IMPORTANCE MEASURES FOR NUCLEAR WASTE REPOSITORIES

Prepared by

Norman A. Eisenberg
U.S. Nuclear Regulatory Commission
Washington, DC 20555

Budhi Sagar
Center for Nuclear Waste Regulatory Analyses
San Antonio, Texas 78238-5166

June 1998

ABSTRACT

Several importance measures are identified for possible use in the performance assessment of a high-level nuclear waste repository. These importance measures are based on concepts of importance used in system reliability analysis, but the concepts are modified and adapted to the special characteristics of the repository and similar passive systems. In particular, the importance measures proposed here are intended to be more suitable to systems comprised of components whose behavior is most easily and naturally represented as continuous, rather than binary. These importance measures appear to be able to evaluate systems comprised of both continuous-behavior and binary-behavior components. Three separate examples are provided to illustrate the concepts and behavior of these importance measures. The first example demonstrates various formulations for the importance measures and their implementation for a simple radiation safety system comprised of a radiation source and three shields. The second example demonstrates use of these importance measures for a system comprised of components modeled with binary behavior and components modeled with continuous behavior. The third example investigates the use of these importance measures for a proposed repository system, using a total system model and code currently under development. Currently, these concepts and formulations of importance are undergoing further evaluation for a repository system to determine to what degree they provide useful insights and to determine which formulations are most useful.

CONTENTS

FIGURES

Figure | Page

TABLES

ACKNOWLEDGMENTS

This report was prepared to document work performed by the Center for Nuclear Waste Regulatory Analyses (CNWRA) for the Nuclear Regulatory Commission (NRC) under Contract No. NRC-02-97-009. The activities reported here were performed on behalf of the NRC Office of Nuclear Material Safety and Safeguards (NMSS), Division of Waste Management (DWM). The report is an independent product of the CNWRA and does not necessarily reflect the views or regulatory position of the NRC.

The authors gratefully acknowledge the substantial technical comment on this paper from Nathan O. Siu and Lee Abramson, as well as the continuing support and encouragement for this activity from Margaret V. Federline. Thanks are also due to Ronald W. Janetzke for his help in implementing importance analysis in the Total-system Performance Assessment (TPA) code and developing the results presented in section 4.3 of this report. Reviews by Timothy J. McCartin and Wesley C. Patrick helped to improve the report significantly.

QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: No CNWRA-generated original data is contained in this report.

ANALYSES AND CODES: The TPA Version 3.1.4-I computer code (an experimental extension of the controlled Version 3.1.4) was used for analyses contained in this report. The TPA Version 3.1.4-I code is not controlled under the CNWRA Software Configuration Procedures.

1 INTRODUCTION

For passive systems, such as a nuclear waste repository, it is desirable to have importance measures for application in guiding site characterization, engineering design, and licensing of such facilities. Importance measures derived from system reliability concepts appear to have limitations for such passive systems. Thus, a set of importance measures, extending conventional concepts, but more suited to a repository system, is proposed.

In system reliability literature (Andrews and Moss, 1993; Siu and Kelly, 1997), importance measures are quantities that indicate the contribution each component, cut set, or basic event makes to causing the top event. These importance measures and the associated reliability analyses are frequently implemented using set theoretic and Boolean algebraic methods to describe systems and their constituent components, which are modelled as exhibiting largely binary behavior. Many components in a variety of physical systems (electrical, fluid, mechanical) may exhibit largely binary behavior and may be modeled that way with some degree of accuracy. Some examples include: (i) a fuse, which may conduct electricity or fail to conduct, depending upon whether it has been blown; (ii) a relay, which may latch and make connections when energized or which may fail to make connections; (iii) an actuated valve, which opens on command or fails and stays closed; and (iv) a pipe, which carries fluid under pressure between two components (say a pump and tank) or which breaks and allows fluid to escape and the pressure to fall. These components, modeled as possessing binary behavior, are considered to have two states (hence, binary) which may be designated as: (i) operating and failed, (ii) open and shut, and (iii) on and off. In any case, the state of the component is represented as a Boolean algebra variable that can take on a value of either 1 or 0. Some components may be modeled as binary, when, in fact, their behavior is not quite binary. For example, a relay when energized may latch, but the connection made is too weak or resistive to power downstream components. In such a case, the relay would be modeled as having failed, even though it worked in part. The response of a component can be discretized into more than two states, to extend the applicability of traditional reliability analyses, but such a discussion is beyond the scope of this paper.

Applications of conventional importance measures, coupled with the use of fault and event trees, to a geologic repository for disposal of radioactive wastes have met with limited success because of the following factors (a repository and a nuclear reactor are used as examples of different system types): (i) a repository system is comprised of subsystems or components that behave in a largely continuous manner, rather than in a discrete or binary fashion, which is typical of reactor components; (ii) the components and subsystems in the repository are passive; the reactor has many active, redundant safety systems; (iii) the repository system is physically large (it spans several square kilometers), dispersed, and comprised of many similar components, which may be in different states depending on their location; the reactor is a smaller and relatively more coherent system; (iv) the repository has the potential to cause doses that vary continuously in time, space, and with parameters describing performance; the reactor may cause a top event, such as core damage or large early releases (a surrogate for early fatalities), at a given frequency; and (v) because the mission time of the repository (10^3 - 10^6 yr) is of the same time scale as the development of consequences, multiple events are likely to occur; for the reactor, the mission time (decades) is long compared to the development time of consequences (hours to days). Because of these implementation problems (i.e., differences arising from the use of fault and event trees) and because of difficulties with the fundamental concepts underlying conventional importance measures (i.e, differences arising from definitions related to the probability of failure for systems or components when failure for the repository system and components is not well defined) a set of importance measures more directly applicable to the repository or to other systems with passive, continuous components has been developed. Continuous components do not have binary or discrete states, but operate over a range of performance that yields an essentially continuous range of system performance.

2 FUNDAMENTAL CONCEPT FOR IMPORTANCE MEASURES

Fundamentally, the importance of a system component is the contribution that this component makes to the system successfully performing its assigned or designed function(s). The assigned function of a repository is to isolate nuclear waste in a manner that limits exposure to radiation in the human environment. The function of a system is represented by one or more performance measures, y, (treated for now as a deterministic, scalar variable) with an associated goal or regulatory limit, y_G. Examples of repository performance measures include individual dose and the normalized cumulative release of radionuclides over 10,000 yr summed over all radionuclides. The importance of a component of the repository system then can be simply defined as its contribution to constraining such a performance measure.

An intuitive way to obtain the contribution of a repository component is to "remove" the component (or neutralize its functions) from the system and determine how the repository system functions without it. In addition to the heuristic appeal of this approach, it is suggested by the definition of various conventional importance measures. In particular, the risk achievement worth importance measure compares frequency of system unavailability, given that the frequency of unavailability of component u is set to unity, to the unconditional frequency of system unavailability (Sherry, 1996). In a very broad sense, setting the failure frequency of component u to unity, forces the component u to fail and essentially neutralizes any contribution it could make to system safety. In contrast, consider a simple, passive system in which two shields operating in series reduce the dose from a radioactive source to a receptor to an acceptable level. The hypothetical dose received by the receptor when each shield is removed from the system in turn, is an indication of how important that particular shield is in achieving the performance of the system, (i.e., dose at an acceptable level). Note that for the types of systems with continuous behavior considered here, the presence or functioning of all components does not assure that no consequence will occur, as it does in standard reliability analyses. Instead, there is merely better or worse performance on a continuous scale. We have adopted the premise that removing or neutralizing the function of a component from the system fundamentally represents system behavior modified by removing that component, denoted by $_{-u}y$, and comparison of this modified system behavior to the nominal behavior of the system, denoted by $_{s}y$, provides a measure of the importance of the component. We have adopted the convention "$-u$" to visually indicate that the component functions are to be neutralized.

To remove or neutralize a component in this context means that the functions normally performed by that component are no longer performed. However, it doesn't mean that the component is physically removed, since physical removal may cause conceptual difficulties in modeling the system. Also, the component functions that are to be neutralized are the functions that are included in the system model. In this sense, the estimated importance is dependent on the model used for evaluating system performance and, as is the usual case in system analysis, the value of an analysis depends upon how well the essential features of the system are represented by the system model. One aspect of implementing this approach is that consideration of removal of a component may force the investigator to reformulate the original system model. For many types of physical systems, a system-theoretic approach based on pairs of through and across variables has been successful in generalized analyses of system behavior (Shearer et al., 1971). The system theoretic approach considers systems comprised of components connected to each other through a set of connection points or nodes. Various components may share nodes, thereby producing a "circuit" or "network" of interconnected components. The system is connected to the rest of the world through a few special nodes designated as input or output nodes. In general, the components are connected in series or parallel collections. In a very basic sense, one may view these dynamical systems as falling into one of two classes: (i) dynamical systems in which a single variable can account for the interactions of various components and (ii) dynamical systems in which a pair of complementary variables (usually designated as through and across variables) must be used to describe the interactions of the various components. Systems constructed using operational amplifiers, which have very low internal impedances, are a classic example of systems of the first type. The components attached to the operational amplifiers have relatively high impedances, so the voltage variation at the output of the amplifier does not depend on the dynamic load it "sees"; instead the voltage variation at the output of the amplifier depends only on the voltage applied to its input and the amplifier gain. Very complicated circuits comprised of resistors, capacitors, and inductors may be analyzed by looking at how each component transforms the dynamic voltage applied to it. This leads to the classic treatment of dynamical systems using transfer functions. For a simple system of this type in which several components are connected in series, it is easy to conceptualize what "removal" of a component means. It means that if in the unmodified system, component n+1 (the intervening component) connects component n (the "upstream" component) and component n+2 (the "downstream" component), then in the modified system component n is connected directly to component n+2. In other words, whatever modification component n+1 might have made to the voltage, that modification ceases and the signal (voltage) from component n passes directly to component n+2. For systems in which a pair of variables must be tracked to determine overall system dynamics, the situation is not as simple. In these cases, because a substantial current (or equivalent flux) may be drawn, the modification of a component "downstream" from another component, may affect the voltage (or equivalent potential) produced by the "upstream" component. In these cases, removal of an intervening component essentially means that the components immediately upstream and downstream are connected directly to each other. In this context, subsystems and components may be described by a transformation matrix. In the context of importance analysis, removal of the component is defined as setting the transformation matrix for the appropriate potentials and fluxes equal to the identity matrix.

We will consider systems whose performance measure, y, is positive and increases with poorer performance and whose regulatory standards limit the magnitude of y; a good example of this is radiation dose. Although the following formulation is based on these assumptions about the performance measure, the concepts are easily extended to more general behavior of the performance measure. A complication not treated here is that for the repository system many components change gradually over time. In general the performance, ${}_{s}y$, is calculated through models, not physically measured, because of the long time of performance. Several options for defining a measure of importance were considered and four that appear to be useful are:

$$ {}_{-u}i_1 = {}_{-u}y / {}_{s}y \tag{2-1}$$

provided ${}_{s}y$ is not equal to zero (i.e, the nominal system does not produce zero performance measure or consequence).

$$ {}_{-u}i_2 = \left({}_{-u}y - {}_{s}y\right) / {}_{s}y \tag{2-2}$$

again provided ${}_{s}y$ is nonzero.

$$ {}_{-u}i_3 = {}_{-u}y / y_G \tag{2-3}$$

where y_G is a nonzero safety limit for y.

$$ {}_{-u}i_4 = \left({}_{-u}y - y_G\right) / y_G \tag{2-4}$$

again provided y_G is nonzero.

9/40

We have chosen measures of importance that are dimensionless, so the value of importance does not depend on the units used to quantify the performance. For the systems of interest here, because of the possibility of nonlinear interactions and of multiple scenarios (discussed in the following), the "removal" of a component may not always result in worse performance. That is, if a component makes a positive contribution to the system performance, then ${}_{-u}y > {}_{s}y$; otherwise ${}_{-u}y < {}_{s}y$. Note that because of the way redundant systems are designed and because of the way fault trees are constructed, the failure of a component in traditional reliability analysis will generally result in a higher overall failure rate (or unavailability) for the entire system, albeit slight. For the repository system, the situation may be different in at least four ways. First, some of the repository components are natural, not engineered; consequently, there is no guarantee that each repository component will enhance performance. Even though a repository site, including the proposed Yucca Mountain site, may be chosen for its desirable physical, chemical, and geological characteristics, this does not mean that every component or subsystem of the site must enhance performance. Site selection is inherently a matter of compromise, so it appears entirely reasonable, if not expected, that some aspects of site performance, as exemplified by the contribution of a particular component to overall repository performance, would not be positive. Second, the repository operates under a variety of scenarios which may change the nature of how various components contribute to overall performance. For example, a component may greatly aid performance in a nominal scenario, where the receptors receive a dose from groundwater transport of radionuclides, but be of little help in a disruptive scenario, such as volcanism. Thus, a saturated zone transport leg with substantial sorption (say both for fractures and matrix) may have significant importance in the nominal scenario, but will have essentially no influence on performance in the volcanism scenario. Alternatively, a waste package constructed of a high-temperature alloy may be an important contributor to performance in the volcanism scenario, but, because the alloy is easily corroded by the conditions found in the repository, may have little contribution to performance in the nominal case. Third, the conditions in the repository are not spatially homogeneous. Hydrologic, geochemical, thermal, and rock mechanics conditions vary from one location to another in the repository. Engineered components are usually designed for some reference environment. To the extent that conditions depart from the nominal design requirements, the components may not behave in the intended fashion and have the possibility to adversely affect performance locally. If these adverse affects are large or widespread, then that particular component may be found to have a negative importance. Fourth, the subsystems of the repository are, in general, nonlinear and interact with each other in a nonlinear fashion. Because of this possibility for nonlinear behavior, engineered components chosen to enhance performance on a subsystem basis or natural components thought to enhance performance on a subsystem basis, may prove to be a net negative for overall system performance.

If one takes the conceptual definition of the Birnbaum importance measure (Siu and Kelly, 1997) as the partial derivative of system failure frequency with respect to the failure frequency of component *u*, then one could theoretically calculate these frequencies from a Monte Carlo evaluation of repository performance. However, three problems remain: (i) for a good system, a top event defined as exceeding the regulatory limit may never occur, regardless of the condition of component *u*; thus the system failure frequency may always be zero; (ii) it is generally impossible to define a component "failure" for continuous components that exhibit better or worse, rather than "failed" performance; and (iii) an importance measure based on the probability of failure is unable to consider the extent of system improvement or degradation, which is an important aspect to be considered for continuous systems. In spite of these differences, there are similarities among the measures proposed and conventional performance measures (e.g., if the performance measure for the system is defined as its unavailability and removal of the component is considered equivalent to the failure of the component, then ${}_{-u}i_1$ reduces to the risk achievement worth importance measure for a system with components described by binary states).

3 IMPORTANCE MEASURES WITH VARIOUS UNCERTAINTY TYPES

In most cases of interest to the repository, the system is modeled as a probabilistic system. This means that the parameters of the system performance model are described as random variables. In addition, the external environment in which the repository system operates or conditions within the system may be described by a set of scenarios or event classes that have frequencies of occurrence assigned to them. Under either of such conditions, the performance of the system, *y*, (i.e., the consequence) becomes a random variable, as do the importance measures defined in terms of the performance measures, ${}_{-u}y$, ${}_{s}y$, and y_G. For comparison of relative importance, appropriate statistics derived from the probability distribution of I can be used, (e.g., mean, median, 90th percentile, etc.). Following the practice of many standard texts, we will use upper case to represent a random variable.

