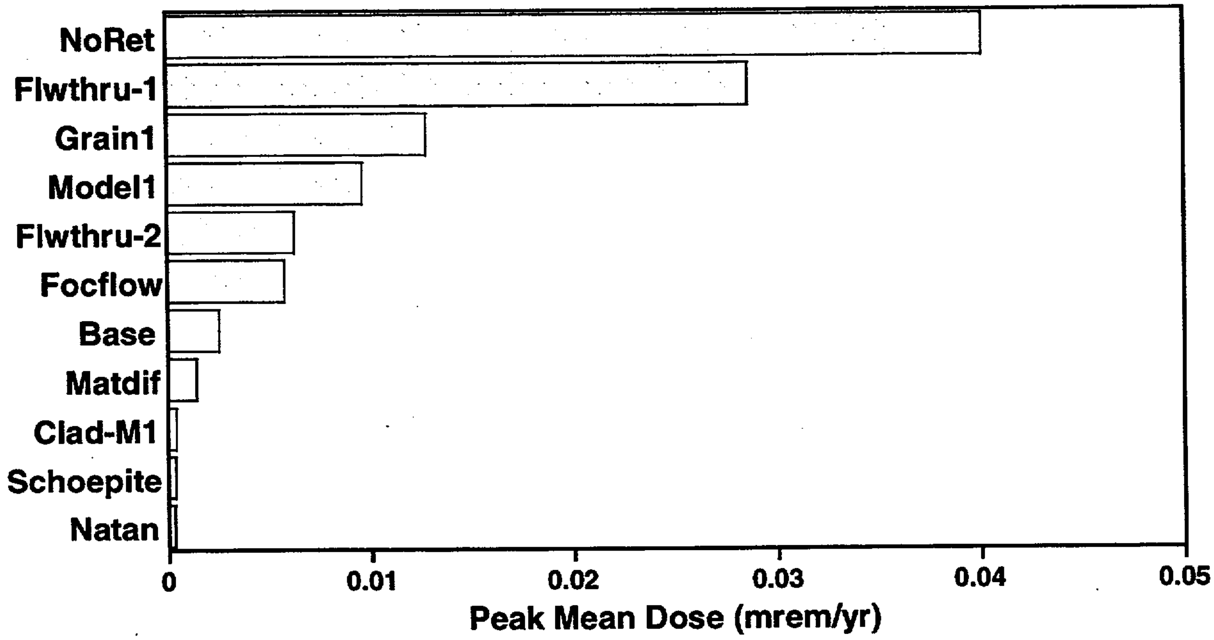


Figure 4-14. Bar chart showing the effects of alternative conceptual models at 10,000 yr.

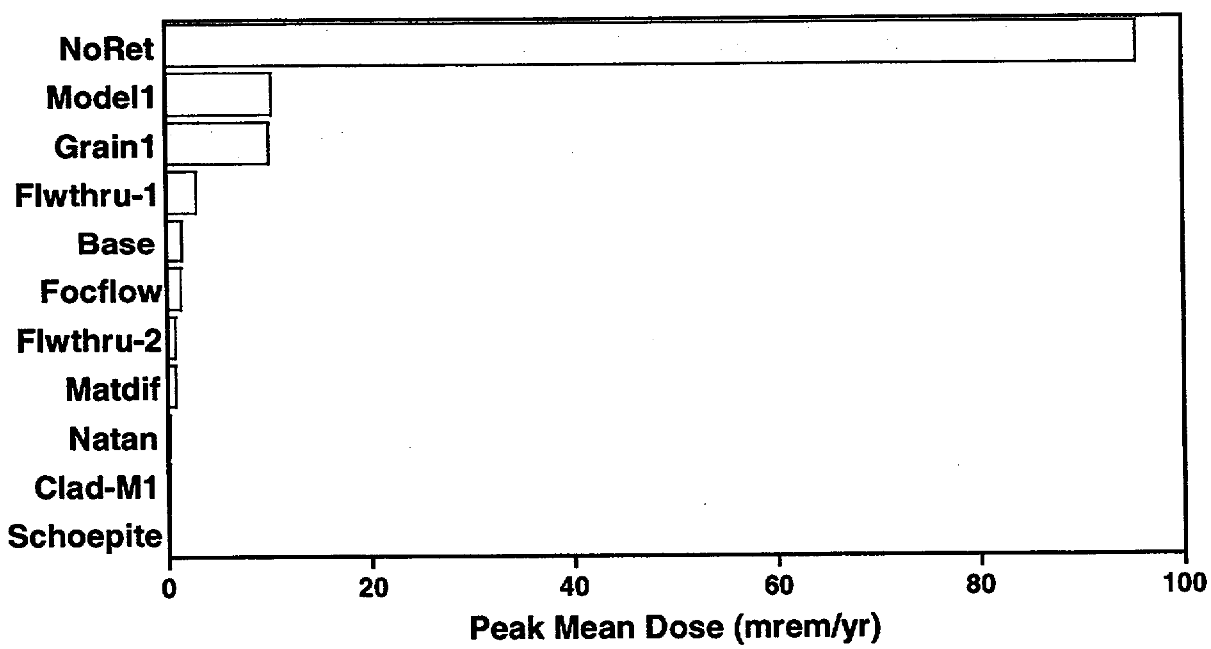


Figure 4-15. Bar chart showing the effects of alternative conceptual models at 50,000 yr.

5 SYNTHESIS OF SENSITIVITY RESULTS AND LINKAGE OF SENSITIVE PARAMETERS TO INTEGRATED SUBISSUES

This chapter attempts to identify influential parameters using the analyses presented in Chapters 3 and 4. Chapter 4 presented the sensitivity analyses and their results, as well as results from alternative conceptual models. This chapter focuses on identifying the parameters and alternative models that significantly influence performance.

5.1 SELECTION OF INFLUENTIAL PARAMETERS

In the previous chapter, seven different sensitivity analyses methods (i.e., regression with normalized variables, regression with log-normalized variables, differential analysis, Morris method, FAST method, t-test on means, and parameter tree method) were used to determine the most influential parameters. The first five methods are scaled (i.e., standardized) so that the sensitivity results reflect the variability of the inputs. The last two are not scaled because their results are based on ranking the input variables using a set of predetermined criteria. Only six of the methods were used at a time for either the 10,000- or 50,000-yr TPI. The parameter tree method was used only for 10,000 yr and the t-test on means was used only for 50,000 yr. The seven methods have different approaches to determining sensitivity. For example, regression with log-transformed variables places greater emphasis on smaller doses than regression with untransformed variables. Also, the t-test on means was conducted to determine sensitive parameters relating only to relatively high doses. It is not clear that any one method is superior to another for this determination of sensitivity (or influence) and, consequently, no method can be fully relied on to provide a unique ranking of parameters. Therefore, the final list of parameters was selected on the basis of frequency of occurrence among various methods.

The selected parameters are presented in Tables 5-1 and 5-2. The score in these tables specifies the number of methods that selected a particular parameter among the top 10. For example, a score of 6/6 for the subarea wet fraction parameter (SbArWt%) implies that the parameter ranked among the top 10 (five for the parameter tree method) in all six methods. Also note that, among the seven methods, there are two statistical methods (regression with normalized variables, and regression with log-normalized variables) and three nonstatistical methods (differential analysis, Morris method, and FAST method). It should be noted that the FAST method selected the most influential parameters only out of the top 20 listed in Tables 4-1 and 4-2. The parameters that did not make the final list include those selected as influential by only one of the seven methods, those selected by only two statistical methods, and those selected by only two out of three nonstatistical methods. This resulted in only eight parameters being selected for 10,000- and 50,000-yr TPIs. Comparison of scores between these two TPIs also indicates that the influential parameters are common to most methods for the 10,000-yr TPI, whereas significant variation exists for the 50,000-yr TPI. Also note that for the 10,000-yr TPI, all parameters that ranked as the top five in the parameter tree method also were picked by other sensitivity analyses methods.

Table 5-1. Influential parameters for 10,000-yr time period of interest, from sensitivity analysis studies

Parameter abbreviation	Parameter Name	Score
Fow*	Flow focusing factor	6/6
WP-Def%	Initially defective fraction of WPs	5/6
Fmult*	Fmult factor for flow entering a WP	5/6
AAMAI@S	Areal average mean annual infiltration at start	5/6
WPRRG@20	Well-pumping rate at 20 km receptor group	5/5
ARDSAV-I	Alluvium R_d for ^{129}I	5/6
SbArWt%	Subarea wet fraction	5/5
ARDSAV-Tc	Alluvium R_d for ^{99}Tc	3/5**

**Parameter Tree method selected only the top 5 parameters of which ARDSAV-Tc is one. Hence, the score is 3/5 and not 3/6.

Table 5-2. Influential parameters for 50,000-yr time period of interest, from sensitivity analysis studies

Parameter Abbreviation	Parameter Name	Score
SbArWt%	Subarea wet fraction	6/6
WPRRG@20	Well-pumping rate at 20-km receptor group	5/6
ARDSAV-Np	Alluvium R_d for ^{237}Np	4/6
ARDSAV-Tc	Alluvium R_d for ^{99}Tc	3/6
Fmult*	Fmult factor for flow entering a WP	3/6
ARDSAV-I	Alluvium R_d for ^{129}I	3/6
ARDSAV-U	Alluvium R_d for ^{234}U	3/6
AAMAI@S	Areal average mean annual infiltration at start	3/6

For both TPIs several parameters were found most influential for the basecase (the basecase is defined as the undisturbed scenario along with the effects of rockfall because of seismicity). The parameters include:

- Areal fraction of the repository wetted by water infiltrating into the repository (SbArWt%);
- Well-pumping rate at 20-km receptor group (WPRRG@20);
- Areal average mean annual infiltration at start (AAMAI@S);
- Alluvium R_d for ^{99}Tc (ARDSAV-Tc);
- Alluvium R_d for ^{129}I (ARDSAV-I); and
- The fraction of water infiltrating to the repository from the UZ above the repository that will enter the WP and contribute to the release of radionuclides (Fmult*).

In addition, the parameters influential for the 10,000-yr TPI, but not for the 50,000-yr, are:

- A flow-focusing factor that expresses the flow potentially reaching a wetted WP (Fow*); and
- Initially defective fraction of WPs (WP-Def%).

Two parameters influential for the 50,000-yr TPI, but not for the 10,000-yr, are:

- Alluvium R_d for ^{237}Np (ARDSAV_Np); and
- Alluvium R_d for ^{234}U (ARDSAV_U).

5.2 COMPARING INFLUENTIAL PARAMETERS WITH INTEGRATED SUBISSUES

The influential parameters identified previously were crosswalked to the NRC integrated subissues [previously specified as key elements of subsystem abstraction in the Revision 1, "TSPA&I Methodology KTI Issue Resolution Status Report" (U.S. Nuclear Regulatory Commission, 1998)]. The crosswalking of these parameters for the basecase results and for the igneous activity disruptive events is presented in Table 5-3. The alternative conceptual models investigated in this report are also cross-referenced to integrated subissues in Table 5-3. The influential parameters corresponding to the disruptive events were determined from only differential analysis.

The influential parameters identified in Tables 5-1 to 5-3 must be viewed in the proper context. The following are key points to consider when examining these tabulated results:

- All analysis results are based on the models and reference input values used in the TPA Version 3.2 code. Chapter 2 of this report gives a description of the conceptual models. TPA Version 3.2 code "User's Guide" (Mohanty and McCartin, 1998) lays out the key assumptions for the conceptual models. Chapter 3 lists the reference input values.

- No consideration is given to corrosion or the defects of welds.

- No credit is given to retardation in fractures or matrix diffusion in the UZ.

- Fracture-only flow occurs in the UZ if the flux exceeds the saturated hydraulic conductivity of a stratigraphic unit.

- The DCFs are kept as constants in all the analyses performed, which implies that the DCFs are known with certainty.

- The receptor group is located 20 km (12.4 mi) from the repository and uses partially contaminated groundwater for drinking and farming.

- All WPs in a subarea fail from corrosion when the representative WP fails.

- No consideration is given to the effect of dripping of chloride-rich water on WP corrosion.

Table 5-3. A crosswalk between the integrated subissues, alternative conceptual models, and the influential parameters

Integrated Subissues	Alternative Models Investigated	Influential Parameters
WP degradation (temperature, humidity, and chemistry)	Not evaluated	-Initially defective fraction of waste packages (10,000-yr)
Mechanical disruption of WPs (seismicity, faulting, rockfall, and dike intrusion)	Not evaluated	-Time of next faulting event in the region of interest* -Spent fuel wetted fraction for faulting event* -North-East fault-zone width*
Quantity and chemistry of water contacting WPs and waste forms	Clad-M1 Flwthru-1 Flwthru-2 Focflow Grain1	-Fmult factor for flow entering into a WP (10,000-yr, 50,000-yr) -Subarea wet fraction (10,000-yr, 50,000-yr) -Flow-focusing factor (10,000-yr)
Radionuclide release rates and solubility limits	Model1 Flwthru-1 Flwthru-2 Natan Schoepite	— — — — —
Spatial and temporal distributions of flow	Focflow	-Areal average mean annual infiltration at start (10,000-yr, 50,000-yr)
Distribution of mass flux between fracture and matrix in unsaturated zone	—	—
Retardation in fractures in the unsaturated zone	Not evaluated	(No retardation or matrix diffusion in the unsaturated zone)
Flow rates in water production zones	Not evaluated	—
Retardation in water production zones and alluvium	NoRet Matdif	-Alluvium matrix R_d for ^{129}I (10,000-yr, 50,000-yr) -Alluvium matrix R_d for ^{237}Np (50,000-yr) -Alluvium matrix R_d for ^{99}Tc (10,000-yr, 50,000-yr) -Alluvium matrix R_d for ^{234}U (50,000-yr)

Table 5-3. A crosswalk between the integrated subissues, alternative conceptual models, and the influential parameters (cont'd)

Integrated Subissues	Alternative Models Investigated	Influential Parameters
Volcanic disruption of WPs	Evaluated as a special case	-Diameter of volcanic cone (10,000-yr, 50,000-yr) * -Volcanic event power (10,000-yr, 50,000-yr)* -Volcanic event duration (10,000-yr, 50,000-yr)* -Time of next volcanic event in region of interest (10,000-yr, 50,000-yr)*
Airborne transport of radionuclides	Evaluated as a special case	-Airborne mass load for igneous activity dose calculation (10,000-yr, 50,000-yr)* -Ash mean particle log diameter (10,000-yr, 50,000-yr) -Wind Speed (10,000-yr, 50,000-yr)*
Dilution of radionuclides in groundwater through well pumping	Not evaluated	-Well pumping rate at receptor group at 20 km (10,000-yr, 50,000-yr)
Dilution of radionuclides in soil through surface processes	Not evaluated	—
Critical group lifestyle	Not evaluated	(DCFs were set as constants)

*Sensitive parameters obtained directly from disruptive event scenario calculations without any consideration of event probability

The following conclusions, drawn solely on the basis of the sensitivity analyses, provide an indication of which integrated subissues may deserve more attention relative to others. Because the model abstractions are preliminary and data are continuously updated, results shown in this report provide a snapshot of the current relative importance and should not be used alone to determine the significance of any of the integrated subissues.

