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# IMPORTANCE AND SENSITIVITY OF PARAMETERS AFFECTING THE ZION SEISMIC RISK

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# ABSTRACT

This report presents the results of a study on the importance and sensitivity of structures, systems, equipment, components and design parameters used in the Zion Seismic Risk Calculations. This study is part of the Seismic Safety Margins Research Program (SSMRP) supported by the NRC Office of Nuclear Regulatory Research.

The objective of this study is to provide the NRC with results on the importance and sensitivity of parameters used to evaluate seismic risk. These results can assist the NRC in making decisions dealing with the allocation of research resources on seismic issues. This study uses marginal analysis in addition to importance and sensitivity analysis to identify subject areas (input parameter areas) for improvements that reduce risk, estimate how much the improvement efforts reduce risk, and rank the subject areas for improvements. Importance analysis identifies the systems, components, and parameters that are important to risk. Sensitivity analysis estimates the change in risk per unit improvement. Marginal analysis indicates the reduction in risk or uncertainty for improvement effort made in each subject area.

The results described in this study were generated using the SEISIM (Systematic Evaluation of Important Safety Improvement Measures) and CHAIN computer codes. Part 1 of the SEISIM computer code generated the failure probabilities and risk values. Part 2 of SEISIM, along with the CHAIN computer code, generated the importance and sensitivity measures.

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# FOREWORD

This report is a product of the Zion Risk Sensitivity Analysis Task using the SEISIM computer code. It used the results from the Seismic Safety Margins Research Program (SSMRP) *Zion Seismic Risk Study*.

The sensitivity analysis team involved in this task is as follows:

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# EXECUTIVE SUMMARY

This report summarizes a study of importance and sensitivity of seismic risk to factors such as structures, event sequences, systems, components, and parameters of a nuclear power plant. The study is based on a risk assessment report in NUREG/CR-3428, "Application of the SSMRP Methodology to the Seismic Risk at the Zion Nuclear Power Plant." This study was done by the Seismic Safety Margins Research Program (SSMRP) for the US Nuclear Regulatory Commission, Office of Nuclear Regulatory Research.

The objective of the study is to provide a rational decision method for allocating resources to reduce risk. The study uses importance, sensitivity, and marginal analyses to identify factors that affect seismic risk, estimate the effects of changes in the factors, and rank the factors by their relative cost-efficiency for reducing risk.

The study is limited. First, the results are specifically for Unit 1 of the nuclear power plant in Zion, Illinois. Nevertheless, the methods can be applied to any plant, and the results are the most detailed of their kind. Second, the results specify changes that would reduce seismic risk and its uncertainty. But they should not be interpreted as recommendations, nor should this study be interpreted to mean the risk at Zion is too great. Third, the results are based on the "base case" model of the Zion plant. The study does not examine whether the rankings would change given other modeling assumptions.

The study uses the SEISIM and CHAIN computer programs. SEISIM computes risk, probabilities, importance and sensitivity measures (partial derivatives with respect to input parameters). CHAIN models SEISIM input parameters as functions of primary input variables and computes derivatives of risk with respect to primary input variables. SEISIM and CHAIN outputs include:

- importance measures of factors,
- sensitivity measures such as partial derivatives of risk with respect to the means and standard deviations of fragilities and responses, and,
- ranks of important factors.

These results answer three types of questions:

- which factors are most important compared with other factors of the same type. (The answers to this type of question tell where to concentrate efforts to reduce risk.)
- how much will risk be reduced for equal changes to any factors, and
- how much will risk be reduced for equal effort or dollars expended making changes to any factors? (A ranking of these reductions tell where to get the greatest impact on risk, i.e. where to get the biggest bang for the buck.)

Some importance results are as follows. Twenty terminal event sequences (TES) contribute more than 90% of the risk. Six accident sequences have five different initiating events and contribute more than 90% of the risk. Five of the six include CSIS and CFCS system failure during the injection phase and RHR system failure. The second most important accident sequence has a transient initiating event and includes failures of the auxiliary feedwater and bleed and feed systems.

The following input factors have the biggest bang for buck because the sensitivity of risk to equal-cost changes in these factors rank highest:

- soil properties,
- piping layout between buildings,
- piping fragility,
- roof fragility of the crib house pump enclosure, and
- base slab uplift fragility.

Here are reasons why these factors rank highest.

The soil properties, material damping and shear stiffness, influence the amplification of seismic acceleration from the bedrock to the ground surface. The Zion site has a relatively shallow soil layer on a crystalline bedrock.

Piping between buildings is a component of several safety systems. This piping is subject to strain from relative displacement of two buildings on independent soil foundations. This piping may fail in earthquakes larger than the safe shutdown earthquake, and the safety margin is less than for most other piping.

It was surprising that piping fragility ranks so high. Previous seismic risk analyses, including the SSMRP, have found that only a few piping systems were important in safety systems and then under special circumstances such as piping between buildings. Our result in this study arises because (a) piping failures (in the reactor coolant loop piping system) are important in the initiating events and (b) the piping fragility function applied to all the piping components.

Roof fragility of the crib house pump enclosure ranks high because of (a) the design of the connection between the roof and the supporting walls and (b) the assumption that the collapse of this roof causes the loss of function of all six service water pumps. This result points out: (1) the importance of connection detail (which is a known problem from past earthquakes) and (2) the capability of structures to initiate common-cause failures.

Base slab uplift is failure of the soil foundation of the reactor building at accelerations beyond the SSE. This is important because it is assumed to lead to failure of the piping between the reactor building and auxiliary-fuel-turbine complex at Zion.

The report has a more extensive ranking of factors to be improved through research and modifications. When research and modifications are planned, the marginal analysis should be repeated and the factors should be ranked again.

The results in this report can be used to guide risk reduction. The methods -- importance, sensitivity and marginal analyses -- can be used to guide reduction of uncertainty regarding risk.

# 1. INTRODUCTION

The SSMRP Zion Phase II base case results [3] were employed as the reference point in the importance and sensitivity studies described below. In order to make full use of the SSMRP Zion results, importance and sensitivity studies were carried out with the SEISIM (Systematic Evaluation of Important Safety Improvement Measures) computer code [1]. SEISIM computes radioactive release probabilities and risk for a nuclear power plant subjected to an earthquake [2]. It also computes importance and sensitivity measures and ranks them. Sensitivity measures can be used to help allocate resources and to reduce risk if a reduction is necessary. This report describes the importance, sensitivity, and marginal analyses used in analyzing the Zion nuclear power plant. These analyses help satisfy several needs. One need is to identify systems, components, parameters, and combinations of events such as accident sequences and terminal event sequences important to reactor safety during an earthquake. There is also a need to allocate resources to reduce risk. These analyses address the following questions:

a. Which inputs contribute substantially to release probability and risk? Which are the important components, safety systems, accident sequences and terminal event sequences?

b. What are the rates of change in probabilities and risk when input parameters such as means, standard deviations, and correlations of responses, strengths, and primary input variables change for one category of components, for one type of response, or for one primary input variable? The answers to these questions help decide how much effort should be spent on each improvement.

c. What are the changes in probabilities for discrete shifts in input parameters? The answer to this question indicates the benefit of research or manufacturing change that shifts an input parameter by a finite amount.

Part 2 of SEISIM, SEISIM2, provides answers to these questions. SEISIM2 measures the importance of inputs, computes derivatives, and recomputes probabilities after shifting input parameters. Figure 1.1 describes the SEISIM2 computations.

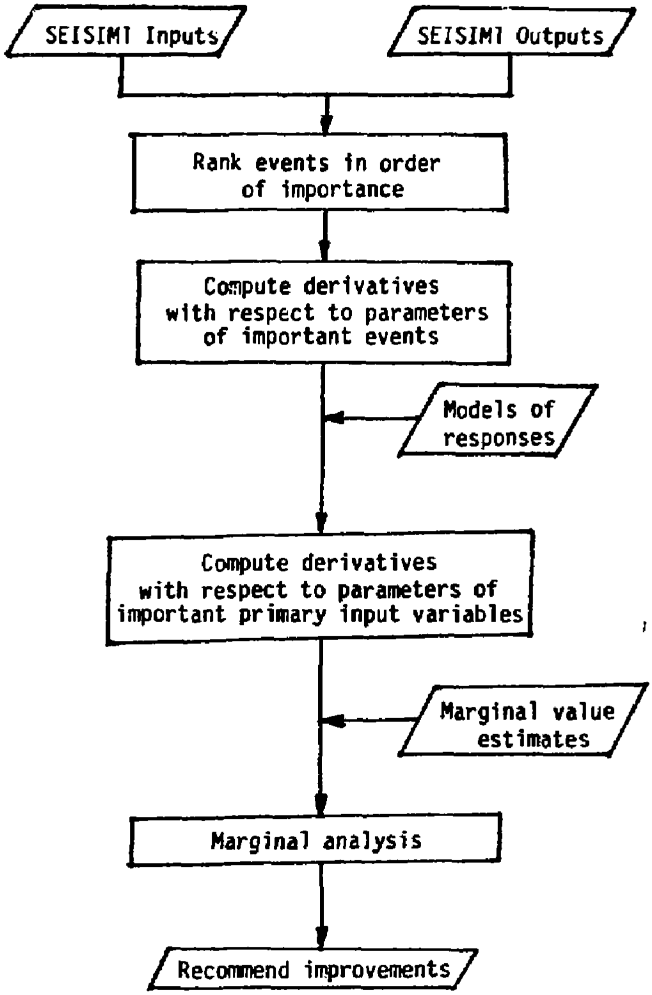


Figure 1.1. Importance, Sensitivity, and Marginal Analyses Computational Sequence.

The remainder of this section introduces importance and sensitivity analyses and specifies how to use marginal analysis for resource allocation. How to allocate resources to reduce risk and how to allocate resources to reduce uncertainty about risk are both discussed.

Section 2 reviews the risk computations and dynamic response computations which provide subject matter and inputs for the sensitivity analysis. Section 2 lists the inputs and outputs of the risk analysis which are examined in the sensitivity analysis.

Section 3 defines the importance and sensitivity measures. These measures are suggested naturally by the structure of the risk computation outlined in Section 2. The importance measures screen components and events for use in the sensitivity analysis. Section 3 describes how SEISIM1, SEISIM2, and other programs interact in the sensitivity calculations. The sensitivities require derivatives of risk with respect to inputs. How SEISIM2 computes the derivatives also develops naturally from the structure of the risk computation. The explanation of the SEISIM2 derivative calculations is deferred until the Appendices.

Section 4 provides the importance and sensitivity results that were obtained from analyzing the Zion nuclear power plant. The results cover the Zion plant model called the "random only" model. This was the "base case" of the SSMRP's Zion analysis [3]. It is referred to as random only because only inherent randomness is included in probability computations. "Modeling uncertainty" due to lack of knowledge has been excluded when possible. Reference [3] treats modeling uncertainty at a second level, indicating the degree of uncertainty in the risk results. We do not expect that the relative rankings in our sensitivity analysis would change by much if we were to include modeling uncertainty, but we have not computed this.

Section 5 describes the marginal analysis results. It uses the sensitivity measures described in Section 4 to estimate the marginal values of reduction in release probability and risk through changes in parameters of fragilities and primary input variables.

The appendices provide mathematical background for the importance and sensitivity analyses. Appendix A presents the derivative of basic event (component failure) probability with respect to means, standard deviations, and correlations of component response and strength. Appendix B describes the use of derivatives as sensitivity measures and describes the approximation of derivatives by slopes. Appendix C describes the approximation to the Vesely-Fussell measure used for measuring component importance. Appendix D describes the Birnbaum measure, the derivative of risk with respect to component failure probability, and presents results for important components comparaing their Vesely-Fussell and Birnbaum rankings. Appendix E reports the Birnbaum measures of important components for each release category.

## 1.1 Importance Analysis

Importance analysis is used to determine which input parameters have the most effect on probabilities and risk. Both probability and the Vesely-Fussell measure [3] indicate the importance of events and can be used for ranking (See Appendix C). The rankings generated from the analysis indicate which accident sequences, structures, systems, components or parameters are important to release probability. The computed importance measures indicate importance to failure events, not to successes. Input parameters which do not significantly affect outputs are eliminated.

## 1.2 Sensitivity Analysis

There are two types of sensitivity analysis. The first uses derivatives of one variable with respect to another. SEISIM2 was designed to compute derivatives or approximate them by slopes (See Appendix B). The second type of sensitivity analysis answers questions about discrete changes. Large changes in parameters, such as the addition of new safety systems, alternative designs, and changes in maintenance, are examples of discrete changes. These two types of sensitivity analysis can both be performed by using SEISIM2. They can be performed by making changes in the inputs or by judicious extrapolation of SEISIM1 results using the derivatives computed by SEISIM2.

Sensitivity analysis indicates how outputs change as input parameters change. Ideally it would indicate how outputs change over the domain of the input parameters. Local sensitivity analysis is used to indicate how outputs change in the neighborhood of nominal input parameter values.

SEISIM2, as indicated earlier, computes derivatives of probabilities and risk as functions of the important input parameters. Only parameters for important events, components, and systems are included in the sensitivity analysis. Only these parameters influence release probability and risk to an appreciable extent. (See Appendices for definitions and examples.)

Derivatives are appropriate sensitivity measures when changes are not large enough to go outside the neighborhood where outputs are linear functions of inputs for nominal values of inputs. Derivatives measure the rates of change of outputs with respect to inputs. Derivatives of SEISIM1 outputs can not always be computed analytically. When this occurs slopes are used to measure the changes in outputs due to changes in the input parameters.

Once the sensitivity measures have been computed, resources can be allocated to reduce release probability and risk. Resources should be allocated to systems, components, or input parameters that have large changes in release probability or risk per unit of resource spent changing inputs. The sensitivity analysis will indicate which systems, components, or parameters are candidates for additional resources.

Sensitivity analysis may also be used to estimate bounds on SEISIM1 outputs. Bounds can not replace better input information, but they can indicate the limits on the worst outputs. In order to estimate these bounds, bounds on the inputs must be specified first, then combinations of inputs that yield the worst outputs can be found.

## 1.3 Marginal Analysis for Resource Allocation

### 1.3.1 Allocating Resources to Reduce Risk

In this section we will indicate how to allocate resources to reduce release probability and risk. The method is called marginal analysis. The information needed to perform a marginal analysis is:

a. derivatives of release probability with respect to inputs;

b. derivatives of inputs with respect to resources that may be allocated to changing inputs; and

c. resources to be allocated to changing inputs.

The derivatives of release probability and risk with respect to inputs indicate which component and parameter inputs are better candidates for improvements. The derivatives of inputs with respect to resources indicate how much benefit an expenditure gives at the input level. The product of these two derivatives indicates the benefit an expenditure provides in reducing release probability and risk. The inputs containing the larger product are better candidates for resource allocations.

There is a connection between the release probability, risk, and allocated resources. Allocated resuorces should reduce component failure probabilities which in turn reduce release probability and risk. The law of diminishing marginal returns states that all resources should not be allocated to improve one component. There is a need to know when to stop and how to allocate resources among alternative component improvements.

Suppose we wish to allocate a resource D among components of safety systems to reduce release probability. Let release probability $P_R$ be a function of component failure probabilities $P(B_j)$, $j=1,2,\ldots,n$. By allocating $X_j$ resources on component j, $P(B_j) = P(B_j(X_j))$ changes and in turn reduces $P_R$. The objective is to allocate resource D among alternatives $X_1, X_2, \ldots, X_n$ to minimize the $P_R$ subject to the constraint

$$\sum_{j=1}^{n} X_j \leq D. \tag{1.1}$$

The optimal allocation provides for the same rate of change of $P_R$ per resource $X_j$ for all components. The law of diminishing marginal returns states this equilibrium exists. The allocation is based on the derivative,

$$\partial P_R/\partial X_j = [\partial P_R/\partial P(B_j)]\cdot[\partial P(B_j)/\partial X_j]. \tag{1.2}$$

The assumption is made that resources allocated to one component do not affect the probability of failure of another. The first term is the rate of change of release probability as the component failure probability changes. It is a sensitivity measure. (Refer to Appendix B and reference [4] to see how it is computed.) The second term is an estimate of the marginal rate of change in component failure probability per resource allocated on the component. Adjust the allocation among components by allocating resources on the components with higher values of $\partial P_R/\partial X_j$.

Here is the proof assuming the necessary continuity and convexity conditions hold. The value of $P_R$ is a function of the component failure probabilities, $P_R = g[P(B_j(X_j)), j=1,2,...,n]$, and the probabilities of component failures are functions of the amount $X_j$ allocated to improve the components. The objective is

$$\min_{X_1,...,X_n} g[P(B_j(X_j)), j=1,2,...,n] \quad , \tag{1.3}$$

subject to the resource constraint noted in equation 1.1. Form the Lagrangian $L = g[P(B_j(X_j)), j=1,2,...,n] - \lambda(\Sigma X_j - D)$. Use calculus to minimize L with respect to $X_j$. The condition

$$\frac{\partial L}{\partial X_j} = \frac{\partial P_R}{\partial X_j} - \lambda = 0 \tag{1.4}$$

for all j is necessary for an optimal allocation.

The interpretation of this condition is to adjust the resources allocated to component j until the marginal rate of change of release probability is the same as for all other components. You should allocate the entire resource as long as the marginal rate of change of release probability provides an acceptable resource/benefit ratio.

### 1.3.2 Allocating Resources to Reduce Risk and its Uncertainty

In this section we will indicate how to reduce risk and its uncertainty simultaneously. Risk can be reduced by activities in design, construction, operation, and shutdown while uncertainty can be reduced by activities in testing, quality assurance, inspection, and analysis. Often activties that reduce risk also reduce uncertainty and vice versa. The material in this section will illustrate how to allocate resources among these activities to optimally reduce both risk and its uncertainty.

The risk associated with nuclear power plants can be measured in several different ways. The measure may be dollars, man-rems per year, lives, reduction in life or some other stated measure. Uncertainty can be defined as lack of knowledge about our estimate of risk. The uncertainty measure may be variance, the entropy width of a confidence interval, or some other stated measure. Because risk and its uncertainty are incommensurate, rationally allocating resources to both requires multi-objective decision making.

To solve this problem we must identify those activities that reduce risk and uncertainty, show how to allocate resources to these activities subject to resource limitations, and to rank alternative recommendations. A list of alternative activities, ranked in order of simultaneous benefit for reducing risk and its uncertainty would be the result. Activities which reduce risk include:

design and analysis,
quality assurance,
construction and quality control,
training and operation,
maintenance and inspection, and
emergency preparation.

Activities which reduce the uncertainty about risk include:

more detailed estimation of seismic hazard,
analysis of power plant response to earthquakes,
testing of component and system resistance to earthquake responses
quality assurance,
more detailed estimates of operation, inspection and maintenance error probabilities, and
more detailed estimates of radioactive release probabilities and the consequences of radioactive releases.