3.1 A SYSTEM WITH PARAMETER UNCERTAINTY

In general, the performance of the system depends upon a set of *K* input parameters or system variables, X_k, which are random variables described by appropriate probability distribution functions. Since, $Y = Y(X_k)$, then the various performance measures described above also become random variables:

$$ {}_{-u}I_1 = {}_{-u}Y / {}_{s}Y \tag{3.1-1}$$

$$ {}_{-u}I_2 = \left({}_{-u}Y - {}_{s}Y \right) / {}_{s}Y \tag{3.1-2}$$

$$ {}_{-u}I_3 = {}_{-u}Y / Y_G \tag{3.1-3}$$

$$ {}_{-u}I_4 = \left({}_{-u}Y - Y_G \right) / Y_G \tag{3.1-4}$$

There are many ways to evaluate these importance measures, which are now random variables, but two cases of note are to take the mean value. The mean values may be taken **before** the quotient is formed (e.g., ${}_{-u}I_1^b = E\{{}_{-u}Y\}/E\{{}_{s}Y\}$, where $E\{\ \}$ denotes the expectation value of the quantity in brackets and the superscript "*b*" denotes that the expectation is taken before forming the quotient). Another alternative is to take the expectation **after** the quotient is formed (e.g., ${}_{-u}I_1^a = E\{{}_{-u}Y/{}_{s}Y\}$, where the "a" superscript denotes the expectation is taken after forming the quotient). For repository systems, further experience in evaluating the behavior of these variations of the importance measures is needed before understanding which are most useful in a given situation. Since the performance of the system with and without a particular component is given as a random variable, concepts such as the central factor of safety and reliability index (Harr, 1987), which explicitly define safety margin probabilistically, may also be useful.

3.2 A SYSTEM WITH SCENARIO UNCERTAINTY

For those cases in which a discrete set of scenario or event classes are used to describe the external environment in which the repository system operates or conditions within the system, a frequency of occurrence or probability is assigned to each class. As with parameter uncertainty, the various performance and importance measures are represented as random variables; however, in this case, they are discrete. Thus, we have, for example,

$$ {}_{-u}I_{1j} = {}_{-u}Y_j / {}_{s}Y_j \tag{3.2-1} $$

where the subscript "j" represents the performance or importance measure associated with the jth scenario. In order to combine the importance measures for each scenario to obtain a measure for the overall system, we may take the expected value, either before or after the quotient is formed, just as for parameter uncertainty. For example, one may obtain the expectation value after the quotient is formed by summing the component importance for each scenario, weighting the individual importance by the scenario probability; i.e.,

$$ {}_{-u}I_1 = \sum_{j=1}^{J} \left({}_{-u}I_{1j}\right)\left(p_j\right) \tag{3.2-2} $$

where the p_j is the probability of the jth scenario. Extending the concept articulated previously that the performance difference obtained by removal of a component is a measure of its importance, the importance of a particular scenario class may be shown to be $I_j = -y_j p_j$, where I_j is the importance of scenario class j and y_j is the performance measure for scenario class j. The definition of importance measures using the concept of scenario classes permits obtaining importance measures for systems containing both binary and continuous components. This is illustrated by the example in section 4.2, in which importance measures are obtained for a system containing both types of components.

3.3 A GENERAL SYSTEM ALLOWING ALL TYPES OF UNCERTAINTY

The considerations discussed above for importance measures can be reformulated so that scenario and parameter uncertainty are treated simultaneously. Limiting cases would be to take both expectations either before or after forming the quotient; two additional mixed cases are also possible. The limiting cases are, where the notation is as before:

$$ {}_{-u}I_1^b = \sum_{j=1}^{J} p_j\, E\left[{}_{-u}Y_j\right] / \sum_{j=1}^{J} p_j\, E\left[{}_{s}Y_j\right] \tag{3.3-1} $$

where both expectations are taken before forming the quotient and,

$$ {}_{-u}I_1^a = \sum_{j=1}^{J} p_j\, E\left[{}_{-u}Y_j / {}_{s}Y_j\right] \tag{3.3-2} $$

where both expectations are taken after forming the quotient. For taking the expectation after forming the quotient, it is required that the denominator, ${}_{s}Y_{j}$, be nonzero. In addition, to apply the formulation of Eq. (3.3-2) it is required that the scenario probability not change when the component "u" is removed; for systems containing both binary and continuous components, the probability will, in general, change when a component exhibiting binary behavior is removed (e.g., see example in Section 4.2). Similar formulations result for importance defined in terms of the ratio of the difference, I_2, for importance normalized by the regulatory limit, I_3, and for different ordering of the expectation.

4 EXAMPLES

This section contains three examples of different systems illustrating the importance measures derived in section 3. Section 4.1 is an example of a simple radiation source and shields, illustrating the fundamental ideas developed in section 3 for systems and components modelled as exhibiting continuous behavior. Section 4.2 is an example of a system containing two types of components, those modelled as exhibiting binary behavior and one modelled as exhibiting continuous behavior; this example shows the feasibility of obtaining performance measures for both types of components. Section 4.3 is an example of a repository system modelled using modifications of the TPA 3.1.4 code. The purpose of this example is to show the feasibility of using these performance measures for the complex repository system; because the TPA code, its input values and distributions, and the modifications made to these to evaluate the feasibility of this type of importance analysis are all subject to further improvements and modifications, the results of this analysis only represent the importance of various components given current understanding (as reflected in the TPA code and its modification) and may change as new information is incorporated into the TPA code, including its input files.

4.1 A SIMPLE SHIELDING SYSTEM

Consider a simple passive system shown in figure 4.1-1 designed to provide shielding from a source of gamma radiation. Assume the following with respect to the system features, model, and parameters.

4.1.1 System Features

Container: self-shielding solid container with a removable lid at one end
Source Strength: 0.1 curie (3.7 GBq) of Cs-137
Lid: three layers, first layer is lead, and second and third layers are steel
Regulatory Limit on Radiation Dose (y_G): 0.02 mSv/hr

4.1.2 System Model

The radiation beam is attenuated as it passes through the three-layered lid. The attenuation is a function of the thickness, w, of each material in the lid and its linear absorption coefficient, a. The model for the dose rate from the system is,

$$ {}_s y = y_o \prod_{k=1}^{3} \exp\left(-a_k w_k\right) = y_o e^{-a_1 w_1} e^{-a_2 w_2} e^{-a_3 w_3} \tag{4.1.2-1} $$

where, y_0 is the dose rate exiting the container from the top. For a source of 3.7 GBq, y_0 is estimated to be 10.0 mSv/hr.

4.1.3 System Parameters (Deterministic Case)

Linear Absorption Coefficients: $a_1 = 1.066$, $a_2 = a_3 = 0.433$
Thickness: $w_1 = w_2 = w_3 = 5$cm

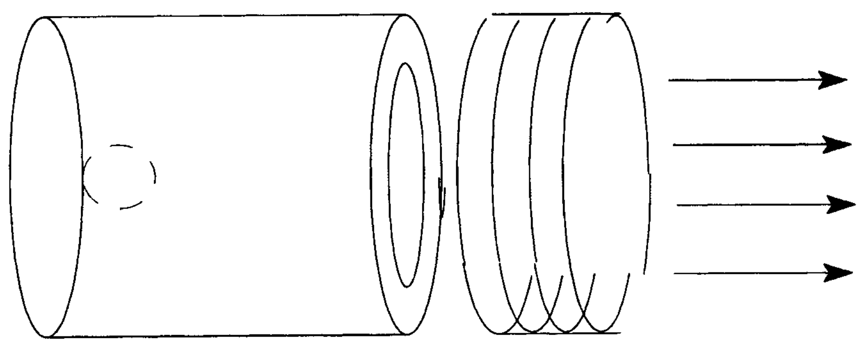

Figure 4.1-1. A passive shielding system

4.1.4 Sensitivity and Importance Analysis (Deterministic Case)

Using Eq. (4.1.2-1), ${}_sy = 6.37 \times 10^{-4}$ mSv/hr which is less than the regulatory limit of 0.02 mSv/hr; hence, the system meets the regulatory requirement.

Dimensionless sensitivity coefficients with respect to w_k can be calculated by differentiating Eq. (4.1.2-1) as,

$$\alpha_k = \frac{w_k \, \partial_s y}{{}_sy \, \partial w_k} = -a_k w_k \qquad (4.1.4\text{-}1)$$

The sensitivity coefficients are negative indicating that an increase in w_k will cause a decrease in ${}_sy$ and vice versa. Using the values of the system parameters, $\alpha_1 = -5.33$, $\alpha_2 = \alpha_3 = -2.165$, it can be determined that the dose is 2.46 times as sensitive to the thickness of the lead shielding layer than it is to the thickness of the steel shielding layer.

The values of importance measures can be obtained by first calculating doses when one of the layers is removed from the system. These doses are (in mSv/hr), ${}_{-1}y = 0.132$, ${}_{-2}y = {}_{-3}y = 5.559 \times 10^{-3}$. Values of the three importance measures defined earlier are shown in table 4.1.4-1.

Table 4.1.4-1. Values of importance measures for example 1

	${}_{-u}I_1$	${}_{-u}I_2$	${}_{-u}I_3$
$-u_1$	206.4	205.4	6.58
$-u_2$	8.72	7.72	0.28
$-u_3$	8.72	7.72	0.28

From table 4.1.4-1, it is clear that the relative importance of the lead shielding layer is about 25 times that of the steel shielding layer. This result is different from the sensitivity result which indicated the sensitivity of the lead shield thickness to be 2.46 times the sensitivity to steel shield thickness. It may be worthwhile to consider the implication of differences in these results. The sensitivity analysis indicates that for a unit change in the thickness of the lead layer, the dose will change by a factor of $-5.33(\alpha_1)$. If the model was linear with respect to w_1, removal of the entire thickness of the lead layer (5 cm) will increase the dose by a factor of 5.33x5=26.65. However, the model is not linear in w_1, and the sensitivity coefficient does not provide an accurate estimate of the effect of removing the entire thickness of the lead plate. The importance analysis provides an estimate of this effect; the removal of the lead plate will increase the dose by a factor of 206.4. Thus the information provided by both the sensitivity and importance analyses is useful but in different contexts.

4.1.5 System Parameters (Probabilistic Case)

For the probabilistic case, consider that the thicknesses of the shielding layers are uncertain and are described by normal probability distributions with means, $\mu_{w_1} = \mu_{w_2} = \mu_{w_3} = 0.5$ cm and standard deviations, $\sigma_{w_1} = \sigma_{w_2} = 5$ cm, and $\sigma_{w_3} = 1$ cm. The values of the linear absorption coefficients are taken as constants and are the same as in the deterministic case.

4.1.6 Sensitivity and Importance Analysis (Probabilistic Case)

Let $\lambda_k = a_k w_k$, $k = 1,2,3$. Because w_k is Gaussian and a_k is constant, λ_k is also Gaussian. The mean and standard deviation of λ_k can be easily obtained (e.g., see Benjamin and Cornell, 1970, p. 100) as, $\mu_{\lambda_1} = 5.33$, $\mu_{\lambda_2} = \mu_{\lambda_3} = 2.16$, and $\sigma_{\lambda_1} = 0.533$, $\sigma_{\lambda_2} = 0.216$, and $\sigma_{\lambda_3} = 0.658$. Since the system model in this example is simple, the sensitivity coefficients and importance measures can be derived as closed form equations. To do this, take the natural logarithm (natural logarithm is taken so that transformed variables will have lognormal probability distribution) of Eq. (4.1.2-1),

$$ln\ {}_s y = ln\ y_o - \sum_{k=1}^{3} \lambda_k = Z \qquad (4.1.6\text{-}1)$$

where Z is normally distributed and ${}_sY$ has a lognormal distribution (following our notation, the random variables are represented by capital letters). The mean and variance of Z and ${}_sY$ are given by (e.g., see Benjamin and Cornell, 1970, p. 264),

$$\mu_Z = ln\ y_o - \sum_{k=1}^{3} \mu_{\lambda_k} \qquad (4.1.6\text{-}2)$$

$$\sigma_z^2 = \sum_{k=1}^{3} \sigma^2{}_{\lambda_k} \qquad (4.1.6\text{-}3)$$

$$\mu_{sY} = \exp(\mu_z)\bullet\exp\left(\frac{1}{2}\sigma_z^2\right) \qquad (4.1.6\text{-}4)$$

and

$$\sigma_{sY}^2 = \mu_{sY}^2 \exp\left(\sigma_z^2 - 1\right) \qquad (4.1.6\text{-}5)$$

By substituting Eqs. (4.1.6-2) and (4.1.6-3) in Eqs. (4.1.6-4) and (4.1.6-5) and differentiating with respect to μ_{λ_k} or σ_{λ_k}, several sensitivity coefficients can be derived. In the following, the sensitivity coefficient is denoted by α with three subscripts. The first subscript represents the mean (m), standard deviation (d), or the probability (p) of dose; the second subscript denotes the same functions of the parameter, and the third subscript represents the parameter number. For example, differentiating the equation for expected value of ${}_sY$ with respect to expected value of λ_k one can write the sensitivity coefficient,

$$\alpha_{m,m,k} = \frac{\mu_{\lambda_k}}{\mu_{sY}} \frac{\partial \mu_{sY}}{\partial \mu_{\lambda_k}} = - \mu_{\lambda_k} \qquad (4.1.6\text{-}6)$$

where $\alpha_{m,m,k}$ is the sensitivity of the mean dose to the mean values of parameters of the kth layer. Thus, the expected value of dose is 2.47 times as sensitive to the parameters of the lead layer than it is to the same parameters of the steel layer. Similarly, one could get the sensitivity of the mean dose to the standard deviation of the parameters, i.e.,

$$\alpha_{m,s,k} = \frac{\sigma_{\lambda_k}}{\mu_{sY}} \frac{\partial \mu_{sY}}{\partial \sigma_{\lambda_k}} = \sigma^2{}_{\lambda_k} \qquad (4.1.6\text{-}7)$$

Other sensitivity coefficients can be similarly obtained, e.g.,

$$\alpha_{s,m,k} = \frac{\mu_{\lambda_k}}{\sigma_{sY}} \frac{\partial \sigma_{sY}}{\partial \mu_{\lambda_k}} = \frac{2\mu_{\lambda_k}}{\sigma_{sY} \sum_{k=1}^{3} \mu_{\lambda_k}} \qquad (4.1.6\text{-}8)$$

$$\alpha_{s,s,k} = \frac{\sigma_{\lambda_k}}{\sigma_{sY}} \frac{\partial \sigma_{sY}}{\partial \sigma_{\lambda_k}} = \frac{4\sigma_{\lambda_k}^2}{\sigma_{sY}} \qquad (4\text{-}1.6\text{-}9)$$

$$\alpha_{p,m,k} = \frac{\partial}{\partial \mu_{\lambda_k}} \left[P\left({}_sY > Y_G\right) \right] = -\int_0^{Y_G} \frac{f_{sY}(y)}{\sqrt{2\sum_{k=1}^{3} \sigma_{\lambda_k}}} dy \qquad (4.1.6\text{-}10)$$

and

$$\alpha_{p,s,k} = \frac{\partial}{\partial \sigma_{\lambda_k}} \left[P\left({}_sY > Y_G\right) \right] = \int_0^{Y_G} \frac{\sigma_{\lambda_k} f_{sY}(y)}{\sum_{k=1}^{3} \sigma_{\lambda_k}} \left[\frac{\mu_{\lambda_k}}{\sqrt{\sum_{k=1}^{3} \sigma_{\lambda_k}}} - 1 \right] dy \qquad (4.1.6\text{-}11)$$

The first four sensitivity coefficients described above are calculated for the example problem and shown in table 4.1.6-1 below.