5.2.1 Key Integrated Subissues for 10,000-yr TPI

For the 10,000-yr TPI, the basecase results have shown that total system performance is most sensitive to the following integrated subissues:

- WP degradation;
- Quantity and chemistry of water contacting WPs and waste forms;
- Spatial and temporal distribution of flow;

- Retardation in water-production zone and alluvium; and
- Dilution of radionuclides in groundwater because of well pumping.

When disruptive events are included, the following two integrated subissues are the most important:

- Volcanic disruption of Wps; and
- Airborne transport of radionuclides.

The predominance of the integrated subissues identified previously is the result of several processes and model abstractions that may merit further examination. These include: (i) thermal period delays the onset of flow into the repository; (ii) bathtub fill-up could take several hundreds to thousands of years, thus delaying releases; and (iii) corrosion-resistant material significantly increases the life of the container, thus pushing the release time to late times or even beyond 10,000 yr. Consequently, the results are extremely sensitive to the initially defective failures and igneous activity disruptive event.

Based on the sensitivity and alternative conceptual model analyses results, the following specific points can be made with regard to the integrated subissues for the 10,000-yr TPI:

- Factors causing WPs to fail by mechanisms other than corrosion play a much more important role because of the long WP life. Total system performance is sensitive to the percent of initial defective WPs. Consistent with the deterministic analyses in Chapter 3, repository performance is not sensitive to seismic rockfall or instantaneous fault displacement on new or under-appreciated faults (Integrated subissue—mechanical disruption of WPs).

- The number of WPs that are dripped on (immaterial before WP failure) and the amount of dripping water entering the WP are important to system performance (Integrated subissue—quantity and chemistry of water contacting WPs and waste forms).

- The alternative conceptual model that assumes no retardation in the SZ produced a much higher peak expected dose than the basecase and illustrates the importance of evaluating retardation in the SZ. By comparison with retardation, matrix diffusion does not have nearly as pronounced an effect on the system performance (Integrated subissues—retardation in water production zones and alluvium; quantity and chemistry of water contacting WPs and waste forms).

- Choice of the WP water retention model for release calculations (bathtub or flowthrough) has an effect on total system performance. The fuel dissolution rate also has an effect on total system performance (Integrated subissue—radionuclide release rates and solubility limits).

- Retardation of ^{129}I and ^{99}Tc in the alluvium is important to system performance (Integrated subissue—retardation in water-production zones and alluvium).

- The alternative conceptual model that assumes partial cladding protection produced a much lower peak expected dose than the basecase, which illustrates the need to improve modeling capability and focus reviews in this area if the DOE decides to take credit for cladding (Integrated subissue—quantity and chemistry of water contacting WPs and waste forms).

- The peak expected dose resulting from the igneous-activity scenario class is 2 orders of magnitude higher than the basecase after being weighted by its probability (Integrated subissues—volcanic disruption of WPs; airborne transport of radionuclides).

- The well-pumping rate at the receptor group significantly influences the system performance. The well-pumping rate is used in determining the dilution of radionuclide concentration. Dose is directly proportional to the radionuclide concentration in water. (Integrated subissue—dilution of radionuclides in groundwater through well pumping).

5.2.2 Key Integrated Subissues for 50,000-yr TPI

For the 50,000-yr TPI, the results have shown that total system performance is most sensitive to the following integrated subissues (in the absence of igneous-activity disruptive event):

- Quantity and chemistry of water contacting WPs and waste forms;
- Radionuclide release rates and solubility limits;
- Spatial and temporal distributions of flow;
- Retardation in water production zones and alluvium; and
- Dilution of radionuclides in groundwater through well pumping.

The peak expected dose resulting from the igneous-activity scenario class was not computed for the 50,000-yr TPI because the peak expected dose caused by igneous activity occurs during the first 1000 yr after closure (see Figure 3-50). The following specific points can be made with regard to the integrated subissues for the 10,000-yr TPI:

- The number of WPs that are dripped on and the amount of water contacting the waste affect the system performance (Integrated subissue—spatial and temporal distribution of flow; quantity and chemistry of water contacting WPs and waste forms).

- The choice of the release model (bathtub or flowthrough) has negligible effect on system performance. The fuel-dissolution rate has a relatively greater effect on the system performance. The grain/particle size has a relatively large effect on the system performance (Integrated subissue—radionuclide release rates and solubility limits).

- As in the 10,000-yr case, partial cladding protection significantly reduced peak expected dose (Integrated subissue—quantity and chemistry of water contacting WPs and waste forms).

- The alternative conceptual model that assumes no retardation in the SZ produced a much higher peak expected dose than the basecase, which illustrates the importance of evaluating radionuclide transport in the SZ. By comparison, matrix diffusion does not have a great effect on system performance (Integrated subissue—retardation in water-production zones and alluvium).

- Retardation of ^{237}Np, ^{129}I, ^{99}Tc, and ^{234}U in the alluvium is important to system performance as indicated by sensitivity analysis (Integrated subissue—retardation in water production zones and alluvium).

- Total system performance is sensitive to dilution introduced by well pumping (Integrated subissue—dilution of radionuclides in groundwater through well pumping).

6 CONCLUSIONS

This report describes a series of computations performed for assessing the confidence in estimations of future repository performance in light of the uncertainty in conceptual models and the parameters of those models. These estimations allowed the staff to focus attention on what are likely to be the most important phenomena affecting repository performance and point out deficiencies in the current state of knowledge. The results of these analyses were also used to review the TSPA-VA and refine the issue resolution process, as described in Chapter 5, tying the parameter sensitivities and alternative conceptual model results to the integrated subissues identified in the "Total System Performance Assessment and Integration Methodology Issue Resolution Status Report."

6.1 BASECASE RESULTS

To gain insight into the basic functionality of the TPA code, the trend in results, and the influence of various code components on the overall results, TPA runs were analyzed using basecase data, scenario cases, and alternative conceptual model data sets. To explain the trend in the intermediate and final outputs, results from a single realization (using the mean value data set) were analyzed. Then the results from multiple realizations (250) using the basecase data set were presented to highlight the variability in dose as a function of variability in 246 sampled parameters.

At 2×10^{-5} mSv/yr (0.002 mrem/yr), the peak dose from the mean value data set was found similar to a peak expected dose of 3×10^{-5} mSv/yr (0.003 mrem/yr) from multiple realizations for the 10,000-yr TPI. But for 100,000-yr TPI, the peak dose from the mean value data set was 3×10^{-3} mSv/yr (0.3 mrem/yr) compared with the 4×10^{-2} mSv/yr (4-mrem/yr) peak expected dose from multiple realizations. The analysis indicated that, though the expected dose from these two cases (mean value versus multiple realization) are quite similar, analysis using the mean value data set can be misleading. For example, for the 10,000-yr TPI, the major contributors to dose in the mean value data set case were ^{129}I and ^{36}Cl; for multiple realizations, ^{237}Np, ^{129}I, ^{99}Tc, and ^{234}U were the major contributors. For the multiple realizations, the minimum and maximum of the peak dose varied over 5 orders of magnitude for both TPIs. Dose at early times is primarily caused by initially defective failures. A sharp rise in dose between 10,000 and 20,000 yr occurs predominantly because of corrosion failure. From 20,000 to 100,000 yr, the dose is generally constant except at about 85,000 yr, where the climatic conditions switch from pluvial back to nonpluvial. For the 10,000-yr TPI, the dose contributors were ^{237}Np, ^{129}I, ^{99}Tc, ^{234}U, ^{36}Cl, and ^{79}Se. For the 100,000-yr TPI, the dose contributors were ^{237}Np, ^{234}U, ^{99}Tc, and ^{129}I, with 92 percent of the contribution solely from ^{237}Np. When probability-weighted, faulting did not influence the peak expected dose for either TPI, whereas igneous activity increased the dose from 3×10^{-5} mSv/yr (0.003 mrem/yr) for the basecase, which includes the effects of rockfall caused by seismicity, to 0.006 mSv/yr (0.6 mrem/yr).

6.2 ALTERNATIVE CONCEPTUAL MODELS

Chapters 3 and 4 describe results of the basecase compared with alternative conceptual model cases. The analyses in these chapters used the TPA Version 3.2 code and a WP design using an Alloy C-22 inner corrosion-resistant layer. Other stipulations about the basecase model were no backfilling of the repository drifts, no matrix diffusion into the rock matrix, no credit for cladding protection of fuel, even distribution of infiltrating water to WPs, and the bathtub model for fuel wetting. These basecase analyses considered seismically induced rockfall, but not the effects of fault displacement or igneous activity on repository performance. Separate analyses were conducted for the faulting and igneous activity disruptive scenarios.

Alternative conceptual models considered in this study were: (i) matrix diffusion of radionuclides into the rock matrix in the SZ; (ii) a faster dissolution rate of exposed fuel, but offset by large credit for protection of fuel by cladding; (iii) focusing flow to a smaller number of WPs; (iv) flowthrough model with no pooling of water in WP; (v) flowthrough model, but with faster fuel dissolution; (vi) release rate based on a natural analog to SF; (vii) release based on the dissolution rate of schoepite; (viii) release based on fuel grain size rather than particle size; and (ix) no retardation of Pu, Th, and Am.

The results of the analyses of alternative conceptual models highlight the importance of some of the assumptions made about the processes modeled in the TPA code. Note, however, that the relative effects of the alternative conceptual models change substantially between the 10,000- and 50,000-yr TPIs and are not always intuitive. For example, matrix diffusion for the mean value run reduces the peak dose for the 10,000-yr TPI, but actually increases the peak dose for the 50,000-yr TPI. This result might be caused by a computational idiosyncracy of the code rather than a real phenomenon (see Section 3.5.3.3). Results from the Monte Carlo runs in Chapter 4 indicate that the peak mean dose is always decreased by matrix diffusion.

Elimination of major barrier components such as retardation and cladding protection resulted in the largest dose increases. The largest peak expected doses resulted from the no-retardation assumption, demonstrating the importance of retardation of Pu, Am, and Th, especially if these radionuclides can travel as colloids unretarded through the geosphere.

Switching to models for fast dissolution increased peak expected dose at 10,000-yr TPI, but not at a rate proportional to the increased rate of dissolution. In some cases, the high rate of dissolution did not contribute to an overall increase in dose for the 50,000-yr TPI, indicating near-total depletion of the SF inventory. Conversely, results using alternative release rate models for phenomena such as cladding protection and observations of uranium transport at natural analog sites could result in considerably smaller doses. Tying the release rate to the dissolution of the secondary mineral schoepite also showed a large decrease in dose, which warrants further investigation, to develop a better understanding of this geochemical process.

6.3 SENSITIVITY ANALYSES

The sensitivity analyses employed the TPA Version 3.2 code and applied a variety of statistical techniques to a large (>1000 vector) set of Monte Carlo runs and nonstatistical techniques (differential analysis, Morris method, and FAST method) to 250–4000 TPA realizations. Most of these analyses pertained to the basecase. Igneous activity and faulting were considered separately from the basecase, with their analyses limited to differential analysis. Statistical and nonstatistical analyses of the basecase were used to identify sensitive parameters for which a small input change can have a large effect on estimated repository performance. Other ranking techniques were applied to the Monte Carlo results to determine which parameters were important. The parameter tree method allowed the determination of combinations of variables that led to the highest doses. The Morris method and the FAST method were used in the current study to determine what further insights could be gained from techniques specifically designed for nonlinear models.

Regression analyses were performed on a 1000-vector basecase run for 10,000- and 50,000-yr TPIs. Results from the regression analyses were based on both normalized and log-transforms of the normalized inputs. The normalized results weight each result equally, whereas the log-normalized results tend to overemphasize smaller doses. However, the log-transformed results generally provide a better fit for the regression equations. Results of the regression analyses are standardized to account for the ranges of the input variables and allow a more accurate ranking of sensitivity coefficients. The results from differential analysis, and the Morris and FAST methods were also scaled by the standard deviation of the input variables so that the ranks of these variables could be compared with those from the statistical analyses. Tables 4-6 and 4-7 summarize the results for the 10,000- and 50,000-yr TPIs from the regression, differential analysis, and the Morris and FAST methods.

Several of the other sensitivity analyses could not be ranked directly for sensitivity and were, therefore, not included in Tables 4-6 and 4-7, but nevertheless supply insight to the sensitivity process. The parameter tree method fits into this category. Another is the statistical test in which the 1000 vectors for the 50,000-yr TPI were sorted into two bins, depending on whether the dose was greater or less than 10 millirem. The means of the input variables in each bin were then compared statistically for significant differences between the two bins.

To capture the information contained in all the sensitivity methods, Tables 5-1 and 5-2 list the influential parameters for the 10,000- and 50,000-yr TPIs that appear from the results of at least three out of the six sensitivity methods explored in this report. Some important conclusions that can be drawn by examining the lists of parameters in Tables 5-1, 5-2, and tables in Chapter 4, include:

- Numerous parameters affecting the flow of water onto and eventually into the failed WP (and onto SF) are important (e.g., Fow*, Fmult*, SF wetted fraction, and SbArWt%). There is no mechanistic basis for the input parameter ranges for these variables used in the TPA Version 3.2 code.

- Regression techniques were able to distinguish as many as 18 statistically significant variables (at the 95th percent confidence level) for the 10,000-yr TPI and 20 variables at the 50,000-yr TPI. For the 10,000-yr TPI, 10 of the 18 significant variables were related to WP and fuel wetting, and five variables were related to retardation. For the 50,000-yr TPI, eight of the 20 significant variables were related to WP and fuel wetting, five to retardation, and three to seismically induced rockfall.

- In the analysis of the mean value of input variables leading to the highest doses, there were 24 variables whose difference in means were determined statistically significant. Of these, four were associated with wetting, 13 with retardation, and four with UZ fracture and matrix flow. Thus, retardation factors take on added importance when considering the conditions that led to the largest doses. However, the dependence on UZ flow was for parameters that are not likely to have an effect on the results. It is likely that the sample size in the high-dose category (51 samples) was too small, and that some of these results are spurious.