One multi-objective decision making technique is called goal programming. Goal programming is an iterative mathematical programming to optimize one objective with the others as constraints. Then, using the current optimum value of the last objective as a constraint, it next uses mathematical programming to optimize the next objective which was previously a constraint. This method continues until convergence.

Let us now formulate the mathematical programming problem of reducing risk subject to budget and uncertainty constraints. Assume there is a budget of b dollars. Let r denote risk, and s(r) denote its uncertainty (an estimate of the standard deviation of risk). Parameterize the level of risk reduction activities as a vector $\underline{x}$ and the level of uncertainty reduction activities as a vector $\underline{y}$. Let b(x(i)) and b(y(j)) denote the amounts of the budget to be spent on risk reduction activities i and uncertainty reduction activities j. The objective is to minimize risk subject to constraints on budget and uncertainty;

$$\min r = r(\underline{x}, \underline{y})$$

subject to

$$\sum_{i,j} b(x(i))+b(y(j))) \leq b$$

and

$$s(r) \leq g(r) \quad .$$

The function g(r) defines the maximum acceptable uncertainty as a function of risk. It specifies the optimum level of activities subject to the budget constraint and the acceptable level of uncertainty. The Kuhn-Tucker conditions give some insight into the form of the solution under general assumptions about the forms of the risk, budget, and uncertainty functions.

## 2. INPUTS TO THE IMPORTANCE AND SENSITIVITY ANALYSES

SEISIM1 provides most of the inputs for the importance and sensitivity analyses. Section 2.1 reviews SEISIM1 probability and risk computations and describes those items from SEISIM1 needed by SEISIM2. Computer code DPRI [7] provides the response models for calculating the sensitivity measures associated with the primary input variables. Section 2.2 reviews this response modeling.

### 2.1 Review of SEISIM1 Models and Computations

Table 2.1 lists the SEISIM1 inputs and outputs. These data were used in the sensitivity analysis. One input, the primary input variables, is input to the computer code SMACS (Seismic Methodology Analysis Chain with Statistics) [8] whose output, dynamic responses to earthquakes, are inputs to SEISIM1.

This subsection defines the events whose probabilities are computed and explains how the probabilities are approximated. The definitions and explanations are needed to better understand the importance and sensitivity measures described in section 3. These definitions and explanations clarify the accident sequence probabilities calculations used in SEISIM2.

Two features of the probability computations are significant when calculating the importance and sensitivity measures. First, all event sequences except component and system failures are mutually exclusive. This simplifies the SEISIM2 importance measure computations. Second, parameters of fragility and response distribution functions affect outputs through basic events, therefore sensitivity measures for the parameters can be computed at the same time as sensitivity measures for the basic events.

Event trees describe the possible event sequences which follow an earthquake [9]. Figure 2.1 describes the events that can occur following an earthquake. Each path is possible but only one can occur; i. e. paths are mutually exclusive and exhaustive. Given an earthquake large enough to cause the plant to trip, one of several initiating events can occur. The plant safety systems then attempt to bring the reactor to a safe shutdown.

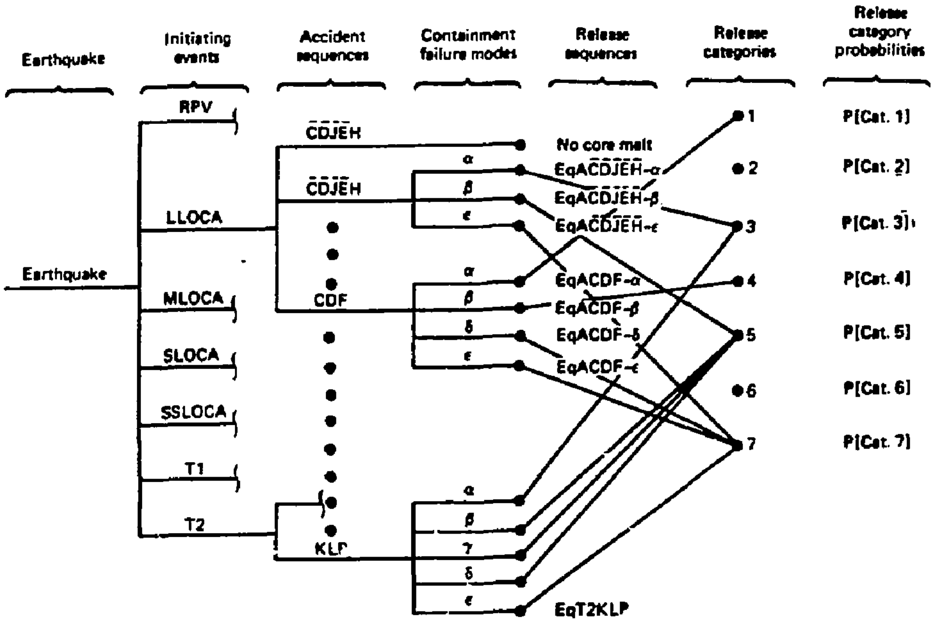


Figure 2.1. Description of Sequences Occurring Following an Earthquake.

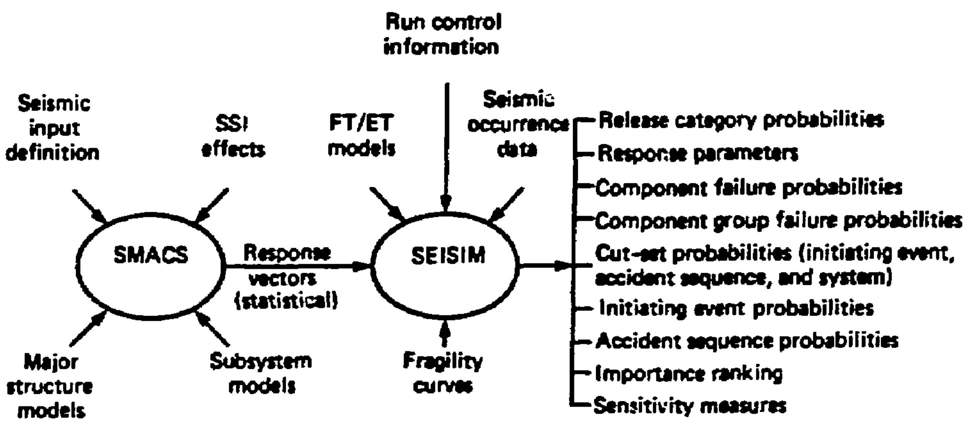


Figure 2.2. Programs and Data Flow for Risk Calculation.

Combinations of safety system successes or failures are called accident sequences. Some of these accident sequences cause containment failure which could result in the release of radioactive material.

Table 2.1. Inputs and outputs examined in the Zion risk sensitivity analysis.

| | |
|---|---|
| Inputs : | • Terminal event sequences<br>• Containment Failure Modes<br>• Accident sequences<br>• Initiating events<br>• Safety systems<br>• Non-fragility related basic event failure data<br>• Fragility means and standard deviations<br>• Response means and standard deviations<br>• Primary input variable means and standard deviations |
| Outputs: | • Probability of each release category<br>• Probability of core melt<br>• Risk in man-rems per year |

A Terminal Event Sequence (TES) is defined as an earthquake, an initiating event, an accident sequence, and a containment failure. The Zion Seismic Risk Study divided the earthquake into six intensity intervals. This was necessary because the probabilities of the TESs and containment failure modes depend on earthquake intensity and because, within each interval, the cummulative distribution functions (CDFs) of responses can be approximated by lognormal CDFs. Each path through the event tree shown in Figure 2.1 is a TES with an earthquake in interval i, i=1,...,6.

Each TES that results in radioactive release is assigned to one of seven release categories according to the time, energy, and type of radioactive material released [10].

SEISIM1 computes the probability of each path throught the event tree shown in Figure 2.1 that leads to a radioactive release. SEISIM1 then adds these probabilities to obtain:

1. the probability of release category k and an earthquake in interval i, k=1,..,7, in a year,

2. the probability of release category k and any earthquake in a year, and

3. the probability of the j-th TES in a year.

The occurrence of a release category leads through a release of radioactive material to a loss. This loss is measured in man-rems [10]. Risk is the expected value of this loss. It is defined as the sum over all release categories of loss multiplied by release category probability.

Figure 2.2 illustrates the sequence of risk computations. The probability of a TES and an earthquake in interval i in a year is

$$P[TES(j) \text{ and } EQ(i)] = P[EQ(i)] * P[IE|EQ(i)] * P[AS|EQ(i) \text{ and } IE] * P[CFM|EQ(i), IE, \text{ and } AS] \quad . \qquad (2.1)$$

where:

EQ(i) = earthquake that causes a peak ground acceleration in the interval i, i=1,2,...,6,
IE = initiating event,
AS = accident sequence, and
CFM = containment failure mode.

SEISIM1 computes the conditional probabilities of initiating events and accident sequences conditional on initiating events. Its inputs include the probabilities the largest earthquake in a year has intensity in interval i and the conditional probabilities of containment failure modes conditional on release.

The probability of having a release in a specific release category and an earthquake in interval i in a year is defined as the sum over all TES(j)s that lead to a release in release category k,

$$P[\text{Release Category } k \text{ and } EQ(i)] = \sum_j P[TES(j) \text{ and } EQ(i)] \quad . \tag{2.2}$$

(Note that the event "and an earthquake in a year in interval i" will not be stated in the remainder of the report when it is clear from the computation.)

The probability of a TES is defined as the sum of the probability of a TES *and* EQ(i) *over* all earthquake levels,

$$P[TES(j)] = \sum_i P[TES(j) \text{ and } EQ(i)] \quad . \tag{2.3}$$

The probability of a release category is defined as the sum over all earthquake intervals,

$$P[\text{Release Category } k] = \sum_i P[\text{Release Category } k \text{ and } EQ(i)]. \tag{2.4}$$

The probability of release is defined as the sum over all release categories,

$$P[\text{Release}] = \sum_k P[\text{Release Category } k] = P[\text{core melt}]. \tag{2.5}$$

Note that given an earthquake, P[Release] = P[Core melt], since the earthquake affects the containment, and in our analysis of containment failure modes we assume that given an earthquake and core melt, there is always some containment failure.

Risk, as indicated earlier, is defined as the sum over all release categories of the loss in man-rems due to release category k times the probability of release category k,

$$\text{Risk} = \sum_k \text{Loss}(k)*P[\text{Release Category } k]. \tag{2.6}$$

Dependence among basic events is considered for each initiating event, system failure, and accident sequence. Initiating events, system failures, and accident sequences are modeled as unions of their respective minimal cut sets. (A cut set is the intersection of basic events. A basic event is a component failure or survival). Dependence among basic events is included when computing cut set probabilities. SEISIM1 computes the probabilities of cut sets by using multivariate normal integrals thereby taking into account dependence within cut sets [11].

SEISIM1 then computes the min cut set upper bound [12] based on the probabilities of unions of cut sets,

$$P[\bigcup_j \text{Cut Set } j] = 1 - \prod_j (1-P[\text{Cut Set } j]) \quad . \qquad (2.7)$$

The min cut set upper bound is exact if cut sets are independent. It provides a good approximation if all cut set probabilities are small. It is an upper bound if there are no negative correlations between the basic events in the cut sets, if the cut sets have no events in common (e.g., basic events appear in only one cut set), and if all random variables have a multinormal CDF [13].

SEISIM1 and SEISIM2 differ in their calculation of accident sequence probabilities. SEISIM1 normalizes the min cut set bounds on accident sequence probabilities conditional on an initiating event if the sum of the bounds exceeds 1.0. SEISIM2 does not normalize since normalization masks the effect of changes in outputs due to changes in inputs. Sensitivity measures of normalized probabilities are more difficult to interpret than sensitivity measures of unnormalized probabilities.

The probability of a cut set j in Equation (2.7) and the probabilities of the basic events in the cut set, depend on the probability distributions of the fragilities and seismic responses for the components whose failures constitute the basic events. The responses depend in turn on the structural primary variables (frequencies, damping, soil stiffness). The primary input variables and input fragility variables are specified to have independent lognormal distributions. Then the logarithms of these input variables have normal distributions. It is the means and variances of these normal distributions of these logarithmic input variables which we use to characterize the input distributions and with respect to which we will compute sensitivities. The structural responses were also found to have skewed distributions, but the logarithms of responses have (approximately) symmetric distributions which we treat as normal distributions.

## 2.2 Regression Models of Seismic Response Inputs

SEISIM2 and associated programs (Section 3.1, Figure 3.1) compute the derivatives of release probability and risk with respect to the parameters of the probability distributions of the logarithmic primary input variables, using the chain rule (see Section 3.2.6). To do this we need the derivatives of the parameters of response distributions with respect to the parameters of the primary input variable distributions. To compute these derivatives, the responses are first modeled as functions of the primary input variables. The parameters of the probability distributions of the responses are then computed as functions of the parameters of the probability distributions of the primary input variables. As noted in Section 2.1, we use the logarithmic input and response variables.

Regression analysis is used to model the logarithmic responses R as functions of the logarithmic primary input variables $V_j$ [7]. The computer code DPRI estimates model coefficients by multivariate linear regression [11]. A separate model is used to estimate each response R, which is one response location, e.g., a valve or a run of pipe.

$$R = b_o + \sum_{j=1} b_j(V_j - V_{jo}) + c\,(V_p - V_{po})^2, \qquad (2.8)$$

where $b_o$, $b_j$ and c are coefficients to be determined and $V_j$ = the j-th logarithmic primary input variable and $V_p$ a piping frequency variable. Note that R is a linear combination of known, not necessarily linear, functions of the inputs. At most 12 $V_j$ are included for each response. That is, at most 12 of the 54 $V_j$ have an influence on a response R; these $V_j$ are the variables of the soil, structures and up to two piping systems which may affect a piping response on an extended piping run.

Having the model and the coefficient estimates for the response, the mean and standard deviation of the response distribution are developed as functions of the means and standard deviations of the primary input variables [7].

# 3. DEFINITION OF IMPORTANCE AND SENSITIVITY MEASURES

## 3.1 Computing and Ranking Importance and Sensitivity Measures

Events are considered important if they are important to any release category probabilities at any earthquake level. Table 3.1 shows the events (contributors) and their importance and sensitivity measures and indicates which measure is used for important ranking. Importance ranking affects sensitivity measures since derivatives are computed only for important events. This is done for computational convenience and because improvements are not likely for events not considered important.

Importance of release categories is measured by probability since release probability is defined as the sum of release category probabilities. Importance of terminal event sequences (TES) is measured by probability since the release category probability is defined as the sum of TES probabilities for terminal event sequences that lead to the release category. For systems or components probability alone is not the importance measure. Systems and components with small failure probabilities may be important if they are contained in many terminal event sequences or if they are the only singleton cut set. System and component importance are measured by the Vesely-Fussell measure [4,15,16], and sensitivity is determined by the Birnbaum measure [15,16]. These measures are defined in Section 3.2.4 and Appendices C and D.

Probability is used to indicate the importance of cut sets in a first screening. Only cut sets that satisfy either of two criteria, (3.1) and (3.2), are input to SEISIM1 and consequently to SEISIM2. This culling procedure [17] is necessary since it is impractical to define all cut sets and compute their probabilities using multinormal integrals. The criteria are

$$\min_i P[BE(i)] > 10^{-5} \tag{3.1}$$

and

$$\prod_i P[BE(i)] > 10^{-10} \tag{3.2}$$

Table 3.1 Contributors to release probabilities and their importance and sensitivity measures

| Contributors | Importance Measure | Sensitivity Measure | Measure used for ranking |
|---|---|---|---|
| Earthquake | Probability | Probability | Importance |
| Terminal Event Sequence | Probability | Probability | Importance |
| Containment Failure Modes | Probability of TESs | | Importance |
| Initiating Event | Probability of TESs | | Importance |
| Accident Sequence | Probability of TESs | | Importance |
| Safety Systems | Probability of TESs and Vesely-Fussell measure | | Importance |
| Component(response and fragility related) | Vesely-Fussell measure | Derivative with respect to failure probability | Sensitivity |
| Components (random basic events) | Vesely-Fussell Measure | Derivative with respect to failure probability | Sensitivity |
| Means and standard deviations of logarithms of strengths | | Derivative with respect to mean or standard deviation of distribution | Sensitivity |
| Means and standard deviations of logarithms of responses | | Derivative with respect to mean or standard deviation of distribution | Sensitivity |
| Means and standard deviations of logarithms of primary input variables | | Derivative with respect to mean or standard deviation of distribution | Sensitivity |

where i is the index of basic events in a cut set. Criteria 3.1 is an upper bound on the cut set probability and criteria 3.2 is the cut set probability given the basic events are independent. Cut sets input to SEISIM2 are used in the derivative calculations if they contain any important component basic events.

Release probability and risk are nonlinear functions of component parameters such as probabilities and the means and standard deviations of responses, strengths, and primary input variables. The computation of their derivatives is therefore not trivial. SEISIM2 has the capability of computing slopes when it is not possible to compute derivatives analytically.

Figure 3.1 illustrates the programs and data flow used for importance and sensitivity analyses. The DPRI calculations are reported separately [7]. SEISIM2 computes the sensitivity measures described in Section 3.2. It computes exact derivatives of cut set probabilities for cut sets with two or fewer basic events. It also computes slopes by changing inputs and computing the changes in probabilities and risk between the SEISIM1 results and probabilities and risk affected by the changes. For a small input change, the slope $\Delta P/\Delta$ Input is used to approximate the derivative since all functions modeled in SEISIM1 are continuous. CHAIN then combines results from DPRI and SEISIM2 to obtain the sensitivities of release probability and risk to the parameters of the SMACS primary input variables. CHAIN also sums results over all earthquake intervals to obtain sensitivity measures over all possible earthquakes.