Table 4.1.6-1. Sensitivity coefficients for example 1 (probabilistic case)

	With Respect to λ_1	With Respect to λ_2	With Respect to λ_3
$\alpha_{m,m,k}$	-5.33	-2.16	-2.16
$\alpha_{m,s,k}$	0.284	0.047	0.433
$\alpha_{s,m,k}$	1,607	653	653
$\alpha_{s,s,k}$	1,655	273	2,523

Note the relatively higher value of $\alpha_{m,s,3}$ (equal to 0.433) in table 4.1.6-1. It indicates that a small variation in the standard deviation of the thickness of the second steel layer (layer 3) causes a relatively greater change in the estimate of the expected value of the dose (e.g., compared to the thickness of the first steel plate-layer 2). The only difference between the two steel layers is that the standard deviation of the thickness of second steel layer (layer 3) is twice that of the first (layer 2). Thus, for this example, the greater the uncertainty in the thickness of the plate, the greater is the sensitivity of expected value of dose to this uncertainty.

To estimate the importance measures, the dose is estimated by removing each component in turn. These doses are shown in table 4.1.6-2.

Table 4.1.6-2. Estimated doses for example 1

	Mean Dose, μ_{sY} (mSv/hr)	Standard Deviation of Dose, σ_{sY} (mSv/hr)	$P({}_sY > Y_G)$
Nominal Case	8.73E-4	6.86E-4	1E-6
-Lead Layer, ${}_{-1}Y$	1.48E-1	1.01E-1	0.999
-First Steel Layer, ${}_{-2}Y$	7.04E-3	5.40E-3	0.0312
-Second Steel Layer, ${}_{-3}Y$	6.56E-3	4.69E-3	0.0139

The values of the three importance measures discussed in the previous section are calculated and presented in table 4.1.6-3.

Table 4.1.6-3. Values of importance measures for example 1. The values in parenthesis are normalized values.

	Importance Measure of Lead Layer , k = 1		**Importance Measure of First Steel Layer, k = 2**		**Importance Measure of Second Steel Layer, k = 3**	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
${}_{-k}I_1 = \frac{{}_{-k}Y}{{}_sY}$	169.51 (0.916)	147.46 (0.913)	8.06 (0.043)	7.87 (0.049)	7.51 (.041)	6.84 (0.038)
${}_{-k}I_2 = \frac{{}_{-k}Y - {}_sY}{{}_sY}$	168.51 (0.925)	146.46 (0.920)	7.06 (0.039)	6.87 (0.043)	6.51 (0.036)	5.84 (0.037)
${}_{-k}I_3 = \frac{{}_{-k}Y}{Y_G}$	7.402 (0.916)	NA	0.352 (0.043)	NA	0.329 (0.041)	NA

Note that the normalization is performed by dividing the importance measures by the sum of importance measures of the three layers. The first importance measure in table 4.1.6-3 can be interpreted as the increase in dose if one of the shielding layers did not perform its function (did not attenuate the radiation beam). Thus, if the lead layer was inoperative, the expected value of the dose will be 169.51 times the dose from the nominal system while if the first steel layer (layer 2) was inoperative, the expected value of the dose increases only by a factor of 8.06. Therefore, with respect to the mean dose, the lead layer is 21.58 times as important as the steel layer for the overall system. Note that even though the sensitivity of the expected value of dose to the standard deviation of the second steel layer was relatively larger (table 4.1.6-1), the same is not true of the importance measure. This is because the importance measure is based on the overall probability distribution of the parameters of the shielding layers and does not reflect the effect of unit changes in standard deviation as does the sensitivity coefficient.

Overall, the sensitivity coefficients and the importance measures provide useful but different information about the system. While the sensitivity coefficients are mostly representations of a variation in system performance due to a small (or unit) variation in the system parameter, the importance measures represent the variation in system performance if an entire system component did not function.

4.2 AN EXAMPLE OF A "MIXED" SYSTEM WITH BOTH ACTIVE AND PASSIVE COMPONENTS

A potential advantage of these importance measures is that they might be used for systems containing two types of components, those modelled as exhibiting binary behavior and those modelled as exhibiting continuous behavior, and yet provide information on the importance of these components, regardless of type. To explore this potential a simple example system is evaluated.

4.2.1 Description of the Example

Consider a system centered around a storage tank for some environmentally hazardous liquid material (see figure 4.2-1). For simplicity, assume that the degree of harm resulting from operation of this system is directly proportional to the amount of liquid released to the environment. Thus, the performance measure for the system is the volume of liquid released to the environment, R. The tank is filled periodically through a port on the bottom by pumping replacement liquid from a barge. The tank has, as a safety system, a dike around its base formed by an earthen berm. The tank also has a vent pipe at its top that allows air to escape while the tank is filling and air to enter when the tank is discharged in use. However the nature of the fluid (density and viscosity) and the diameter of this pipe are such that if the tank is overfilled only an inconsequential amount of fluid will exit through the vent pipe. Consequently the vent pipe is not considered in the safety analysis. The tank also has an electromechanical level indicator that signals the barge operator when the tank is 99.9 percent full; the operator is instructed to stop filling the tank, when the 99.9 percent full signal is received. As an additional safety measure the tank has a pressure relief valve (a bursting disk type), that will allow fluid to escape from the tank, if a preset pressure is exceeded. However, the escaping fluid runs into the dike. This operation is not very safety conscious, so the barge operator stays in the barge during the filling operation and awaits the signal from the electromechanical level indicator. The operator has no direct view of the tank and does not independently monitor the amount of fluid pumped. As a consequence, the barge operator may pump fluid into the tank causing an overflow into the dike or even a rupture of the tank, if the pressure relief valve does not work.

Further assume that the probability of failure of various components is as given in table 4.2.1-1.

Table 4.2.1-1. Probability of failure of components

Component	Probability of Failure on Demand
Electromechanical Level Indicator	0.01
Operator	0.1
Pressure Relief Valve	0.2

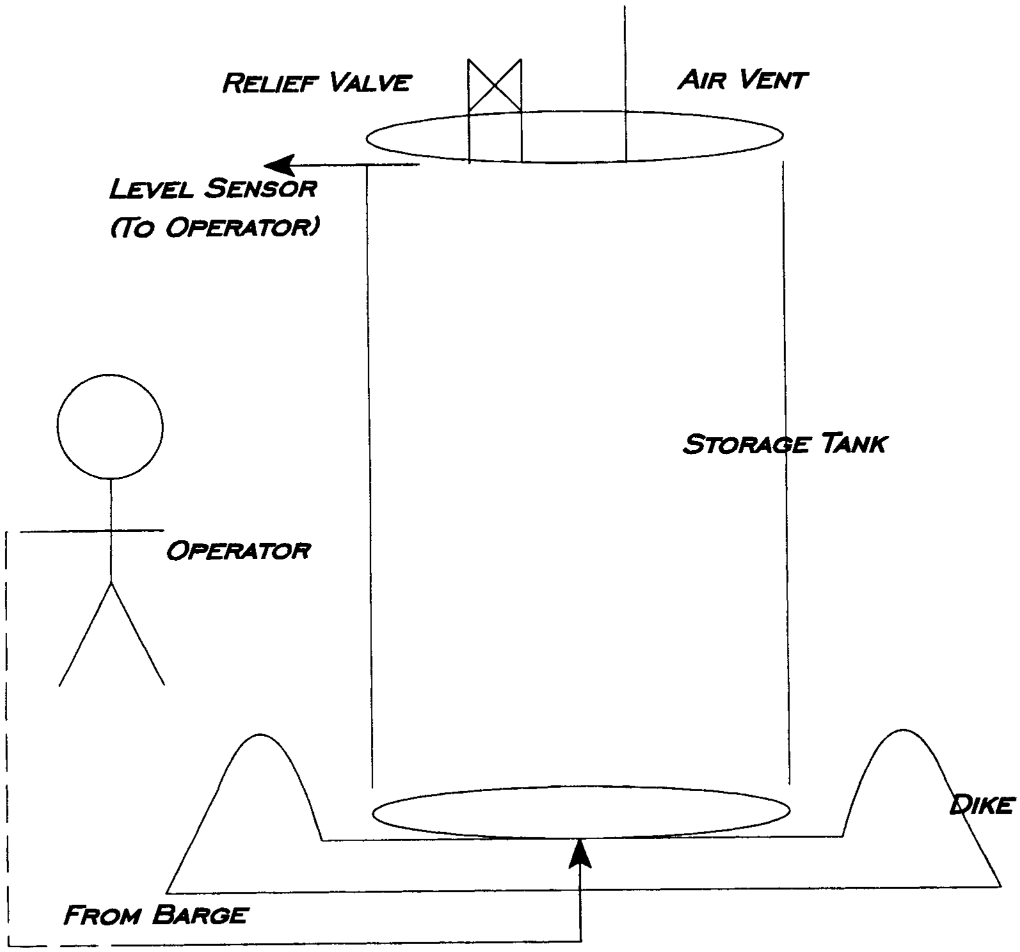

Figure 4.2-1. Example of a safety system using a tank to store an environmentally hazardous liquid, a dike, a pressure relief valve, and fill control (level sensor)

Suppose we are given that the volume capacity of the tank is 10,000 m^3, the volume capacity of the diked-in area at the base of the tank is 10,000 m^3, and the volume capacity of the barge is 20,000 m^3. It is assumed that the tank is always empty when the barge is called to fill it. It is further assumed that this tank is always the first stop on the voyage of the barge. For the case when the pumping is not terminated when the tank is full, if the tank stays intact, the barge will pump its entire contents of 20,000 m^3, but 10,000 m^3 will stay in the tank and 10,000 m^3 will be released to the dike; if the tank ruptures, the entire contents of the barge, 20,000 m^3, will be released to the dike, which would overflow.

Another aspect of the operation, that is not very safety conscious, is that the dike is allowed to fill up, to a varying degree, with rainwater. Since the refilling operation proceeds regardless of the condition of the dike, the varying degree of volume available to retain the liquid must be factored into the safety analysis. The release from the dike is assumed to depend on the nature of the release and the degree to which the dike is filled with rainwater. For a tank rupture, it is assumed that the momentum of the liquid released from the burst tank is sufficient to completely purge the dike of rainwater. Furthermore, 80 percent of the tank contents (8,000 m^3) are assumed released to the environment, while the remaining 20 percent (2,000 m^3) is retained by the dike. Since the pumps will continue even after the tank ruptures, another 10,000 m^3 of liquid will be released to the dike, of which the dike has capacity to retain 8,000 m^3. Thus a total of 10,000 m^3 will be released to the environment (8,000 m^3 from the initial rupture and 2,000 m^3 from continued pumping). Without tank rupture, the amount released to the dike is always 10,000 m^3. Assume that the dike is filled with varying amounts of rainwater, from 0 to 10,000 m^3 (full dike capacity) and that the amount is a random variable with a uniform distribution. Further assume that the product liquid always floats on the rainwater, so the amount released to the environment is given by:

$$R = 10{,}000\ \mathrm{m}^3 - V_{RD} \qquad (4.2.1\text{-}1)$$

where V_{RD} is the volume of rainwater in the dike, described by a uniform distribution from 0 to 10,000 m^3.

4.2.2 Analysis of the Example

Given that the system has been described as in the preceding section, the system behavior can be depicted using an event tree. Such an event tree is given in table 4.2.2-1.

Table 4.2.2-1. Event tree for the mixed system

Initiate Pumping	Pumping stops when tank is full	Pressure relief valve operates	Tank Status	Release to Dike
			no release	none
	Y, 0.891		release, no burst	10,000 m^3 - V_{RD}
	N, 0.109	Y, 0.8		
		N, 0.2	release, tank burst	10,000 m^3

The probability of the first branch of the event tree can be obtained from a simple fault tree. Assume that the electromechanical level indicator has a probability of failure on demand of 0.01. This means that the operator will get an accurate signal with a probability of .99. Assume that the barge operator fails to turn off the pump, given a signal to do so, with a probability of 0.1. This means that the total probability of failure to turn off the pump when the tank is full is .01 + (.99)(.1) = 0.109; the complement, 0.891 is the probability that the pump will be shut off when the tank is full. Assume that the pressure relief valve fails to operate on demand with a probability of 0.2. The combination of these events leads to three "tank states": (i) no overfill, (ii) overfill with release but no rupture, and (iii) overfill with rupture and release; the probabilities corresponding to these three states are respectively: (i) 0.891, (ii) 0.00872, and (iii) 0.00218. The release volume to the dike for these three cases is taken to be: (i) 0, (ii) 10,000 m^3, and (iii) 20,000 m^3.

Now consider the performance of the system and the importance measures that can be derived from the performance. For the system performance, ,*Y*, is given in table 4.2.2-2. In this and the tables that follow, the first column gives the scenario number, as discussed above.

Table 4.2.2-2. Performance measures for the mixed system

Scenario No.	Tank State	Probability	Release to Dike (m^3)	Release to Environment (m^3)	Expected Value of R (m^3)	p_i*$E(_{RI})$ (m^3)
1	No overfill	0.891	0	0	0	0
2	Release, no tank rupture	0.0872	10,000	10,000 -0 uniformly distributed	5,000	436
3	Release with tank rupture	0.0218	20,000	10,000	10,000	218
					Sum	654

Thus the denominator in Eq. (3.3-1) is 654 m^3.

Now consider removal of the various components in sequence. Removal of the indicator light will cause there to be always an overfill. The system response is given in table 4.2.2-3.

Table 4.2.2-3. Value of performance measure after removal of indicator light

Scenario No.	Tank State	Probability	Release to Dike (m^3)	Release to Environment (m^3)	Expected Value of R (m^3)	p_i*$E(_{RI})$ (m^3)
1	No overfill	0	0	0	0	0
2	Release, no tank rupture	.8	10,000	10,000 -0 m^3 uniformly distributed	5,000	4000
3	Release with tank rupture	.2	20,000	10,000	10,000	2000
					Sum	6000

The same result as indicated above is obtained for the case where the operator is removed (of course, after the fill has begun). Thus both the operator and level indicator will have the same importance measure.

If the pressure relief valve is removed (i.e., fails to perform its function), then the performance of the system will be as given in 4.2.2-4.

Table 4.2.2-4. Value of performance measure after removal of pressure value

Scenario No.	Tank State	Probability	Release to Dike (m^3)	Release to Environment (m^3)	Expected Value of R (m^3)	p_i*E($_{RI}$) (m^3)
1	No Overfill	0.891	0	0	0	0
2	Release, no tank rupture	0	10,000	10,000 -0 uniformly distributed	5,000	0
3	Release with tank rupture	0.109	20,000	10,000	10,000	1090
					Sum	1090

Finally, if the dike is removed from the system, then the performance of the system will be as given in table 4.2.2-5.