6.4 IMPORTANCE OF RADIONUCLIDES

For a TPI of 10,000 yr, most of the peak mean dose came from the isotope ^{129}I, with ^{99}Tc and ^{237}Np (in descending order) accounting for most of the balance. For a TPI of 50,000 yr, most of the peak mean dose contribution came from ^{237}Np, with ^{129}I, ^{99}Tc, and ^{234}U (in descending order) accounting for most of the balance. For either the 10,000- or 50,000-yr TPIs, however, the largest peak doses from any realization came from ^{237}Np.

6.5 INTEGRATED SUBISSUES REQUIRING FURTHER STUDIES

The influential parameters, identified using various statistical and nonstatistical sensitivity analysis methods and screened further by comparing the outcomes of these methods, were crosswalked to the NRC integrated subissues. Nine of the 14 subissues were found to have at least one influential parameter (including the integrated subissues related to disruptive events). Because the staff has not yet developed an acceptable method for factoring event probability into sensitivity analysis, the influential parameters from the scenario events were crosswalked with the integrated subissues. Assuming an event probability of 1, the integrated subissues that deserve attention are summarized in Table 5-3. The integrated subissues for the 10,000-yr TPI that deserve further examination are primarily because of the delay in radionuclide releases resulting from: (i) corrosion-resistant material of the inner overpack pushing the WP failure time beyond 10,000 yr; (ii) thermal reflux delaying the onset of flow into the repository; (iii) bathtub filling time delaying the radionuclide release time by hundreds to thousands of years; and (iv) radionuclide sorption in the alluvium causing significant delay in the arrival time of radionuclides.

Conclusions drawn from these analyses may change as the models and assumptions are updated, and certain parameters or processes may become more or less important. Also, the assumptions and limitations, as described in Chapter 2 of this report, should be considered when interpreting the results. NRC preparation to review the DOE TSPA products is an iterative process, of which this report represents one facet.

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APPENDIX A

DESIGN MATRIX FOR THE MORRIS METHOD

This appendix explains the steps necessary to obtain the matrix used by the Total-system Performance Assessment (TPA) code as the input parameters. Let x_i, i = 1, 2, ..., I, be the elements of x, where x is the input parameter vector with I elements. Assuming $0 \leq x_i \leq 1$, the interval [0, 1] is now divided into p discrete levels. A randomly chosen base vector, x^*, is then obtained by assigning each element of x randomly from a set of discrete values: $\{0, 1/(p-1), 2/(p-1), \cdots, 1-\Delta\}$, where $\Delta = p/2(p-1)$. To obtain the matrix, first, a $(I+1)$-by-I sampling matrix, B, with elements of 0's and 1's is selected:

$$B = \begin{bmatrix} 0 & 0 & 0 & \cdots & 0 \\ 1 & 0 & 0 & \cdots & 0 \\ 1 & 1 & 0 & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ 1 & 1 & 1 & \cdots & 1 \end{bmatrix} \tag{A-1}$$

Matrix B has an important property, namely, that any row differs from its immediate neighboring rows only in one column. For instance, the second row differs from the first row only in the first column and the third row in the second column. A matrix obtained by multiplying B with Δ can be used to produce I values of $\partial y/\partial x_i$, based on (I + 1) runs. But the elements of the matrix are not randomly selected.

To randomize the matrix ΔB, the following operations are performed:

$$B^* = J_{(I+1),I}\, x^* + (\Delta/2)[(B - J_{(I+1),I})D^* + J_{(I+1),I}] \tag{A-2}$$

where

$$J_{(I+1),I} = \begin{bmatrix} 1 & 1 & 1 & \cdots & 1 \\ 1 & 1 & 1 & \cdots & 1 \\ 1 & 1 & 1 & \cdots & 1 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ 1 & 1 & 1 & \cdots & 1 \end{bmatrix}_{(I+1),I} \tag{A-3}$$

D^* is an I-dimensional diagonal matrix in which each diagonal element is either +1 or −1 with equal probability. The operations defined in Eq. (A-2) randomize the matrix ΔB. The matrix B* is called the design matrix.

Since the input variables are considered random, so is the output $y(x)$. If a distribution of r samples is required for each $\partial y / \partial x_i$, the previous process defined in Eq. (A-2) can be repeated r times to produce an r(I+1)-by-I design matrix X:

$$X_{r(I+1),I} = \begin{bmatrix} B_1^* \\ B_2^* \\ \cdots \\ B_r^* \end{bmatrix} \tag{A-4}$$

Each row of X will next be used as input to the TPA code, to calculate $y(x)$, and the matrix X will be used to produce rI number of $\partial y / \partial x_i$, which, in turn, will produce I distributions for the input variables, each with r samples.

APPENDIX B

FORMALISM OF FOURIER AMPLITUDE SENSITIVITY TEST TECHNIQUE

Consider again the nonlinear computational model of Eq. (3-1), which has only one output variable and I input variables. The I input variables through I transformation functions can be represented as:

$$x_i = g_i(\sin \omega_i s), i = 1,2,\ldots,I \tag{B-1}$$

where g_i, $i = 1, \ldots, I$, is a set of trigonometric transform functions and ω_i, $i = 1, \ldots, I$, a set of integer frequencies, with one frequency assigned arbitrarily to each x_i of x (Cukier, 1973). Equation (B-1) is a parametric representation of an I-dimensional curve in the vector space of x. As s varies over the range $0 \leq s \leq 2\pi$, $x_1, x_2, \ldots, x_I$ traverse the I-dimensional space simultaneously, with a relative rate of traversal in each direction proportional to the frequency assigned to the direction.

After applying the transformation functions defined in Eq. (B-1) to the input vector x, the output variable $y(x)$ becomes a periodic function of s:

$$y(x) = y[g_1(\sin\omega_1 s), g_2(\sin\omega_2 s), \ldots, g_I(\sin\omega_I s)] = y(s) \tag{B-2}$$

and y can be expanded into a Fourier series:

$$y(s) = \frac{A_0}{2} + \sum_{i=1}^{I} A_i \sin(\omega_i s) = y(s + 2\pi) \tag{B-3}$$

The Fourier amplitudes A_i, $i = 1, 2, \ldots, I$, of the output variables corresponding to each frequency ω_i, $i = 1, \ldots, I$, can be obtained as (Schaibly and Schuler, 1973):

$$A_i = \frac{1}{\pi}\int_0^{2\pi} y(s)\sin(\omega_i s)ds, \; i = 1, 2, \ldots, I \tag{B-4}$$

The question now becomes whether the amplitudes A_i, $i = 1, 2, \ldots, I$, are strictly related to the input variable x_i, i = 1, 2, ..., I, and x_i, only. If it can be shown that the Fourier amplitudes A_i, $i = 1, 2, \ldots, I$, are affected by the i^{th} parameter x_i, only, and not by any other parameters, then the Fourier amplitudes isolate, one by one, the sensitivity of the parameters x_i, i = 1, 2, ..., I, on the output. In other words, the magnitudes of the Fourier A_i, $i = 1, 2, \ldots, I$, give the quantitative measurements of sensitivities of the input variables x_i, $i = 1, 2, \ldots, I$. Because the measures are obtained by varying x_i, $i = 1, 2, \ldots, I$, simultaneously, the FAST method simulates a more realistic situation than other sensitivity analysis methods that vary only one parameter at a time.

The amplitudes A_i, $i = 1, 2, \ldots, I$, calculated according to Eq. (B-4), are truly related to the input variable x_i, $i = 1, 2, \ldots, I$, only if a set of incommensurate frequencies is used in Eq. (B-1), where incommensurate means that there does not exist a common divisor among the frequencies. But this would require that the Eq. (B-4) be evaluated over an infinite period. Instead, a set of integer frequencies is used. By using integer frequencies, the output variable becomes a periodic function with a period of $2p$ and the amplitudes A_i, i = 1, 2, ..., I, can be obtained as:

$$A_i = \frac{2}{N}\sum_{j=1}^{N} y(s_j)\sin(\omega_i s_j) \tag{B-5}$$

The use of integer frequencies causes some problems. For instance, if $\omega_4 = \omega_1 + \omega_2 - \omega_3$, then $A(\omega_4) = A(\omega_1 + \omega_2 - \omega_3)$, and A_4 will not only reflect the sensitivity of x_4, but also x_1, x_2, and x_3. In the FAST method, the integer frequency set is chosen such that:

$$\sum_{i=1}^{I} r_i\omega_i \neq 0, \tag{B-6}$$

$$\sum_{i=1}^{I} |r_i| \leq M+1 \tag{B-7}$$

where M and r_i, i = 1, 2, ..., I, are integers.

This set of frequencies is called approximately incommensurate to order M; it has the important property that no single frequency can be obtained by adding or subtracting any M frequencies. When the set of frequencies is used to determine the Fourier amplitudes A_i, i = 1, 2, ..., I, the amplitudes segregate the sensitivity of the input variables on the output to the order M. For instance, if M = 4, then there is no mutual interference between any four Fourier amplitudes, but there might be among five amplitudes coefficients. Therefore, the larger the value of M, the greater the likelihood that the Fourier amplitude of each input frequency reflects solely the influence of the corresponding rate coefficient. On the other hand, the larger the M, the more difficult it is to select integer frequencies that satisfy both Eqs. (B-6) and (B-7).

After selecting integer frequencies, N number of points are selected for s, which are used in Eq. (B-1) to generate x_i, i = 1, 2, ..., I, for numerical calculations:

$$s = \frac{2\pi j}{N},\ j = 1, 2, \ldots, N \tag{B-8}$$

But N cannot be an arbitrary integer. For instance, if $\omega_i = mN - \omega_k$, where m is an integer, then:

$$y(\omega_i s) = y(mNs - \omega_k s) = y(2\pi im - \omega_k s) = y(\omega_k s) \tag{B-9}$$

and the amplitude A_i will not be distinguishable from A_k. To avoid this problem, N is chosen such that:

$$\sum_{i=1}^{I} b_i \omega_\iota \neq mN \tag{B-10}$$

$$\sum_{i=1}^{I} |b_i| \leq M + 1 \tag{B-11}$$

where b_i, $i = 1, 2, ..., I$, and M are the same integers as in Eq. (B-7), in accordance with Eqs. (B-6) and (B-7).

The particular trigonometric transformation functions used are

$$x_i = \frac{1}{2} + \frac{1}{\pi}\arcsin\left[\sin\left(\omega_i s + r_i\right)\right],\ i = 1, 2, ..., I \tag{B-12}$$

where r_i, $i = 1, 2, ..., I$, are random numbers. The N points of s are then used in Eq. (B-12) to obtain x_i, $i = 1$, 2, ..., I to calculate $y(x) = y(s)$. The values of x_i and y are then used in Eq. (B-5) to obtain the Fourier amplitudes A_i, $i = 1, 2, ..., I$.

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APPENDIX C

FORMALIZATION OF PARAMETER TREE SENSITIVITY ANALYSIS APPROACH

The following is a formal explanation of the parameter tree sensitivity analysis approach presented in Section 4.1.5. Let $\hat{x}_i$ be the median value of x_i, $\hat{y}$ the median value of y, and I the total number of sampled parameters. In this development, median values are used for partitioning criteria, but any other statistical or physical branching criterion could also be used. The first step is to partition all of the realizations into two bins:

$$x_{1^+} = \left[\forall \text{ realizations with } x_{1,j} \geq x_1\right] \tag{C-1a}$$

$$x_{1^-} = \left[\forall \text{ realizations with } x_{1,j} < \hat{x}_1\right] \tag{C-1b}$$

where j represents a particular realization, assume that the two bins contain N_{I^+} and N_{I^-} members, where $N_{1^+} + N_{1^-} = N$ is the total number of samples or realizations. Note that when the partitioning criterion is the median value, $N_{1^+} = N_{I^-} = N/2$, but that will not be true for other branching criteria.

Now consider the N_{1^+} realizations of y that are produced by the x_{1^+} set. From these N_{I^+} realizations, we select those that meet the following criterion:

$$y_{1^+} = \left[\forall \text{ realizations with } y_j \geq \hat{y} \mid x_{1,j} \in x_{1^+}\right] \tag{C-2}$$

Let the number of realizations satisfying this criteria be L_{1^+}. It follows that

$$p_{1^+} = P\{y \geq \hat{y} | x_1 \geq \hat{x}_1\} = \frac{L_{1^+}}{N_{1^+}} \tag{C-3}$$

The second branch of the tree is associated with the y_1- bin containing L_{I^-} members, where

$$y_{1^-} = \left[\forall \text{ realizations with } y_j \geq \hat{y} \mid x_{1,j} \in x_{1^-}\right] \tag{C-4}$$

In this case, similar to Eq. (C-3),

$$p_{1^-} = P\{y \geq \hat{y} \; | x_1 < \hat{x}_1\} = \frac{L_{1^-}}{N_{1^-}} \tag{C-5}$$

Equal values of p_{1^+} and p_{1^-} would imply that whether x_1 takes values greater or smaller than its median, it does not affect the bin into which y values fall, thus indicating a lack of correlation or lack of sensitivity of y to x_1. Consequently, a measure of relative sensitivity of y with respect to x_1 can be constructed as $|p_{1^+} - p_{1^-}|$. It is noted that the proposed measure provides only relative sensitivity because it does not provide a precise description of the change in y for a given change in x_1, as a measure for absolute sensitivity would provide. However, the relative sensitivity measure is sufficient for ranking important parameters. In general, one can partition the $x_{1,j}$ (and subsequent parameter realizations) into more than two bins, but such a generalization will lead to a complicated tree structure (i.e., with potentially large numbers of branches per level) and is not pursued further here.