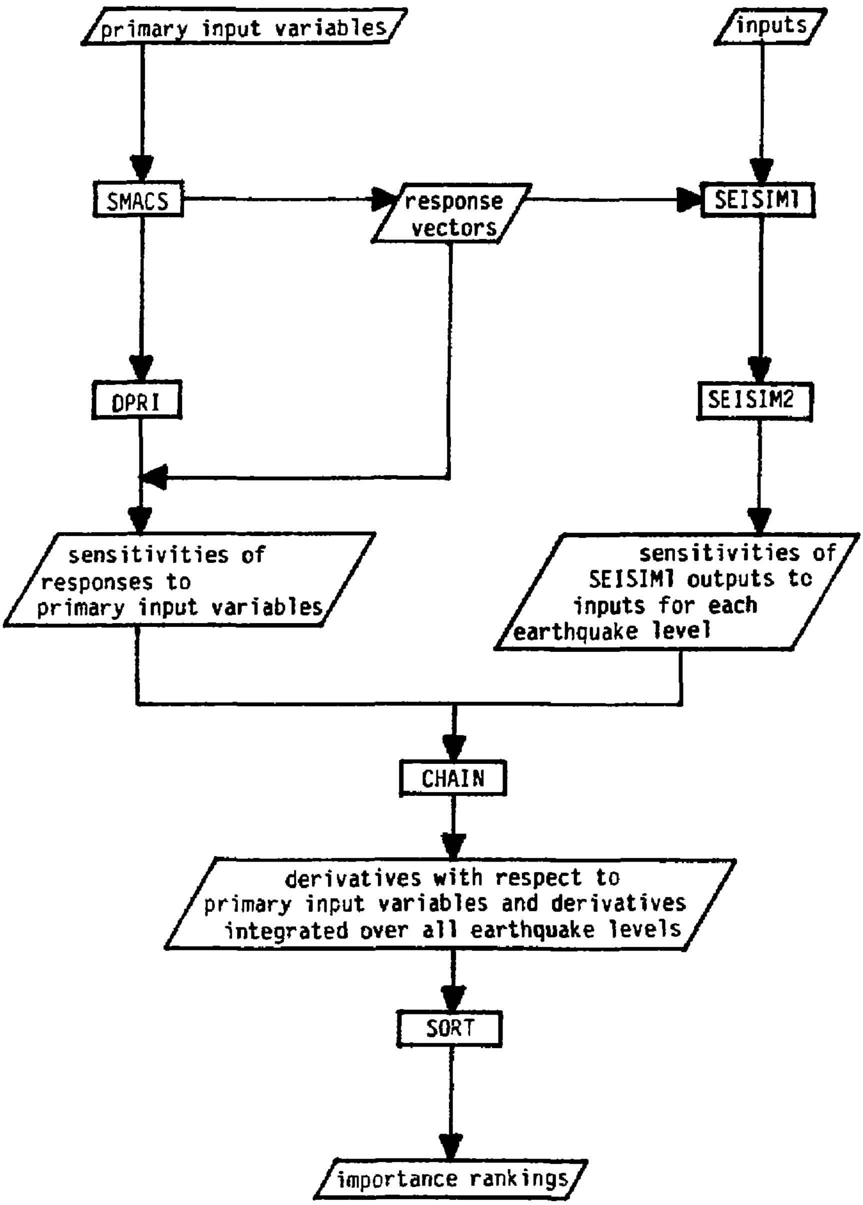


Figure 3.1 Programs and Data Flow for Importance and Sensitivity Analyses

## 3.2 Importance and Sensitivity Measures

### 3.2.1 Terminal Event Sequences (TES)

The importance of a TES to release probability is defined as the probability of the TES. This is necessary since the release probability is the sum of terminal event sequence probabilities, and the contribution of a summand to the sum is the summand. The importance of a TES to risk is its risk contribution, i.e. probability of the TES multiplied by the man-rems resulting from the containment failure mode caused by the TES. The importance of a TES to a release category is also its probability.

One sensitivity measure of release category probability to TES probability yields the same ranking as the measure of TES importance to a release category. The "local fractional" sensitivity measure is the relative change in P(Release Category k) divided by the relative change in the probability of TES(j),

$$\frac{P[TES(j)]}{P(\text{Release Category } k)} * \frac{\delta\, P(\text{Release Category } k)}{\delta\, P[TES(j)]} \quad . \tag{3.3}$$

From Equation 2.2, the second term in equation 3.3 is 1.0, and the local fractional sensitivity measure is the first term in equation 3.3. Since each TES contributes to at most one release category, rankings of TESs by importance to a release category and by local fractional sensitivity measures are the same.

### 3.2.2 Initiating Events (IE) and Accident Sequences (AS)

The importance of an IE or AS to release probability is the sum of P[TES(j)] for those TES(j) in Equation 2.2 which include that IE or AS. The sensitivity of release probability to the probability of an IE or of an AS is not computed. The probability of release appears to be linear. (See Equations 2.1 to 2.6.) However, an increase in the probability of one IE causes decreases in others so probability of release is not considered linear. The same is true for AS probabilities.

### 3.2.3 Safety Systems

Safety system failures and successes appear in the ASs. The sum of TES probabilities, for all the TESs in which a safety system appears as a failure event, is a measure of importance to release probability of that safety system. Another importance measure used is analogous to the Vesely-Fussell measure. It differs from the first measure in that only failures of the safety system caused by its component failures are included, not failures due to external components. Both of these importance measures have been programmed. The results for the first measure are reported in Section 4.

### 3.2.4 Component Failures and Other Basic Events (BE)

The Vesely-Fussell measure is used for ranking and selecting components that will be used for computing sensitivity measures. This measure, when used to define basic event importance, is the probability of the cut sets which contain the basic event divided by the probability of the top event. Another interpretation is that it is the conditional probability given the top event occurs that the top event is caused by one of the cut sets containing the basic event. For example, for a basic event BE appearing only in IEs, the Vesely-Fussell measure is

$$I(BE) = \frac{1}{P(\text{Release})} \sum_j \sum_i P(EQ(i)) * \tilde{P}[IE|EQ(i)] * P[AS|EQ(i) \text{ and } IE] * P[CFM|EQ(i), IE, AS] \quad (3.4)$$

where $\tilde{P}[IE|EQ(i)]$ is computed using only those cut sets in the logical specification of IE|EQ(i) which contain the BE. The sum over index j sums over all the TESs that include the IEs that contain the BE. The Vesely-Fussell measure of component importance to P(Release) or to any P(Release Category k) is analogous. See also Appendix C.

The sensitivity measure for release probability or risk to a BE is the derivative, $\delta P(\text{Release Category })/\delta P(BE)$, also referred to as the Birnbaum importance measure [15,16]. For a fragility-and response-related BE, SEISIM2 changes the mean or standard deviation of its fragility or response while keeping correlations constant. It then computes $\Delta$P(Release Category k) and $\Delta$P(BE) due to that change, takes the ratio of the two changes, and then averages the ratios obtained from shifting the mean and the standard deviation. For a random basic event, SEISIM2 computes the Birnbaum measure by shifting the basic event probability a small amount. (A random basic event is defined as one that is neither response dependent nor dependent on any other basic event.)

### 3.2.5 Fragility and Response Parameters

As noted in Section 2.1, the parameters are the mean $\mu$ and the standard deviation $\sigma$ (or variance $\sigma^2$) of the probability distribution of the logarithmic response and fragility variables. Derivatives and slopes are used to indicate the importance of parameters. Derivatives with respect to the mean indicate the importance of the nominal value of the random variable while the derivative with respect to the standard deviation indicates the importance of the inherent randomness and uncertainty in the random variable. For instance, the slope of release probability, $P_R$, as a function of mean strength, $\mu_S$, is obtained by recomputing the probabilities of all cut sets that contain an important basic event whose mean strength is reduced by a small amount. The slope is computed as (new $P_R$ - old $P_R$)/$\Delta\mu_S$.

The measure for sensitivity of release probability or risk to the mean or standard deviation of a fragility or response is strictly speaking an approximation to the derivative, i.e., the derivative computed considering only the important components in the terminal event sequences. Although a change in one parameter may change the probabilities of many cut sets, the sensitivity measures computed by SEISIM2 include only those cut sets with components deemed important by the Vesely-Fussell measure. If a change in a parameter causes an increase in a P(IE), then changes in the probabilities of other IEs are included in computations. If a change in a parameter causes an increase in a P(AS), then decreases in the probabilities of other ASs containing component (or safety system) success rather than failure are not included. In some cases these latter ASs do not lead to core melt. If they do then there is no inaccuracy caused by neglecting their increases.

### 3.2.6 Primary Input Variables

The measure used for sensitivity of release probability $P_R$ or of risk to the mean and standard deviation of a logarithmic primary input variable V is the derivative,

$$\frac{\delta P_R}{\delta \mu(V)} = \sum_{i=1}^{333} \frac{\delta P_R}{\delta \mu(R_i)} \cdot \frac{\delta \mu(R_i)}{\delta \mu(V)} + \frac{\delta P_R}{\delta \sigma(R_i)} \cdot \frac{\delta \sigma(R_i)}{\delta \mu(V)} \qquad (3.5)$$

where $\mu(V)$ is the mean of primary input variable V and $\mu(R_i)$ and $\sigma(R_i)$ are distribution parameters of the responses $R_i$. There are 333 responses. The chain rule [14] is used since the release probability is a function of response means and standard deviations, which are in turn functions of the mean and standard deviation of a primary input variable (See Figure 2.2). The derivatives with respect to the parameters of the distributions of primary input variables, $\delta\mu(R_i)/\delta\mu(V)$ and $\delta\sigma(R_i)/\delta\mu(V)$, are estimated from regression models of responses as functions of primary input variables. They are computed by DPRI. The derivatives of response correlations, $\delta \mathrm{Corr}(R_i,R_j)/\delta\mu(V)$, are omitted from the derivative (3.5).

### 3.2.7 Earthquake Level Probabilities

Derivatives are used to measure sensitivity of release category probabilities to earthquake level probabilities. The release category probability is actually the probability of release in a category <u>and</u> having an earthquake of a specified level <u>and</u> having the plant in operation at the time of the earthquake. The earthquake level probability is defined as the product of the probabilities of the earthquake level <u>and</u> having the plant in operation at the time of the earthquake. Therefore, the derivative of release category probability with respect to earthquake level probability is the conditional release category probability given the earthquake level and plant operation. It is computed by dividing the release category probability by earthquake level probability. We do not tabulate this derivative.

## 4. RESULTS OF THE IMPORTANCE AND SENSITIVITY ANALYSES

This report provides results for the "random only" base case similar to the base case in the Zion risk study [3]. This case assumes feed and bleed is potentially available, structural failures can have severe effect on safety systems, and variances due to inherent randomness only are included. Modeling uncertainty in the parameters is not represented by inflating variances, so the results are as unbiased as possible. By contrast, reference [3] considers several cases with different assumptions. These may be thought of as large-step sensitivity studies of changes in modeling assumptions. Or the cases may be used as alternative starting points for parameter sensitivity studies. We believe that some qualitative results of the sensitivity analysis would change with base case assumptions. Nevertheless, this report analyzes the base case which is judged to have the most reasonable set of assumptions among the conceivable sets of assumptions given the extent of the analysis resources.

The base case reported here differs from the base case in reference [3] as follows. The release categories resulting from transient accident sequences in earthquake levels 1-3 were changed. This made the risk reported in [3] about 50% higher than in this report. That change could change some importance rankings by one or two ranks.

SEISIM2 is run once for each of six earthquake levels [3] producing six importance and sensitivity results. Computer code CHAIN combines the results and unconditions on earthquake level.

The important contributors to release probability and risk are listed in this section in this order:

- o Release Categories
- o Terminal event sequences (TES) for each release category
- o Containment Failure Modes (CFM)
- o Initiating Events (IE)
- o Accident Sequences (AS) for each IE

- Safety Systems
- Components
- Parameters of response and fragility cdfs
- Parameters of primary input variable cdfs

Each set of contributors listed is ranked by both its contribution to release probability and to risk. Note that the total release probability is equivalent to the probability of core melt. Since TESs within a release category cause the same loss, only one ranking is used for all TESs in a release category.

Following the rankings we note the important response- and fragility-related components (basic events) and their Birnbaum measures at each earthquake level. We then list important parameters for the:

- Fragility functions
- Response (accelerations or moments) distribution functions
- Primary input variables distribution functions in the models of the soil, structures, and piping systems.

The fragility and response distributions affect release probability through the important basic events. Basic events are considered important if they have Vesely-Fussell measures greater than 1 percent of the largest Vesely-Fussell measure. Only cut sets with important basic events are included in computation of the sensitivity measures.

## 4.1 Probabilities and Risk Contributions of Release Categories

Table 4.1 indicates that release category 7 contributes two thirds of release probability. When considering loss in terms of man-rems, release category 7 is only the fourth most important risk contributor (see Table 4.2). It follows that probability of a category 7 release is important to core melt probability but not to risk. Release categories 3 and 2 are considered important since they rank second and third based on probability and first and second when based on risk.

The release categories are described in Appendix J of Reference 13. Release categories 1 and 2 are most severe in terms of quantity of radionuclides released, sensible energy content to further disperse the nuclides, and rate of release. The other release categories have progressively lower quantities of radionuclides released. Release categories 6 and 7 involve melting through the containment basemat.

Table 4.1. Release categories ranked by probability of release.

| Release Category | Probability of Release |
|---|---|
| 7 | 2.5e-06 |
| 3 | 5.9e-07 |
| 2 | 5.0e-07 |
| 6 | 1.8e-07 |
| 1 | 3.2e-08 |
| 5 | 1.1e-09 |
| 4 | 2.6e-10 |

Table 4.2. Release categories ranked by risk.

| Release Category | Risk (man-rem/yr) |
|---|---|
| 3 | 3.2e+00 |
| 2 | 2.4e+00 |
| 1 | 1.7e-01 |
| 7 | 5.7e-02 |
| 6 | 2.8e-02 |
| 5 | 1.1e-03 |
| 4 | 7.1e-04 |

## 4.2 Probabilities and Risk Contributions of Important Terminal Event Sequences

Tables 4.3-4.5 rank the terminal event sequences according to their probability of causing a release and their risk (man-rem/yr) contribution. The letters in the accident sequences designate safety systems; see Table 4.24. A bar over the letter means the system has performed successfully.

Sixteen TESs involving all seven of initiating events contribute 90% of the release probability (see Table 4.3). Certain TESs appear twice because they are associated with two release categories depending on success of the containment spray and fan cooling systems.

Table 4.3. Terminal event sequences important to probability of release ranked by probability of terminal event sequence.

| Release Category | Probability of TES | Initiating Event | Accident Sequence | Containment Failure Mode |
|---|---|---|---|---|
| 7 | 1.0e-06 | transient class 2 | $\bar{K}LB\bar{P}\bar{Q}\bar{C}$ | epsilon |
| 3 | 4.1e-07 | small LOCA | $\bar{K}C\bar{D}\bar{J}F\bar{H}$ | delta |
| 7 | 3.5e-07 | small-small LOCA | $\bar{K}LCF$ | epsilon |
| 7 | 2.4e-07 | large LOCA | $\bar{C}D\bar{E}$ | epsilon |
| 7 | 1.9e-07 | small LOCA | $\bar{K}CDF$ | epsilon |
| 7 | 1.8e-07 | small LOCA | $\bar{K}CDF$ | delta |
| 2 | 1.6e-07 | vessel rupture | CF | gamma |
| 2 | 1.6e-07 | transient class 2 | $\bar{K}LB\bar{P}\bar{Q}\bar{C}$ | delta |
| 3 | 1.2e-07 | small-small LOCA | $\bar{K}\bar{L}C\bar{D}JF\bar{H}$ | delta |
| 7 | 1.0e-07 | vessel rupture | $\bar{C}\bar{E}$ | epsilon |
| 7 | 7.8e-08 | large LOCA | CDF | epsilon |
| 7 | 7.6e-08 | large LOCA | CDF | delta |
| 7 | 7.5e-08 | transient class 1 | $\bar{K}MLB\bar{P}\bar{Q}\bar{C}$ | epsilon |
| 7 | 7.2e-08 | medium LOCA | $\bar{K}\bar{C}\bar{D}\bar{E}$ | epsilon |
| 2 | 6.7e-08 | transient class 2 | $KLB\bar{P}\bar{Q}\bar{C}$ | gamma |
| 6 | 6.5e-08 | large LOCA | $CD\bar{F}G$ | epsilon |
| 6 | 5.3e-08 | transient class 2 | $\bar{K}LB\bar{P}\bar{Q}\bar{C}$ | epsilon |
| 2 | 5.0e-08 | small-small LOCA | $\bar{K}LCF$ | gamma |
| 6 | 4.8e-08 | small-small LOCA | $\bar{K}LC\bar{F}G$ | epsilon |
| 3 | 3.6e-08 | medium LOCA | $\bar{K}C\bar{D}\bar{J}F\bar{H}$ | delta |
| 7 | 3.3e-08 | medium LOCA | $\bar{K}CDF$ | epsilon |
| 7 | 3.2e-08 | medium LOCA | $\bar{K}CDF$ | delta |
| 2 | 1.7e-08 | vessel rupture | $C\bar{F}G$ | gamma |
| 2 | 1.7e-08 | small-small LOCA | $\bar{K}LCF$ | delta |
| 7 | 1.1e-08 | small LOCA | $\bar{K}\bar{C}D\bar{E}$ | epsilon |
| 1 | 1.1e-08 | vessel rupture | CF | alpha |
| 3 | 1.0e-08 | transient class 2 | $\bar{K}LB\bar{P}\bar{Q}\bar{C}$ | alpha |

From Table 4.4 it can be seen that eight TESs contribute 90% of the risk. These TESs lead to release in either categories 2 or 3. The first five contributors to risk are among the sixteen leading contributors to probability of release.