Table 4.2.2-5. Value of performance measure after removal of dike

Scenario No.	Tank State	Probability	Release to Dike (m^3)	Release to Environment (m^3)	Expected Value of R (m^3)	p_i*E($_{RI}$) (m^3)
1	No Overfill	0.891	0	0	0	0
2	Release, no tank rupture	0.0872	10,000	10,000	10,000	872
3	Release with tank rupture	0.0218	20,000	20,000	20,000	436
					Sum	1308

We can now form the importance measures (at least some of them) for this system (note that $\sum pjE[-sYj]=654$) as given in table 4.2.2-6.

Table 4.2.2-6. Value of importance measures for the mixed system

Component	$\sum p_j E[_{-u}Y_j]$	$_{-u}I_1^b$	$_{-u}I_2^b$
Level Indicator	6,000	9.17	8.17
Operator	6,000	9.17	8.17
Pressure Relief Valve	1,090	1.67	0.67
Dike	1,308	2	1
Total System, $\sum p_j E[_s Y_j]$	654	NA	NA

So what do these importance measures mean and why do they have the relationship to each other? The reason the $_{-u}I_1^b$ measure is 2 for the dike is because, on average, the releases to the environment from the system exactly double when the dike is removed. The reason the operator and level indicator have a value of about 9 for the same importance measure, is that with either of these "components" in a defected state, the probability of an overfill goes from 0.109 to 1. The value in the table is the reciprocal of 0.109. The importance of the pressure relief valve is determined by the combined changes in the probabilities of release with no tank rupture and release with tank rupture, combined with the average consequences of such events. What this example clearly shows is that by combining both consequences and probabilities to obtain the importance measures, the relative importance of continuous and binary components can be determined. Because the impacts of a particular component on probability, consequences, or both are considered in these importance measures, they can appropriately be considered "risk-based" importance measures.

4.3 AN EXAMPLE APPLICATION TO REPOSITORY PERFORMANCE

4.3.1 Implementation in the Total-system Performance Code

The approach for importance analysis described in the previous sections has been implemented in the NRC/CNWRA TPA Version 3.1.4 computer code. This computer code is designed for the analysis of performance of the total repository system and is currently being updated to Version 3.2. For testing computational feasibility, importance analysis was included in an experimental version of the code called Version 3.1.4-I. Implementation for only the base case (in the absence of disruptive scenarios) has been completed at this time. If found sufficiently promising, the modifications for disruptive scenarios will be completed and the entire set of changes will be incorporated in Version 3.2 and later versions. The results presented here are from a test example, are for illustration purposes only, and should not be construed either as final results or as an indicator of the performance of the proposed Yucca Mountain repository.

A few basic ground rules were followed in implementing importance analysis in the TPA code. One ground rule required that the conceptual models built into the TPA code not be modified in any way. That means that the original choice of components that the TPA team has selected for inclusion in the system code and the mathematical description of the functions of each component and their inter-relationships with other components is maintained. The *removal* or neutralization of a component for importance analysis is accomplished by turning off the functions of that component. The method of turning off the functions of a component was determined from the way that particular component is embedded in the overall structure of the code (see appendix A for a list of modified parameters.) Since the original plans for the code did not include importance analysis, the structure of the code is not necessarily optimal for implementing importance analysis. A more suitable code structure for importance analysis would be to identify up-front individual system components and construct a separate module for describing the functions of each component. In addition to facilitating certain types of importance analysis, such a modular structure would appear to be more consistent with current object-oriented approaches to code architecture. However, we followed another basic rule and that was that the basic structure of the code is not to be modified. Because of this the implementation of importance analysis may not always be transparent. However, the TPA Version 3.1.4-I code has been internally documented to easily identify the changes made for this implementation. For each component, a binary flag has been set in the main input file of the TPA code. A value of 0 for a component flag means the component is disabled (functions turned off) and a 1 means the component functions nominally. For turning off functions of some of the components, changes had to be made to several modules. The Software Requirements Document prepared for this code change is included in appendix B.

It is possible that after reviewing the results of an importance analysis, the TPA team may want to modify the original conceptual models to either include more functions of a component or even to reformulate the way the functions are mathematically represented. This is neither an unexpected nor an undesirable outcome of considering model results from another viewpoint. On the contrary, such insights into the role of various components enhance the overall understanding of the system and can improve the numerical models that represent it.

Importance analysis is implemented at the lowest level of a system, called the component in this report. A component is the smallest distinct physical part of a system that is assigned distinct function(s) in the system performance assessment model. Obviously, definition of system components and their functions is an integral part of building the conceptual model and is not unique. Results of importance analysis depend strongly on this conceptualization. In addition to estimating the importance of an individual component, one may also be interested in estimating the importance of a combination of components, for example, all the engineered components together. This is accomplished by setting the flags of all the components in the group to zero. In Version 3.1.4-I, a separate run of the code must be launched for each component or combination thereof. However, some thought has been given to automating this process and it may be implemented in a later version.

In reactor engineering and reliability engineering, more generally, importance measures of various types have been used for many years; those importance measures are routinely used for making decisions regarding maintenance, inspection, and design. In contrast, importance measures have been used very rarely, if at all, in evaluating repository performance. Therefore, any potential user of TPA Version 3.1.4-I should use the code and interpret its results with great caution. The authors believe that substantial insights may be gained through importance analysis. In particular, these importance measures may provide insight into the effectiveness with which a particular repository concept implements a multiple-barrier approach to safety. However, a few additional cautions regarding the use of the TPA Version 3.1.4-I are warranted. First, the value of the importance measure itself, although indicative of the degree to which the component influences performance, does not alone indicate the relative importance of various components. Second, the relative importance of a given component, compared to all other components, should always be evaluated and considered. Third, the absolute and relative importance of various components for different scenarios should also be considered, since those results give an indication of the degree to which the system has diversity, a desirable attribute for system safety.

4.3.2 Example Results

4.3.2.1 Importance of Components

For testing of TPA Version 3.1.4-I, the existing standard input file(s) are used without any modifications to the input data. It should be noted that the corrosion resistant inner container in these input file(s) is assumed to be alloy 625 and not alloy C-22, which is the material in the current reference case of the DOE. Also, note that the base case system does not include backfill and therefore backfill is not a component that we could *remove* from the system. For test purposes, only 50 Latin Hyper Cube parameter realizations were executed. This number of realizations is too small to give convergent results (200 or more will generally be required), but is sufficient for preliminary test results. The preliminary results are shown in figure 4.3.2-1. Because of the small number of realizations, the curves shown in figures 4.3.2-1 are not smooth and may change as larger numbers of realizations are used. Figure 4.3.2-1 shows complementary cumulative distribution functions (CCDFs) of individual dose to an average member of the critical group when different system components are *removed.* Because of the large number of curves, the display has been split into two figures (4.3.2-1a and 4.3.2-1b). The CCDF for the *nominal* system is shown in both the displays. Any curve falling to the right and/or above the nominal curve indicates positive contribution of that component, while curves to the left and/or under the nominal curve indicates negative contribution. The greater the distance between the individual curve and the nominal curve, the greater is the contribution of that component.

Table 4.3.2-1 and figure 4.3.2-2 summarize the results for the base case (without considering disruptive scenarios). The performance measure used in these calculations is the maximum (or peak) dose in 10,000 yr. The peak value is selected in each of the 50 realizations and statistics formed from these 50 values (note that the peaks in each realization occur at different times, so the mean peak dose does not represent dose at any particular time—this procedure is currently being modified in the TPA code). The mean, 95th percentile, median, standard deviation, and the probability of exceeding the regulatory limit (assumed to be 30 mrem for the mean value) are shown in the table. The difference between the dose calculated for the *nominal system* and the dose from the *system minus a component* can be viewed as the dose averted by that component (and hence a contribution to system performance). The reader is cautioned that with only 50 realizations, these results are very approximate, especially the results related to the probability of exceedance. From the last column of table 4.3.2-1 note that only four components lead to nonzero probability of system failure (i.e., exceeding the regulatory dose limit).

The importance measure ${}_{-u}I_2 = \left({}_{-u}Y - {}_{s}Y\right)/\,{}_{s}Y$ for various statistics is reported in table 4.3.2-2 and also shown in figure 4.3.2-3 The Risk Increase Interval (RII) in the last column of table 4.3.2-2 is estimated as, $P\left[{}_{-u}Y > Y_G\right] - P\left[{}_{s}Y > Y_G\right]$ which is the increase in the probability of system failure over the probability of the *nominal* system failing. The RII is a type of risk achievement worth which is an importance measure in analysis of nuclear reactors (Siu and Kelly, 1997).

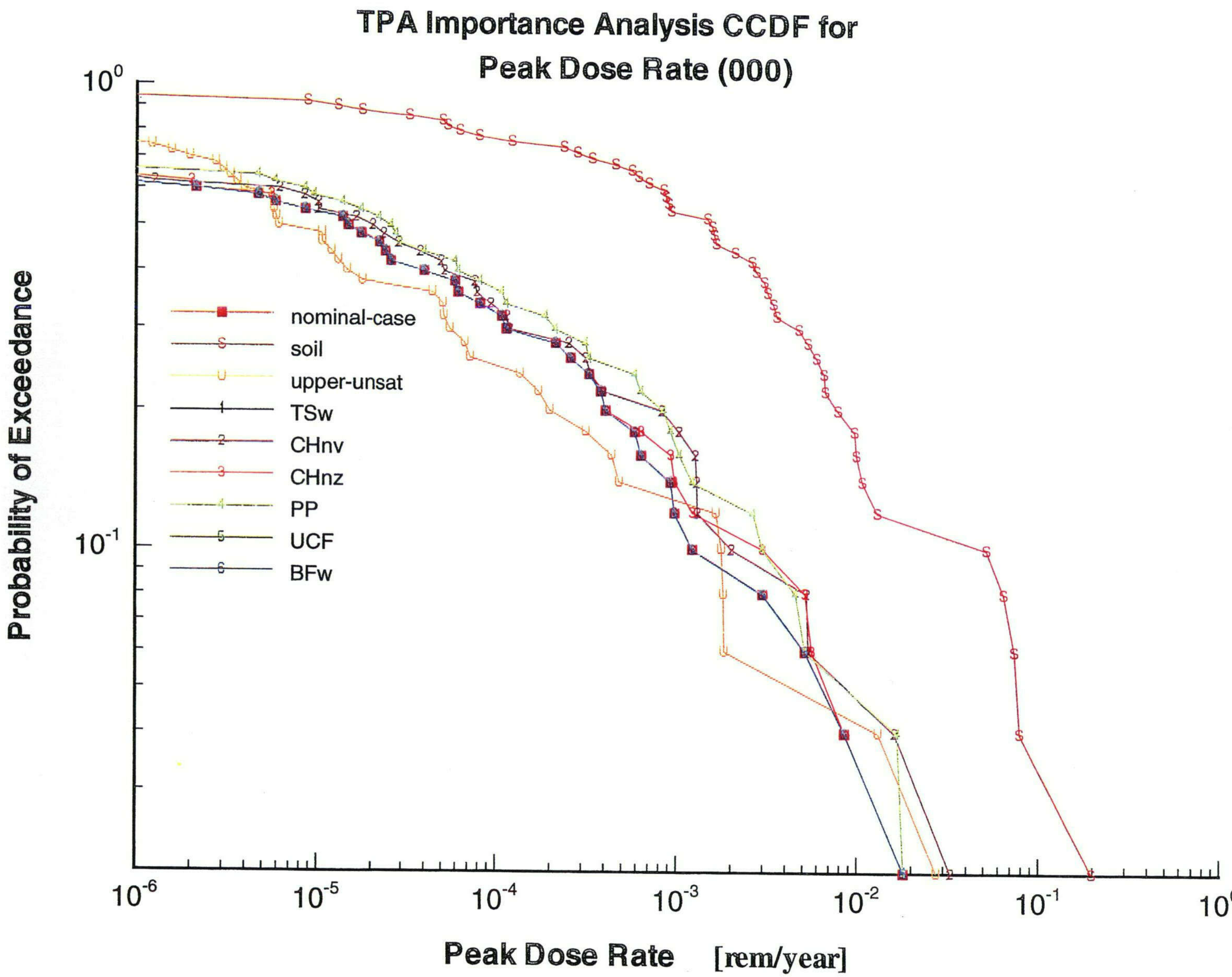

Figure 4.3.2-1(a). Complementary cumulative distribution functions for the performance of the nominal system and performance after turning off the functions of a component. The farther to the right a CCDF is relative to the CCDF of the nominal system, the greater is the importance of that component.

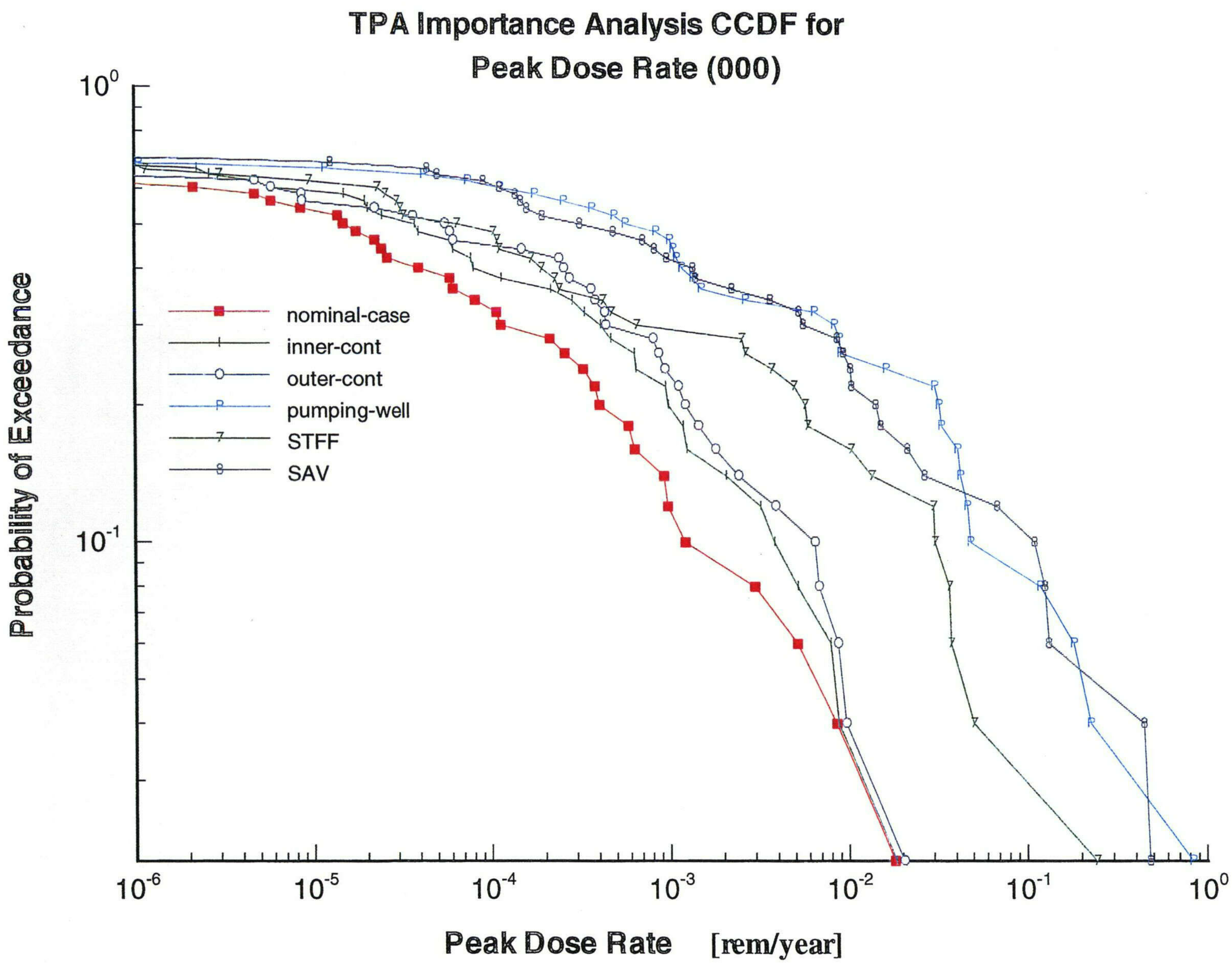

Figure 4.3.2-1(b). Complementary cumulative distribution functions for the performance of the nominal system and performance after turning off the functions of a component. The farther to the right a CCDF is relative to the CCDF of the nominal system, the greater is the importance of that component.