The branching strategy explained previously is now implemented for the second, third, and subsequent parameters until most of the output is sufficiently explained. For the second parameter, the procedure is as follows. Partition the bin x_{1^+} containing N_{1^+} realizations into two bins:

$$x_{1^+2^-} = \left[\forall \text{ realizations with } x_{1,j} \geq \hat{x}_1 \cap x_{2,j} < \hat{x}_2\right] \tag{C-6a}$$

and

$$x_{1^+2^+} = \left[\forall \text{ realizations with } x_{1,j} \geq \hat{x}_1 \cap x_{2,j} \geq \hat{x}_2\right]. \tag{C-6b}$$

Similarly, the x_{1^-} bin can also be partitioned into two bins:

$$x_{1^-2^+} = \left[\forall \text{ realizations with } x_{1,j} < \hat{x}_1 \cap x_{2,j} \geq \hat{x}_2\right] \tag{C-6c}$$

and

$$x_{1^-2^-} = \left[\forall \text{ realizations with } x_{1,j} < \hat{x}_1 \cap x_{2,j} < \hat{x}_2\right]. \tag{C-6d}$$

Let the number of members in each of the four bins be $N_{1^+2^+}$, $N_{1^+2^-}$, $N_{1^-2^+}$, and $N_{1^-2^-}$. The output realizations associated with members of a bin are now scrutinized to count the number of realizations in which $y \geq \hat{y}$. Thus, the four output bins associated with the four branches of the tree at the second parameter level are:

$$y_{1^+2^+} = \left[y_j \geq \hat{y} \middle| x_{1,j}, x_{2,j} \in x_{1^+2^+}\right] \tag{C-7a}$$

$$y_{1^+2^-} = \left[y_j \geq \hat{y} \middle| x_{1,j}, x_{2,j} \in x_{1^+2^-}\right] \tag{C-7b}$$

$$y_{1^-2^+} = \left[y_j \geq \hat{y} \middle| x_{1,j}, x_{2,j} \in x_{1^-2^+}\right] \tag{C-7c}$$

$$y_{1^-2^-} = \left[y_j \geq \hat{y} \middle| x_{1,j}, x_{2,j} \in x_{1^-2^-}\right] \tag{C-7d}$$

Let the number of realizations associated with the four bins of Eq. (C-7) be $L_{1^+2^+}$, $L_{1^+2^-}$, $L_{1^-2^+}$, and $L_{1^-2^-}$. Then at the second level of the tree, we can make the following probability statements:

$$p_{1^+2^+} = P\left\{y \geq \hat{y} \middle| x_{1,j} \geq \hat{x}_1 \cap x_{2,k} \geq \hat{x}_2\right\} = \frac{L_{1^+2^+}}{N_{1^+2^+}} \tag{C-8a}$$

and with similar interpretations,

$$p_{1^+2^-} = \frac{L_{1^+2^-}}{N_{1^+2^-}} \tag{C-8b}$$

$$p_{1^-2^+} = \frac{L_{1^-2^+}}{N_{1^-2^+}} \tag{C-8c}$$

$$p_{1^-2^-} = \frac{L_{1^-2^-}}{N_{1^-2^-}} \tag{C-8d}$$

If $p_{1^+2^+} = p_{1^+2^-}$, then the second parameter, x_2, (given $x_1 \geq \hat{x}_1$) has no influence on y. Thus, relative sensitivities of x_2 can be partially measured by $\left|p_{1^+2^+} - p_{1^+2^-}\right|$ and $\left|p_{1^-2^+} - p_{1^-2^-}\right|$ for the cases of $x_1 \geq \hat{x}_1$ and $x_1 < \hat{x}_1$. The total relative sensitivity of y to x_2 can be determined from:

$$S_{x_2} = \left| p_{1^+2^+} - p_{1^+2^-} \right| P\{x_1 \geq \hat{x}_1\} + \left| p_{1^-2^+} - p_{1^-2^-} \right| P\{x_1 < \hat{x}_1\} \tag{C-9}$$

Also, $p_{1^+2^+}$ equal to $p_{1^-2^-}$ implies that whether the first two parameters together had high (greater than their medians) or low (smaller than their medians) values, there is an equal chance of producing a y lower or higher than its median value. We use the quantity $\dfrac{\left|p_{1^+2^+} - p_{1^-2^-}\right|}{1-\left|p_{1^+2^+} - p_{1^-2^-}\right|}$ as a measure of the relative sensitivity of y jointly to x_1 and x_2. For this example, it is assumed that both x_1 and x_2 are positively correlated with y (i.e., large values of x_1 and x_2 lead to large values of y and vice-versa). In general, this is not a valid assumption and input parameters can be positively or negatively correlated with the output variable. Hence, we now change our nomenclature for the joint relative sensitivity such that the coefficient is now defined as $\dfrac{\left|p_H - p_L\right|}{1-\left|p_H - p_L\right|}$, where p_H and p_L are the greatest and least values of p among the bins. In this formulation, the numerator represents the "distance" of the output variable from perfect noncorrelation with the input parameter set (i.e., if y has no correlation with the input parameter set under study, then p is the same in all bins, and the numerator is zero). Similarly, the denominator represents the distance of the output variable from perfect correlation with the input parameter (i.e., if y shows perfect correlation with the input parameter set under study, p is unity in the highest bin and zero in the lowest bin, and the denominator is zero). With this formulation, the joint relative sensitivity is on the range $[0,\infty]$. This formulation can be extended to any number of parameters.

APPENDIX D

DESCRIPTION OF ABBREVIATIONS USED FOR TPA VERSION 3.2 CODE INPUT PARAMETERS

Short Name	Full Name	Description
AA_2_1	AA_2_1[C/m^2/yr]	A corrosion rate (passive current density) for the waste package (WP) inner overpack in EBSFAIL.
AAMAI@S	ArealAverageMeanAnnualInfiltrationAtStart[mm/yr]	Mean areal average infiltration into the subsurface at the start of a TPA Version 3.2 code run.
ABMLFVDC	AirborneMassLoadForVolcanismDoseCalculation[g/m3]	Mass load of ash/SF from volcanic event in the air available for inhalation by a receptor.
APrs_SAV	AlluviumMatrixPorosity_SAV	Amargosa Valley alluvium saturated zone (SZ) matrix porosity.
AqThick5	AquiferThickness5km[m]	Thickness of the aquifer at a location 5 km south of Yucca Mountain (YM).
ARDSAV_I	AlluviumMatrixRD_SAV_I	Matrix retardation for iodine (I) in the SZ of the Amargosa Valley alluvium.
ARDSAV_U	AlluviumMatrixRD_SAV_U	Matrix retardation for uranium (U) in the SZ of the Amargosa Valley alluvium.
ARDSAVAm	AlluviumMatrixRD_SAV_Am	Matrix retardation for americium (Am) in the SZ of the Amargosa Valley alluvium.

DESCRIPTION OF ABBREVIATIONS USED FOR TPA VERSION 3.2 CODE INPUT PARAMETERS (cont'd)

Short Name	Full Name	Description
ARDSAVCs	AlluviumMatrixRD_SAV_Cs	Matrix retardation for cesium (Ce) in the SZ of the Amargosa Valley alluvium.
ARDSAVNb	AlluviumMatrixRD_SAV_Nb	Matrix retardation for niobium (Nb) in the SZ of the Amargosa Valley alluvium.
ARDSAVNi	AlluviumMatrixRD_SAV_Ni	Matrix retardation for nickel (NiI) in the SZ of the Amargosa Valley alluvium.
ARDSAVNp	AlluviumMatrixRD_SAV_Np	Matrix retardation for neptunium (Np) in the SZ of the Amargosa Valley alluvium.
ARDSAVPb	AlluviumMatrixRD_SAV_Pb	Matrix retardation for lead (Pb) in the SZ of the Amargosa Valley alluvium.
ARDSAVPu	AlluviumMatrixRD_SAV_Pu	Matrix retardation for plutonium (Pu) in the SZ of the Amargosa Valley alluvium.
ARDSAVRa	AlluviumMatrixRD_SAV_Ra	Matrix retardation for radium (Ra) in the SZ of the Amargosa Valley alluvium.
ARDSAVSe	AlluviumMatrixRD_SAV_Se	Matrix retardation for selenium (Se) in the SZ of the Amargosa Valley alluvium.
ARDSAVTc	AlluviumMatrixRD_SAV_Tc	Matrix retardation for technetium (Tc) in the SZ of the Amargosa Valley alluvium.

DESCRIPTION OF ABBREVIATIONS USED FOR TPA VERSION 3.2 CODE INPUT PARAMETERS (cont'd)

Short Name	Full Name	Description
ARDSAVTh	AlluviumMatrixRD_SAV_Th	Matrix retardation for thorium (Th) in the SZ of the Amargosa Valley alluvium.
AshMnPLD	AshMeanParticleLogDiameter[d_in_cm]	Relative size of ash/spent fuel (SF) particulates from a volcanic event.
*Chlorid	ChlorideMultFactor	Factor by which chloride concentration in matrix is multiplied to compensate for dripping and drying that would lead to salt accumulation.
CladCorF	CladdingCorrectionFactor	A variable allowing for increased SF protection in a WP because of the presence of cladding on the SF.
CritRHAC	CriticalRelativeHumidityAqueousCorrosion	Critical relative humidity above which aqueous corrosion may initiate.
FEROI-Tn	TimeOfNextFaultingEventinRegionOfInterest[yr]	Time of the next faulting event in the repository area (years from present).
FEROI-X	XlocationOfFaultingEventInRegionOfInterest[m]	X location of the center of the faulting event within the repository area.
FEROI-Y	YlocationOfFaultingEventInRegionOfInterest[m]	Y location of the center of the faulting event within the repository area.

DESCRIPTION OF ABBREVIATIONS USED FOR TPA VERSION 3.2 CODE INPUT PARAMETERS (cont'd)

Short Name	Full Name	Description
Fmult*	FmultFactor	The fraction of water, infiltrating to the repository from the unsaturated zone above the repository, that will enter the WP and contribute to the release of radionuclides. Water dripping toward the drifts may be diverted around the drift because of capillary action, may be diverted down the side of the drift, or may not enter the WP for other reasons.
FO-Rn#Sd	RntoDetermineFaultOrientation	Random number selected to determine the orientation of the fault within the repository area.
FOC-R	FractionOfCondensateRemoved[1/yr]	Fraction of water condensate removed in each reflux3 time step.
FOCTR	FractionOfCondensateTowardRepository[1/yr]	Fraction of water condensate moving toward the repository.
FOCTR-R	FractionOfCondensateTowardRepositoryRemoved[1/yr]	Fraction of water condensate moving toward the repository but escaping before entering the repository.
Fow*	FowFactor	A flow focusing factor that expresses the flow potentially reaching a wetted WP (can be greater or less than 1.0).
FPrm_BFw	FracturePermeability_BFw_[m^2]	Bullfrog-welded fracture permeability unsaturated zone (UZ).
FPrm_CHv	FracturePermeability_CHnv[m^2]	Calico Hills-nonwelded vitric fracture permeability (UZ).
FPrm_CHz	FracturePermeability_CHnz[m^2]	Calico Hills-nonwelded zeolitic fracture permeability (UZ).
FPrm_PPw	FracturePermeability_PPw_[m^2]	Prow Pass-welded fracture permeability (UZ).

DESCRIPTION OF ABBREVIATIONS USED FOR TPA VERSION 3.2 CODE INPUT PARAMETERS (cont'd)

Short Name	Full Name	Description
FPrm_TSw	FracturePermeability_TSw_[m2]	Topopah Spring-welded fracture permeability (UZ).
FPrm_UCF	FracturePermeability_UCF_[m2]	Upper Crater Flat fracture permeability (UZ).
FPrm_UFZ	FracturePermeability_UFZ_[m2]	UFZ fracture permeability (UZ).
FPrs_BFw	FracturePorosity_BFw_	Bullfrog-welded fracture porosity (UZ).
FPrs_CHv	FracturePorosity_CHnv	Calico Hills-nonwelded vitric fracture porosity (UZ).
FPrs_CHz	FracturePorosity_CHnz	Calico Hills-nonwelded zeolitic fracture porosity (UZ).
FPrs_PPw	FracturePorosity_PPw_	Prow Pass-welded fracture porosity (UZ).
FPrs_STF	FracturePorosity_STFF	Fracture porosity of saturated tuff (SZ).
FPrs_TSw	FracturePorosity_TSw_	Topopah Spring-welded fracture porosity (UZ).
FPrs_UCF	FracturePorosity_UCF_	Upper Crater Flat fracture porosity (UZ).
FPrs_UFZ	FracturePorosity_UFZ_	UFZ porosity (UZ).
H2O-FThk	ThicknessOfWaterFilm[m]	Thickness of water film on WP surface.
InitRSFP	InitialRadiusOfSFParticle[m]	Initial radius of spent fuel particle — affects SF alteration rate and transport out of a failed WP in EBSREL.
InnOvrEI	InnerOverpackErpIntercept	Inner overpack E_{rp} intercept.

DESCRIPTION OF ABBREVIATIONS USED FOR TPA VERSION 3.2 CODE INPUT PARAMETERS (cont'd)

Short Name	Full Name	Description
InvMPerm	InvertMatrixPermeability[m^2]	Matrix permeability of the invert.
MAPM@GM	MeanAveragePrecipitationMultiplierAtGlacialMaximum	Mean annual precipitation increase at glacial maximum—affects infiltration from the land surface in UZFLOW.
MATI@GM	MeanAverageTemperatureIncreaseAtGlacialMaximum[°C]	Magnitude of mean annual temperature change at glacial maximum—affects infiltration from the land surface in UZFLOW.
MixZnT20	MixingZoneThickness20km[m]	Mixing zone thickness in a well at a receptor group 20 km from YM.
MKD_BFwU	MatrixKD_BFw_U[m3/kg]	Bullfrog-welded matrix K_d for U.
MKD_CHvU	MatrixKD_CHnvU[m3/kg]	Calico Hills-nonwelded vitric matrix K_d for U.
MKD_CHzU	MatrixKD_CHnzU[m3/kg]	Calico Hills-nonwelded zeolitic matrix K_d for U.
MKD_PPwU	MatrixKD_PPw_U[m3/kg]	Prow Pass-welded matrix K_d for U.
MKD_TSwU	MatrixKD_TSw_U[m3/kg]	Topopah Spring-welded matrix K_d for U.
MKD_UCFU	MatrixKD_UCF_U[m3/kg]	Upper Crater Flat matrix K_d for U.
MKDBFwAm	MatrixKD_BFw_Am[m3/kg]	Bullfrog-welded matrix K_d for Am.
MKDBFwCs	MatrixKD_BFw_Cs[m3/kg]	Bullfrog-welded matrix K_d for Cs.