Table 4.4. Terminal event sequences important to risk ranked by their risk contributions.

| Release Category | Risk (man-rem/yr) | Initiating Event | Accident Sequence | Containment Failure Mode |
|---|---|---|---|---|
| 3 | 2.2e+00 | small LOCA | $\bar{K}C\bar{D}\bar{J}F\bar{H}$ | delta |
| 2 | 7.7e-01 | vessel rupture | CF | gamma |
| 2 | 7.5e-01 | transient class 2 | $\bar{K}LB\bar{P}\bar{Q}\bar{C}$ | delta |
| 3 | 6.6e-01 | small-small LOCA | $\bar{K}\bar{L}C\bar{D}\bar{J}F\bar{H}$ | delta |
| 2 | 3.2e-01 | transient class 2 | $\bar{K}LB\bar{P}\bar{Q}\bar{C}$ | gamma |
| 2 | 2.4e-01 | small-small LOCA | $\bar{K}LCF$ | gamma |
| 3 | 2.0e-01 | medium LOCA | $\bar{K}C\bar{D}\bar{J}F\bar{H}$ | delta |
| 2 | 8.1e-02 | vessel rupture | $C\bar{F}G$ | gamma |
| 2 | 8.0e-02 | small-small LOCA | $\bar{K}LCF$ | delta |
| 1 | 5.7e-02 | vessel rupture | CF | alpha |
| 3 | 5.6e-02 | transient class 2 | $\bar{K}LB\bar{P}\bar{Q}C$ | alpha |
| 2 | 4.5e-02 | large LOCA | $CD\bar{F}G$ | gamma |
| 2 | 3.3e-02 | small-small LOCA | $\bar{K}LC\bar{F}G$ | gamma |
| 2 | 2.5e-02 | vessel rupture | CF | delta |
| 7 | 2.3e-02 | transient class 2 | $\bar{K}LB\bar{P}\bar{Q}\bar{C}$ | epsilon |
| 1 | 2.3e-02 | small LOCA | $\bar{K}C\bar{D}\bar{J}F\bar{H}$ | alpha |
| 1 | 2.3e-02 | small-small LOCA | $\bar{K}LCF$ | alpha |

Table 4.5. Terminal event sequences important to each release category ranked by the probability of the terminal event sequences.

| Release Category | Probability of TES | Initiating Event | Accident Sequence | Containment Failure Mode |
|---|---|---|---|---|
| 1 | 1.1e-08 | vessel rupture | CF | alpha |
| 1 | 4.2e-09 | small LOCA | $\bar{K}\bar{C}\bar{D}\bar{J}\bar{F}\bar{H}$ | alpha |
| 1 | 4.2e-09 | small-small LOCA | $\bar{K}LCF$ | alpha |
| 1 | 3.8e-09 | small LOCA | $\bar{K}CDF$ | alpha |
| 1 | 2.8e-09 | transient class 2 | $\bar{K}LB\bar{P}\bar{Q}\bar{C}$ | alpha |
| 1 | 1.6e-09 | large LOCA | CDF | alpha |
| 1 | 1.2e-09 | small-small LOCA | $\bar{K}\bar{L}\bar{C}\bar{D}JF\bar{H}$ | alpha |
| 1 | 1.1e-09 | vessel rupture | $D\bar{F}G$ | alpha |
| | | | | |
| 2 | 1.6e-07 | vessel rupture | CF | gamma |
| 2 | 1.6e-07 | transient class 2 | $\bar{K}LB\bar{P}\bar{Q}\bar{C}$ | delta |
| 2 | 6.7e-08 | transient class 2 | $\bar{K}\bar{L}B\bar{P}\bar{Q}\bar{C}$ | gamma |
| 2 | 5.0e-08 | small-small LOCA | $\bar{K}LCF$ | gamma |
| 2 | 1.7e-08 | vessel rupture | $C\bar{F}G$ | gamma |
| 2 | 1.7e-08 | small-small LOCA | $\bar{K}LCF$ | delta |
| | | | | |
| 3 | 4.1e-07 | small LOCA | $\bar{K}C\bar{D}JF\bar{H}$ | delta |
| 3 | 1.2e-07 | small-small LOCA | $\bar{K}\bar{L}\bar{C}\bar{D}\bar{J}\bar{F}\bar{H}$ | delta |
| 3 | 3.6e-08 | medium LOCA | $\bar{K}C\bar{D}\bar{J}F\bar{H}$ | delta |
| 3 | 1.0e-08 | transient class 2 | $\bar{K}LB\bar{P}\bar{Q}\bar{C}$ | alpha |

| Release Category | Probability of TES | Initiating Event | Accident Sequence | Containment Failure Mode |
|---|---|---|---|---|
| 4 | 2.0e-10 | small-small LOCA | $\bar{K}\bar{L}\bar{C}\bar{B}EF$ | gamma |
| 4 | 6.5e-11 | small-small LOCA | $\bar{K}\bar{L}\bar{C}\bar{B}EF$ | delta |
| 5 | 1.0e-09 | small-small LOCA | $\bar{K}\bar{L}\bar{C}\bar{B}E\bar{F}\bar{H}$ | gamma |
| 5 | 2.0e-11 | small-small LOCA | $K\bar{C}E$ | gamma |
| 6 | 6.5e-08 | large LOCA | $CD\bar{F}G$ | epsilon |
| 6 | 5.3e-08 | transient class 2 | $\bar{K}LB\bar{P}\bar{Q}\bar{C}$ | epsilon |
| 6 | 4.8e-08 | small-small LOCA | $\bar{K}LC\bar{F}G$ | epsilon |
| 6 | 8.6e-09 | medium LOCA | $\bar{K}CD\bar{F}G$ | epsilon |
| 6 | 7.1e-09 | small-small LOCA | $\bar{K}L\bar{C}\bar{B}E\bar{F}G$ | epsilon |
| 6 | 1.6e-09 | small LOCA | $\bar{K}CD\bar{F}G$ | epsilon |
| 7 | 1.0e-06 | transient class 2 | $\bar{K}LB\bar{P}\bar{Q}\bar{C}$ | epsilon |
| 7 | 3.5e-07 | small-small LOCA | $\bar{K}LCF$ | epsilon |
| 7 | 2.4e-07 | large LOCA | $\bar{C}D\bar{E}$ | epsilon |
| 7 | 1.9e-07 | small LOCA | $\bar{K}CDF$ | epsilon |
| 7 | 1.8e-07 | small LOCA | $\bar{K}CDF$ | delta |
| 7 | 1.0e-07 | vessel rupture | $\bar{C}\bar{E}$ | epsilon |

For Release Category 7, the most important one from Table 4.1, we see in Table 4.3 that most probable TES leading to release category 7 contributes 42% of the category 7 probability whereas the nine most probable TESs contribute 90% of category 7 probability. Note that all initiating events appear in this top 90% except medium LOCA. This indicates that no initiating event is dominating the probability ranking for release category 7. Important TESs for each release category are given in Table 4.5.

The TES rankings for each release category agree with the rankings reported earlier [3]. Those rankings were conditional on earthquake level. This report sums over all earthquake levels and ranks all the TESs important to release probability. Only those considered important are listed, down to the 1% level in Tables 4.3 and 4.4 and down to the 10% level in Table 4.5.

### 4.3 Probabilities and Risk Contributions of Containment Failure Modes

The contributions to release probability and risk from each containment failure mode are ranked in Tables 4.6 and 4.7 respectively. Containment failure mode epsilon (melt-through) contributes most to probability but is fourth with respect to risk. Containment failure mode delta (overpressure) contributes the most to risk and is second in probability. Containment failure mode beta (containment leakage) contributes least, five orders of magnitude less with respect to both probability and risk.

Table 4.6. Containment failure modes and the probabilities of the terminal event sequences that include the containment failure mode.

| Containment Failure Mode (CFM) | Probability of Release Via that CFM |
|---|---|
| alpha (rupture) | 4.7e-08 |
| beta (leakage) | 3.3e-13 |
| gamma (burning) | 3.1e-07 |
| delta (overpressure) | 1.1e-06 |
| epsilon (melt-through) | 2.4e-06 |

Table 4.7. Containment failure modes and risk contributions of the terminal event sequences that include the containment failure mode.

| Containment Failure Mode | Risk (man-rem/yr) |
|---|---|
| alpha | 2.6e-01 |
| beta | 1.3e-06 |
| gamma | 1.5e+00 |
| delta | 4.0e+00 |
| epsilon | 7.8e-02 |

### 4.4 Probabilities and Risk Contributions of Initiating Events

From Table 4.8 it can be seen that initiating events transient class T2 and small LOCA, contribute over 50% to the total release probability. The same two initiating events also contribute over 50% to the risk (see Table 4.9). Five of the seven initiating events contribute over 90% of the release probability, and four of the seven initiating events contribute over 90% of the risk.

Table 4.8. Initiating events ranked by the probabilities of terminal event sequences that include the initiating event.

| Initiating Event | Probability of TES |
|---|---|
| transient class 2 | 1.3e-06 |
| small LOCA | 8.1e-07 |
| small-small LOCA | 6.2e-07 |
| large LOCA | 4.8e-07 |
| vessel rupture | 3.0e-07 |
| medium LOCA | 1.8e-07 |
| transient class 1 | 7.5e-08 |

Table 4.9. Initiating events ranked by risk contribution of terminal event sequences that include the initiating event.

| Initiating Event | Risk (man-rem/yr) |
|---|---|
| small LOCA | 2.3e+00 |
| transient class 2 | 1.2e+00 |
| small-small LOCA | 1.1e+00 |
| vessel rupture | 9.5e-01 |
| medium LOCA | 2.2e-01 |
| large LOCA | 1.0e-01 |
| transient class 1 | 5.8e-03 |

## 4.5 Probabilities and Risk Contributions of Important Accident Sequences

The most important accident sequences for each initiating event are listed in Tables 4.10 and 4.11. The probabilities and risk contributions are computed by summing the probabilities and risk contributions of the terminal event sequences containing the accident sequences. The accident sequence rankings with respect to probability and risk differ since the accident sequence's associated containment failure mode probabilities and release categories differ.

Table 4.10. Accident sequences given initiating events ranked by the probabilities of terminal event sequences that include the accident sequence.

| Initiating Event | Accident Sequence | Probability of TES that Include the Accident Sequence |
|---|---|---|
| vessel rupture | $CF$ | 1.8e-07 |
| vessel rupture | $\overline{C}\overline{E}$ | 1.0e-07 |
| vessel rupture | $C\overline{F}G$ | 1.9e-08 |
| large LOCA | $\overline{C}D\overline{E}$ | 2.4e-07 |
| large LOCA | $CDF$ | 1.6e-07 |
| large LOCA | $CD\overline{F}G$ | 7.8e-08 |
| large LOCA | $\overline{C}\overline{D}\overline{J}\overline{E}H$ | 3.8e-09 |
| medium LOCA | $\overline{K}\overline{C}D\overline{E}$ | 7.3e-08 |
| medium LOCA | $\overline{K}CDF$ | 6.5e-08 |
| medium LOCA | $\overline{K}C\overline{D}\overline{J}F\overline{H}$ | 3.6e-08 |
| medium LOCA | $\overline{K}CD\overline{F}G$ | 1.0e-08 |
| small LOCA | $\overline{K}C\overline{D}\overline{J}F\overline{H}$ | 4.2e-07 |
| small LOCA | $\overline{K}CDF$ | 3.8e-07 |
| small LOCA | $\overline{K}\overline{C}D\overline{E}$ | 1.1e-08 |
| small-small LOCA | $\overline{K}LCF$ | 4.2e-07 |
| small-small LOCA | $\overline{K}\overline{L}C\overline{D}\overline{J}F\overline{H}$ | 1.2e-07 |
| small-small LOCA | $\overline{K}LC\overline{F}G$ | 5.8e-08 |
| small-small LOCA | $\overline{K}L\overline{C}\overline{B}E\overline{F}\overline{H}$ | 8.6e-09 |
| small-small LOCA | $\overline{K}L\overline{C}\overline{B}E\overline{F}G$ | 8.6e-09 |
| small-small LOCA | $\overline{K}L\overline{C}B\overline{E}$ | 5.8e-09 |
| transient class 2 | $\overline{K}LB\overline{P}\overline{Q}\overline{C}$ | 1.3e-06 |
| transient class 1 | $\overline{K}MLB\overline{P}Q\overline{C}$ | 7.5e-08 |

Table 4.11. Accident sequences given initiating events ranked by the risk contributions of terminal event sequences that include the accident sequence.

| Initiating Event | Accident Sequence | Risk (man-rem/yr) |
|---|---|---|
| vessel rupture | CF | 8.5e-01 |
| vessel rupture | CFG | 9.0e-02 |
| large LOCA | $CD\bar{F}G$ | 7.4e-02 |
| large LOCA | $\bar{C}D\bar{E}$ | 1.8e-02 |
| large LOCA | CDF | 1.2e-02 |
| medium LOCA | $\bar{K}C\bar{D}JF\bar{H}$ | 2.0e-01 |
| medium LOCA | $\bar{K}CD\bar{F}G$ | 9.8e-03 |
| medium LOCA | $\bar{K}\bar{C}D\bar{E}$ | 5.6e-03 |
| medium LOCA | $\bar{K}CDF$ | 5.0e-03 |
| small LOCA | $\bar{K}C\bar{D}\bar{J}F\bar{H}$ | 2.3e+00 |
| small LOCA | $\bar{K}CDF$ | 2.9e-02 |
| small-small LOCA | $\bar{K}\bar{L}C\bar{D}\bar{J}F\bar{H}$ | 6.7e-01 |
| small-small LOCA | $\bar{K}LCF$ | 3.5e-01 |
| small-small LOCA | $\bar{K}LC\bar{F}G$ | 5.5e-02 |
| small-small LOCA | $\bar{K}L\bar{C}BE\bar{F}G$ | 8.1e-03 |
| transient class 2 | $\bar{K}LB\bar{P}\bar{Q}\bar{C}$ | 1.2e+00 |
| transient class 1 | $\bar{K}MLB\bar{P}\bar{Q}\bar{C}$ | 5.8e-03 |

The probability and risk contributions of all important accident sequences (for all initiating events together) are listed in Tables 4.12 and 4.13. Accident sequences with transient class T2 and small LOCA ranked highest with respect to both probability and risk. A sequence involving vessel rupture ranked third when considering risk.

Table 4.12. Accident sequences important to release probability ranked by the sums of the probabilities of terminal event sequences that include the accident sequence.

| Initiating Event | Accident Sequence | Probability of Release |
|---|---|---|
| transient class 2 | $\bar{K}LB\bar{P}\bar{Q}\bar{C}$ | 1.3e-06 |
| small LOCA | $\bar{K}C\bar{D}\bar{J}F\bar{H}$ | 4.2e-07 |
| small-small LOCA | $\bar{K}LCK$ | 4.2e-07 |
| small LOCA | $\bar{K}CDF$ | 3.8e-07 |
| large LOCA | $CD\bar{E}$ | 2.4e-07 |
| vessel rupture | CF | 1.8e-07 |
| large LOCA | CDF | 1.6e-07 |
| small-small LOCA | $\bar{K}\bar{L}C\bar{D}\bar{J}F\bar{H}$ | 1.2e-07 |
| vessel rupture | CE | 1.0e-07 |
| large LOCA | $CD\bar{F}G$ | 7.8e-08 |
| transient class 1 | $\bar{K}\bar{M}LB\bar{P}\bar{Q}\bar{C}$ | 7.5e-08 |
| medium LOCA | $\bar{K}\bar{C}DE$ | 7.3e-08 |
| medium LOCA | $\bar{K}CDF$ | 6.5e-08 |
| small-small LOCA | $\bar{K}LC\bar{F}G$ | 5.8e-08 |
| medium LOCA | $\bar{K}C\bar{D}\bar{J}F\bar{H}$ | 3.6e-08 |
| vessel rupture | $C\bar{F}G$ | 1.9e-08 |

Table 4.13. Accident sequences important to risk ranked by the risk contributions of the terminal event sequences that include the accident sequence.

| Initiating Event | Accident Sequence | Risk (man-rem/yr) |
|---|---|---|
| small LOCA | $\bar{K}C\bar{D}\bar{J}F\bar{H}$ | 2.3e+00 |
| transient class 2 | $\bar{K}LB\bar{P}\bar{Q}\bar{C}$ | 1.2e+00 |
| vessel rupture | CF | 8.5e-01 |
| small-small LOCA | $\bar{K}\bar{L}C\bar{D}\bar{J}F\bar{H}$ | 6.7e-01 |
| small-small LOCA | $\bar{K}LCF$ | 3.5e-01 |
| medium LOCA | $\bar{K}C\bar{D}JF\bar{H}$ | 2.0e-01 |
| vessel rupture | CFG | 9.0e-02 |
| large LOCA | $CD\bar{F}G$ | 7.4e-02 |
| small-small LOCA | $\bar{K}LC\bar{F}G$ | 5.5e-02 |
| small LOCA | $\bar{K}CDF$ | 2.9e-02 |

## 4.6 The Vesely-Fussell and Birnbaum Measures of Important Components and Systems

The response- and fragility-related component failures important to release in each of six earthquake intervals and their Birnbaum measures are listed in Appendix D with regard to risk and in Appendix E with regaro to release category probabilities. The importance ranking is determined by the Vesely-Fussell measure. The Birnbaum measure is then computed only for important components. Failures due to basemat uplift of the containment building, collapse of the service water pump enclosure roof (crib house roof) and shear walls in the AFT complex are important structural component failures. Pipes between buildings and electrical component failures are also important.

Safety systems are ranked in Table 4.15. The probabilities and risk contributions are the sums of the probabilities and risk contributions of the terminal event sequences containing the safety systems. The containment spray injection system (CSIS) and containment fan cooler system (CFCS) are the most important systems with respect to both release probability and risk. They are important to release probability by association with terminal event sequences that have high probability. Their failures, of course, do not cause the core melt but affect the severity of release. In terminal event sequences with transient initiating events followed by bleed and feed operation, CSIS and CFCS influence occurrence of release. The secondary steam relief (SSR), auxiliary feedwater (AFW), and residual heat removal during a LOCA (RHR-LOCA) systems are important to release probability and risk. The reactor protection system (RPS) is not considered important to release probability because most releases occur despite success of the RPS and because the RPS has a low probability of failure.

Table 4.15 Safety Systems Ranked by the Probabilities and Risk Contributions of Terminal Event Sequences That Include the Safety Systems.

Events ordered by:

| Name | $\left(\frac{P[Release]}{Total\ P[Release]}\right)$ | Name | $\left(\frac{Risk\ Contribution}{Total\ Risk}\right)$ |
|---|---|---|---|
| CSIS and CFCS | 5.86e-1 | CSIS and CFCS | 9.74e-1 |
| SSR and AFWS | 4.96e-1 | RHRS (LOCA) | 7.48e-1 |
| RHRS (LOCA) | 4.69e-1 | SSR and AFWS | 2.73e-1 |
| Bleed and feed | 3.66e-1 | Bleed and feed | 2.02e-1 |
| ECI | 2.68e-1 | CSRS recirc. | 4.08e-2 |
| CSRS recirc. | 4.64e-2 | ECI | 2.68e-2 |
| PCS | 2.00e-2 | CFCS recirc. | 2.62e-3 |
| CFCS recirc. | 5.23e-3 | PCS | 9.91e-4 |
| ECR | 1.12e-3 | ECR | 9.07e-5 |
| RPS | 9.10e-5 | RPS | 1.90e-5 |
| RHRS (Transient) | 9.50e-9 | RHRS (Transient) | 1.44e-9 |
| ECF, S/RV-O,-R and CVCS | 0.0 | ECF, S/RV-O,-R and CVCS | 0.0 |

## 4.7 Derivatives of Probabilities and Risk with Respect to Means and Standard Deviations for Fragilities and Responses with Respect to Important Components

### 4.7.1 Fragilities

Table 4.16 provides a description of the fragility categories that have derivatives at least 1 percent as large as the largest derivative. They are ranked in the order of Table 4.17. More detailed descriptions can be found in [18]. These fragility category numbers are used in Table 4.17 and 4.18 to exhibit the sensitivities of important fragility categories with respect to both release probability and risk. The second column of Table 4.17, dp/dmv, lists the values of the derivatives of release probability with respect to the means of the logarithms, and the third column, dp/dsv, lists these derivatives with respect to the standard deviations of the logarithms. Table 4.18 provides similar information except that derivatives of risk are listed. Fragility category importance is based on these derivatives.