Table 4.3.2-1. Peak annual dose for nominal performance and dose after removing components (rem) - 50 latin hypercube realizations

	Expected Value	95th Percentile	Median	Std. Deviation	P[Y > 3E-2]
Nominal System	8.29E-4	5.18E-3	8.72E-6	8.71E-4	0.0
-Inner Container	1.15E-3	7.93E-3	3.11E-5	3.09E-3	0.0
-Outer Container	1.39E-3	8.76E-3	4.62E-5	3.49E-3	0.0
-Top Soil Layer	1.16E-2	7.37E-2	1.53E-3	3.2E-2	0.04
-Unsaturated Zone Above Rep	9.97E-4	1.84E-3	5.98E-6	4.22E-3	0.0
-Unsaturated Topopah Springs	8.29E-4	5.18E-3	1.43E-5	2.86E-3	0.0
-Unsaturated Calico Hills Vitric	1.39E-3	5.28E-3	1.83E-5	5.13E-3	0.0
-Unsaturated Calico Hills Zeolitic	9.30E-4	5.64E-3	1.43E-5	2.94E-3	0.0
-Unsaturated Prow Pass	1.15E-3	5.18E-3	1.43E-5	2.86E-3	0.0
-Unsaturated Upper Crater Flat	8.31E-4	5.18E-3	1.43E-5	2.86E-3	0.0
-Unsaturated Bull Frog	8.29E-4	5.18E-3	1.43E-5	2.86E-3	0.0
-Saturated Tuff	9.64E-3	3.78E-2	4.87E-5	3.52E-2	0.12
-Saturated Alluvium	3.02E-2	1.33E-1	2.57E-4	9.36E-2	0.12
-Pumping well	3.40E-2	1.83E-1	5.34E-4	1.22E-1	0.2

In calculating the importance measures of tables 4.3.2-2 and 4.3.2-4, the statistics of Y are taken before the importance measures are formed. For each individual realization, we could not form the ratio as $_sY$ was zero in some of the realizations. The pumping well is included as a component of the system because the dilution at the well head can be a major factor in calculating dose. Turning off the functions of the pumping well imply that this dilution does not occur, yet the critical group receives the same amount of water as in the nominal case. Effectively then, removal of the pumping well implies turning off the dilution.

The normalized $_{-u}I_2$ is shown in table 4.3.2-3 and figure 4.3.2-4. The normalization is done so that the importance measures add up to 100. For this normalization to be meaningful, all of the components should be at the same level, that is, combinations of components should not be in the list. This is a caution that should be used throughout in interpreting importance measures.

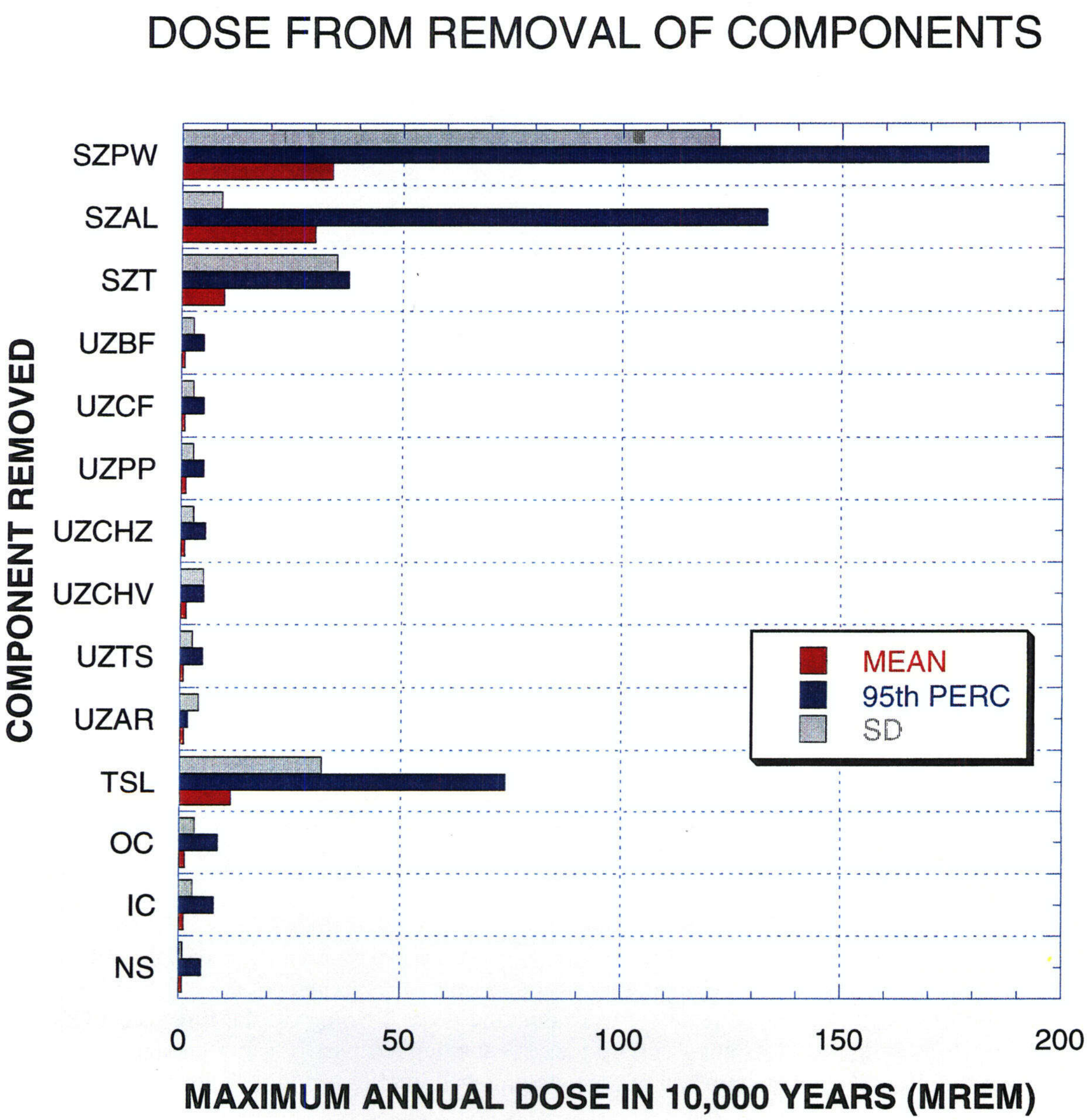

Figure 4.3.2-2. Summary of the statistic of the estimated annual individual dose from the nominal system and the system after the functions of a component are turned off

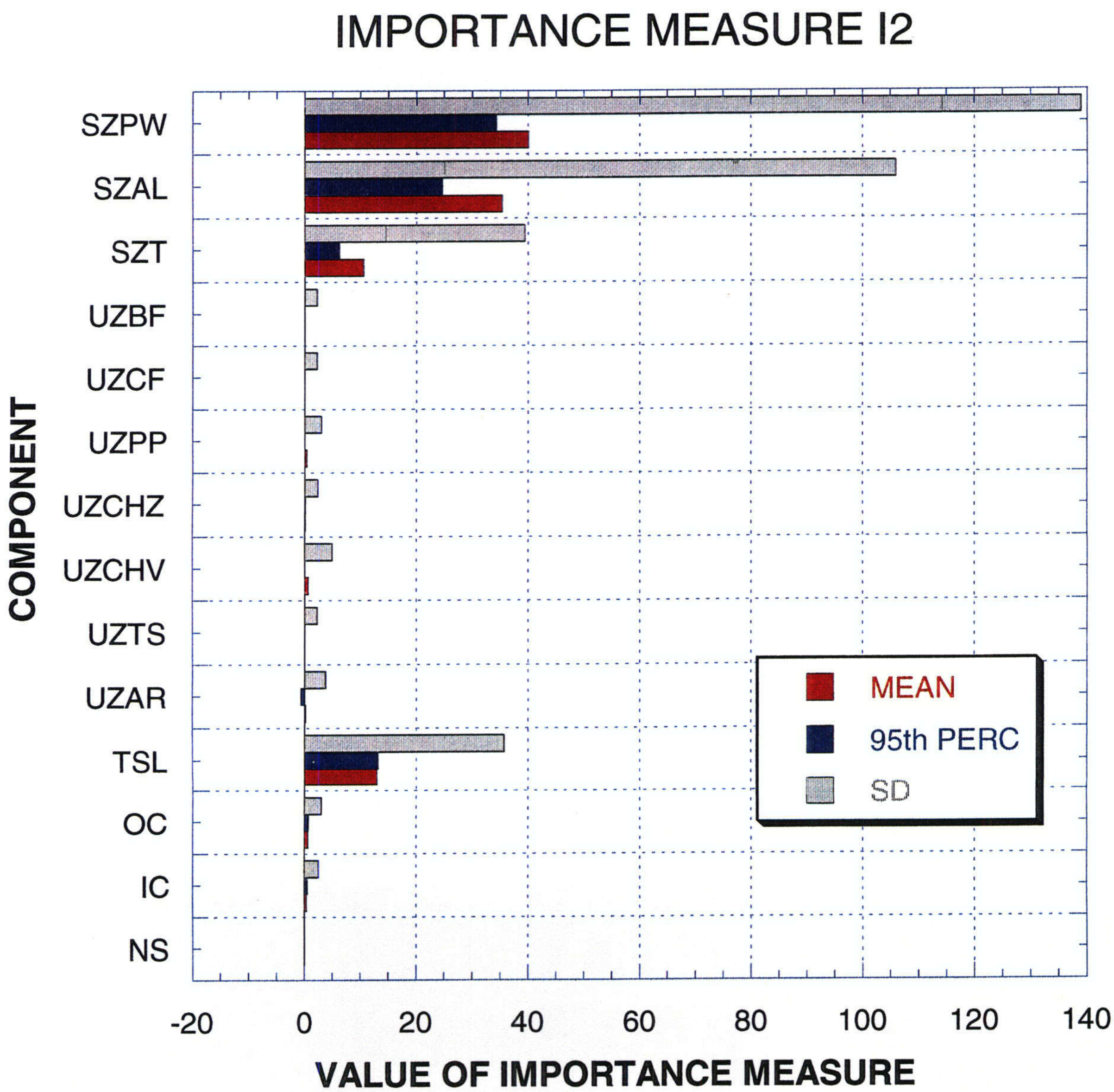

Figure 4.3.2-3. Values of importance measure $_{-u}I_2$ (dimensionless unnormalized values)

Table 4.3.2-2 Values of importance measure $_{-u}I_2 = \left({}_{-u}Y - {}_{s}Y\right)/{}_{s}Y$ for the repository example problem; the same statistics are used as in table 4.3.1. The risk increase interval in the last column is calculated as. $P\left[{}_{-u}Y > Y_G\right] - P\left[{}_{s}Y > Y_G\right]$

	Expected Value	95th Percentile	Median	Std. Deviation	Risk Increase Interval
-Inner Container	0.39	0.53	2.56	2.55	0.0
-Outer Container	0.68	0.69	4.30	3.01	0.0
-Top Soil Layer	13.01	13.2	174	35.74	0.04
-Unsaturated Zone Above Rep	0.20	-0.64	-0.31	3.8	0.0
-Unsaturated Topopah Springs	0.00	0.00	0.64	2.28	0.0
-Unsaturated Calico Hills Vitric	0.68	0.02	1.10	4.89	0.0
-Unsaturated Calico Hills Zeolitic	0.12	0.09	0.64	2.37	0.0
-Unsaturated Prow Pass	0.38	0.00	1.76	3.02	0.0
-Unsaturated Upper Crater Flat	0.00	0.00	0.64	2.28	0.0
-Unsaturated Bull Frog	0.00	0.00	0.64	2.28	0.0
-Saturated Tuff	10.62	6.30	4.58	39.4	0.12
-Saturated Alluvium	35.39	24.67	28.4	106.00	0.12
-Pumping well	40.07	34.33	60.2	139.00	0.2
Sum	101.54	79.19	278.51	344.34	0.48

Table 4.3.2-3. Normalized values of $_{-u}I_2$ as percentages; the normalization is done with respect to the sum in the last row of table 4.3.2-2.

	Expected Value	95th Percentile	Median	Std. Deviation	Risk Increase Interval
-Inner Container	0.38	0.67	0.92	0.74	0.00
-Outer Container	0.67	0.87	1.54	0.87	0.00
-Top Soil Layer	12.81	16.67	62.47	10.38	8.30
-Unsaturated Zone Above Rep	0.20	-0.81	-0.11	1.10	0.00
-Unsaturated Topopah Springs	0.00	0.00	0.23	0.66	0.00
-Unsaturated Calico Hills Vitric	0.67	0.02	0.39	1.42	0.00
-Unsaturated Calico Hills Zeolitic	0.12	0.11	0.23	0.69	0.00
-Unsaturated Prow Pass	0.37	0.00	0.63	0.88	0.00
-Unsaturated Upper Crater Flat	0.00	0.00	0.23	0.66	0.00
-Unsaturated Bull Frog	0.00	0.00	0.23	0.66	0.00
-Saturated Tuff	10.45	7.95	1.64	11.44	25.00
-Saturated Alluvium	34.80	31.15	10.20	30.78	25.00
-Pumping well	39.53	43.37	21.40	39.72	41.7

Table 4.3.2-4. Values of $_{-u}I_3 = {}_{-u}Y/Y_G$ performance measure for the repository example problem. Y_G is taken as 30 mrem (Y_{G1}) for the expected value and 100 mrem (Y_{G2}) for 95th percentile. The normalized values are also shown.