DESCRIPTION OF ABBREVIATIONS USED FOR TPA VERSION 3.2 CODE INPUT PARAMETERS (cont'd)

Short Name	Full Name	Description
MKDBFwNi	MatrixKD_BFw_Ni[m3/kg]	Bullfrog-welded matrix K_d for Ni.
MKDBFwNp	MatrixKD_BFw_Np[m3/kg]	Bullfrog-welded matrix K_d for Np.
MKDBFwPb	MatrixKD_BFw_Pb[m3/kg]	Bullfrog-welded matrix K_d for Pb.
MKDBFwPu	MatrixKD_BFw_Pu[m3/kg]	Bullfrog-welded matrix K_d for Pu.
MKDBFwRa	MatrixKD_BFw_Ra[m3/kg]	Bullfrog-welded matrix K_d for Ra.
MKDBFwSe	MatrixKD_BFw_Se[m3/kg]	Bullfrog-welded matrix K_d for Se.
MKDBFwTh	MatrixKD_BFw_Th[m3/kg]	Bullfrog-welded matrix K_d for Th.
MKDCHvAm	MatrixKD_CHnvAm[m3/kg]	Calico Hills-nonwelded vitric matrix K_d for Am.
MKDCHvCs	MatrixKD_CHnvCs[m3/kg]	Calico Hills-nonwelded vitric matrix K_d for Cs.
MKDCHvNi	MatrixKD_CHnvNi[m3/kg]	Calico Hills-nonwelded vitric matrix K_d for Ni.
MKDCHvNp	MatrixKD_CHnvNp[m3/kg]	Calico Hills-nonwelded vitric matrix K_d for Np.
MKDCHvPb	MatrixKD_CHnvPb[m3/kg]	Calico Hills-nonwelded vitric matrix K_d for Pb.
MKDCHvPu	MatrixKD_CHnvPu[m3/kg]	Calico Hills-nonwelded vitric matrix K_d for Pu.
MKDCHvRa	MatrixKD_CHnvRa[m3/kg]	Calico Hills-nonwelded vitric matrix K_d for Ra.

DESCRIPTION OF ABBREVIATIONS USED FOR TPA VERSION 3.2 CODE INPUT PARAMETERS (cont'd)

Short Name	Full Name	Description
MKDCHvSe	MatrixKD_CHnvSe[m3/kg]	Calico Hills-nonwelded vitric matrix K_d for Se.
MKDCHvTh	MatrixKD_CHnvTh[m3/kg]	Calico Hills-nonwelded vitric matrix K_d for Th.
MKDCHzAm	MatrixKD_CHnzAm[m3/kg]	Calico Hills-nonwelded zeolitic matrix K_d for Am.
MKDCHzCs	MatrixKD_CHnzCs[m3/kg]	Calico Hills-nonwelded zeolitic matrix K_d for Cs.
MKDCHzNi	MatrixKD_CHnzNi[m3/kg]	Calico Hills-nonwelded zeolitic matrix K_d for Ni.
MKDCHzNp	MatrixKD_CHnzNp[m3/kg]	Calico Hills-nonwelded zeolitic matrix K_d for Np.
MKDCHzPb	MatrixKD_CHnzPb[m3/kg]	Calico Hills-nonwelded zeolitic matrix K_d for Pb.
MKDCHzPu	MatrixKD_CHnzPu[m3/kg]	Calico Hills-nonwelded zeolitic matrix K_d for Pu.
MKDCHzRa	MatrixKD_CHnzRa[m3/kg]	Calico Hills-nonwelded zeolitic matrix K_d for Ra.
MKDCHzSe	MatrixKD_CHnzSe[m3/kg]	Calico Hills-nonwelded zeolitic matrix K_d for Se.
MKDCHzTh	MatrixKD_CHnzTh[m3/kg]	Calico Hills-nonwelded zeolitic matrix K_d for Th.
MKDPPwAm	MatrixKD_PPw_Am[m3/kg]	Prow Pass-welded matrix K_d for Am.
MKDPPwCs	MatrixKD_PPw_Cs[m3/kg]	Prow Pass-welded matrix K_d for Cs.
MKDPPwNi	MatrixKD_PPw_Ni[m3/kg]	Prow Pass-welded matrix K_d for Ni.

DESCRIPTION OF ABBREVIATIONS USED FOR TPA VERSION 3.2 CODE INPUT PARAMETERS (cont'd)

Short Name	Full Name	Description
MKDPPwNp	MatrixKD_PPw_Np[m3/kg]	Prow Pass-welded matrix K_d for Np.
MKDPPwPb	MatrixKD_PPw_Pb[m3/kg]	Prow Pass-welded matrix K_d for Pb.
MKDPPwPu	MatrixKD_PPw_Pu[m3/kg]	Prow Pass-welded matrix K_d for Pu.
MKDPPwRa	MatrixKD_PPw_Ra[m3/kg]	Prow Pass-welded matrix K_d for Ra.
MKDPPwSe	MatrixKD_PPw_Se[m3/kg]	Prow Pass-welded matrix K_d for Se.
MKDPPwTh	MatrixKD_PPw_Th[m3/kg]	Prow Pass-welded matrix K_d for Th.
MKDTSwAm	MatrixKD_TSw_Am[m3/kg]	Topopah Spring-welded matrix K_d for Am.
MKDTSwCs	MatrixKD_TSw_Cs[m3/kg]	Topopah Spring-welded matrix K_d for Cs.
MKDTSwNi	MatrixKD_TSw_Ni[m3/kg]	Topopah Spring-welded matrix K_d for Ni.
MKDTSwNp	MatrixKD_TSw_Np[m3/kg]	Topopah Spring-welded matrix K_d for Np.
MKDTSwPb	MatrixKD_TSw_Pb[m3/kg]	Topopah Spring-welded matrix K_d for Pb.
MKDTSwPu	MatrixKD_TSw_Pu[m3/kg]	Topopah Spring-welded matrix K_d for Pu.
MKDTSwRa	MatrixKD_TSw_Ra[m3/kg]	Topopah Spring-welded matrix K_d for Ra.
MKDTSwSe	MatrixKD_TSw_Se[m3/kg]	Topopah Spring-welded matrix K_d for Se.

DESCRIPTION OF ABBREVIATIONS USED FOR TPA VERSION 3.2 CODE INPUT PARAMETERS (cont'd)

Short Name	Full Name	Description
MKDTSwTh	MatrixKD_TSw_Th[m3/kg]	Topopah Spring-welded matrix K_d for Th.
MKDUCFAm	MatrixKD_UCF_Am[m3/kg	Upper Crater Flat matrix K_d for Am.
MKDUCFCs	MatrixKD_UCF_Cs[m3/kg]	Upper Crater Flat matrix K_d for Cs.
MKDUCFNi	MatrixKD_UCF_Ni[m3/kg]	Upper Crater Flat matrix K_d for Ni.
MKDUCFNp	MatrixKD_UCF_Np[m3/kg]	Upper Crater Flat matrix K_d for Np.
MKDUCFPb	MatrixKD_UCF_Pb[m3/kg]	Upper Crater Flat matrix K_d for Pb.
MKDUCFPu	MatrixKD_UCF_Pu[m3/kg]	Upper Crater Flat matrix K_d for Pu.
MKDUCFRa	MatrixKD_UCF_Ra[m3/kg]	Upper Crater Flat matrix K_d for Ra.
MKDUCFSe	MatrixKD_UCF_Se[m3/kg]	Upper Crater Flat matrix K_d for Se.
MKDUCFTh	MatrixKD_UCF_Th[m3/kg]	Upper Crater Flat matrix K_d for Th.
MKDUFZ_U	MatrixKD_UFZ_U[m3/kg]	UFZ matrix K_d for U.
MKDUFZAm	MatrixKD_UFZ_Am[m3/kg]	UFZ matrix K_d for Am.
MKDUFZCs	MatrixKD_UFZ_Cs[m3/kg]	UFZ matrix Kd for Cs.
MKDUFZNi	MatrixKD_UFZ_Ni[m3/kg]	UFZ matrix K_d for Ni.

DESCRIPTION OF ABBREVIATIONS USED FOR TPA VERSION 3.2 CODE INPUT PARAMETERS (cont'd)

Short Name	Full Name	Description
MKDUFZNp	MatrixKD_UFZ_Np[m3/kg]	UFZ matrix K_d for Np.
MKDUFZPb	MatrixKD_UFZ_Pb[m3/kg]	UFZ matrix K_d for Pb.
MKDUFZPu	MatrixKD_UFZ_Pu[m3/kg]	UFZ matrix K_d for Pu.
MKDUFZRa	MatrixKD_UFZ_Ra[m3/kg]	UFZ matrix K_d for Ra.
MKDUFZSe	MatrixKD_UFZ_Se[m3/kg]	UFZ matrix K_d for Se.
MKDUFZTh	MatrixKD_UFZ_Th[m3/kg]	UFZ matrix K_d for Th.
Mprm_BFw	MatrixPermeability_BFw_[m2]	Bullfrog-welded matrix permeability.
MPrm_CHv	MatrixPermeability_CHnv[m2]	Calico Hills-nonwelded vitric matrix permeability.
MPrm_CHz	MatrixPermeability_CHnz[m2]	Calico Hills-nonwelded zeolitic matrix permeability.
MPrm_PPw	MatrixPermeability_PPw_[m2]	Prow Pass-welded matrix permeability.
MPrm_TSw	MatrixPermeability_TSw_[m2]	Topopah Spring-welded matrix permeability.
MPrm_UCF	MatrixPermeability_UCF_[m2]	Upper Crater Flat matrix permeability.
MPrm_UFZ	MatrixPermeability_UFZ_[m2]	UFZ matrix permeability.
NEFZnW	NEFaultZoneWidth[m]	North-East fault zone width.

DESCRIPTION OF ABBREVIATIONS USED FOR TPA VERSION 3.2 CODE INPUT PARAMETERS (cont'd)

Short Name	Full Name	Description
NELCDAmt	NEAmountOfLargestCredibleDisplacement[m]	North-East largest credible displacement.
NWFZnW	NWFaultZoneWidth[m]	North-West fault zone width.
NWLCDAmt	NWAmountOfLargestCredibleDisplacement[m]	North-West largest credible displacement.
OO-CofLC	CoefForLocCorrOfOuterOverpack	Coefficient for localized corrosion rate of outer overpack.
PlumeTh5	PlumeThickness5km[m]	Plume thickness at 5 km.
SbArWt%	SubAreaWetFraction	Subarea wet fraction.
SbGFRATF	SubGrainFragmentRadiusAfterTransFrac[m]	Subgrain fragment radius of UO_2 particle after transgranular fracture; used only if fuel conversion takes place from UO_2 to $UO_{2.4}$ and U_3O_8; used only by the SF dissolution models that are dependent on exposed surface area.
SFWt%C1	SFWettedFraction_Corrosion_1	SF wet fraction for corrosion failures in subarea 1.
SFWt%C2	SFWettedFraction_Corrosion_2	SF wet fraction for corrosion failures in subarea 2.
SFWt%C3	SFWettedFraction_Corrosion_3	SF wet fraction for corrosion failures in subarea 3.
SFWt%C4	SFWettedFraction_Corrosion_4	SF wet fraction for corrosion failures in subarea 4.
SFWt%C5	SFWettedFraction_Corrosion_5	SF wet fraction for corrosion failures in subarea 5.
SFWt%C6	SFWettedFraction_Corrosion_6	SF wet fraction for corrosion failures in subarea 6.

DESCRIPTION OF ABBREVIATIONS USED FOR TPA VERSION 3.2 CODE INPUT PARAMETERS (cont'd)

Short Name	Full Name	Description
SFWt%C7	SFWettedFraction_Corrosion_7	SF wet fraction for corrosion failures in subarea 7.
SFWt%F0	SFWettedFraction_FAULTO	SF wet fraction for faulting failures.
SFWt%I1	SFWettedFraction_Initial_1	SF wet fraction for initial failures in subarea 1.
SFWt%I2	SFWettedFraction_Initial_2	SF wet fraction for initial failures in subarea 2.
SFWt%I3	SFWettedFraction_Initial_3	SF wet fraction for initial failures in subarea 3.
SFWt%I4	SFWettedFraction_Initial_4	SF wet fraction for initial failures in subarea 4.
SFWt%I5	SFWettedFraction_Initial_5	SF wet fraction for initial failures in subarea 5.
SFWt%I6	SFWettedFraction_Initial_6	SF wet fraction for initial failures in subarea 6.
SFWt%I7	SFWettedFraction_Initial_7	SF wet fraction for initial failures in subarea 7.
SFWt%S11	SFWettedFraction_SEISMO1_1	SF wet fraction for seismic failures for seismic interval 1 in subarea 1.
SFWt%S12	SFWettedFraction_SEISMO1_2	SF wet fraction for seismic failures for seismic interval 1 in subarea 2.
SFWt%S13	SFWettedFraction_SEISMO1_3	SF wet fraction for seismic failures for seismic interval 1 in subarea 3.

DESCRIPTION OF ABBREVIATIONS USED FOR TPA VERSION 3.2 CODE INPUT PARAMETERS (cont'd)

Short Name	Full Name	Description
SFWt%S14	SFWettedFraction_SEISMO1_4	SF wet fraction for seismic failures for seismic interval 1 in subarea 4.
SFWt%S15	SFWettedFraction_SEISMO1_5	SF wet fraction for seismic failures for seismic interval 1 in subarea 5.
SFWt%S16	SFWettedFraction_SEISMO1_6	SF wet fraction for seismic failures for seismic interval 1 in subarea 6.
SFWt%S17	SFWettedFraction_SEISMO1_7	SF wet fraction for seismic failures for seismic interval 1 in subarea 7.
SFWt%S21	SFWettedFraction_SEISMO2_1	SF wet fraction for seismic failures for seismic interval 2 in subarea 1.
SFWt%S22	SFWettedFraction_SEISMO2_2	SF wet fraction for seismic failures for seismic interval 2 in subarea 2.
SFWt%S23	SFWettedFraction_SEISMO2_3	SF wet fraction for seismic failures for seismic interval 2 in subarea 3.
SFWt%S24	SFWettedFraction_SEISMO2_4	SF wet fraction for seismic failures for seismic interval 2 in subarea 4.
SFWt%S25	SFWettedFraction_SEISMO2_5	SF wet fraction for seismic failures for seismic interval 2 in subarea 5.

DESCRIPTION OF ABBREVIATIONS USED FOR TPA VERSION 3.2 CODE INPUT PARAMETERS (cont'd)

Short Name	Full Name	Description
SFWt%S26	SFWettedFraction_SEISMO2_6	SF wet fraction for seismic failures for seismic interval 2 in subarea 6.
SFWt%S27	SFWettedFraction_SEISMO2_7	SF wet fraction for seismic failures for seismic interval 2 in subarea 7.
SFWt%S31	SFWettedFraction_SEISMO3_1	SF wet fraction for seismic failures for seismic interval 3 in subarea 1.
SFWt%S32	SFWettedFraction_SEISMO3_2	SF wet fraction for seismic failures for seismic interval 3 in subarea 2.
SFWt%S33	SFWettedFraction_SEISMO3_3	SF wet fraction for seismic failures for seismic interval 3 in subarea 3.
SFWt%S34	SFWettedFraction_SEISMO3_4	SF wet fraction for seismic failures for seismic interval 3 in subarea 4.
SFWt%S35	SFWettedFraction_SEISMO3_5	SF wet fraction for seismic failures for seismic interval 3 in subarea 5.
SFWt%S36	SFWettedFraction_SEISMO3_6	SF wet fraction for seismic failures for seismic interval 3 in subarea 6.
SFWt%S37	SFWettedFraction_SEISMO3_7	SF wet fraction for seismic failures for seismic interval 3 in subarea 7.