Table 4.16. Descriptions of important fragility categories.

| Category | Description |
|---|---|
| 29 | crib house roof |
| 6 | base slab uplift |
| 5 | piping |
| 12 | reactor coolant pumps |
| 36 | wiring and buses |
| 22 | switchgear and relays |
| 4 | steam generators |
| 3 | pressurizer |

Table 4.17. Important fragility categories and derivatives of release probability with respect to the mean or standard deviation of the logarithm of strength, ranked by values of dP(release)/dmv.

| Fragility Category | dp/dmv[a] | dp/dsv[b] | Probability of release[c] |
|---|---|---|---|
| 29 | -5.9e-06 | 7.2e-06 | 3.8e-06 |
| 6 | -5.3e-06 | 1.0e-05 | |
| 5 | -2.5e-06 | 9.9e-07 | |
| 12 | -2.1e-06 | 2.2e-06 | |
| 36 | -2.0e-07 | 7.5e-08 | |
| 22 | -1.5e-07 | 4.6e-08 | |
| 4 | -1.1e-07 | 4.5e-07 | |

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a Derivative of P(release) with respect to the mean m of the logarithmic fragility variable v.

b Derivative of P(release) with respect to the standard deviation s of the logarithmic fragility variable v.

c Point about which the derivative is taken.

Table 4.18. Important fragility categories and derivatives of risk with respect to the mean or standard deviation of the logarithm of strength, ranked by values of dr/dmv = dRisk/dmv.

| Fragility Category | dr/dmv[a] | dr/dsv | Risk[b] (man-rem/yr) |
|---|---|---|---|
| 5 | -7.1e+00 | 2.1e+00 | 5.8e+00 |
| 29 | -3.6e+00 | 2.2e+00 | |
| 6 | -2.0e+00 | 2.3e+00 | |
| 12 | -6.8e-01 | -4.8e-01 | |
| 36 | -3.5e-01 | 1.8e-01 | |
| 4 | -2.4e-01 | -7.0e-01 | |
| 22 | -1.3e-01 | 4.0e-02 | |
| 3 | -3.2e-02 | 4.2e-02 | |

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a Derivative of Risk with respect to the mean m of the logarithmic fragility variable v.

b Point about which the derivative is taken.

Referring to Table 4.16 crib house roof failure is failure of the pump enclosure roof. Failure of this roof is assumed to cause all six service water pumps to fail, causing failure of the service water system. Base slab uplift (soil failure beneath containment building) causes failure of all interbuilding pipes. Piping fragility is related to initiating events and several safety system failures.

#### 4.7.2 Responses

Table 4.19 provides a description of the responses and associated component failures for those derivatives at least 1 percent as large as the largest derivative. They are listed in order ranked by the derivatives. More detailed descriptions can be found in [3]. These response numbers are used in Table 4.20 and 4.21 to exhibit the sensitivities of important responses with respect to both release probability and risk. The second column of Table 4.20, dp/dmv, lists the values of the derivatives of release probability with respect to the means of the logarithms while the third column, dp/dsv, lists these derivatives with respect to the standard deviations of the logarithms. Table 4.21 provides similar information except that derivatives of risk are listed. Response importance is based on these derivatives.

Table 4.19. Description of important responses.

| Response Number | Response Location | Component Failure |
|---|---|---|
| 1 | free field | crib house roof |
| | various[a] | piping |
| 5 | contain. found. | base slab uplift |
| 14 | contain. int. structure | reactor coolant pumps |
| 311 | AFT building | wiring and buses switchgear and relays |
| 15 | contain. int. structure | steam generators |
| 16 | contain. int. structure | pressurizer |
| 310 | AFT building | Diesel generator room shear walls |

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a The important piping responses, with response numbers between 41-301 and 314-333, are in the RCL, RHR, SI, and the auxiliary feedwater and steam piping systems.

Table 4.20. Important responses and derivatives of release probability with respect to the mean or standard deviation of the logarithm of response, ranked by values of dP(release)/dmv.

| Response Number | dp/dmv[a] | dp/dsv | Probability of release[b] |
|---|---|---|---|
| 1 | 5.9e-06 | 6.4e-06 | 3.8e-06 |
| 5 | 5.3e-06 | 5.7e-06 | ↓ |
| 14 | 2.1e-06 | 4.6e-06 | |
| 241 | 6.3e-07 | 3.8e-07 | |
| 296 | 4.3e-07 | 1.2e-06 | |
| 87 | 3.3e-07 | 3.4e-07 | |
| 311 | 3.0e-07 | 3.7e-07 | |
| 301 | 2.0e-07 | 3.9e-07 | |
| 121 | 1.8e-07 | 1.4e-07 | |
| 120 | 1.8e-07 | 2.3e-07 | |
| 265 | 1.5e-07 | 1.2e-07 | |
| 15 | 1.1e-07 | 4.0e-07 | |

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a Derivative of P(release) with respect to the mean m of the logarithmic response variable v.
b Point about which the derivative is taken.

Table 4.21. Important responses and derivatives of risk with respect to the mean or standard deviation of the logarithm of response ranked by values of drisk/dmv.

| Response Number | dr/dmv | dr/dsv | Risk (man-rem/yr) |
|---|---|---|---|
| 1 | 3.6E+00 | 1.9E+00 | 5.8E+00 |
| 241 | 3.1E+00 | 1.8E+00 | |
| 5 | 2.0E+00 | 1.2E+00 | |
| 87 | 1.3E+00 | 1.1E+00 | |
| 120 | 6.9E-01 | 8.3E-01 | |
| 14 | 6.8E-01 | 2.1E+00 | |
| 301 | 5.3E-01 | 1.0E+00 | |
| 311 | 4.7E-01 | 4.6E-01 | |
| 199 | 3.5E-01 | 5.0E-01 | |
| 215 | 2.7E-01 | 5.3E-01 | |
| 265 | 2.4E-01 | 2.9E-01 | |
| 15 | 2.4E-01 | 1.4E+00 | |
| 121 | 2.3E-01 | 2.8E-01 | |
| 122 | 1.3E-01 | 2.5E-01 | |
| 296 | 1.2E-01 | 2.9E-01 | |
| 333 | 9.9E-02 | 2.0E-01 | |

## 4.8 Derivatives of Probabilities and Risk With Respect to Parameters of Important Primary Input Variables

The primary input variables (PIVs) are ranked in importance by the sensitivity of release probability or risk to the mean or standard deviation of the logarithm of the PIV. Table 4.22 provides a description of the important primary input variables listed in ranking order. The primary input variables in Table 4.23 are ranked by values of dP(release)/dmv.

Table 4.22. Description of the important primary input variables.

| Variable No.[a] | Structure or System |
|---|---|
| 1,2 | Soil |
| 5,6 | Containment internal structure and RCL piping |
| 3,4 | Containment shell structure |
| 7,8 | AFT buiding |
| 19,20 | AFW piping system outside containment |
| 33,34 | RHR/SI-2 piping system |
| 29 | RHR suction piping system |
| 31 | RHR/SI-1 piping system |
| 35 | Piping system |
| 49 | Main steam piping system outside containment |
| 53 | Auxiliary main steam piping system--6 inches diameter |

All odd numbered PIVs except the first are frequency variables of the structure or system. The first PIV is a stiffness variable. All even numbered PIVs are damping variables.

The soil variables are most important primarily because of the local site effects. Peak ground acceleration at the site is sensitive to the soil variables, especially damping. Peak ground acceleration affects all of the structural, piping, and equipment responses. PIVs 5 and 6 affect the internal structure, heavy primary loop components and piping. The containment shell structure variables affect the foundation motion (through SSI) and interbuilding piping. The AFT building variables affect the shear walls, internal equipment and piping, and pipes between buildings.

The piping system variables (frequency and damping) are important by association with the responses reported in Section 4.7.2. The RCL piping, for example, is important to LOCAs whereas the other piping systems are parts of the RHR and SI systems, the auxiliary feedwater to the steam generators, and the main and auxiliary steam piping from the steam generators. Some of the small diameter RCL branch pipes were not modeled, and responses assigned to other small diameter pipes were substituted. Variable 35, for example, appears in the list of important variables because one of its responses was used for a small but important unmodeled RCL pipe. The other non-RCL piping systems above have important components both in their own systems, important to safety systems success, and (through substitution of responses) in the RCL, important to initiating events.

The peak rock outcrop acceleration is an input to the SMACS computer code but was not included in this sensitivity analysis. It is felt it is more important than soil damping. Dividing mean soil damping by two, for example, increases the soil free field acceleration by a factor of 1.3 to 1.4; this makes the soil damping very important. Increasing peak rock outcrop acceleration by a factor of two (for fixed values of the probability of recurrence) increases peak ground acceleration by a factor of two, therefore, the rock outcrop acceleration is considered more important than soil damping.

The sensitivities of the PIVs are approximations because the response correlations have not been included in the derivatives. Approximate methods [19] could provide the derivatives with respect to response correlations and the derivatives of response correlations with respect to parameters of primary input variables. Nevertheless, all sensitivities are computed here the same way so they can be used for ranking PIVs.

Table 4.23. Important primary input variables and derivatives of release probability P(release) and risk r with respect to the mean m or standard deviation s of the logarithm of the primary input variables v; ranked by values of dP(release)/dmv.

| Variable Number | dp/dmv[a] | dp/dsv | Release[b] Probability | dr/dmv | dr/dsv | Risk[b] (man-rem/yr) |
|---|---|---|---|---|---|---|
| 2 | -4.2E-06 | 3.6E-06 | 3.8E-06 | -5.6E+00 | 5.0E+00 | 5.8E+00 |
| 1 | 1.9E-06 | 8.1E-06 | ↓ | -4.0E+00 | 6.3E+00 | ↓ |
| 5 | -1.7E-06 | 1.2E-06 | | -1.1E+00 | 1.8E+00 | |
| 19 | 1.7E-06 | 2.4E-06 | | 4.8E+00 | 6.8E+00 | |
| 6 | -1.3E-06 | 1.1E-06 | | -4.6E-01 | 5.8E-01 | |
| 33 | 1.2E-06 | 7.7E-07 | | 5.6E+00 | 4.0E+00 | |
| 3 | 4.9E-07 | 1.7E-06 | | -4.9E-03 | 7.5E-01 | |
| 4 | -4.7E-07 | 5.8E-07 | | -9.6E-01 | 3.0E-01 | |
| 8 | 4.5E-07 | 7.1E-07 | | 3.7E-01 | 1.9E-01 | |
| 35 | 4.0E-07 | 5.1E-07 | | 5.6E-01 | 9.0E-01 | |
| 31 | 1.9E-07 | 3.7E-07 | | 6.9E-01 | 1.4E+00 | |
| 29 | 1.7E-07 | 5.4E-07 | | 5.5E-01 | 1.7E+00 | |
| 7 | 1.5E-07 | 5.6E-07 | | -7.1E-01 | 1.1E+00 | |
| 20 | 9.9E-08 | 2.3E-08 | | 2.2E-01 | 5.0E-02 | |
| 53 | 6.2E-08 | 1.5E-07 | | 1.7E-01 | 4.2E-01 | |
| 34 | -3.7E-08 | 2.4E-09 | | -2.2E-01 | 1.3E-02 | |
| 49 | 3.0E-08 | 8.9E-08 | | 2.5E-02 | 7.5E-02 | |

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a Derivative of P(release) with respect to the mean m of the logarithmic primary input variable v.

b Point about which the derivative is taken.

Table 4.24. Glossary of Accident Sequence Descriptors

| Letter | Description |
|---|---|
| B | Bleed and Feed |
| C | Containment Spray Injection System and Containment fan |
| D | Emergency Coolant Injection - ECI |
| E | Containment Fan Cooler System (Recirculation Phase) - (CFCS-R) |
| F | Residual Heat Removal System (LOCA) - RHRS |
| G | Containment Spray Recirculation System - CSRS |
| H | Emergency Coolant Recirculation - ECR |
| J | Emergency Core Functionability - ECF |
| K | Reactor Protection System - RPS |

(Continued)

| | |
|---|---|
| L | Auxiliary Feedwater System and Secondary Steam Relief - AFWS and SSR |
| M | Power Conversion System - PCS |
| P | Safety/Relief Valves - Open - S/RV-O |
| Q | Safety/Relief Valves - Closed - S/RV-R |
| U | Chemical and Volume Control System - CVCS |
| W | Residual Heat Removal System (Transient) - RHRS |
| $\alpha$ | Containment Rupture - Vessel Steam Explosion |
| $\beta$ | Containment Leakage |
| $\gamma$ | Containment Rupture - Burning |
| $\delta$ | Containment Rupture - Overpressure |
| $\epsilon$ | Containment Rupture - Melt-through |

## 5. ALLOCATION OF RESOURCES TO REDUCE RISK

In Section 5.1, we estimate the changes achievable in important input parameters for equal investments in research or fabrication improvements.

In Section 5.2, we use these estimates, together with the derivatives of risk with respect to input parameters obtained in Section 4, to rank the input parameters in which investments would be most worthwhile for reducing risk. Based on this, we recommend future efforts be concentrated on the high-ranked input parameters. This is the "recommend improvements" activity of Fig. 1-1.

There are two important qualifications to the results in this Section.

First, our marginal value estimates, although the most unbiased we can estimate now without a separate study, are rough estimates and need refinement. Planning for research, while concentrating on the parameters ranked highest and fairly high, will develop more specific estimates for use in final allocation of resources.

Second, the procedure here using ranking is simplified compared to the allocation procedure outlined in Section 1.3. More detailed marginal value estimates, which might be developed during detailed planning for research, would be needed to carry out the full procedure and find the optimal allocation.

With these qualifications in mind, the following illustrates how to do marginal analysis for resource allocation and for ranking of input areas to concentrate research on for the most cost-effective reductions to risk and to release probability, if any reductions are determined to be necessary.

## 5.1 Estimates of Rates of Changes of Component Fragility Parameters and Primary Input Variable Parameters

Table 5.1 lists the derivatives of release probability and risk with respect to the probability distribution parameters of inputs. Inputs are the fragilities and the primary input variables. The parameters are the means and the standard deviations of the logarithms of these variables. The derivative values are taken from Section 4.

Table 5.1 also lists estimates of the changes in the parameters that would result due to equal efforts to improve the parameters. It was not in the scope of this program to estimate the absolute marginal values of changes, the rates of change per dollar, so estimates that are consistent proportionally with each other were developed. The estimates are what it is believed can be achieved in a fixed time, e. g. one fiscal year, for equal, e. g. heroic, efforts to make improvements that change the parameters of the probability distributions of fragilities, responses and primary input variables. These estimates are developed as fractions of $\beta_U$, the standard deviations of the medians $m_v$ and $s_v$ (called $\beta_R$ in Ref. [3]), the standard deviations of the random variables v [3]. Table 5.1 lists $\beta_U$ and $\beta_R$. We estimate the means $m_v$ can be changed by a fraction of $\beta_U$ and the standard deviations $s_v$ can be changed by a fraction of $s_v$ (= $\beta_R$).

The columns of Table 5.1 are:

1. Var No — numbers of the important fragility categories or primary input variables. These numbers are described by Var Name; see also Table 5.2.

2. Para — the parameters (mean m or standard deviation s) of the probability distribution of the important logarithmic variables (fragility categories or primary input variables);

3. Var Type — indicate whether the variable is a fragility or primary input variable. PIV refers to a primary input variable and FRAG refers to a fragility.

4. Var Name — names of the important fragility categories or primary input variables; for primary input variables the last two digits refer to stiffness (st), damping (dp) or frequency (fr). When the first four digits are "subs" then number following this indicates the piping subsystem number. These are identified in Table 5.3.

5. betau or betar — the standard deviations $\beta_R$ representing inherent randomness, and $\beta_U$ representing uncertainty, of the logarithms of the important fragility categories or primary input variables; the $\beta_U$ values are listed with the means m, and then the $\beta_R$ values are listed with the standard deviations s.

6. delm or dels — the estimated changes, $\Delta m$ in the means or $\Delta s$ in the standard deviations, for equal efforts.

7. dp/dmv or dp/dsv — the derivatives of release probability with respect to the means or standard deviations of the variable v identified in columns 1, 2 and 4.

8. dr/dmv or dr/dsv — the derivatives of risk with respect to the means or standard deviations of the variable v.

Table 5.1 Derivatives of release probabilities and risk and estimates of changes in parameters of distribution functions of fragilities and primary input variables for equal efforts in improvements.

| Var No | Para | Var Type | Var Name | betau or betar | delm or dels | dp/dmv or dp/dsv | dr/dmv or dr/dsv |
|---|---|---|---|---|---|---|---|
| 1 | m | PIV | soil-st | 5.7E-01 | 7.1E-02 | 1.9E-06 | -4.0E+00 |
| 2 | m | PIV | soil-dp | 8.6E-01 | 1.0E-01 | -4.1E-06 | -5.6E+00 |
| 3 | m | PIV | ctnmtfr | 4.3E-01 | 1.0E-01 | 4.9E-07 | -4.8E-03 |
| 4 | m | PIV | ctnmtdp | 6.0E-01 | 1.5E-01 | -4.7E-07 | -9.6E-01 |
| 5 | m | PIV | ctnint-fr | 4.3E-01 | 1.0E-01 | -1.7E-06 | -1.1E+00 |
| 6 | m | PIV | ctnint--dp | 6.0E-01 | 1.5E-01 | -1.3E-06 | -4.6E-01 |
| 7 | m | PIV | auxturb-fr | 4.3E-01 | 1.0E-01 | 1.5E-07 | -7.1E-01 |
| 8 | m | PIV | auxturb-dp | 6.0E-01 | -1.5E-01 | 4.5E-07 | 3.6E-01 |
| 13 | m | PIV | subs.01.fr | 4.3E-01 | -1.0E-01 | 2.3E-08 | 1.3E-02 |
| 14 | m | PIV | subs.01.dp | 6.0E-01 | 1.5E-01 | -1.1E-09 | -3.1E-04 |
| 15 | m | PIV | subs.02.fr | 4.3E-01 | -1.0E-01 | 1.6E-10 | 1.4E-04 |
| 16 | m | PIV | subs.02.dp | 6.0E-01 | 1.5E-01 | -7.4E-11 | -6.5E-05 |
| 17 | m | PIV | subs.03.fr | 4.3E-01 | -1.0E-01 | 1.0E-14 | 1.3E-08 |
| 18 | m | PIV | subs.03.dp | 6.0E-01 | -1.5E-01 | 5.5E-15 | 7.1E-09 |
| 19 | m | PIV | subs.04.fr | 4.3E-01 | -1.0E-01 | 1.6E-06 | 4.8E+00 |
| 20 | m | PIV | subs.04.dp | 6.0E-01 | -1.5E-01 | 9.9E-08 | 2.2E-01 |
| 21 | m | PIV | subs.05.fr | 4.3E-01 | -1.0E-01 | 0.0E+00 | 0.0E+00 |
| 22 | m | PIV | subs.05.dp | 6.0E-01 | 1.5E-01 | 0.0E+00 | 0.0E+00 |
| 23 | m | PIV | subs.06.fr | 4.3E-01 | -1.0E-01 | 0.0E+00 | 0.0E+00 |
| 24 | m | PIV | subs.06.dp | 6.0E-01 | 1.5E-01 | 0.0E+00 | 0.0E+00 |
| 25 | m | PIV | subs.07.fr | 4.3E-01 | 1.0E-01 | -8.1E-10 | -2.6E-03 |
| 26 | m | PIV | subs.07.dp | 6.0E-01 | 1.5E-01 | -4.4E-09 | -9.3E-03 |
| 27 | m | PIV | subs.08.fr | 4.3E-01 | -1.0E-01 | 0.0E+00 | 0.0E+00 |
| 28 | m | PIV | subs.08.dp | 6.0E-01 | 1.5E-01 | 0.0E+00 | 0.0E+00 |