	$E[_{-u}Y]/Y_{G1}$ $\times 10^{-2}$	Normalized $E[_{-u}Y]/Y_{G1}$	95th $P[_{-u}Y]/Y_{G2}$ $\times 10^{-5}$	Normalized 95th $P[_{-u}Y]/Y_{G2}$
-Inner Container	3.83	1.21	7.93	1.67
-Outer Container	4.6	1.46	8.76	1.83
-Top Soil Layer	38.7	12.23	73.7	15.4
-Unsaturated Zone Above Rep	3.32	1.05	1.84	0.38
-Unsaturated Topopah Springs	2.76	0.87	5.18	1.08
-Unsaturated Calico Hills Vitric	4.63	1.46	5.28	1.10
-Unsaturated Calico Hills Zeolitic	3.10	0.98	5.64	1.18
-Unsaturated Prow Pass	3.83	1.21	5.18	1.08
-Unsaturated Upper Crater Flat	2.77	0.87	5.18	1.08
-Unsaturated Bull Frog	2.76	0.87	5.18	1.08
-Saturated Tuff	32.1	10.14	37.8	7.91
-Saturated Alluvium	101.0	31.9	133.0	27.84
-Pumping Well	113.0	35.7	183.0	38.3
	316.43		477.67	

In table 4.3.2-4, values of $_{-u}I_3 = {}_{-u}Y/Y_G$ are shown for the mean and the 95th percentile statistics. In arriving at these values, Y_G is taken as 30 mrem for the mean and 100 mrem for the 95th percentile. Normalized values as percentages are also reported.

Observe from tables 4.3.2-2 to 4.3.2-4 that four system components together contribute more than 90 percent to importance. In order of importance, these are pumping well, saturated alluvium, top soil layer, and saturated tuff. Through the process of dilution, the pumping well alone accounts for 40 percent of the repository performance. The saturated alluvium is very effective (importance measure of greater than 30 percent) in reducing dose through the process of retardation. The top soil layer through reduction of

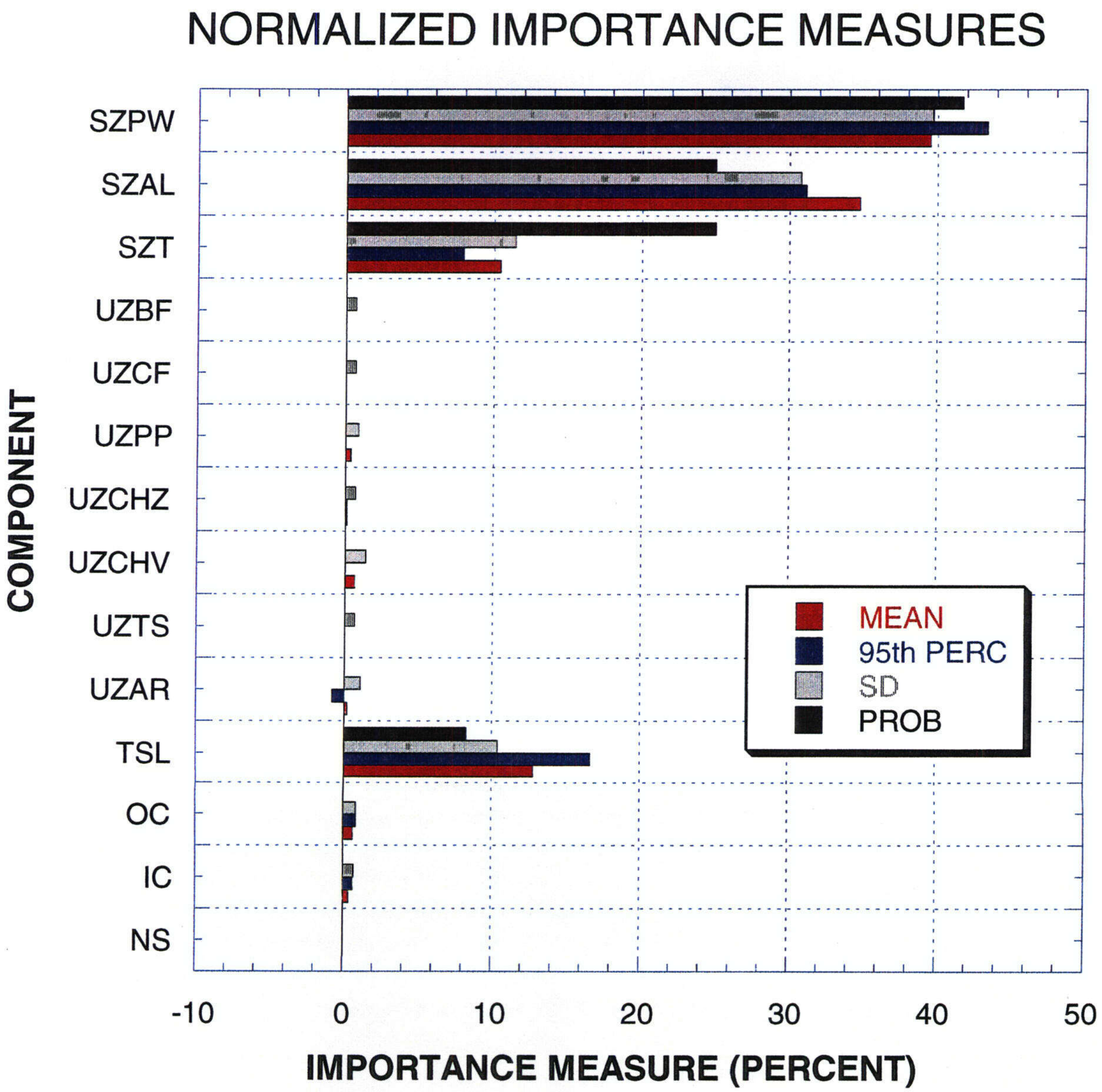

Figure 4.3.2-4. Values of importance measure $_{-u}I_2$ normalized with the sum of importance of all components (dimensionless)

Table 4.3.2-5. Peak annual dose for nominal performance and dose after removing barriers (rem) - 50 latin hypercube realizations

	Expected Value $\times 10^{-3}$	95th Percentile $\times 10^{-2}$	Median $\times 10^{-4}$	Std. Deviation $\times 10^{-2}$	$P[Y > 3\times10^{-2}]$
-Waste Container	5.90	2.93	12.5	1.04	0.04
-Unsaturated Zone Above Repository	2.01	0.85	0.41	0.82	0.02
-Unsaturated Zone Below repository	1.96	0.93	0.34	0.59	0.02
-Saturated Zone	35.8	13.7	2.72	11.9	0.12
-Pumping Well	34.0	18.3	5.34	12.2	0.20

infiltration rate contributes substantially (more than 10 percent) also. For the 10,000 yr period used in these calculations, the importance of the waste container is relatively small.

A somewhat surprising result is for the unsaturated zone above the repository which has negative importance value in table 4.3.2-3. This means that the performance of the system improves (lesser value of dose is calculated) when this component is removed. We believe that this result reflects primarily the greater dilution of the solution coming in contact with the waste packages and thereby delaying the onset of waste package failures. In addition, the temperature of the repository is lowered, because the insulating effect of the unsaturated zone above the repository is removed.

The standard deviation may be interpreted as an index of the magnitude of uncertainty in a variable. From the results, it is apparent that the same four components that are most important to performance also contribute the most to the standard deviation of the dose.

The results using the median statistic are some what different from the others. With the median, the top soil layer turns out to be the most important. This implies that because of reduction in the infiltration rate due to the top soil layer, the dose in the 50 realizations is more uniformly distributed (median is changed a lot when the top soil layer is removed) than is the case from other components.

4.3.2.2 Importance of Combination of Components

To get better idea about importance of what are normally referred to as *barriers* in performance assessment, we partitioned the repository into five combinations of components (i) waste container, (ii) unsaturated zone above the repository, (iii) unsaturated zone below the repository, (iv) saturated zone,

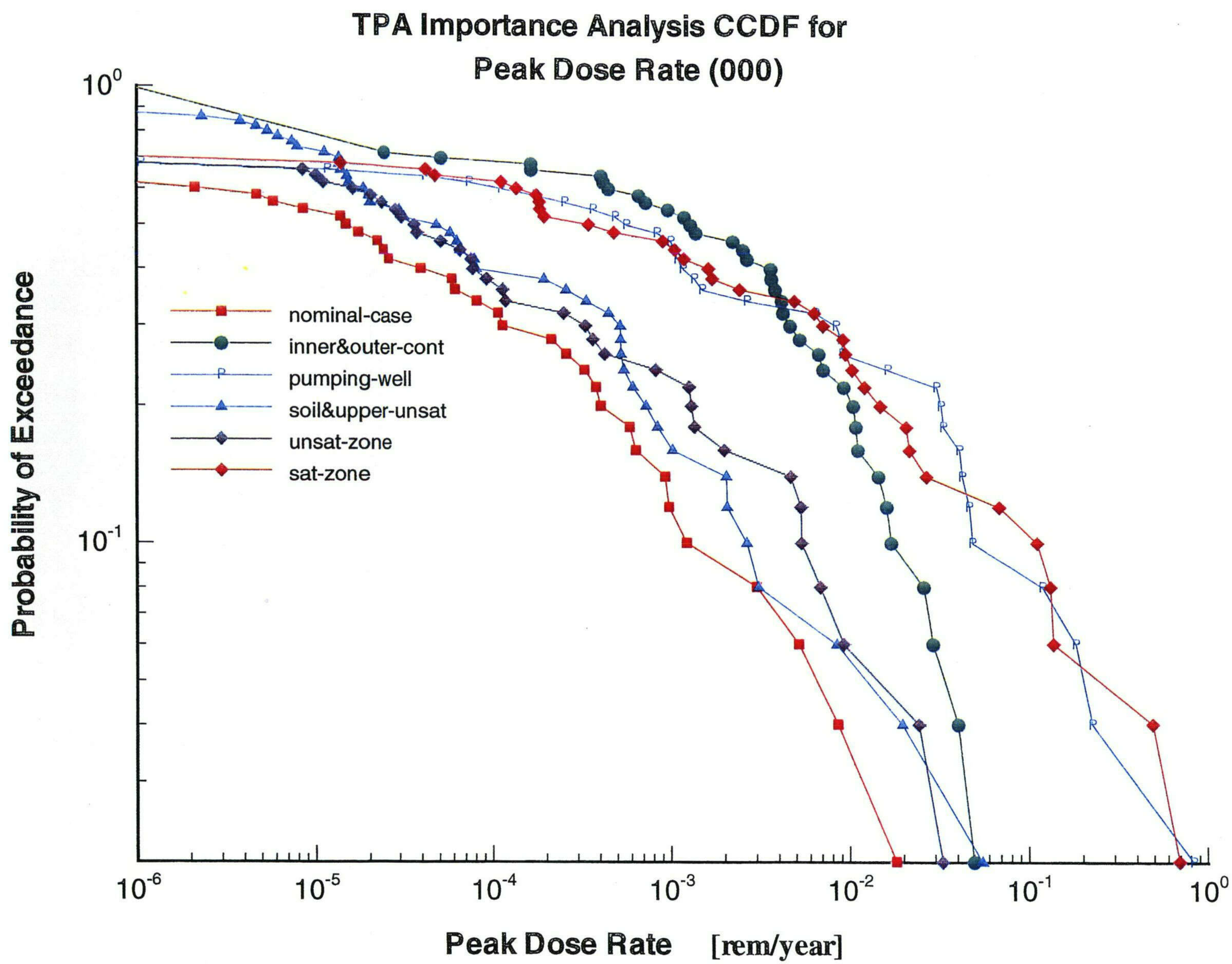

Figure 4.3.2-5. Complementary cumulative distribution functions for the system in which combination of components has been removed

and (v) pumping well. The input data used for these calculations is the same as was used for estimating the importance of components. The statistics of calculated dose are shown in table 4.3.2-5 and figure 4.3.2-1.

From table 4.3.2-5, it can be seen that two *barriers*, the pumping well and the saturated zone contribute the most to averting dose. The other important observation is based on comparing table 4.3.2-5 with table 4.3.2-3 and noting that the importance of a *barrier* is not equal to the sum of importance of the components constituting that barrier. For example the importance of the waste container (considering the inner and outer containers together) is approximately 8 times the sum of the individual importance measures of the inner and outer containers. Thus, importance measures are not unique; for a given conceptualization, their values are dependent on how components are identified and then combined to define *barriers*. This, in all probability, is a consequence of the nonlinear way the system components interact with each other.

Table 4.3.2-6 provides the importance measure $_{-u}I_3$ for the *barriers*. In this case, over 87 percent of importance is shared by the pumping well and the saturated zone.

The components can be consolidated even further to look at just the importance of engineered barriers (which in this model are just the inner and outer container) and the natural barriers (which in this case is the unsaturated and saturated zones and the pumping well). Figure 4.3.2-6 shows the CCDFs for the nominal system ($_sY$), nominal system minus the engineered barriers ($_{-eb}Y$), and nominal system minus the natural barriers ($_{-nb}Y$) with their respective mean values as, 0.83, 5.90, and 44,340 mrem/yr. For the conceptualization and input data used in this computation, the importance of the natural barriers dominates the overall system. The use of alloy C-22 as the container material may alter these results significantly. Also, we note again that the results are for illustration purposes only and are strongly dependent on the conceptual models employed.

We have not included in our presentation of results the effect of removing the waste form component of the system. In the current formulation of TPA Version 3.1.4, only the spent fuel waste form is considered. Removing it from the system will lead to zero dose and obviously improve the system performance, although without the waste form, the repository system has no waste containment objectives to fulfill. There are plans to include wastes other than spent fuel (e.g., vitrified defense waste, special DOE wastes). Once such other wastes are included in the model, removal of one waste form at a time will be useful in assessing the relative importance of each waste form to total system performance.

There may be reasons to not include a component in the importance analyses. For example, one may wish to not include the pumping well as a system component because without it the critical group does not have access to contaminated water (recall that in example 4.3, the dilution function of the well was neutralized but ingestion of water remained the same). Note that if a component (such as the pumping well) is not included, the unnormalized values of the importance measures of the remaining components are unchanged; the normalized values, however, will be different but can be easily calculated.

Table 4.3.2-6. Values of importance measure for barriers, ${}_{-u}I_2 = ({}_{-u}Y - {}_sY) / {}_sY$ for the repository example problem; the same statistics are used as in table 4.3.2-5. The risk increase interval in the last column is calculated as $P[{}_{-u}Y > Y_G] - P[{}_sY > Y_G]$. Values in parenthesis are in percent.

	Expected Value (percent)	95th Percentile (percent)	Median (percent)	Std. Deviation (percent)	Risk Increase Interval (percent)
-Waste Container	6.12 (6.71)	5.66 (7.99)	143.35 (58.67)	11.94 (3.92)	0.04 (10.0)
-Unsaturated Zone Above Repository	1.42 (1.56)	1.64 (2.31)	4.66 (1.91)	9.37 (3.07)	0.02 (5.0)
-Unsaturated Zone Below repository	1.36 (1.49)	1.79 (2.52)	3.90 (1.60)	6.73 (2.20)	0.02 (5.0)
-Saturated Zone	42.18 (46.30)	26.45 (37.32)	31.19 (12.76)	136.62 (44.83)	0.12 (30.0)
-Pumping Well	40.01 (43.94)	35.33 (49.86)	61.24 (25.06)	140.07 (45.98)	0.2 (50.0)

Table 4.3.2-7. Values of performance measure ${}_{-u}I_3 = {}_{-u}Y / Y_G$ for *barriers* for the repository example problem. Y_G is taken as 30 mrem (Y_{G1}) for the expected value and 100 mrem (Y_{G2}) for 95th percentile. The normalized values are also shown.