DESCRIPTION OF ABBREVIATIONS USED FOR TPA VERSION 3.2 CODE INPUT PARAMETERS (cont'd)

Short Name	Full Name	Description
SFWt%S41	SFWettedFraction_SEISMO4_1	SF wet fraction for seismic failures for seismic interval 4 in subarea 1.
SFWt%S42	SFWettedFraction_SEISMO4_2	SF wet fraction for seismic failures for seismic interval 4 in subarea 2.
SFWt%S43	SFWettedFraction_SEISMO4_3	SF wet fraction for seismic failures for seismic interval 4 in subarea 3.
SFWt%S44	SFWettedFraction_SEISMO4_4	SF wet fraction for seismic failures for seismic interval 4 in subarea 4.
SFWt%S45	SFWettedFraction_SEISMO4_5	SF wet fraction for seismic failures for seismic interval 4 in subarea 5.
SFWt%S46	SFWettedFraction_SEISMO4_6	SF wet fraction for seismic failures for seismic interval 4 in subarea 6.
SFWt%S47	SFWettedFraction_SEISMO4_7	SF wet fraction for seismic failures for seismic interval 4 in subarea 7.
SFWt%V0	SFWettedFraction_VOLCANO	SF wet fraction for volcanic failures.
Solbl-Am	SolubilityAm[kg/m3]	Solubility limit for Am.
Solbl-Np	SolubilityNp[kg/m3]	Solubility limit for Np.
Solbl-Pu	SolubilityPu[kg/m3]	Solubility limit for Pu.

DESCRIPTION OF ABBREVIATIONS USED FOR TPA VERSION 3.2 CODE INPUT PARAMETERS (cont'd)

Short Name	Full Name	Description
SSMO-JS3	SEISMOJointSpacing3[m]	Joint spacing (JS) for rock condition 3. Not all rocks falling from the roof of the emplacement will impact WPs. The effective size of the rock that impacts WPs will be controlled by JS.
SSMO-JS4	SEISMOJointSpacing4[m]	JS for rock condition 4.
SSMO-JS1	SEISMOJointSpacing1[m]	JS for rock condition 1.
SSMO-RE	RockModulusOfElasticityforSEISMO[Pa]	Rock modulus of elasticity.
SSMO-JS2	SEISMOJointSpacing2[m]	JS for rock condition 2.
SSMO-JS5	SEISMOJointSpacing5[m]	JS for rock condition 5.
SSMO-RPR	RockPoissonRatioforSEISMO[]	Rock poisson ratio.
SSMOV201	VerticalExtentOfRockFall2_1[m]	Vertical extent of rock fall for rock condition 2 and ground acceleration 0.05 g. The lower limit is approximately equivalent to the average rock joint spacing of rock condition 1. The upper limit is estimated from numerical results.
SSMOV202	VerticalExtentOfRockFall2_2[m]	Same as above except with ground acceleration 0.10g.
SSMOV203	VerticalExtentOfRockFall2_3[m]	Same as above except with ground acceleration 0.15g.
SSMOV204	VerticalExtentOfRockFall2_4[m]	Same as above except with ground acceleration 0.20g.

DESCRIPTION OF ABBREVIATIONS USED FOR TPA VERSION 3.2 CODE INPUT PARAMETERS (cont'd)

Short Name	Full Name	Description
SSMOV205	VerticalExtentOfRockFall2_5[m]	Same as above except with ground acceleration 0.25g.
SSMOV206	VerticalExtentOfRockFall2_6[m]	Same as above except with ground acceleration 0.30g.
SSMOV207	VerticalExtentOfRockFall2_7[m]	Same as above except with ground acceleration 0.35g.
SSMOV208	VerticalExtentOfRockFall2_8[m]	Same as above except with ground acceleration 0.40g.
SSMOV209	VerticalExtentOfRockFall2_9[m]	Same as above except with ground acceleration 0.45g.
SSMOV210	VerticalExtentOfRockFall2_10[m]	Same as above except with ground acceleration 0.50g.
SSMOV301	VerticalExtentOfRockFall3_1[m]	Vertical extent of rock fall for rock condition 3 and ground acceleration 0.05 g.
SSMOV302	VerticalExtentOfRockFall3_2[m]	Same as above except with ground acceleration 0.10g.
SSMOV303	VerticalExtentOfRockFall3_3[m]	Same as above except with ground acceleration 0.15g.
SSMOV304	VerticalExtentOfRockFall3_4[m]	Same as above except with ground acceleration 0.20g.
SSMOV305	VerticalExtentOfRockFall3_5[m]	Same as above except with ground acceleration 0.25g.
SSMOV306	VerticalExtentOfRockFall3_6[m]	Same as above except with ground acceleration 0.30g.
SSMOV307	VerticalExtentOfRockFall3_7[m]	Same as above except with ground acceleration 0.35g.
SSMOV308	VerticalExtentOfRockFall3_8[m]	Same as above except with ground acceleration 0.40g.

DESCRIPTION OF ABBREVIATIONS USED FOR TPA VERSION 3.2 CODE INPUT PARAMETERS (cont'd)

Short Name	Full Name	Description
SSMOV309	VerticalExtentOfRockFall3_9[m]	Same as above except with ground acceleration 0.45g.
SSMOV310	VerticalExtentOfRockFall3_10[m]	Same as above except with ground acceleration 0.50g.
SSMOV401	VerticalExtentOfRockFall4_1[m]	Vertical extent of rock fall for rock condition 4 and ground acceleration 0.05 g.
SSMOV402	VerticalExtentOfRockFall4_2[m]	Same as above except with ground acceleration 0.10g.
SSMOV403	VerticalExtentOfRockFall4_3[m]	Same as above except with ground acceleration 0.15g.
SSMOV404	VerticalExtentOfRockFall4_4[m]	Same as above except with ground acceleration 0.20g.
SSMOV405	VerticalExtentOfRockFall4_5[m]	Same as above except with ground acceleration 0.25g.
SSMOV406	VerticalExtentOfRockFall4_6[m]	Same as above except with ground acceleration 0.30g.
SSMOV407	VerticalExtentOfRockFall4_7[m]	Same as above except with ground acceleration 0.35g.
SSMOV408	VerticalExtentOfRockFall4_8[m]	Same as above except with ground acceleration 0.40g.
SSMOV409	VerticalExtentOfRockFall4_9[m]	Same as above except with ground acceleration 0.45g.
SSMOV410	VerticalExtentOfRockFall4_10[m]	Same as above except with ground acceleration 0.50g.
SSMOV501	VerticalExtentOfRockFall5_1[m]	Vertical extent of rock fall for rock condition 5 and ground acceleration 0.05 g.

Short Name	Full Name	Description
SSMOV502	VerticalExtentOfRockFall5_2[m]	Same as above except with ground acceleration 0.10g.
SSMOV503	VerticalExtentOfRockFall5_3[m]	Same as above except with ground acceleration 0.15g.
SSMOV504	VerticalExtentOfRockFall5_4[m]	Same as above except with ground acceleration 0.20g.
SSMOV505	VerticalExtentOfRockFall5_5[m]	Same as above except with ground acceleration 0.25g.
SSMOV506	VerticalExtentOfRockFall5_6[m]	Same as above except with ground acceleration 0.30g.
SSMOV507	VerticalExtentOfRockFall5_7[m]	Same as above except with ground acceleration 0.35g.
SSMOV508	VerticalExtentOfRockFall5_8[m]	Same as above except with ground acceleration 0.40g.
SSMOV509	VerticalExtentOfRockFall5_9[m]	Same as above except with ground acceleration 0.45g.
SSMOV510	VerticalExtentOfRockFall5_10[m]	Same as above except with ground acceleration 0.50g.
TempGrBI	TemperatureGradientInVicinityOfBoilingIsotherm[K/m]	Temperature gradient in the vicinity of the boiling isotherm. (Parameter specific to reflux3 model.)
VC-Dia	DiameterOfVolcanicCone[m]	Cone diameter.
VD-Angle	AngleOfVolcanicDikeMeasuredFromNorthClockwise[degrees]	Volcanic dike angle.
VD-Width	WidthOfVolcanicDike[m]	Volcanic dike width.
VD-Lengt	LengthOfVolcanicDike[m]	Volcanic dike length.

DESCRIPTION OF ABBREVIATIONS USED FOR TPA VERSION 3.2 CODE INPUT PARAMETERS (cont'd)

Short Name	Full Name	Description
VE-Power	VolcanicEventPower[W]	Volcanic event power.
VE-Durat	VolcanicEventDuration[s]	Volcanic event duration.
VEi/e-R#	RNtoDetermineIfExtrusiveOrIntrusiveVolcanicEvent	Random number to determine volcanic event type.
VEROI-Tn	TimeOfNextVolcanicEventinRegionOfInterest[yr]	Time of next volcanic event.
WindSpd	WindSpeed[cm/s]	Wind speed.
WP-Def%	DefectiveFractionOfWPs/cell	Fraction of total WPs in a subarea that fail at time t = 0.
WPFD-ThD	ThresholdDisplacementforFaultDisruptionOfWP[m]	Threshold fault displacement for disruption. Data input order: number of fault displacement values to be provided followed by equiprobable displacement values.
WPRRG@10	WellPumpingRateAtReceptorGroup10km[gal/day]	Well pumping rate for residential receptor group located less than 10 km from YM.
WPRRG@20	WellPumpingRateAtReceptorGroup20km[gal/day]	Well-pumping rate for residential receptor group located less than 20 km from YM.
YMR-TC	ThermalConductivityofYMRock[W/(m-K)]	Thermal conductivity of rock.

APPENDIX E

DETAILED RESULTS FROM DIFFERENTIAL ANALYSES

The tables in this appendix present the results of the differential analysis. Tables E-1 and E-2 present the results for the basecase analysis for 10,000-yr and 50,000-yr Time Period of Regulatory Interest (TPI). Tables E-3 and E-4 present the results for the faulting scenario for 10,000-yr and 50,000-yr TPI. Table E-5 presents the results for the volcanism scenario. The results for the 50,000-yr TPI are not expected to be different than the 10,000-yr results, because after the 10,000-yr TPI, when the groundwater dose dominates, the primary contributors to ground-surface dose have decreased (see Section 4.3.1). Therefore, only the table for the 10,000-yr TPI is shown.

The tables are organized in the following manner. The first column lists an abbreviation of the parameter that was tested. Only those parameters that had a non-zero result in any of the seven runs are included on the table. The second column contains the arithmetic average of the sigma-weighted sensitivity coefficients of the seven runs. This value considers the uncertainty of the parameter as well as the magnitude of the dose for the given run in calculating the sensitivity of a parameter and is the result by which the parameters are sorted. The third column contains the arithmetic average of the scaled sensitivity coefficients, which show the absolute sensitivity that a parameter has on the results of the TPA code, without taking the input range of the parameter into account. The fourth column shows the geometric average of the same value to weight more highly those parameters that show high sensitivity for all runs instead of just a high sensitivity for a couple of runs. The fifth column contains the highest value of the scaled sensitivity coefficients calculated in any of the runs. The remainder of the columns show the individual run results for both the sigma-weighted sensitivity coefficient and the scaled sensitivity coefficients.

Table E-1. Differential analysis results for the basecase for a time period of interest of 10,000 yr