*PIV - Primary Input Variable
FRAG - Fragility

(Continued)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 29 | m | PIV | subs.09.fr | 4.3E-01 | -1.0E-01 | 1.6E-07 | 5.4E-01 |
| 30 | m | PIV | subs.09.dp | 6.0E-01 | 1.5E-01 | -4.7E-09 | -1.7E+02 |
| 31 | m | PIV | subs.10.fr | 4.3E-01 | -1.0E-01 | 1.8E-07 | 6.8E-01 |
| 32 | m | PIV | subs.10.dp | 6.0E-01 | 1.5E-01 | -6.3E-09 | -1.8E-02 |
| 33 | m | PIV | subs.11.fr | 4.3E-01 | -1.0E-01 | 1.2E-06 | 5.6E+00 |
| 34 | m | PIV | subs.11.dp | 6.6E-01 | 1.5E-01 | -3.6E-08 | -2.1E-01 |
| 35 | m | PIV | subs.12.fr | 4.3E-01 | -1.0E-01 | 4.0E-07 | 5.5E-01 |
| 36 | m | PIV | subs.12.dp | 6.0E-01 | 1.5E-01 | 1.5E-08 | -5.6E-02 |
| 41 | m | PIV | subs.15.f4 | 4.3E-01 | -1.0E-01 | 0.0E+00 | 0.0E+00 |
| 42 | m | PIV | subs.15.dp | 6.0E-01 | -1.5E-01 | 0.0E+00 | 0.0E+00 |
| 43 | m | PIV | subs.16.fr | 4.3E-01 | -1.0E-01 | 1.9E-09 | 6.4E-03 |
| 44 | m | PIV | subs.16.dp | 6.0E-01 | -1.5E-01 | 2.5E-10 | 8.3E-04 |
| 45 | m | PIV | subs.17.fr | 4.3E-01 | -1.0E-01 | 2.9E-09 | 1.3E-02 |
| 46 | m | PIV | subs.17.dp | 6.0E-01 | 1.5E-01 | 1.9E-12 | -8.1E-06 |
| 47 | m | PIV | subs.18.fr | 4.3E-01 | -1.0E-01 | 0.0E+00 | 0.0E+00 |
| 48 | m | PIV | subs.18.dp | 6.0E-01 | -1.5E-01 | 0.0E+00 | 0.0E+00 |
| 49 | m | PIV | subs.19.fr | 4.3E-01 | -1.0E-01 | 2.9E-08 | 2.5E-02 |
| 50 | m | PIV | subs.19.dp | 6.0E-01 | 1.5E-01 | -1.7E-09 | -1.4E-03 |
| 51 | m | PIV | subs.20.fr | 4.3E-01 | -1.0E-01 | 0.0E+00 | 0.0E+00 |
| 52 | m | PIV | subs.20.dp | 6.0E-01 | -1.5E-01 | 0.0E+00 | 0.0E+00 |
| 53 | m | PIV | subs.21.fr | 4.3E-01 | 1.0E-01 | 6.1E-08 | 1.6E-01 |
| 54 | m | PIV | subs.21.dp | 6.0E-01 | 1.5E-01 | -4.5E-09 | -1.0E-02 |
| 1 | s | PIV | soil-st | 4.0E-01 | -3.3E-02 | 8.1E-06 | 6.2E+00 |
| 2 | s | PIV | soil-dp | 8.6E-01 | 1.0E-01 | 4.1E-06 | 5.6E+00 |
| 3 | s | PIV | ctnmtfr | 2.5E-01 | -4.1E-02 | 1.6E-06 | 7.4E-01 |
| 4 | s | PIV | ctnmtdp | 3.5E-01 | -5.8E-02 | 5.7E-07 | 3.0E-01 |
| 5 | s | PIV | ctnint--fr | 2.5E-01 | -4.1E-02 | 1.2E-06 | 1.7E+00 |
| 6 | s | PIV | ctnint--dp | 3.5E-01 | -5.8E-02 | 1.1E-06 | 5.8E 01 |
| 7 | s | PIV | auxturb-fr | 2.5E-01 | -4.1E-02 | 5.6E-07 | 1.1E+00 |
| 8 | s | PIV | auxturb-dp | 3.5E-01 | -5.8E-02 | 7.1E-07 | 1.9E-01 |
| 13 | s | PIV | subs.01.fr | 2.5E-01 | -4.1E-02 | 3.5E-08 | 1.8E-02 |
| 14 | s | PIV | subs.01.fr | 3.5E-01 | -5.8E-02 | 2.6E-10 | 9.2E-05 |
| 15 | s | PIV | subs.02.fr | 2.5E-01 | -4.1E-02 | 3.2E-10 | 2.8E-04 |
| 16 | s | PIV | subs.02.dp | 3.5E-01 | -5.8E-02 | 9.8E-11 | 8.6E-05 |
| 17 | s | PIV | subs.03.fr | 2.5E-01 | 4.1E-02 | -1.9E-14 | -2.5E-08 |
| 18 | s | PIV | subs.03.dp | 3.5E-01 | 5.8E-02 | -8.1E-15 | -1.0E-08 |
| 19 | s | PIV | subs.04.fr | 2.5E-01 | -4.0E-02 | 2.4E-06 | 6.7E+00 |
| 20 | s | PIV | subs.04.dp | 3.5E-01 | -5.8E-02 | 2.3E-08 | 5.0E-02 |
| 21 | s | PIV | subs.05.fr | 2.5E-01 | -4.1E-02 | 0.0E+00 | 0.0E+00 |
| 22 | s | PIV | subs.05.dp | 3.5E-01 | -5.8E-02 | 0.0E+00 | 0.0E+00 |
| 23 | s | PIV | subs.06.fr | 2.5E-01 | -4.1E-02 | 0.0E+00 | 0.0E+00 |
| 24 | s | PIV | subs.06.dp | 3.5E-01 | -5.8E-02 | 0.0E+00 | 0.0E+00 |
| 25 | s | PIV | subs.07.fr | 2.5E-01 | -4.1E-02 | 3.3E 10 | 1.4E-03 |
| 26 | s | PIV | subs.07.dp | 3.5E-01 | -5.8E-02 | 1.2E 08 | 2.5E-02 |
| 27 | s | PIV | subs.08.fr | 2.5E-01 | -4.1E-02 | 0.0E+00 | 0.0E+00 |
| 28 | s | PIV | subs.08.dp | 3.5E-01 | -5.8E-02 | 0.0E+00 | 0.0E+00 |
| 29 | s | PIV | subs.09.fr | 2.5E-01 | -4.1E-02 | 5.4E-07 | 1.6E+00 |
| 30 | s | PIV | subs.09.dp | 3.5E-01 | -5.8E-02 | 1.8E 09 | 6.6E-03 |
| 31 | s | PIV | subs.10.fr | 2.5E-01 | -4.1E-02 | 3.6E 07 | 1.4E+00 |
| 32 | s | PIV | subs.10.dr | 3.5E-01 | -5.8E-02 | 1.8E 09 | 4.8E-03 |
| 33 | s | PIV | subs.11.fr | 2.5E-01 | -4.1E-02 | 7.7E-07 | 3.9E+00 |
| 34 | s | PIV | subs.11.dp | 3.5E-01 | -5.8E-02 | 2.4E-09 | 1.3E-02 |

(Continued)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 35 | s | PIV | subs.12.fr | 2.5E-01 | -4.1E-02 | 5.1E-07 | 8.9E-01 |
| 36 | s | PIV | subs.12.dp | 3.5E-01 | -5.8E-02 | 4.1E-09 | 4.0E-02 |
| 41 | s | PIV | subs.15.fr | 2.5E-02 | -4.1E-02 | 0.0E+00 | 0.0E+00 |
| 42 | s | PIV | subs.15.dp | 3.5E-01 | -5.8E-02 | 0.0E+00 | 0.0E+00 |
| 43 | s | PIV | subs.16.fr | 2.5E-01 | -4.1E-02 | 5.6E-09 | 1.9E-02 |
| 44 | s | PIV | subs.16.dp | 3.5E-01 | -5.8E-02 | 4.8E-10 | 1.6E-03 |
| 45 | s | PIV | subs.17.fr | 2.5E-01 | -4.1E-02 | 1.0E-08 | 4.5E-02 |
| 46 | s | PIV | subs.17.dp | 3.5E-01 | -5.8E-02 | 6.5E-13 | 5.1E-06 |
| 47 | s | PIV | subs.18.fr | 2.5E-01 | -4.1E-02 | 0.0E+00 | 0.0E+00 |
| 48 | s | PIV | subs.18.dp | 3.5E-01 | -5.8E-02 | 0.0E+00 | 0.0E+00 |
| 49 | s | PIV | subs.19.fr | 2.5E-01 | -4.1E-02 | 8.8E-08 | 7.5E-02 |
| 50 | s | PIV | subs.19.dp | 3.5E-01 | -5.8E-02 | 7.9E-10 | 6.6E-04 |
| 51 | s | PIV | subs.20.fr | 2.5E-01 | -4.1E-02 | 0.0E+00 | 0.0E+00 |
| 52 | s | PIV | subs.20.dp | 3.5E-01 | -5.8E-02 | 0.0E+00 | 0.0E+00 |
| 53 | s | PIV | subs.21.fr | 2.5E-01 | -4.1E-02 | 1.4E-07 | 4.6E-01 |
| 54 | s | PIV | subs.21.dp | 3.5E-01 | -5.8E-02 | 2.8E-09 | 6.4E-03 |
| 3 | m | FRAG | pressurizer | 3.4E-01 | -8.5E-02 | -5.4E-09 | 3.1E-02 |
| 4 | m | FRAG | steam generator | 3.7E-01 | -9.2E-02 | 1.0E-07 | 2.3E-01 |
| 5 | m | FRAG | piping (master) | 3.3E-01 | -8.2E-02 | 2.5E-06 | 7.1E-00 |
| 6 | m | FRAG | base slab uplift | 4.0E-01 | -1.0E-01 | 5.3E-06 | 1.9E+00 |
| 7 | m | FRAG | vert tanks-formed | 3.5E-01 | -8.7E-02 | 1.0E-08 | 1.0E-02 |
| 12 | m | FRAG | rcp | 3.7E-01 | -9.2E-02 | 2.1E-06 | 6.7E-01 |
| 14 | m | FRAG | lg vert pumps | 3.2E-01 | -8.0E-02 | 4.3E-09 | 1.3E-02 |
| 16 | m | FRAG | lg MOVs (> 4in) | 6.0E-01 | -1.5E-01 | 5.6E-09 | 4.6E-03 |
| 22 | m | FRAG | switchgear | 6.6E-01 | -1.6E-01 | 1.4E-07 | 1.2E-01 |
| 23 | m | FRAG | dry transformer | 3.0E-01 | -7.5E-02 | 4.4E-11 | 2.3E-04 |
| 29 | m | FRAG | crib house roof | 2.7E-01 | -6.7E-02 | 5.8E-06 | 3.5E+00 |
| 32 | m | FRAG | cond stor tank | 3.0E-01 | 7.5E-02 | -1.0E-13 | -1.4E-07 |
| 36 | m | FRAG | cable trays | 1.9E-01 | -4.7E-02 | 2.0E-07 | 3.4E-01 |
| 45 | m | FRAG | dies gen walls | 1.8E-01 | -4.5E-02 | 2.5E-08 | 2.6E-02 |
| 49 | m | FRAG | ceram insulator | 2.5E-01 | 6.2E-02 | -5.3E-13 | -7.7E-07 |
| 3 | s | FRAG | pressurizer | 2.1E-01 | -3.5E-02 | -7.7E-09 | 4.1E-02 |
| 4 | s | FRAG | steam generator | 2.4E-01 | 4.0E-02 | 4.4E-07 | -7.0E-01 |
| 5 | s | FRAG | piping (master) | 1.8E-01 | -3.0E-02 | 9.9E-07 | 2.0E+00 |
| 6 | s | FRAG | base slab uplift | 4.0E-01 | -6.6E-02 | 1.0E-05 | 2.3E+00 |
| 7 | s | FRAG | vert tanks-formed | 2.0E-01 | -3.3E-02 | 9.8E-09 | 9.3E-03 |
| 12 | s | FRAG | rcp | 2.4E-01 | 4.0E-02 | 2.2E-06 | -4.8E-01 |
| 14 | s | FRAG | lg vert pumps | 2.2E-01 | -3.6E-02 | 3.0E-02 | 9.7E-03 |
| 16 | s | FRAG | lg MOVs (> 4in) | 2.6E-01 | -4.3E-02 | 5.6E-09 | 4.6E-03 |
| 22 | s | FRAG | switchgear | 4.7E-01 | -7.8E-02 | 4.5E-08 | 4.0E-02 |
| 23 | s | FRAG | dry transformer | 2.8E-01 | -3.6E-02 | 5.7E-11 | 3.0E-04 |
| 29 | s | FRAG | crib house roof | 2.4E-01 | -4.0E-02 | 7.1E-06 | 2.2E+00 |
| 32 | s | FRAG | cond stor tank | 3.8E-01 | -4.6E-02 | 9.7E-14 | 1.2E-07 |
| 36 | s | FRAG | cable trays | 3.4E-01 | -5.6E-02 | 7.4E-08 | 1.8E-01 |

Table 5.2 expands on the variable number-name identification for the PIVs. PIVs 9-12 for structures 4 and 5 were omitted as unimportant. PIVs 37-40 for RCL piping were set equal to variables 5 and 6 for the containment internal structure, because the RCL piping was modeled in the structure model. The "subsystems" are piping systems. Table 5.3 cross references subsystem numbers and piping system names. The numbers are used in the "var name" column of Table 5.1. Description for many of these names can be found in Reference [13].

Table 5.2. Primary input variables (PIVs).

| PIV Variable No. | Name and Structure or System |
|---|---|
| 1 | Soil shear stiffness |
| 2 | Soil damping |
| 3 | Frequency, structure 1 (containment shell structure) |
| 4 | Damping, structure 1 |
| 5 | Frequency, structure 2 (containment internal structure) |
| 6 | Damping, structure 2 |
| 7 | Frequency, structure 3 (aux-fuel-turbine structure) |
| 8 | Damping, structure 3 |
| 13 | Freqency, subsystem 1 |
| 14 | Damping, subsystem 1 |
| 15 | Frequency, subsystem 2 |
| 16 | Damping, subsystem 2 |
| . | . |
| . | . |
| . | . |
| 53 | Frequency, subsystem 21 |
| 54 | Damping, subsystem 21 |
| 55 | Free field (soil) PGA |

Table 5.3. Piping systems used in the analysis.

| Piping Sys. No. | Description |
|---|---|
| 1 | Charging water pump discharge |
| 2 | Pressurizer relief lines |
| 3 | AFW inside containment (to steam generator 1A) |
| 4 | AFW outside containment |
| 5 | SW pump discharge |
| 6 | SW strainer |
| 7 | SW to AFW pump |
| 8 | RHR pump discharge |
| 9 | RHR Pump suction |
| 10 | RHR/SI-1 |

(Continued)

| Piping Sys. No. | Description |
|---|---|
| 11 | RHR/SI-2 |
| 12 | Charging water discharge--boron injection tank to containment |
| 13-14 | RCL including branch lines |
| 15 | Feedwater and AFW, SG-1B to containment penetrations |
| 16 | Feedwater and AFW, SG-1C to containment penetrations |
| 17 | Feedwater and AFW, SG-1D to containment penetrations |
| 18 | SG-1A steam to containment penetration P5 |
| 19 | Steam outside containment from P5 to safety valve manifold, aux. main steam |
| 20 | Steam to turbine driven AFW pump 1A |
| 21 | Main steam from SG-1A and SG-1D to containment penetration |

The changes in the column labeled "delm or dels" of Table 5.1 are to be multiplied by the derivative values in column 7 or 8 to obtain the changes in release probability and risk for equal efforts.

## 5.2 Priority Ranking of Changes

Table 5.5 ranks parameters by the changes of release probability due to equal efforts to change the parameters. Negative changes in release probability are good. The parameter changes in column 6 are due to improvements that require equal efforts. Column 5 contains (del p), the changes in release probability for equal efforts to change means or standard deviations.

Table 5.6 ranks parameters by the changes of risk due to equal efforts to change the parameters. The parameter changes in column 6 are due to improvements that require equal efforts. Column 5 differs from Table 5.5. It contains (del r), the changes in risk for equal efforts to change means or standard deviations. Note, a change that reduces risk may increase release probability; e. g., in the median of soil stiffness.

If improvements are found necessary we recommend research and modifications to the Zion nuclear power plant that cause the parameter changes ranking high in Table 5.6. The specific research and types of modifications are not identified in the present work; only the subject areas are identified. We recommend efforts in the relative proportions listed in column 5 of Table 5.6. The plans for the research and modifications to make the recommended improvements should be used to update the estimates of the changes delm and dels in Table 5.1 and then update Tables 5.5 and 5.6 before final allocation.