	$E[{}_{-u}Y]/Y_{G1}$	Normalized $E[{}_{-u}Y]/Y_{G1}$	95th $P[{}_{-u}Y]/Y_{G2}$	Normalized 95th $P[{}_{-u}Y]/Y_{G2}$
-Waste Container	0.197	7.44	0.98	7.71
-Unsaturated Zone Above Repository	0.067	2.53	0.28	2.30
-Unsaturated Zone Below repository	0.065	2.45	0.31	2.44
-Saturated Zone	1.19	44.92	4.57	37.55
-Pumping Well	1.13	42.66	6.1	50.12

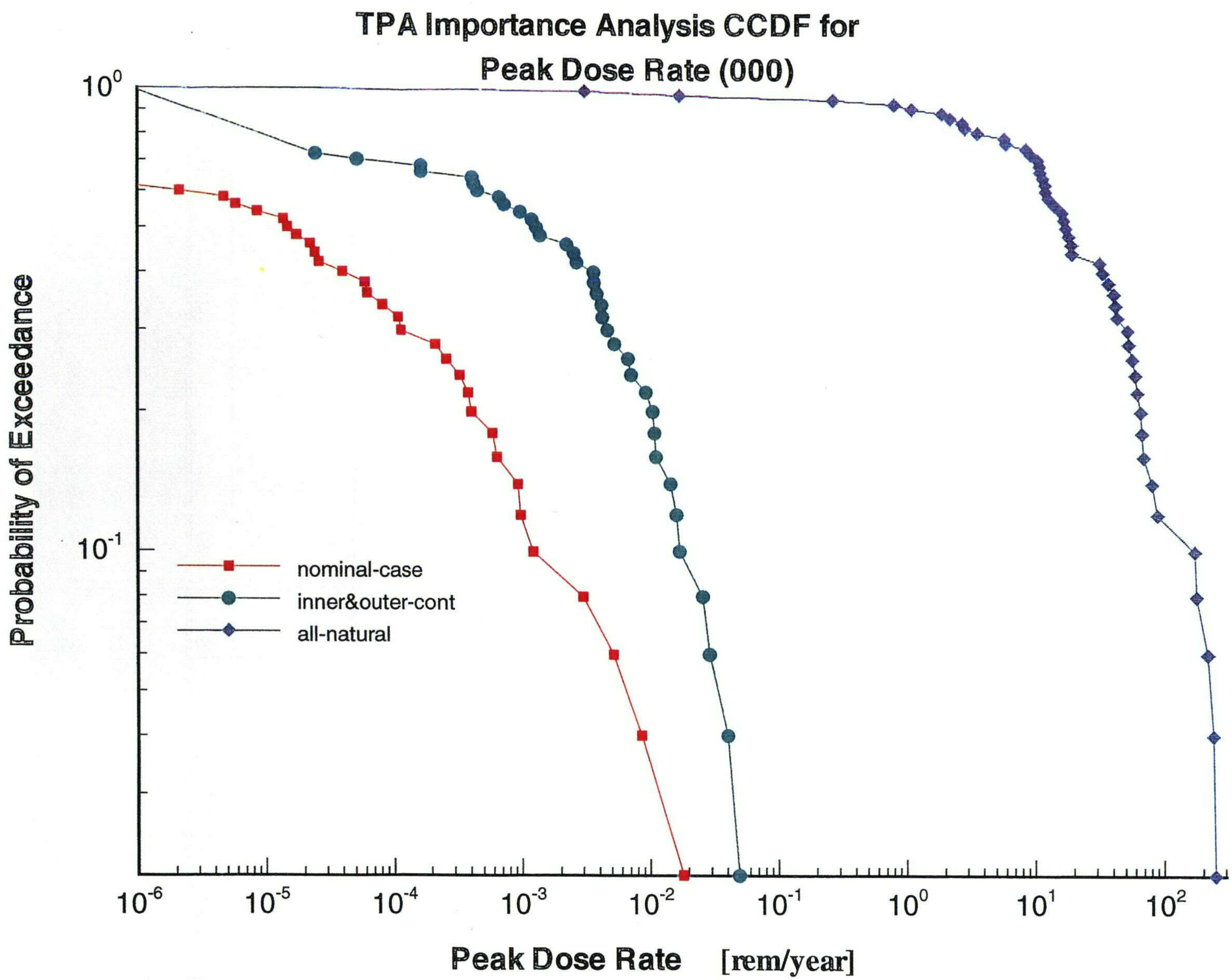

Figure 4.3.2-6. Complementary cumulative distribution functions for the nominal system, for the system with functions of engineering barriers turned off and for system with functions of natural barriers turned off

5 SUMMARY

We have suggested a number of importance measures thought to be useful in evaluating nuclear waste repositories and similar systems. These importance measures were largely extensions of concepts for importance analysis used in reliability engineering. The main advantage of the importance measures proposed here is that they are more suitable to systems comprised of components whose behavior is most easily and naturally represented as continuous, rather than binary functions. As a modeling artifice, the particular component whose importance is evaluated is treated as not functioning in order to evaluate its importance to the total system. Nevertheless, the importance measures continue to incorporate the fundamentally continuous nature of the system, because the unmodified (nominal) system, including the component under evaluation, is modeled as a continuous system and the modified system, absent the component under evaluation, is modeled as a continuous system. The other significant difference between the importance measures defined in this report and those available in system reliability literature is their dependence on risk. That is, both the probability of a consequence and the magnitude of consequence are considered in their formulation. These importance measures appear to facilitate evaluation of systems comprised of both continuous-behavior and binary-behavior components. Currently, these concepts and formulations of importance are under evaluation for a repository system to determine the degree to which they provide useful insights and to determine which formulations are most useful.

Thus far, the fundamental concepts of these importance measures have been described and then extended to systems with scenarios and parameter uncertainty. What has not been described is how these concepts might be used to aid regulatory decision-making. Although such a topic deserves a full exposition, which is beyond the scope of this early paper describing work in progress, a few remarks will be made on this topic. As is shown in the examples in Section 4, the fundamental concept of importance developed here appears to be implementable for a variety of safety systems. Those importance measures based on nominal system performance (equations 3.1-1 and 3.1-2) and their generalizations, indicate the degree to which performance is degraded if the component or subsystem at issue is neutralized or made nonfunctional. The larger the importance measure, the larger the effect of the neutralizing the component. Conversely, importance measures near unity (or zero for the second measure) indicate that the component has very little impact on system performance. Investigating more thoroughly a component with high importance may or may not lead to a significant increase in system performance; it may, however, lead to greater confidence in system performance, since total system performance is highly dependent on such components. As shown in example 4.1, the performance measures for several components may be normalized by dividing each component's importance measure by the sum of all the importance measures. This produces a "fractional importance measure" that indicates the relative importance of various components. This provides an additional perspective on how the various components relate to each other and their relative roles in achieving the total system performance. A component with a fractional importance near 1 (or 100 percent) has a dominant role in determining system performance; a component with a very small fractional importance has little role in determining system performance. Such indicators could be used as one measure of the effectiveness of a multiple barrier or defense-in-depth approach to system safety. If most importance is lodged in a single component and little is lodged in the rest, then the system may not be an effective implementation of multiple barriers. Similarly, the importance measures based on the regulatory limit (equations 3.1-3 and 3.1-4) and their generalizations provide additional insights. If the third measure is smaller than 1 (or less than zero for the fourth measure), then neutralization of the component has not led to exceedance of the regulatory limit; this means that the unexpected poor performance of the component will not cause a violation of a regulatory standard. If this is the case for every component, then the system is extremely robust and can meet the standard, even if a component behaves in a completely unexpected fashion and essentially is neutralized.

6 REFERENCES

Andrews, J.D. and T.R. Moss. 1993. *Reliability and Risk Assessment.* Logman Scientific & Technical. Essex.

Benjamin, J.R. and C.A. Cornell. 1970. *Probability, Statistics, and Decision for Civil Engineers,* McGraw-Hill Book Company, New York, NY.

Harr, M.E. 1987. Reliability-based design in civil engineering, chapter 3. Mineola, NY: Dover Publications, Inc.

Shearer, J.L., A.T. Murphy, and H.R. Richardson. 1971. *Introduction to System Dynamics.* Reading, MA. Addison-Wesley.

Sherry, R. 1996. Importance measures for risk-informed regulatory applications information content and uncertainties. *High-Level Radioactive Waste Management: Proceedings of the Seventh Annual International Conference, Las Vegas, NV, September 29-October 3, 1996.* La Grange Park, IL. American Nuclear Society: 222-229.

Siu, N.O. and D.L. Kelly. 1997. On the use of importance measures for prioritizing systems, structures, and components. *In Proceedings of the 5th International Topical Meeting on Nuclear Thermal Hydraulics, Operations and Safety (NUTHOS-5).* Beijing, China: I4-1-I4-6.

APPENDIX A

APPENDIX A—IMPLEMENTATION IN THE TOTAL-SYSTEM PERFORMANCE ASSESSMENT CODE

The new input flags created and the parameters modified to implement importance analysis in TPA Version 3.1.4 are presented in table A-1.

Table A-1. Details of implementation of Importance Analysis in Total Performance Assessment Version 3.1.4.

Input Flag	Parameter Name	Value	Module Name	Module Variable
InnerContainerPresenceFlag(yes=1,no=0)	InnerWPThickness[m]	1.0e-22	seismo	AInnerWPThickness
			ebsfail	cthick2
			nfenv	tss
OuterContainerPresenceFlag(yes=1,no=0)	OuterWPThickness[m]	1.0e-22	seismo	OuterWPThickness
			ebsfail	cthick1
			nfenv	tcs
SoilPresenceFlag(yes=1,no=0)	MinimumInfiltrationPrecipitationRatio	1.0e+00	uzflow	pixAAI
UpperUnsaturatedLayerPresenceFlag(yes=1,no=0)	ElevationOfGroundSurface[m]	1.072e+03	nfenv	elevgs
	MassDensityofYMRock[kg/m^3]	1.0e-27	nfenv	rho
	SpecificHeatofYMRock[J/(kg-K)]	1.0e-01	nfenv	cp
	ThermalConductivityofYMRock[W/(m-K)]	1.0e+03	nfenv	cond
	EmissivityOfDriftWall[-]	4.0e-01	nfenv	emissrw
	ChlorideConcentration	0.0e+00	nfenv	xmfcl(ii)
	SubAreaWetFraction	1.0e+00	ebsrel	SAWETFRAC
	FowFactor	1.0e+00	ebsrel	fow
			exec	fow
	FmultFactor	1.0e-01	exec	fmult
		1.0e-01	ebsrel	fmult
TSwPresenceFlag(yes=1,no=0)	TSw_Thickness_1SubArea[m]	0.0e+00	uzft	leglen(np,1)
	TSw_Thickness_2SubArea[m]	0.0e+00	uzft	leglen(np,1)

Input Flag	Parameter Name	Value	Module Name	Module Variable
	TSw_Thickness_3SubArea[m]	0.0e+00	uzft	leglen(np,1)
	TSw_Thickness_4SubArea[m]	0.0e+00	uzft	leglen(np,1)
	TSw_Thickness_5SubArea[m]	0.0e+00	uzft	leglen(np,1)
	TSw_Thickness_6SubArea[m]	0.0e+00	uzft	leglen(np,1)
	TSw_Thickness_7SubArea[m]	0.0e+00	uzft	leglen(np,1)
CHnvPresenceFlag(yes=1,no=0)	CHnvThickness_1SubArea[m]	0.0e+00	uzft	leglen(np,2)
	CHnvThickness_2SubArea[m]	0.0e+00	uzft	leglen(np,2)
	CHnvThickness_3SubArea[m]	0.0e+00	uzft	leglen(np,2)
	CHnvThickness_4SubArea[m]	0.0e+00	uzft	leglen(np,2)
	CHnvThickness_5SubArea[m]	0.0e+00	uzft	leglen(np,2)
	CHnvThickness_6SubArea[m]	0.0e+00	uzft	leglen(np,2)
	CHnvThickness_7SubArea[m]	0.0e+00	uzft	leglen(np,2)
CHnzPresenceFlag(yes=1,no=0)	CHnzThickness_1SubArea[m]	0.0e+00	uzft	leglen(np,3)
	CHnzThickness_2SubArea[m]	0.0e+00	uzft	leglen(np,3)
	CHnzThickness_3SubArea[m]	0.0e+00	uzft	leglen(np,3)
	CHnzThickness_4SubArea[m]	0.0e+00	uzft	leglen(np,3)
	CHnzThickness_5SubArea[m]	0.0e+00	uzft	leglen(np,3)
	CHnzThickness_6SubArea[m]	0.0e+00	uzft	leglen(np,3)
	CHnzThickness_7SubArea[m]	0.0e+00	uzft	leglen(np,3)
PPwPresenceFlag(yes=1,no=0)	PPw_Thickness_1SubArea[m]	0.0e+00	uzft	leglen(np,4)
	PPw_Thickness_2SubArea[m]	0.0e+00	uzft	leglen(np,4)

Input Flag	Parameter Name	Value	Module Name	Module Variable
	PPw_Thickness_3SubArea[m]	0.0e+00	uzft	leglen(np,4)
	PPw_Thickness_4SubArea[m]	0.0e+00	uzft	leglen(np,4)
	PPw_Thickness_5SubArea[m]	0.0e+00	uzft	leglen(np,4)
	PPw_Thickness_6SubArea[m]	0.0e+00	uzft	leglen(np,4)
	PPw_Thickness_7SubArea[m]	0.0e+00	uzft	leglen(np,4)
UCFPresenceFlag(yes=1,no=0)	UCF_Thickness_1SubArea[m]	0.0e+00	uzft	leglen(np,5)
	UCF_Thickness_2SubArea[m]	0.0e+00	uzft	leglen(np,5)
	UCF_Thickness_3SubArea[m]	0.0e+00	uzft	leglen(np,5)
	UCF_Thickness_4SubArea[m]	0.0e+00	uzft	leglen(np,5)
	UCF_Thickness_5SubArea[m]	0.0e+00	uzft	leglen(np,5)
	UCF_Thickness_6SubArea[m]	0.0e+00	uzft	leglen(np,5)
	UCF_Thickness_7SubArea[m]	0.0e+00	uzft	leglen(np,5)
BFwPresenceFlag(yes=1,no=0)	BFw_Thickness_1SubArea[m]	0.0e+00	uzft	leglen(np,6)
	BFw_Thickness_2SubArea[m]	0.0e+00	uzft	leglen(np,6)
	BFw_Thickness_3SubArea[m]	0.0e+00	uzft	leglen(np,6)
	BFw_Thickness_4SubArea[m]	0.0e+00	uzft	leglen(np,6)
	BFw_Thickness_5SubArea[m]	0.0e+00	uzft	leglen(np,6)
	BFw_Thickness_6SubArea[m]	0.0e+00	uzft	leglen(np,6)
	BFw_Thickness_7SubArea[m]	0.0e+00	uzft	leglen(np,6)
STFFPresenceFlag(yes=1,no=0)	STFF	0.0e+00	szft	salength(1)
SAVPresenceFlag(yes=1,no=0)	SAV	0.0e+00	szft	salength(2)

Input Flag	Parameter Name	Value	Module Name	Module Variable
PumpingWellPresenceFlag(yes=1,no=0)	WellPumpingRateAtCriticalGroup20km[gal/day]	0.0e+00	dcagw	pump20

APPENDIX B

APPENDIX B—SOFTWARE REQUIREMENTS DOCUMENT

IMPORTANCE ANALYSIS—POTENTIAL IMPLEMENTATION IN THE TOTAL PERFORMANCE ASSESSMENT CODE 2/17/98

Importance measures may be calculated for a component, barrier, or subsystem and either under base case or under disruptive scenarios. The difference between a component, barrier, and subsystem is that of scale (or size) and their description is to a large extent dependent on the way a system is conceptualized during model development and the purposes of the analyses. Briefly, a component is defined as the smallest identifiable discrete element of the overall repository system, the contribution of which to the performance may be of interest. A barrier may be made up of one or more components and it is called a barrier because it inhibits the availability to potential dose receptors of waste disposed in the repository. A subsystem is larger and may be made up of one or more barriers.