Parameter Name—10,000-yr, Ranked by Sigma	Arith. Mean of Sigma Weighted Values	S - Arith. Mean	S - Geom. Mean	S - High Value	R1 - Sigma	R2 - Sigma	R3 - Sigma	R4 - Sigma	R5 - Sigma	R6 - Sigma	R7 - Sigma	R1 - S	R2 - S	R3 - S	R4 - S	R5 - S	R6 - S	R7 - S
Base Value Peak Total Effective Dose Equivalent (rem/yr)					3.85e-06	1.33e-07	1.44e-07	6.48e-06	4.01e-08	2.00e-06	4.02e-06	3.85e-06	1.33e-07	1.44e-07	6.48e-06	4.01e-08	2.00e-06	4.02e-06
ARDSAVTc	1.138e-05	6.139e-01	4.766e-02	1.791e+00	1.11e-08	0.00e+00	1.86e-07	7.92e-05	2.31e-07	9.02e-09	0.00e+00	2.60e-03	7.51e-03	7.31e-01	1.76e+00	1.79e+00	5.00e-03	2.49e-03
FOCTR-R	9.574e-06	9.796e-02	3.942e-02	2.753e-01	2.68e-08	7.02e-09	0.00e+00	5.77e-11	0.00e+00	6.70e-05	7.41e-11	2.75e-01	1.95e-01	6.96e-03	2.62e-02	2.49e-03	4.50e-02	1.34e-01
Fow*	3.822e-06	6.792e-01	4.682e-01	2.291e+00	2.09e-05	2.54e-07	4.54e-07	3.50e-06	7.90e-08	1.68e-07	1.44e-06	2.29e+00	4.66e-01	7.73e-01	3.30e-01	4.81e-01	1.35e-01	2.79e-01
ARDSAV_I	2.982e-06	2.137e+00	1.736e+00	4.264e+00	7.88e-06	7.80e-08	1.37e-07	3.85e-06	1.81e-08	8.31e-07	8.07e-06	2.82e+00	9.54e-01	3.81e+00	8.60e-01	1.10e+00	1.15e+00	4.26e+00
SFWt%I3	2.618e-06	2.058e+00	5.144e-01	7.021e+00	6.78e-06	3.92e-08	5.63e-08	2.18e-06	0.00e+00	4.02e-07	8.86e-06	4.94e+00	7.06e-01	3.20e-01	8.06e-01	2.49e-03	6.05e-01	7.02e+00
WP-Def%	2.167e-06	1.336e+00	1.212e+00	2.539e+00	1.05e-06	1.48e-07	4.57e-08	9.17e-06	3.29e-08	2.69e-06	2.03e-06	6.43e-01	1.38e+00	8.96e-01	2.54e+00	1.87e+00	9.74e-01	1.04e+00
ARDSAVSe	1.808e-06	5.714e-02	1.111e-02	3.090e-01	1.18e-05	0.00e+00	0.00e+00	0.00e+00	8.72e-07	0.00e+00	0.00e+00	6.75e-02	7.51e-03	6.96e-03	1.54e-03	3.09e-01	5.00e-03	2.49e-03
SbArWt%	1.681e-06	1.000e+00	1.000e+00	1.002e+00	1.27e-06	1.82e-06	1.32e-07	5.77e-06	5.23e-08	1.12e-06	1.61e-06	1.00e+00	9.99e-01	1.00e+00	1.00e+00	9.99e-01	1.00e+00	9.98e-01
Fmult*	1.478e-06	6.823e-01	4.721e-01	2.290e+00	8.10e-06	2.10e-08	3.20e-08	9.05e-07	1.82e-08	1.94e-07	1.07e-06	2.29e+00	4.81e-01	7.73e-01	3.33e-01	4.81e-01	1.35e-01	2.84e-01
FOC-R	1.037e-06	4.578e-02	2.877e-02	9.347e-02	2.81e-08	1.84e-08	2.18e-13	1.08e-10	2.28e-10	7.21e-06	0.00e+00	9.35e-02	2.25e-02	2.09e-02	6.64e-02	8.97e-02	2.50e-02	2.49e-03
WPRRG@20	8.463e-07	9.956e-01	9.956e-01	1.010e+00	7.22e-07	4.57e-08	4.28e-08	2.74e-06	8.05e-09	7.29e-07	1.64e-06	9.89e-01	9.91e-01	1.01e+00	9.89e-01	9.89e-01	1.01e+00	9.91e-01
SfWt%I4	6.774e-07	3.365e-01	1.332e-01	1.468e+00	2.89e-07	5.28e-09	2.67e-08	4.20e-06	1.65e-08	5.48e-08	1.45e-07	3.37e-02	1.50e-02	2.51e-01	1.47e+00	3.84e-01	9.50e-02	1.10e-01
APrs_SAV	6.615e-07	2.522e+00	2.159e+00	4.780e+00	9.72e-07	2.25e-08	7.91e-08	1.37e-06	1.45e-08	2.08e-07	1.97e-06	2.00e+00	1.37e+00	4.78e+00	1.52e+00	3.28e+00	8.75e-01	3.83e+00
AAMAI@S	4.890e-07	8.722e-01	4.354e-01	2.446e+00	2.71e-06	6.07e-08	7.76e-08	3.18e-07	1.68e-08	7.36e-08	1.65e-07	2.45e+00	1.13e+00	1.43e+00	9.41e-02	8.12e-01	9.00e-02	1.10e-01
SFWt%I5	4.449e-07	5.342e-01	2.791e-01	1.672e+00	8.38e-08	4.86e-08	1.50e-08	1.07e-06	2.23e-07	2.68e-07	1.41e-06	6.75e-02	1.03e+00	2.37e-01	4.94e-02	1.67e+00	2.00e-01	4.86e-01
MAPM@GM	4.374e-07	1.116e+00	7.458e-01	3.323e+00	1.79e-06	6.59e-09	2.29e-08	5.51e-07	6.07e-09	3.15e-08	6.52e-07	3.32e+00	4.13e-01	1.38e+00	4.89e-01	8.17e-01	1.35e-01	1.26e+00
InitRSFP	4.032e-07	7.456e-01	7.433e-01	8.660e-01	5.68e-07	2.22e-08	2.20e-08	1.25e-06	7.15e-09	3.15e-07	6.40e-07	7.24e-01	7.44e-01	6.82e-01	8.66e-01	7.92e-01	7.00e-01	7.10e-01
SFWt%I1	3.661e-07	2.806e-01	7.829e-02	1.119e+00	2.20e-06	7.06e-08	1.53e-08	1.32e-07	0.00e+00	1.03e-07	4.13e-08	5.14e-01	1.12e+00	1.95e-01	5.40e-02	2.49e-03	6.00e-02	1.99e-02
TempGrBI	3.256e-07	2.104e-01	1.041e-01	4.801e-01	1.64e-06	1.04e-08	1.13e-09	1.30e-07	6.62e-09	3.69e-07	1.26e-07	2.91e-01	2.10e-01	6.96e-03	3.09e-02	4.01e-01	4.80e-01	5.23e-02
SFWt%I6	3.241e-07	1.500e-01	6.516e-02	3.551e-01	1.14e-07	1.29e-08	2.63e-09	9.99e-07	0.00e+00	5.86e-07	5.53e-07	8.57e-02	1.50e-02	6.26e-02	2.58e-01	2.49e-03	3.55e-01	2.71e-01
MPrm_CHv	2.681e-07	1.063e-01	1.048e-02	6.957e-01	1.83e-06	5.53e-09	0.00e+00	0.00e+00	0.00e+00	4.59e-08	0.00e+00	6.96e-01	1.50e-02	6.96e-03	1.54e-03	2.49e-03	2.00e-02	2.49e-03
SFWt%I7	2.057e-07	2.087e-01	6.076e-02	6.154e-01	9.49e-07	1.45e-09	6.36e-08	1.11e-07	0.00e+00	1.30e-07	1.85e-07	6.15e-01	3.76e-02	5.71e-01	7.72e-03	2.49e-03	8.50e-02	1.42e-01
YMR-TC	1.652e-07	1.285e+00	1.252e+00	1.692e+00	1.92e-07	1.20e-08	9.48e-09	4.89e-07	4.09e-09	1.86e-07	2.64e-07	8.39e-01	1.40e+00	1.06e+00	1.32e+00	1.69e+00	1.61e+00	1.07e+00
SFWt%I2	1.537e-07	9.565e-02	3.249e-02	2.854e-01	0.00e+00	5.29e-08	4.26e-08	5.31e-08	0.00e+00	2.60e-08	9.01e-07	2.60e-03	2.85e-01	2.09e-01	2.31e-02	2.49e-03	4.00e-02	1.07e-01
FPrs_STF	1.359e-07	3.274e-02	3.021e-02	5.725e-02	2.31e-07	3.73e-09	6.83e-09	3.15e-07	2.13e-09	2.13e-08	3.71e-07	5.19e-02	2.25e-02	2.78e-02	2.47e-02	1.99e-02	2.50e-02	5.73e-02
FOCTR	6.167e-08	1.745e-01	5.696e-02	5.456e-01	1.18e-08	1.65e-08	4.55e-09	1.67e-07	7.59e-09	1.99e-07	2.54e-08	7.79e-03	3.46e-01	1.39e-02	5.09e-02	5.46e-01	2.50e-01	7.47e-03
MATI@GM	2.717e-08	1.245e-01	4.904e-02	5.580e-01	8.13e-08	1.47e-09	3.08e-10	4.66e-08	3.86e-09	0.00e+00	5.67e-08	1.14e-01	6.01e-02	1.39e-02	2.78e-02	5.58e-01	5.00e-03	9.21e-02
FPrm_UCF	3.686e-09	4.084e-03	3.504e-03	7.507e-03	0.00e+00	2.58e-08	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00	2.60e-03	7.51e-03	6.96e-03	1.54e-03	2.49e-03	5.00e-03	2.49e-03

Table E-2. Differential analysis results for the basecase for a time period of interest of 50,000 yr

Parameter Name—50,000-yr, Ranked by Sigma	Arith. Mean of Sigma Weighted Values	S - Arith. Mean	S - Geometric Mean	S - High Value	R1 - Sigma	R2 - Sigma	R3 - Sigma	R4 - Sigma	R5 - Sigma	R6 - Sigma	R7 - Sigma	R1 - S	R2 - S	R3 - S	R4 - S	R5 - S	R6 - S	R7 - S
Base Value Peak Total Effective Dose Equivalent (rem/yr)					5.60e-04	1.90e-05	9.60e-05	4.40e-04	1.50e-04	5.40e-04	4.70e-04	5.60e-04	1.90e-05	9.60e-05	4.40e-04	1.50e-04	5.40e-04	4.70e-04
ARDSAVNp	2.372e-03	1.205e+00	8.297e-03	8.416e+00	1.66e-02	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00	8.42e+00	5.19e-03	1.04e-03	2.29e-03	6.53e-03	1.86e-03	2.14e-03
Fow*	2.131e-04	4.145e-01	2.794e-01	7.334e-01	1.66e-04	5.53e-05	6.92e-05	4.51e-04	3.11e-04	1.25e-06	4.38e-04	1.26e-01	7.01e-01	1.76e-01	6.33e-01	4.96e-01	3.73e-02	7.33e-01
OO-CofLC	2.105e-04	1.590e+00	7.834e-02	8.939e+00	0.00e+00	0.00e+00	9.12e-08	1.81e-04	1.43e-04	1.14e-03	1.13e-05	1.80e-03	5.19e-03	3.12e-03	6.26e-01	1.48e+00	8.94e+00	7.51e-02
AA_2_1	1.920e-04	1.268e+00	2.346e-01	3.513e+00	5.75e-04	1.53e-07	2.38e-06	6.25e-05	7.93e-05	0.00e+00	6.25e-04	3.15e+00	4.15e-02	4.89e-02	6.28e-01	1.49e+00	1.86e-03	3.51e+00
SbArWt%	1.914e-04	1.000e+00	1.000e+00	1.006e+00	1.83e-04	2.63e-04	8.79e-05	3.87e-04	2.01e-04	3.01e-05	1.87e-04	1.00e+00	9.96e-01	9.99e-01	9.99e-01	1.01e+00	9.99e-01	1.00e+00
ARDSAVTc	1.762e-04	2.593e-01	1.349e-01	5.392e-01	9.80e-05	6.14e-08	9.19e-05	8.21e-04	1.80e-04	2.10e-05	2.11e-05	1.58e-01	5.19e-03	5.39e-01	2.70e-01	3.66e-01	4.34e-01	4.29e-02
Fmult*	8.428e-05	4.160e-01	2.785e-01	7.464e-01	6.52e-05	4.47e-06	4.91e-06	1.15e-04	7.06e-05	1.36e-06	3.28e-04	1.27e-01	7.06e-01	1.77e-01	6.30e-01	4.90e-01	3.54e-02	7.46e-01
WPRRG@20	8.060e-05	9.949e-01	9.949e-01	1.010e+00	1.04e-04	6.61e-06	2.86e-05	1.84e-04	3.06e-05	1.96e-05	1.90e-04	9.89e-01	9.91e-01	1.01e+00	9.90e-01	9.86e-01	1.01e+00	9.89e-01
APrs_SAV	7.848e-05	1.392e+00	4.233e-01	6.021e+00	4.24e-04	6.14e-08	6.85e-06	2.23e-06	7.95e-06	5.39e-06	1.03e-04	6.02e+00	2.59e-02	6.19e-01	3.67e-02	4.70e-01	8.46e-01	1.73e+00
ARDSAV_I	6.033e-05	3.891e-01	2.021e-01	1.389e+00	7.25e-06	1.66e-06	4.26e-06	8.37e-05	8.66e-06	1.13e-05	3.05e-04	1.80e-02	1.40e-01	1.77e-01	2.77e-01	1.37e-01	5.85e-01	1.39e+00
MAPM@GM	4.974e-05	2.108e+00	9.541e-01	8.692e+00	4.83e-05	2.01e-05	6.01e-06	1.15e-04	3.74e-05	3.85e-07	1.21e-04	6.19e-01	8.69e+00	5.41e-01	1.51e+00	1.32e+00	6.15e-02	2.01e+00
AAMAI@S	4.432e-05	3.256e-01	2.190e-01	7.570e-01	2.93e-05	2.96e-06	2.88e-06	1.14e-04	2.73e-05	7.36e-07	1.33e-04	1.83e-01	3.79e-01	7.91e-02	5.02e-01	3.46e-01	3.35e-02	7.57e-01
SFWt%C6	4.162e-05	2.129e-01	1.365e-01	6.713e-01	7.18e-05	1.65e-06	8.79e-06	8.09e-05	7.43e-06	5.53e-06	1.15e-04	5.57e-02	2.75e-01	9.58e-02	2.50e-01	3.26e-02	1.10e-01	6.71e-01
SFWt%C3	4.086e-05	2.989e-01	1.644e-01	4.619e-01	1.24e-04	3.67e-06	1.27e-05	1.15e-04	1.61e-05	7.26e-06	7.40e-06	2.41e-01	4.62e-01	3.53e-01	4.40e-01	2.74e-01	3.20e-01	2.14e-03
SFWt%C2	3.250e-05	2.696e-01	1.330e-01	4.440e-01	3.15e-05	5.42e-06	1.98e-05	1.37e-04	2.88e-05	5.40e-06	0.00e+00	1.47e-01	4.41e-01	3.62e-01	4.10e-01	4.44e-01	8.01e-02	2.14e-03
SFWt%C4	3.239e-05	1.714e-01	1.478e-01	3.160e-01	1.22e-04	1.62e-06	4.47e-06	5.16e-05	6.57e-06	6.87e-07	4.01e-05	3.16e-01	1.25e-01	1.51e-01	1.67e-01	1.31e-01	4.47e-02	2.66e-01
SFWt%C5	3.144e-05	1.410e-01	1.071e-01	2.693e-01	9.99e-05	1.39e-06	7.04e-06	7.72e-05	1.18e-05	5.03e-06	1.78e-05	2.69e-01	4.15e-02	5.73e-02	1.53e-01	1.83e-01	2.46e-01	3.65e-02
SFWt%C1	3.014e-05	2.782e-01	1.902e-01	5.453e-01	2.24e-05	3.48e-06	1.56e-05	8.54e-05	1.57e-05	5.30e-06	6.31e-05	1.97e-02	4.15e-01	2.60e-01	5.45e-01	3.20e-01	7.83e-02	3.09e-01
InitRSFP	3.006e-05	5.978e-01	5.170e-01	1.012e+00	9.42e-05	9.89e-07	2.00e-05	3.34e-05	1.89e-05	1.22e-05	3.08e-05	8.31e-01	2.28e-01	9.27e-01	3.44e-01	5.49e-01	1.01e+00	2.94e-01
ARDSAVSe	2.994e-05	3.938e-03	3.538e-03	6.531e-03	1.36e-04	9.42e-07	1.92e-06	0.00e+00	7.03e-05	4.17e-07	0.00e+00	5.39e-03	5.19e-03	4.16e-03	2.29e-03	6.53e-03	1.86e-03	2.14e-03
MKDCHvNp	2.258e-05	4.043e-02	5.060e-03	2.639e-01	1.58e-04	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00	2.64e-01	5.19e-03	1.04e-03	2.29e-03	6.53e-03	1.86e-03	2.14e-03
SFWt%C7	1.881e-05	4.681e-02	3.565e-02	1.029e-01	7.11e-05	7.45e-07	2.13e-06	1.91e-05	3.66e-06	2.77e-06	3.22e-05	1.62e-02	6.23e-02	7.29e-03	4.58e-02	3.92e-02	5.40e-02	1.03e-01
MATI@GM	1.438e-05	2.448e-01	1.404e-01	7.635e-01	1.46e-05	6.23e-07	1.45e-06	2.02e-05	9.13e-06	9.83e-08	5.46e-05	1.42e-01	1.76e-01	9.79e-02	1.79e-01	3.46e-01	9.32e-03	7.63e-01
YMR-TC	1.392e-05	7.965e-01	6.034e-01	1.861e+00	5.58e-05	3.20e-07	3.15e-06	8.52e-06	1.72e-05	1.61e-06	1.10e-05	1.68e+00	2.60e-01	5.26e-01	3.41e-01	1.86e+00	5.20e-01	3.84e-01
Solbl-Np	1.015e-05	2.376e-02	4.655e-03	1.472e-01	7.11e-05	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00	1.47e-01	5.19e-03	1.04e-03	2.29e-03	6.53e-03	1.86e-03	2.14e-03
WP-Def%	8.342e-06	3.750e-02	7.792e-03	2.331e-01	5.51e-05	6.40e-08	2.77e-07	1.73e-06	2.62e-07	0.00e+00	9.72e-07	2.33e-01	4.15e-03	8.12e-03	7.10e-03	3.92e-03	1.86e-03	4.29e-03
FPrs_STF	2.503e-06	8.337e-03	6.352e-03	1.863e-02	6.94e-06	1.24e-07	3.42e-07	0.00e+00	0.00e+00	4.27e-07	9.69e-06	1.08e-02	5.19e-03	2.08e-03	2.29e-03	6.53e-03	1.86e-02	1.29e-02
SFWt%I4	2.378e-06	5.130e-03	3.833e-03	1.256e-02	1.56e-05	0.00e+00	7.42e-08	0.00e+00	0.00e+00	0.00e+00	9.88e-07	1.26e-02	5.19e-03	1.04e-03	2.29e-03	6.53e-03	1.86e-03	6.43e-03
ARDSAVNi	1.150e-06	2.978e-03	2.480e-03	6.529e-03	0.00e+00	0.00e+00	8.05e-06	0.00e+00	0.00e+00	0.00e+00	0.00e+00	1.80e-03	5.19e-03	1.04e-03	2.29e-03	6.53e-03	1.86e-03	2.14e-03
SFWt%I7	1.023e-06	6.826e-03	3.687e-03	2.873e-02	6.41e-06	0.00e+00	7.75e-08	0.00e+00	3.48e-07	0.00e+00	3.24e-07	2.87e-02	5.19e-03	1.04e-03	2.29e-03	6.53e-03	1.86e-03	2.14e-03
SFWt%I2	7.838e-07	6.332e-03	5.027e-03	1.304e-02	0.00e+00	0.00e+00	5.68e-07	1.77e-06	8.26e-07	2.27e-07	2.10e-06	1.80e-03	5.19e-03	4.16e-03	1.15e-02	6.53e-03	1.30e-02	2.14e-03
SFWt%I1	7.633e-07	7.893e-03	6.537e-03	1.306e-02	0.00e+00	0.00e+00	6.02e-07	1.88e-06	6.24e-07	1.72e-07	2.06e-06	1.80e-03	5.19e-03	1.15e-02	1.15e-02	1.31e-02	3.73e-03	8.58e-03
SFWt%I3	6.962e-07	5.703e-03	4.411e-03	1.257e-02	2.49e-06	0.00e+00	1.22e-07	4.18e-07	5.16e-07	6.64e-08	1.26e-06	1.26e-02	5.19e-03	1.04e-03	2.29e-03	6.53e-03	3.73e-03	8.58e-03
TempGrBI	6.230e-07	1.789e-02	4.422e-03	1.062e-01	1.46e-06	0.00e+00	1.13e-07	0.00e+00	0.00e+00	2.19e-06	5.98e-07	1.80e-03	5.19e-03	1.04e-03	2.29e-03	6.53e-03	1.06e-01	2.14e-03
SFWt%I6	5.317e-07	4.766e-03	4.034e-03	8.977e-03	1.73e-06	0.00e+00	5.84e-08	0.00e+00	3.29e-07	8.26e-08	1.52e-06	8.98e-03	5.19e-03	2.08e-03	2.29e-03	6.53e-03	1.86e-03	6.43e-03
SFWt%I5	4.526e-07	4.311e-03	3.448e-03	8.977e-03	1.61e-06	0.00e+00	4.41e-08	0.00e+00	0.00e+00	6.70e-08	1.45e-06	8.98e-03	5.19e-03	1.04e-03	2.29e-03	6.53e-03	1.86e-03	4.29e-03
MPrm_CHv	3.056e-07	7.332e-03	4.140e-03	2.076e-02	0.00e+00	1.11e-06	0.00e+00	0.00e+00	0.00e+00	1.03e-06	0.00e+00	1.80e-03	2.08e-02	1.04e-03	2.29e-03	6.53e-03	1.68e-02	2.14e-03
MKDCHvSe	1.783e-07	2.978e-03	2.480e-03	6.528e-03	0.00e+00	0.00e+00	0.00e+00	0.00e+00	1.25e-06	0.00e+00	0.00e+00	1.80e-03	5.19e-03	1.04e-03	2.29e-03	6.53e-03	1.86e-03	2.14e-03
FOCTR	1.686e-07	6.439e-03	3.617e-03	2.609e-02	3.95e-07	0.00e+00	2.27e-07	0.00e+00	0.00e+00	5.58e-07	0.00e+00	1.80e-03	5.19e-03	1.04e-03	2.29e-03	6.53e-03	2.61e-02	2.14e-03
CritRHAC	1.548e-07	1.393e-01	6.050e-03	9.558e-01	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00	1.08e-06	0.00e+00	1.80e-03	5.19e-03	1.04e-03	2.29e-03	6.53e-03	9.56e-01	2.14e-03
FOC-R	1.115e-08	3.127e-03	2.738e-03	6.529e-03	7.81e-08	0.00e+00	1.45e-11	0.00e+00	0.00e+00	0.00e+00	0.00e+00	1.80e-03	5.19e-03	2.08e-03	2.29e-03	6.53e-03	1.86e-03	2.14e-03
FOCTR-R	3.631e-09	2.979e-03	2.481e-03	6.529e-03	2.53e-08	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00	1.37e-10	1.80e-03	5.19e-03	1.04e-03	2.29e-03	6.53e-03	1.86e-03	2.14e-03