Table 5.5 Ranking of improvements according to the changes in release probability due to equal efforts in changing parameters.

| Var No | Para | Var Type* | Var Name | Result del p | delm or dels |
|---|---|---|---|---|---|
| 6 | sd | FRAG | base slab uplift | -6.8E-07 | -6.6E-02 |
| 6 | m | FRAG | base slab uplift | -5.3E-07 | 1.0E-01 |
| 2 | m | PIV | soil-dp | -4.5E-07 | 1.0E-01 |
| 29 | m | FRAG | crib house roof | -3.9E-07 | 6.7E-02 |
| 29 | sd | FRAG | crib house roof | 2.8E-07 | -4.0E-02 |
| 1 | sd | PIV | soil-st | -2.7E-07 | -3.3E-02 |
| 5 | [illegible] | FRAG | piping (master) | -2.0E-07 | 8.2E-02 |
| 6 | sd | PIV | ctnint--dp | -1.9E-07 | 1.5E-01 |
| 12 | m | FRAG | rcp | -1.9E-07 | 9.2E-02 |
| 5 | m | PIV | ctnint--fr | -1.8E-07 | 1.0E-01 |
| 19 | m | PIV | subs.04.fr | -1.7E-07 | -1.0E-01 |
| 2 | sd | PIV | soil-dp | -1.4E-07 | -4.1E-02 |
| 33 | m | PIV | subs.11.fr | -1.3E-07 | -1.0E-01 |
| 19 | sd | PIV | subs.04.fr | -1.0E-07 | -4.1E-02 |
| 4 | m | PIV | ctnmtdp | -7.1E-08 | 1.5E-01 |
| 3 | sd | PIV | ctnmtfr | -6.9E-08 | -4.1E-02 |
| 8 | m | PIV | auxturb-dp | -6.8E-08 | -1.5E-01 |
| 6 | sd | PIV | ctnint--dp | -6.5E-08 | -5.8E-02 |
| 5 | sd | PIV | ctnint--fr | -5.0E-08 | -4.1E-02 |
| 35 | m | PIV | subs.12.fr | -4.3E-08 | -1.0E-01 |
| 8 | sd | PIV | auxturb-dp | -4.1E-08 | -5.8E-02 |
| 4 | sd | PIV | ctnmtdp | -3.3E-08 | -5.8E-02 |
| 33 | sd | PIV | subs.11.fr | -3.2E-08 | -4.1E-02 |
| 5 | sd | FRAG | piping (master) | -2.9E-08 | -3.0E-02 |
| 22 | m | FRAG | switchgear | -2.4E-08 | 1.6E-01 |
| 7 | sd | PIV | auxturb-fr | -2.3E-08 | -4.1E-02 |
| 29 | sd | PIV | subs.09.fr | -2.2E-08 | -4.1E-02 |
| 35 | sd | PIV | subs.12.fr | -2.1E-08 | -4.1E-02 |
| 31 | m | PIV | subs.10.fr | -1.9E-08 | -1.0E-01 |
| 29 | m | PIV | subs.09.fr | -1.8E-08 | -1.0E-01 |
| 31 | sd | PIV | subs.10.fr | -1.5E-08 | -4.1E-02 |
| 20 | m | PIV | subs.04.dp | -1.5E-08 | -1.5E-01 |
| 4 | m | FRAG | steam generator | -1.0E-08 | 9.2E-02 |
| 36 | m | FRAG | cable trays | -9.7E-09 | 4.7E-02 |

*PIV - Primary Input Variable
FRAG - Fragility

Table 5.6 Ranking of improvements according to the changes in risk due to equal efforts in changing parameters.

| Var No | Para | Var Type* | Var Name | Result del r | delm or dels |
|---|---|---|---|---|---|
| 2 | m | PIV | soil-dp | -6.1E-01 | 1.0E-01 |
| 33 | m | PIV | subs.11.fr | -6.0E-01 | -1.0E-01 |
| 5 | m | FRAG | piping (master) | -5.8E-01 | 8.2E-02 |
| 19 | m | PIV | subs.04.fr | -5.1E-01 | -1.0E-01 |
| 1 | m | PIV | soil-st | -2.8E-01 | 7.1E-02 |
| 19 | sd | PIV | subs.04.fr | -2.8E-01 | -4.1E-02 |
| 29 | m | FRAG | crib house roof | -2.4E-01 | 6.7E-02 |
| 2 | sd | PIV | soil-dp | -2.0E-01 | -4.1E-02 |
| 1 | sd | PIV | soil-st | -2.0E-01 | -3.3E-02 |
| 6 | m | FRAG | base slab uplift | -1.9E-01 | 1.0E-01 |
| 33 | sd | PIV | subs.11.fr | -1.6E-01 | -4.1E-02 |
| 6 | sd | FRAG | base slab uplift | -1.5E-02 | -6.6E-02 |
| 4 | m | PIV | ctnmtdp | -1.4E-01 | 1.5E-01 |
| 5 | m | PIV | ctnint--fr | -1.2E-01 | 1.0E-01 |
| 29 | sd | FRAG | crib house roof | -3.8E-02 | -4.0E-02 |
| 7 | m | PIV | auxturb-fr | -7.6E-02 | 1.0E-01 |
| 5 | sd | PIV | ctnint--fr | -7.4E-02 | -4.1E-02 |
| 31 | m | PIV | subs.10.fr | -7.3E-02 | -1.0E-01 |
| 6 | m | PIV | ctnint--dp | -7.0E-02 | 1.5E-01 |
| 29 | sd | PIV | subs.09.fr | -6.9E-02 | -4.1E-02 |
| 12 | m | FRAG | rcp | -6.2E-02 | 9.2E-02 |
| 5 | sd | FRAG | piping (master) | -6.2E-02 | -3.0E-02 |
| 35 | m | PIV | subs.12.fr | -5.9E-02 | -1.0E-01 |
| 31 | sd | PIV | subs.10.fr | -5.9E-02 | -4.1E-02 |
| 29 | m | PIV | subs.09.fr | -5.8E-02 | -1.0E-01 |
| 8 | m | PIV | auxturb-dp | -5.5E-02 | -1.5E-01 |
| 7 | sd | PIV | auxturb-fr | -4.7E-02 | -4.1E-02 |
| 35 | sd | PIV | subs.12.fr | -3.7E-02 | -4.1E-02 |
| 6 | sd | PIV | ctnint--dp | -3.3E-02 | -5.8E-02 |
| 20 | m | PIV | subs.04.dp | -3.3E-02 | -1.5E-01 |
| 34 | m | PIV | subs.11.dp | -3.3E-02 | -1.5E-01 |
| 3 | sd | PIV | ctnmtfr | -3.1E-02 | -4.1E-02 |
| 4 | sd | FRAG | steam generator | -2.8E-02 | 4.0E-02 |
| 4 | m | FRAG | steam generator | -2.2E-02 | 9.2E-02 |
| 22 | m | FRAG | switchgear | -2.0E-02 | 1.6E-01 |
| 12 | sd | FRAG | rcp | -1.9E-02 | 4.0E-02 |
| 53 | m | PIV | subs.21.fr | -1.7E-02 | -1.0E-01 |
| 4 | sd | PIV | ctnmtdp | -1.7E-02 | -5.8E-02 |
| 53 | sd | PIV | subs.21.fr | -1.7E-02 | -4.1E-02 |
| 36 | m | FRAG | cable trays | -1.6E-02 | 4.7E-02 |
| 8 | sd | PIV | auxturb-dp | -1.1E-02 | -5.8E-02 |
| 36 | sd | FRAG | cable trays | -1.0E-02 | -5.6E-02 |
| 36 | m | PIV | subs.12.dp | -8.0E-03 | 1.5E-01 |

* PIV - Primary Input Variable
FRAG - Fragility

## APPENDIX A. DERIVATIVE OF BASIC EVENT PROBABILITY WITH RESPECT TO DISTRIBUTION PARAMETERS

This appendix gives formulas for the derivatives of basic event probability with respect to means, variances, and correlations of responses and strengths. The formulas for derivatives with respect to means and variances are in SEISIM2, and the formula for derivatives with respect to correlations can be incorporated. These formulas are used by SEISIM2 when a cut set has only one basic event and when evaluating the denominator for the slope approximation to the Birnbaum measure (see Appendix D). The derivative with respect to mean response is the same, except for sign, as the derivative with respect to mean strength (formula A2 below), and the derivatives with respect to both response and strength variances are the same (formula A3). Furthermore, the derivative with respect to covariance of response and strength is the same except for sign as the derivative with respect to variance (formula A5).

This appendix derives derivatives under the assumption that response and strength are normal random variables, X and Y, with means, $\mu_X$ and $\mu_Y$, and variances, $\sigma_X^2$ and $\sigma_Y^2$. (If response and strength are lognormal random variables, use the the fact that the logarithm of a lognormal random variable is a normal random variable and the chain rule to find derivatives with respect to parameters of the lognormal random variables.)

If response and strength are independent, basic event probability is

$$P[X > Y] = \int_{-\infty}^{\infty} (1 - F_X(x))dF_Y(x) = 1 - \Phi\left(- \frac{\mu_X-\mu_Y}{\sqrt{\sigma_X^2 + \sigma_Y^2}}\right) \qquad \text{(A1)}$$

where $F_X(x)$, $F_Y(x)$, and $\Phi$ (.) are the cumulative distribution functions of X and Y and the standardized normal random variable. The derivatives are

$$\frac{\partial P[X> Y]}{\partial \mu_X} = \frac{1}{\sqrt{2\pi}} \exp\left[- \frac{(\mu_X-\mu_Y)^2}{2(\sigma_X^2+\sigma_Y^2)}\right] \frac{1}{\sqrt{(\sigma_X^2+\sigma_Y^2)}} = - \frac{\partial P[X> Y]}{\partial \mu_Y} \qquad \text{(A2)}$$

and

$$\frac{\partial P[X>Y]}{\partial \sigma_X^2} = \frac{\partial P[X>Y]}{\partial \sigma_Y^2} = \frac{+1}{\sqrt{2\pi}} \exp\left[-\frac{(\mu_X-\mu_Y)^2}{2(\sigma_X^2+\sigma_Y^2)}\right] \frac{(\mu_X-\mu_Y)}{2(\sigma_X^2+\sigma_Y^2)^{3/2}} \cdot \qquad (A3)$$

If Cov(X,Y) ≠ 0, then basic event probability is

$$P[X>Y] = 1 - \Phi\left(-\frac{\mu_X-\mu_Y}{\sqrt{\sigma_X^2+\sigma_Y^2-\mathrm{Cov}(X,Y)}}\right) \quad . \qquad (A4)$$

The sensitivity to covariance is

$$\frac{\partial P[X>Y]}{\partial \mathrm{Cov}[X,Y]} = \frac{1}{\sqrt{2\pi}} \exp\left[-\frac{(\mu_X-\mu_Y)^2}{2(\sigma_X^2+\sigma_Y^2-\mathrm{Cov}(X,Y))}\right] \frac{(\mu_X-\mu_Y)}{2(\sigma_X^2+\sigma_Y^2-\mathrm{Cov}(X,Y))^{3/2}} \qquad (A5)$$

This can be expressed in terms of the correlation coefficient

$$\rho = \frac{\mathrm{Cov}(X,Y)}{\sqrt{\sigma_X^2\sigma_Y^2}} \qquad (A6)$$

by the chain rule as

$$\frac{\partial P[X>Y]}{\partial \rho} = \frac{\partial P[X>Y]}{\partial \mathrm{Cov}(X,Y)} \frac{\partial \mathrm{Cov}(X,Y)}{\partial \rho} = \frac{\partial P[X>Y]}{\partial \mathrm{Cov}(X,Y)} \sqrt{\sigma_X^2\sigma_Y^2} \quad . \qquad (A7)$$

Subroutine TRUD (true derivative) of SEISIM2 contains formulas A2 and A3. SEISIM1 and SEISIM2 reflect the assumption that Cov(X,Y) = 0.0, but that can be easily changed by adding formulas (A6) and (A7) to SEISIM2.

## APPENDIX B. DERIVATIVE OF TOP EVENT PROBABILITIES

### B.1 Derivatives as Sensitivity Measures

#### Definition

This section defines derivatives and provides examples of how they are computed in the sensitivity analysis. Two simple examples show that the derivative of system failure probability with respect to component failure probability is not equal to the component failure probability. Another example shows how to find the derivative of release probability with respect to system failure probability when systems may either fail or survive. That example shows that, if component failures are dependent events, the derivative with respect to a response or strength parameter involves all dependent components whose failure probabilities depend on that response or strength parameter.

The derivative is the limit of the slopes of chords. Let P denote failure probability and $X_1,\ldots,X_k$ input variables. A system failure probability model is a function $g(X_1,\ldots,X_k)$ such that $P = g(X_1,\ldots,X_k)$. Assume the input variables are functionally independent. The partial derivative with respect to $X_1$ is defined as the limit of slopes,

$$\frac{\partial P}{\partial X_1} \equiv \lim_{\Delta \to 0} \frac{g(X_1+\Delta, X_2,\ldots,X_k) - g(X_1,\ldots,X_k)}{\Delta} \tag{B.1}$$

as long as the limit is the same for positive and negative $\Delta$. The numerical value of the derivative may change as $X_1,\ldots,X_k$ change.

If the function g is linear,

$$g(X_1,\ldots,X_k) = a + \sum_{i=1}^{k} b_i X_i \quad , \tag{B.2}$$

then the derivative with respect to $X_i$ is $b_i$. This is true only for the range of values of $X_1,\ldots,X_k$ for which g is linear.

The vector of partial derivatives $\nabla P = (\partial g/\partial X_1, \ldots, \partial g/\partial X_k)$, called the "gradient", indicates the rate of change of P per unit change in any one of $X_1, \ldots, X_k$ at the specified value $(X_1, \ldots, X_k)$. If all $X_i$, $i = 1,2,\ldots,k$, have the same units of measure, then the magnitudes of $\partial g/\partial X_i$ indicate the relative sensitivity of P to $X_i$ at the specified value of $(X_1, \ldots, X_k)$.

One importance measure is the weighted average of the partial derivative,

$$\int \cdots \int \partial g/\partial X_i \, |_{x_1, \ldots, x_k} f(x_1, \ldots, x_k) dx_1 \ldots dx_k \quad . \qquad (B.3)$$

The weighting function $f(x_1, \ldots, x_k)$ indicates the probability density of input values $x_1, \ldots, x_k$. The weighted average indicates the sensitivity of P to $X_i$ averaged over the range of $X_1, \ldots, X_k$. It is useful if the $X_i$ are random variables or if they are uncertain.

SEISMIM2's Application

SEISIM2 uses the above slope (B.1) to approximate derivatives of probabilities of top events (cut sets, initiating events, accident sequences, terminal event sequences, release category, release, and risk) with respect to parameters (mean or standard deviation) of input variables (response or fragility). As we shall see below, SEISIM2 also uses these slopes to evaluate the Birnbaum measure, $\partial P(\text{release})/\partial P(\text{component failure})$.

Examples

The following two examples show the use of derivatives as sensitivity measures for components. They show component failure probability itself does not indicate component importance or sensitivity of system failure probability. The first example is a series system with two components whose probabilities of failures are $P_1$ and $P_2$. The system is shown in figure B.1. The probability of system failure is $P = 1-(1-P_1)(1-P_2)$, assuming the component failures are independent events. The gradient for this system is $\nabla P = (1-P_2, 1-P_1)$. The derivative value $1-P_2$ indicates the rate of change of system reliability as $P_1$ changes. Since both $P_1$ and $P_2$ are between 0 and 1, the magnitudes of $1-P_2$ and $1-P_1$ indicate the importance of components 1 and 2 respectively. If $P_2$ is larger than $P_1$, system failure probability is more sensitive to $P_2$. If $P_1$ has the uniform cdf on [0,.1], $P_2$ has the uniform cdf on [.1,.2], and $P_1$ and $P_2$ are independent, then the weighted average sensitivities of system failure probability to $P_1$ and $P_2$ are .85 and .95. This is an application of equation B.3.

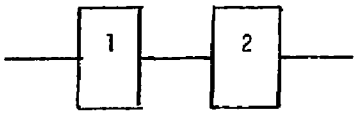



Figure B.1. Series System with Two Components

Now we will compare our first example with a parallel system (Figure B.2). Its failure probability is $P = P_1P_2$ with gradient $\nabla P = (P_2, P_1)$. If $P_2$ is larger than $P_1$, system failure probability is more sensitive to $P_1$, the opposite of a series system.

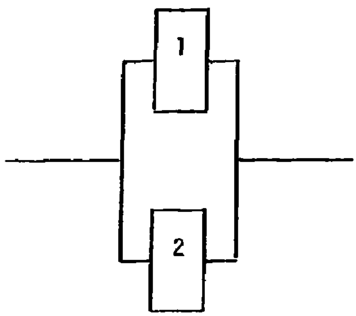
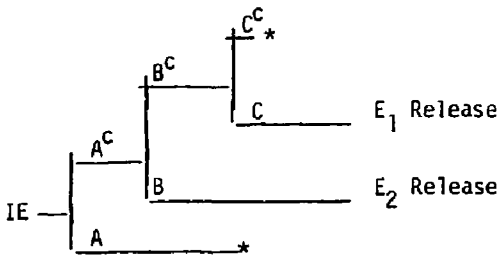



Figure B.2. Parallel System with Two Components

These examples show that component failure probabilities are related to sensitivity, but they also show that the system failure model determines the sensitivity of system failure probability to component failure probabilities.

Sensitivity to Component Failure Probability: Example

We will now discuss sensitivity to components contained in systems contained in event sequences or in release categories. Figure B.3 shows a simple event tree. An initiating event, IE, causes system A to try to function followed by systems B and C. The notation A means system failure and $A^C$ means system success.




P[Release] = $P(E_1) + P(E_2)$

* No release occurs.

Figure B.3. Simple Event Tree

Assume component a is in both systems B and C. Then P[Release], $P_R$, depends on component failure probability, P(a), through both systems and through accident sequences $E_1$ and $E_2$. The sensitivity of release probability to component failure probability is

$$\frac{\partial P_R}{\partial P(a)} = \frac{\partial P(E_1)}{\partial P(a)} + \frac{\partial P(E_2)}{\partial P(a)} \quad \text{(B.4)}$$

which, by the chain rule, is

$$\frac{\partial P_R}{\partial P(a)} = \left[\frac{\partial P(E_1)}{\partial P(B^C)} \cdot \frac{\partial P(B^C)}{\partial P(a)}\right] + \left[\frac{\partial P(E_1)}{\partial P(C)} \cdot \frac{\partial P(C)}{\partial P(a)}\right] + \left[\frac{\partial P(E_2)}{\partial P(B)} \cdot \frac{\partial P(B)}{\partial P(a)}\right]. \quad (B.5)$$

Using next the fact that

$$\frac{\partial P(B)}{\partial P(a)} = \frac{\partial[1-P(B^C)]}{\partial P(a)} = -\frac{\partial P(B^C)}{\partial P(a)} \quad (B.6)$$

will help reduce the number of derivatives. If basic events, a and b, are dependent, then probability of a top event involves not only P(a) and P(b) but P(a and b) or P(a U b). It may also involve the probabilities of the complements of a or b. For example, P(a U b) for dependent events can be anything from P(a) + P(b) - P(a)P(b) to P(a) or P(b), so there is no general way to write the derivative of the probability of a Boolean expression including dependent events. It must be computed indirectly as in equation (B.7) or by shifting the inputs and approximating the derivatives with slopes.

## SEISIM2's Approximation to the Birnbaum Measure

The derivatives of the probabilities of initiating events, system failures, accident sequences, and terminal event sequences with respect to component failure probabilities depend on the representations of these high level events. In SEISIM1, these events are represented as unions of intersections of component success and failure events and not explicitly as functions of system or component success or failure events. Therefore it is not possible to compute directly the derivatives of event sequence probabilities with respect to component failure probabilities. SEISIM2 can approximate derivatives as slopes. It computes the Birnbaum measures for all components as follows. One component is represented by "a". It then computes the rate of change of release probability by shifting the parameters of tne response or strength distribution for the component (numerator in B.7). It then solves for the derivative.

$$\frac{\partial P_R}{\partial P(a)} = \frac{\Delta P_R}{\Delta\mu(R_a)} \bigg/ \frac{\partial P(a)}{\partial\mu(R_a)} \approx \frac{\Delta P_R}{\Delta\sigma^2(R_a)} \bigg/ \frac{\partial P(a)}{\partial\sigma^2(R_a)}. \qquad (B.7)$$

where $R_a$ is the seismic response at component a. The derivatives of P(a) with respect to the mean and variance of component response (denominator in B.7) are computed by the equations in Appendix A.