To determine the importance of a component, barrier, or subsystem, two calculations need to be performed (i) estimate overall system performance assuming the component, barrier, or subsystem functions normally, and (ii) estimate overall system performance under the condition that the component, barrier, or subsystem is 'removed'. The notion of removing a component, barrier, or subsystem is closely tied to the functions that it performs in the overall system. In this context, removing a component, barrier, or subsystem means that all functions normally performed are no longer performed. Thus, the 'removed' component, barrier, or subsystem is still physically present but does not perform its functions (in other words, it has failed). In importance analysis, only those functions that are incorporated in the model can be turned on or off - other functions presumably are not of concern. There may be cases where removal of a particular component, barrier, or subsystem may induce the modeler to reconceptualize the whole system by incorporating functions of the remaining system that were ignored in the original modeling. If this is the case, a new model may have to be developed for carrying out the importance analysis. For implementation of importance analysis in the existing version (and future versions) of the TPA code, we will restrict ourselves to functions already incorporated in the model. Changing conceptual models is not warranted for this initial study.

The following tables provide an assessment of how to implement importance analysis in the present version of the TPA code.

A. Components:

Component	Potential Function(s)	Current Implementation in TPA 3.1	Method to Turn Off Function	Comments
1. Cladding	1. Delay contact of water with waste form. 2. Modify chemistry of water. 3. Modify porosity and permeability of medium by enhancing dissolution or precipitation.	Cladding is assumed to fail when the container fails, but there is a correction factor (between 0 and 1) to determine the fractional area of waste form in contact with water	As cladding is not modeled, its functions cannot be turned on or off	The correction factor does not change with time; it doesn't represent cladding life
1. Inner Container	1. Delay contact of water with waste form. 2. Alter chemistry of water 3. Modify porosity and permeability of medium	First function is modeled; failure by general and localized corrosion; no feed back between corrosion products and water chemistry	Put life of inner container to zero or assume the corrosion rate to be very large (high corrosion potential); put galvanic efficiency equal to zero	If material is changed to C-22, galvanic protection may not play any role
3. Outer Container	1. Delay contact of water and water vapor with inner container 2. Provide cathodic protection to inner container 3. Alter chemistry of water 4. Modify porosity and permeability of medium	First two functions are modeled; failure by corrosion and mechanical stresses ; no feed back between corrosion products and water chemistry	Put life of outer container equal to 0 or assume the corrosion rate to be very large	From coding point of view, changing corrosion rates may be easier than bypassing modules
4. Ceramic Coating	1. Increase life of outer container	Not modeled	Cannot determine importance	Possible DOE design option

Component	Potential Function(s)	Current Implementation in TPA 3.1	Method to Turn Off Function	Comments
5. Backfill	1. Reduce effect of rock fall in base case and in seismic scenario 2. Alter heat transfer rates 3. Alter water flow rates 4. Alter chemistry of water 5. Provide sorption 6. Provide support to drip shield 7. Mediate effects of magma flow and fault movement	Heat transfer is modeled by assigning appropriate thermal properties; a flow factor that determines the diversion of flow away from drifts is also used	Assign properties of air (assuming that is what will replace backfill); determine if the flow factor can be determined for conditions with and with out backfill	An option in DOE design; the flow factor lumps many effects including those of backfill
6. Drip Shield	1. Reduce amount of water entering emplacement drifts 2. Alter heat transfer rates	Not modeled	Importance cannot be determined	An option in DOE design
7. Drift Liners	1. Provide structural support to emplacement drifts 2. Alter water chemistry	Not modeled	Importance cannot be determined; when modeled assume liner properties same as rock	
8. WP Supports	1. Provide elastic support to waste packages 2. Alter water chemistry	Only considered in seismic scenario; effect on water chemistry not modeled	Assume support properties to be the same as that of rock	Used only in seismic scenario
9. Damaged Rock Zone	1. Alter hydrologic properties 2. Alter thermal properties 3. Alter mechanical properties	Not modeled; flow factor may be able to account for it	Cannot determine importance; when modeled, assume damaged rock zone properties same as rock	A component that may detracts from performance; only a minor effect on heat transfer is expected

Component	Potential Function(s)	Current Implementation in TPA 3.1	Method to Turn Off Function	Comments
10. Various geologic strata in the unsaturated zone below the repository (Tsw, Tsv, Chnv, Chnz)	1. Control flow of water 2. Control transport of radionuclides 3. Alter water chemistry 4. Control heat transfer	Flow and transport in 1D columns (subareas); In any one layer, depending upon water flux and saturated conductivity, flow and transport is either through rock matrix or through fractures; water chemistry is not modeled, no role in heat transfer either	1. Use a very large value of hydraulic conductivity 2. Use sorption equal to zero. Alternatively, use a small length of the stratum	Each subarea has different strata, any one stratum can be turned off; uses NEFTRAN, it may be advantageous to bypass the calculation entirely
11. Various geologic strata in the saturated zone (PPw, Av, etc)	1. Control water flow 2. Control transport of radionuclides 3. Alter water chemistry	Discrete flow and transport legs representing stream tubes, water chemistry not modeled	1. Use a very large value of hydraulic conductivity 2. Use a very low value of diffusivity and dispersivity 3. Use zero value for sorption	Uses NEFTRAN, may be advantageous to bypass calculation entirely
12. Various geologic strata in the unsaturated zone above the repository (Tc, Av, etc.)	1. Same as no. 10	Below the alluvium, water is assumed to flow through a fracture (travel time equal to zero); in the near field, enters into heat transfer calculations and gravity driven reflexing	For the near-field, separate tables from MULTIFLO may be required; otherwise strategy is the same as in no. 10 above	Anywhere from 10 - 100 meters above the repository may be involved in the repository
13. Vegetation at the land surface	1. Control shallow infiltration through transpiration	Not modeled	Importance cannot be determined	Vegetation may be considered in the next version of the code

Component	Potential Function(s)	Current Implementation in TPA 3.1	Method to Turn Off Function	Comments
14. Atmosphere above the land surface	1. Control evaporation 2. Control air dispersal of waste in volcanic scenario	evaporation is not explicitly modeled; it is embedded in the equation for shallow infiltration through ground elevation and atmospheric temperature	Assume zero evaporation, set the temperature accordingly; volcanic scenario can be easily turned off by setting a flag	The upper limit on the mean annual infiltration may be determined by the conductivity of the upper most layer
15. Pumping wells	1. Control concentrations in drinking water	Dilution is based on how much of the plume is intercepted by the draw-down cone of the well	Assume water can be obtained with the minimum amount of mixing water required to meet the demand	
16. Various dose pathways (groundwater, direct exposure, inhalation)	1. Control radiation dose to member of critical group	Dose conversion factors for each pathway are used which are calculated outside of TPA	Eliminate specific pathways by putting their dose conversion factors to zero	Dose conversion factors for 5 km are for drinking water only
17. Glass waste form	1. Control radionuclide source term 2. Transport by colloids	Not modeled	Cannot determine importance	This and other waste forms may eventually be included in the code
18. Spent fuel waste form	1. Control radionuclide source term 2. Thermal loading	Bath tub model used	Cannot turn off or answers will be zero; in future it may be turned off by putting transfer rates to zero	When other waste forms are included, it may be possible to turn this off

Component	Potential Function(s)	Current Implementation in TPA 3.1	Method to Turn Off Function	Comments
19. Various other waste forms such as from Navy and research reactors	1. Control radionuclide source term 2. Thermal loading	Not modeled	Same as no. 18	
20. Land surface slope	1. Control overland flow	Not modeled	Importance cannot be determined	
21 Shallow soil on land surface	1. Control shallow infiltration	Included in the calculation of mean annual infiltration	Use coefficients in the MAI equation that apply to no soil	
22. Emplacement Drifts	1. Alter heat transfer 2. Alter water flow 3. Alter water chemistry 4. Control water flow	Included in modeling of the near-field by MULTIFLO; results used in the form of a table	Assume properties of intact rock	
23 Invert	1. Alter heat transfer 2. Alter water flow 3. Alter water chemistry	Only modeled for heat transfer	Assign thermal properties the same as the rock	

B. Barriers

Barrier	Constituent Components	Function(s)	Implementation in TPA	Method of Turning Off Function(s)	Comments
1. Waste Form	1. All types of waste forms	1. Control release of radionuclides into water or air contacting the waste 2. Alter water chemistry	Only spent fuel is in the code at present; no release to air is modeled	Should not be turned off as otherwise all answers will be zero	If and when waste forms other than spent fuel are included, it may be possible to turn off functions of specific waste forms
2. Waste Package	1. Cladding, outer and inner container, ceramic coating,	1. Control access of water to waste form 2. Alter water chemistry 3. Alter medium properties	Failure through corrosion and mechanical stresses is considered	Assume waste packages fail at zero time by adjusting corrosion rates	It may be possible to bypass EBSFAIL entirely
3. Back Fill	1. Back fill	1. Control access of water to waste package 2. Alter water chemistry 3. Alter water reflexing during thermal period	Included only in thermal calculations	Assign thermal properties of rock or air depending upon whether a gap is to be maintained or not	Will have to considered in the near-field and water reflexing calculations

Barrier	Constituent Components	Function(s)	Implementation in TPA	Method of Turning Off Function(s)	Comments
4. Other Engineering Components	1. Drip shield and other engineered components	1. Control access of water to waste package 2. Alter water chemistry 3. Alter heat transfer	Not included in TPA	Will depend upon how these are implemented	
5. Unsaturated Zone above the Repository	1. All geologic strata above the repository, land surface, atmosphere, vegetation	1. Control shallow infiltration, 2. Control influx of water into emplacement drifts 3. Control gravity driven reflexing	UZFLOW and NFENV are the modules	See turning off of components	
6. Unsaturated Zone Below the Repository	1. All geologic strata below the repository in the unsaturated zone	1. Control flow of water to the saturated zone 2. Control transport of radionuclides to the saturated zone	UZFT (actually NEFTRAN) module is used	See turning off of components	The flux from the unsaturated zone is considered only for determining dilution from pumping; it is not added to the saturated zone flow as a matter of course
7. Saturated Zone	1. All geologic strata in the saturated zone and the pumping well	1. Control of water flow to the pumping well 2. Control of radionuclide transport to the pumping well	SZFT (actually NEFTRAN) is used	See turning off of components	One may have to put a Do loop around NEFTRAN to get results for 5K and 20K distances in one run

C. Repository Subsystems

Subsystem	Constituent Components	Function(s)	Implementation in TPA	Method to Turn Off Function(s)	Comment
1. Engineered Subsystem	1. All engineered components accept waste form	1. Waste containment during initial disposal period 2. Support the isolation function of the natural system	Implementation is essentially through the calculation of source term;	Turn off all functions of engineered components or assume the same rate of waste entering the unsaturated zone as with engineered subsystem functioning but waste entry starting at t = 0	The time-dependent rate (or concentration) at which radionuclides enter the unsaturated zone below the repository can be a performance measure for this subsystem
3. Natural Subsystem	1. All geologic components	1. Support containment function of engineered subsystem 2. Isolate waste or control the rate at which waste reaches the critical group	NEFTRAN and UZFLOW are the main modules	1. Assume rain falls directly on engineered barriers 2. Assume the source term is directly available to the critical group	The concentration in the well water pumped by the critical group can be a performance measure for this subsystem

D. Scenarios: Scenario classes: climate change (C), seismic disruption (S), fault movement (F), and volcanic disruption (V). Assume that human intrusion (H) will be dealt with separately.

Scenario	Overall Effect	Components Effected	Implementation in TPA	Comments
C	1. Alter the flux of water through the system 2. Possible redefinition of critical group	Both engineered and natural subsystems	Implemented by changing infiltration rate as a function of time	To turn off scenario, keep infiltration rate fixed at initial value
S	1. Drift failure and rock fall on waste packages 2. Alteration of flow properties	Both engineered and natural subsystems; second effect is not modeled	Effect on waste packages only considered	To turn off, assume seismicity value to be zero.
F	1. Failure of waste packages 2. Alteration of flow system	Both engineered and natural subsystems but second effect is not modeled	effect on waste packages only considered	To turn off set the faulting flag to zero (no new fault and no slip on existing faults)
V	1. Release of waste to ground surface and to atmosphere 2. Alteration in flow system	Both engineered and natural subsystems	Effect on waste packages only considered	To turn off, assume no volcano formation
CS	1. Combinations of climate change and seismic events			
CF	1. Combination of climate change and faulting			

38/40

Scenario	Overall Effect	Components Effected	Implementation in TPA	Comments
CV	1. Combination of climate change and volcanic events			
SF	1. Combination of seismic and faulting events			
SV	1. Combination of seismic and volcanic events			
FV	1. Combination of seismic and volcanic events			
CFS	1. Combination of climate change, faulting, and seismic events			
CFV	1. Combination of climate change, faulting, and volcanic events			
CSV	1. Combination of climate change, seismic, and volcanic events			
FSV	1. Combination of faulting, seismic, and volcanic events			

Scenario	Overall Effect	Components Effected	Implementation in TPA	Comments
CFSV	1. Combination of all four scenario classes			

Scenario	Overall Effect	Components Effected	Implementation in TPA	Comments

Strategy to implement importance analysis in TPA Version 3.1.3:

1. Work at the component level, barriers and subsystems can be defined as combinations of components.

2. Define a 1-dimensional array Importance(n), each element of this array is an index that indicates whether the functions of a component are to be turned on or off. All functions should be either on or off. Importance(I) = 0 means the functions are turned off and Importance(I) = 1 means, they are turned on. Set Importance(I) = 1 as default for all I.

3. Run the case with all functions and scenarios turned on, save the output file for comparison with other cases.

4. In Exec, use will specify in the input whether importance analysis is to be done. If the answer to that is yes than specify the components or barriers, or subsystems of which importance is to be estimated.

5. Set up an outer loop on Importance(I) and based on specifications in 4 above, set the appropriate values of Importance(I) to zero, and accordingly either change the parameters values or alter the calls to modules.

6. Importance can be based on individual dose to a member of the critical group. Calculations can either be done with the mean values of parameters (deterministic run) or with sampling turned on. The values of dose for each realization needs to be recorded. This will require creating extra output files, one each for the component, barrier, and subsystem whose importance is to be determined. Alternatively, if it is too difficult to keep so many output files, then store the statistics (perhaps the first four moments) of the PDF of performance measure (dose).

7. Run the code for the new values of Importance(i). A separate run is needed for each component, barrier, or subsystem subtracted from the original system.

8. Sample all variable during the first run and store sampled values for use with all runs.

9. Write a separate module to calculate importance measures.

10. Write a brief subroutine to calculate the importance measures.