Table E-3. Differential analysis results for the faulting scenario for a time period of interest of 10,000 yr

10,000-yr, Faulting, Random4 Values Increased by 1%	dD/dx	Sigma	X bar	Mean Dose	dD/dx*sigma	S
SFWT%F0	5.09e-04	2.89e-01	2.66e-01	4.34e-04	0.0001471003	0.3124591
FEROI-Tn	-1.16e-07	2.86e+03	7.14e+03	4.34e-04	0.0003312564	1.9061315
WPFD-ThD	0.00e+00	1.12e-01	1.00e-01	4.34e-04	0	0
FEROI-X	0.00e+00	3.47e+03	5.48e+05	4.34e-04	0	0
FEROI-Y	0.00e+00	8.20e+03	4.08e+06	4.34e-04	0	0
FO-Rn#Sd	0.00e+00	2.89e-01	6.56e-01	4.34e-04	0	0
NWFZnW	0.00e+00	1.74e+01	2.50e+01	4.34e-04	0	0
NEFZnW	-6.24e-07	2.32e+01	1.46e+01	4.34e-04	0.0000144944	0.0209178
NWLCDAmt	0.00e+00	1.00e-01	2.03e-01	4.34e-04	0	0
NELCDAmt	0.00e+00	1.00e-01	1.64e-01	4.34e-04	0	0

Table E-4. Differential analysis results for the faulting scenario for a time period of interest of 50,000 yr

50,000-yr, Faulting, Random4 Values Increased by 1%	dD/dx	Sigma	X bar	Mean Dose	dD/dx*sigma	S
NELCDAmt	0.00e+00	1.00e-01	1.64e-01	4.34e-04	0	0
NEFZnW	-6.87e-08	2.32e+01	1.46e+01	4.34e-04	0.0000015956	0.0023027
NWLCDAmt	0.00e+00	1.00e-01	2.03e-01	4.34e-04	0	0
NWFZnW	0.00e+00	1.74e+01	2.50e+01	4.34e-04	0	0
FO-Rn#Sd	0.00e+00	2.89e-01	6.56e-01	4.34e-04	0	0
SFWt%F0	1.50e-05	2.89e-01	2.66e-01	4.34e-04	0.0000043366	0.0092115
WPFD-ThD	0.00e+00	1.12e-01	1.00e-01	4.34e-04	0	0
FEROI-Tn	0.00e+00	2.86e+03	7.14e+03	4.34e-04	0	0
FEROI-X	0.00e+00	3.47e+03	5.48e+05	4.34e-04	0	0
FEROI-Y	0.00e+00	8.20e+03	4.08e+06	4.34e-04	0	0

Table E-5. Differential analysis results for the igneous activities scenario for a time period of interest of 10,000 yr

Parameter	Arith. Mean of Sigma Weighted Values	S - Arith. Mean	S - Geom. Mean	S - High Value	R1 - Sigma	R2 - Sigma	R3 - Sigma	R4 - Sigma	R5 - Sigma	R6 - Sigma	R7 - Sigma	R1 - S	R2 - S	R3 - S	R4 - S	R5 - S	R6 - S	R7 - S
Base Value Peak Total Effective Dose Equivalent(rem/yr)*					2.35e-01	1.51e+00	1.89e+00	9.34e-01	5.90e-02	2.28e+00	2.12e+00	2.35e-01	1.51e+00	1.89e+00	9.34e-01	5.90e-02	2.28e+00	2.12e+00
VE-Power	3.672e+00	8.051e-01	7.434e-01	1.328e+00	7.75e-02	1.55e+01	2.41e+00	1.23e+00	5.12e-02	2.30e+00	4.15e+00	7.88e-01	3.05e-01	9.16e-01	9.13e-01	7.94e-01	5.92e-01	1.33e+00
ABMLFVDC	2.835e+00	7.526e-01	5.856e-01	9.695e-01	6.02e-02	1.39e+01	2.22e+00	1.17e+00	7.37e-02	9.04e-01	1.53e+00	8.23e-01	8.36e-01	9.53e-01	9.70e-01	8.99e-01	7.32e-01	5.65e-02
VE-Durat	2.014e+00	6.285e-01	2.945e-01	9.695e-01	5.70e-01	0.00e+00	7.50e+00	4.70e+00	1.45e-02	1.31e+00	8.16e-03	8.14e-01	6.63e-03	9.43e-01	9.70e-01	8.95e-01	7.10e-01	6.12e-02
VEROI-Tn	1.300e+00	5.050e-01	4.627e-01	8.700e-01	4.06e-02	2.29e+00	6.66e-01	2.10e-01	1.32e-02	4.31e-01	5.45e+00	5.03e-01	8.18e-01	3.32e-01	3.24e-01	3.24e-01	3.64e-01	8.70e-01
VC-Dia	7.689e-01	2.026e+00	2.026e+00	2.071e+00	1.02e-01	1.34e+00	1.14e+00	8.29e-01	4.18e-02	9.63e-01	9.64e-01	2.00e+00	2.02e+00	2.07e+00	1.99e+00	2.04e+00	2.03e+00	2.03e+00
WindSpd	6.267e-01	4.548e-01	2.324e-01	1.930e+00	3.11e-01	1.82e+00	3.90e-01	2.90e-01	6.95e-02	1.14e+00	3.66e-01	3.11e-01	1.93e+00	1.06e-01	1.17e-01	5.94e-02	4.91e-01	1.69e-01
AshMnPLD	2.306e-01	1.546e-01	1.137e-01	4.841e-01	2.26e-02	5.83e-01	1.06e-01	4.59e-02	9.68e-03	3.02e-01	5.45e-01	1.15e-01	4.84e-01	6.89e-02	3.32e-02	9.84e-02	1.23e-01	1.60e-01
VD-Angle	0.000e+00	4.007e-03	3.432e-03	6.632e-03	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00	4.26e-03	6.63e-03	5.30e-03	1.07e-03	1.70e-03	4.38e-03	4.71e-03
VD-Lengt	0.000e+00	4.007e-03	3.432e-03	6.632e-03	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00	4.26e-03	6.63e-03	5.30e-03	1.07e-03	1.70e-03	4.38e-03	4.71e-03
SFWT%V0	0.000e+00	4.007e-03	3.432e-03	6.632e-03	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00	4.26e-03	6.63e-03	5.30e-03	1.07e-03	1.70e-03	4.38e-03	4.71e-03
VD-Width	0.000e+00	4.007e-03	3.432e-03	6.632e-03	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00	0.00e+00	4.26e-03	6.63e-03	5.30e-03	1.07e-03	1.70e-03	4.38e-03	4.71e-03

*Conditional results not weighted by the scenario probability.

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R.B. Codell, M.R. Byrne, T.J. McCartin *
S. Mohanty, J. Weldy, M. Jarzemba, G.W. Wittmeyer **
Y. Lu ***
R.W. Rice ****

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** Center for Nuclear Waste Regulatory Analyses, 6220 Culebra Road, San Antonio, Texas 78238-5166
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**** Independent Consultant, 307 Quincy, El Paso, Texas 79922

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11. ABSTRACT *(200 words or less)*

The total-system performance assessment (TPA) computer code was developed to assist the U.S. Nuclear Regulatory Commission (NRC) staff in evaluating the safety case for the proposed geologic repository at Yucca Mountain, Nevada. This report primarily presents: (i) the system- and component-level (intermediate) results using the U.S. Department of Energy (DOE) Viability Assessment data in TPA computer code Versions 3.2 and 3.2.3 to demonstrate trends and variabilities in outputs;
(ii) the results of system-level sensitivity and uncertainty analyses using a variety of analysis techniques to determine the parameters that have the most influence on repository performance; and (iii) the relative importance of the integrated subissues in reviewing the DOE total-system performance assessment. An influential parameter is one that either drives uncertainty in performance, or one to which performance is sensitive. Results of system-level analyses are based on peak dose and peak expected dose to a receptor group. The influential parameters were compared to the current integrated subissues, which are used by NRC to focus work on items important to repository performance. In spite of simplifying assumptions, this study helped focus staff attention on phenomena most likely to be important relative to repository performance and point out deficiencies in the current state of knowledge.

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