## B.2 Derivatives with Respect to Parameters of Primary Input Variables Using The Chain Rule

The sensitivity of risk to parameters $\mu$ and $\sigma$ of primary input variables V is indicated by derivatives. The derivatives are computed by the chain rule. One derivative in the chain is computed by SEISIM2, and the other is computed by DPRI. CHAIN combines the derivatives according to this formula,

$$\frac{\partial\ \text{Risk}}{\partial\mu_V} = \Sigma \left[ \frac{\partial\ \text{Risk}}{\partial\mu(R_i)} \cdot \frac{\partial\mu(R_i)}{\partial\mu_V} + \frac{\partial\ \text{Risk}}{\partial\sigma(R_i)} \cdot \frac{\partial\sigma(R_i)}{\partial\mu_V} \right] +$$

$$\Sigma \frac{\partial\ \text{Risk}}{\partial\ \text{Cov}(R_i,R_j)} \cdot \frac{\partial\ \text{Cov}(R_i,R_j)}{\partial\mu_V}, \qquad (B.8)$$

and a similar equation for the sensitivity of risk to standard deviation $\sigma_V$. See O'Connell [7] for the modeling of the logarithmic of responses $R_i$ and computation of the derivatives of response parameters with respect to parameters of the primary input variables.

## APPENDIX C. APPROXIMATING THE VESELY-FUSSELL MEASURE OF COMPONENT AND SYSTEM IMPORTANCE

Probability alone does not indicate importance of basic events to release probability and risk. As illustrated in Appendix B, importance of basic events depends on how the basic events enter fault and event trees and on the dependence of random variables defining basic events. SEISIM2 computes an approximation to the Vesely-Fussell measure. This approximation is used to screen basic events and cut sets for subsequent derivative computations as well as to rank basic events in order of importance.

The cut sets that contain basic events important according to the Vesely-Fussell measure are retained for computing derivatives. This has the effect of culling some of the cut sets with small probabilities. This underestimates derivatives slightly.

The Vesely-Fussell measure is

$$I(BE) = P[\bigcup_{j \in J(BE)} (C_j)] \,/ P[\bigcup_{\text{all } j} (C_j)] \quad , \qquad (C.1)$$

where the set J(BE) is the set of cut sets $C_j$ containing basic event BE. The denominator in C.1 is the probability of the top event.

The Vesely-Fussell measure is adapted to measure importance of basic events to release probability and risk as follows. The denominator contains release probability or risk. The numerator is the contribution to release probability or risk of events containing initiating event or accident sequence cut sets in the set J(BE). In SEISIM1, some of the cut sets representing events include survivals instead of failures. SEISIM2 includes only cut sets that contain failure basic events in set J(BE).

The Vesely-Fussell measure is adapted to measure importance of system failures as follows. The numerator is the contribution to release probability or risk of events containing initiating event or accident sequence cut sets in the set J(BE) which now is the set of all cut sets that include failure of any basic events in the system. The denominator is the same as above. If a component is in more than one system, then this measure is larger than the importance measure of the system because of the components contributing to risk through other systems.

SEISIM2 approximates the probabilities in the numerator and denominator of equation C.1 with the min cut set bounds on the unions of cut sets [1]. This is why SEISIM2's answer is an approximation to the Vesely-Fussell measure. We assume the importance of components and systems to the approximations are approximations to the true importance measures. The importance ranking determined by equation C.1 is compared with the importance ranking determined by the Birnbaum measures in Appendix D.

## APPENDIX D. THE BIRNBAUM IMPORTANCE MEASURE AND USING IT TO VALIDATE THE IMPORTANCE RANKING OF EVENTS -- THEORY AND RESULTS

### SEISIM2's Method and Results

The objectives are threefold. The first is to compute the derivatives of release probability and risk with respect to basic event probabilities. The derivatives with respect to basic event probabilities are called Birnbaum's importance measures in [1]. The second objective is to rank basic events by these derivatives. This ranking indicates importance toward changing risk. The third objective is to compare the rankings with the ranking based on the Vesely-Fussell Measure (Appendix C).

Derivatives are better sensitivity measures than the approximate Vesely-Fussell measures in Appendix C because the latter are ratios of bounds which are not the exact Vesely-Fussell measures. Furthermore, the Vesely-Fussell measures cannot be interpreted as rates of change if basic events are dependent.

SEISIM2 computes the Birnbaum measures of basic events as follows. It changes the means or standard deviations of responses or strengths as required by the user. It computes the slopes of release category probabilities $P_k$, $k=1,2,\ldots,7$, as the ratios of the changes in the release category probabilities and the changes in the means or the standard deviations,

$$\Delta P_k/\Delta\mu \text{ and } \Delta P_k/\Delta\sigma. \qquad (D1)$$

It computes the derivatives $\delta P(BE) / \delta\mu$ and $\delta P(BE) / \delta\sigma$ according the formulas in Appendix A. It then approximates the Birnbaum measures by the average of

$$[\Delta P_k / \Delta\mu] / [\delta P(BE) / \delta\mu] \qquad (D2)$$

and

$$[\Delta P_k / \Delta\sigma] / [\delta P(BE) / \delta\sigma] \qquad (D3)$$

It does these computations for each of the six earthquake levels.

Tables D1-D6 contain the results for the six earthquake levels for the Birnbaum measures and for a ranking comparison. The tables contain only events* found important according to the Vesely-Fussell measure and whose Birnbaum measures are computed by SEISIM2. This excludes important random basic events because SEISIM2 does not computer their Birnbaum measures. See page 85 for the method.

The column labeled "name" contains the failure basic events.** The column labeled V-F is the Vesely-Fussell measure on risk,

$$\sum_{k=1}^{7} VF\ (BE/Cat\ .k)\ w_k\ P_k\ /\ \Sigma\ w_k\ P_k$$

where VF(BE/Cat .k) is the importance measure of basic event BE to category k. The column labeled "RANK V-F" is the rank of each failure basic event according to the Vesely-Fussell measure on risk. The column labeled "BRNBM" contains the weighted sums,

$$\sum_{k=1}^{7} w_k\ \delta P_k\ /\ \delta P(BE). \qquad (D4)$$

Each $w_k$ is the man-rem exposures resulting from a release in category k. Then $w_k P_k$ is the risk for release category k. The column labeled "RANK BM" is the rank of each failure basic event according to the Birnbaum measure on risk. The entry labeled "correlation" is the sample correlation between the rank orders according to the two measures.

Most sample correlations are positive. This means the two rankings generally agree.

The two measures are measuring different quantities. Ranking of basic events by their Birnbaum measures ranks by the change in risk which could be achieved by an

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* Plus some that were forced in; see note in Appendix E. p.88.

** *The names are in a ten-character code defined in Appendix E of Ref. 13.*

equal change to any one basic event probability. Ranking by the Vesely-Fussell measures ranks according to how much of the risk is generated by cut sets which involve the basic event; see Appendix C.

An alternative ranking is to rank by the change in release probability $P_R$ which could be achieved by a proportional change to any one basic event probability. That is, rank by changes $\Delta P_R$ for equal proportional changes $(\Delta P(BE))/P(BE)$; that is, rank by values of

$$P(BE) * \frac{\delta(P_R)}{\delta P(BE)}$$

We have a reason to expect that the latter rankings of basic events would also correlate fairly well with the ranking from the Vesely-Fussell measure. We tentatively make two assumptions that do not really apply to our risk model: (1) the basic event $BE_i$ is uncorrelated with other basic events; and (2) all the probabilities P(cut set j) are small compared to one. Under these conditions, we can derive that, approximately,

$$\frac{1}{(1 - P_R)P_R} * P(BE_i) \frac{\delta P_R}{\delta P(BE_i)} \approx VF(BE_i)$$

Then the rankings based on the left or right hand sides would be the same. Even under our real conditions the rankings may be fairly closely correlated. This expectation has not been tested.

The remaining material in this Appendix shows how to analytically compute derivatives, Birnbaum sensitivity measures, as an alternative to the slope method. The computations have not been programmed yet in SEISIM2.

Table D1 Eq Level 1 out of 6

| NAME | V-F | RANK V-F | BRNBM | RANK BM |
|---|---|---|---|---|
| xoe1142-mi | 4.84E+01 | 1 | 1.38E+01 | 3 |
| zzuolift-- | 4.72E+01 | 2 | 4.28E+01 | 1 |
| rzz01osomo | 1.25E+01 | 3 | 1.35E-03 | 13 |
| xoc10126mi | 2.10E+00 | 4 | 3.40E-01 | 5 |
| xoe1141-mi | 1.79E+00 | 5 | 1.38E+01 | 2 |
| xoa10174mi | 9.74E-01 | 6 | 2.07E-02 | 8 |
| 5ta1----mi | 2.35E-01 | 7 | 1.35E-03 | 12 |
| xob10079mi | 2.25E-01 | 8 | 5.56E-02 | 6 |
| xoc10200mi | 1.06E-01 | 9 | 3.41E-01 | 4 |
| xoa10180mi | 5.32E-02 | 10 | 2.02E-02 | 9 |
| xob10011mi | 2.23E-03 | 11 | 3.50E-02 | 7 |
| xoa10173mi | 1.43E-03 | 12 | 2.00E-02 | 10 |
| xoa10010mi | 1.43E-03 | 13 | 2.00E-02 | 11 |

CORRELATION 0.46

Table D2 Eq Level 2 out of 6

| NAME | V-F | RANK V-F | BRNBM | RANK BM |
|---|---|---|---|---|
| zzuglift-- | 7.51E+01 | 1 | 2.27E+01 | 2 |
| rzz01gspmp | 6.90E+01 | 2 | 2.72E-02 | 21 |
| zzch-roof- | 2.20E+01 | 3 | 2.27E+01 | 1 |
| 5tal----mi | 1.41E+01 | 4 | 2.72E-02 | 22 |
| xoa10174mi | 9.95E+00 | 5 | 3.06E-01 | 18 |
| xoei142-mi | 1.25E+00 | 6 | 6.73E+00 | 11 |
| 6oh1005ami | 8.20E-01 | 7 | 4.28E-04 | 23 |
| xoa10180mi | 5.99E-01 | 8 | 3.06E-01 | 17 |
| xoc10126mi | 3.01E-01 | 9 | 1.92E-01 | 20 |
| kpx1rcpamq | 1.98E-01 | 10 | 1.74E+01 | 3 |
| kpx1rcpdmq | 1.98E-01 | 11 | 1.74E+01 | 4 |
| kpx1rcpbmq | 1.98E-01 | 12 | 1.74E+01 | 6 |
| kpx1rcpcmq | 1.98E-01 | 13 | 1.74E+01 | 5 |
| xob10079mi | 1.06E-01 | 14 | 3.75E-01 | 14 |
| xob10044mi | 9.78E-02 | 15 | 4.65E-01 | 12 |
| mhaisqd-mq | 8.21E-02 | 16 | 1.65E+01 | 7 |
| mhaisqc-mq | 8.21E-02 | 17 | 1.65E+01 | 10 |
| mhaisqb-mq | 8.21E-02 | 18 | 1.65E+01 | 9 |
| mhaisqa-mq | 8.21E-02 | 19 | 1.65E+01 | 8 |
| xoa10178mi | 8.04E-02 | 20 | 3.94E-01 | 13 |
| xoa10010mi | 7.37E-03 | 21 | 3.08E-01 | 15 |
| xoa10173mi | 7.37E-03 | 22 | 3.08E-01 | 16 |
| xoc10200mi | 2.79E-03 | 23 | 1.92E-01 | 19 |

CORRELATION 0.003

Table D3 Eq Level 3 out of 6

| NAME | V-F | RANK V-F | BRNBM | RANK BM |
|---|---|---|---|---|
| zzuplift-- | 4.63E+01 | 1 | 2.99E+00 | 6 |
| zzch-roof- | 4.39E+01 | 2 | 2.99E+00 | 5 |
| zoi1006ami | 1.47E-01 | 25 | 2.65E-02 | 40 |
| zoh1001cmi | 2.07E+00 | 16 | 2.70E-02 | 39 |
| zoq1011ami | 1.07E-01 | 26 | 1.92E-02 | 42 |
| xoe1142-mi | 1.86E+00 | 17 | 4.35E-01 | 20 |
| xoc10200mi | 6.78E-01 | 19 | 1.01E-01 | 22 |
| xoc10126mi | 2.54E+00 | 15 | 1.01E-01 | 23 |
| xoc10057mi | 2.00E-03 | 43 | 1.01E-01 | 21 |
| xob10119mi | 8.60E-02 | 41 | 8.67E-01 | 17 |
| xob10091mi | 8.60E-02 | 40 | 8.67E-01 | 18 |
| xob10079mi | 3.68E+00 | 12 | 9.43E-01 | 12 |
| xob10044mi | 2.13E-03 | 42 | 1.04E+00 | 11 |
| xoa10196mi | 8.60E-02 | 39 | 8.67E-01 | 19 |
| xoa10180mi | 1.83E+01 | 6 | 8.67E-01 | 15 |
| xoa10174mi | 3.12E+01 | 3 | 8.67E-01 | 16 |
| xoa10173mi | 3.18E+00 | 14 | 8.70E-01 | 13 |
| xoa10010mi | 3.18E+00 | 13 | 8.70E-01 | 14 |
| rzz01ospmp | 3.00E+01 | 4 | 7.68E-02 | 37 |
| mvq1510-md | 8.74E-02 | 32 | 7.78E-02 | 27 |
| mvd1002omd | 8.74E-02 | 37 | 7.78E-02 | 31 |
| mvd10019md | 8.74E-02 | 36 | 7.78E-02 | 32 |
| mvd10018md | 8.74E-02 | 29 | 7.78E-02 | 34 |
| mvd10017md | 8.74E-02 | 27 | 7.78E-02 | 25 |
| mvd10016md | 8.74E-02 | 31 | 7.78E-02 | 24 |
| mvd10005md | 8.74E-02 | 33 | 7.78E-02 | 35 |
| mva1008-md | 8.74E-02 | 30 | 7.78E-02 | 26 |
| mva1007-md | 8.74E-02 | 38 | 7.78E-02 | 33 |
| mva1006-md | 8.74E-02 | 35 | 7.78E-02 | 30 |
| mva1005-md | 8.74E-02 | 34 | 7.78E-02 | 29 |
| mva10045md | 8.74E-02 | 28 | 7.78E-02 | 28 |
| mhalsod-mq | 2.45E-01 | 20 | 2.89E+00 | 8 |
| mhalsqc-mq | 2.45E-01 | 22 | 2.89E+00 | 9 |
| mhalsqb-mq | 2.45E-01 | 23 | 2.89E+00 | 7 |
| mhalsqa-mq | 2.45E-01 | 21 | 2.89E+00 | 10 |
| kpx1rcpdmq | 9.82E+00 | 7 | 7.19E+00 | 2 |
| kpx1rcpcmq | 9.82E+00 | 10 | 7.19E+00 | 1 |
| kpx1rcpbmq | 9.82E+00 | 9 | 7.19E+00 | 4 |
| kpx1rcpamq | 9.82E+00 | 8 | 7.19E+00 | 3 |
| 6oh1034bmi | 2.36E-01 | 24 | 2.20E-02 | 41 |
| 6oh1005ami | 7.90E+00 | 11 | 1.41E-02 | 43 |
| 6oh1004ami | 1.68E+00 | 18 | 4.20E-02 | 38 |
| 5tal----mi | 1.93E+01 | 5 | 7.75E-02 | 36 |

CORRELATION 0.31

Table D4 Eq Level 4 out of 6

| NAMES | V-F | RANK V-F | BRNBM | RANK BM |
|---|---|---|---|---|
| rzz01osomo | 7.39E+01 | 1 | 5.13E+00 | 11 |
| 6oh1005ami | 2.82E+01 | 2 | 1.06E-01 | 58 |
| xoc10126mi | 2.82E+01 | 3 | 6.08E+00 | 8 |
| 6oh1004ami | 2.50E+01 | 4 | 3.37E+00 | 21 |
| zoh1001bmi | 2.42E+01 | 5 | 3.35E+00 | 24 |
| zoh1001cmi | 2.40E+01 | 6 | 3.35E+00 | 25 |
| zzch-roof- | 2.40E+01 | 7 | 2.86E+00 | 27 |
| xoa10180mi | 2.09E+01 | 8 | 3.36E+00 | 23 |
| xoa10174mi | 2.09E+01 | 9 | 3.36E+00 | 22 |
| xoc10200mi | 2.07E+01 | 10 | 6.08E+00 | 9 |
| xob10079mi | 9.91E+00 | 11 | 9.76E+00 | 1 |
| xoa10173mi | 6.31E+00 | 12 | 3.57E+00 | 19 |
| zoi1006ami | 6.31E+00 | 13 | 3.23E+00 | 26 |
| xob10011mi | 5.57E+00 | 14 | 9.16E+00 | 3 |
| xoe1141-mi | 3.95E+00 | 15 | 4.29E+00 | 17 |
| xoa10010mi | 3.23E+00 | 16 | 3.57E+00 | 20 |
| zoh1002cmi | 3.14E+00 | 17 | 4.81E+00 | 12 |
| kox1rcpdmq | 1.79E+00 | 18 | 7.50E+00 | 7 |
| rec1393ami | 1.66E+00 | 19 | 3.74E-01 | 49 |
| 5ta1----mi | 1.63E+00 | 20 | 2.65E+00 | 44 |
| rec1393bmi | 1.52E+00 | 21 | 3.74E-01 | 48 |
| kox1rcpcmq | 1.49E+00 | 22 | 7.51E+00 | 4 |
| kox1rcpamq | 1.49E+00 | 23 | 7.51E+00 | 5 |
| kox1rcpbmq | 9.89E-01 | 24 | 7.51E+00 | 6 |
| mra11b--mq | 9.04E-01 | 25 | 2.76E-01 | 50 |
| mva1008-md | 8.08E-01 | 26 | 2.66E+00 | 30 |
| mvd10016md | 7.27E-01 | 27 | 2.66E+00 | 42 |
| mvd10017md | 6.55E-01 | 28 | 2.66E+00 | 38 |
| mvq1530-md | 6.52E-01 | 29 | 2.66E+00 | 32 |
| zzuplift-- | 6.25E-01 | 30 | 2.86E+00 | 28 |
| mvq1510-md | 5.29E-01 | 31 | 2.66E+00 | 34 |
| mrallubbmq | 3.93E-01 | 32 | 2.76E-01 | 51 |
| mvd1002omd | 3.70E-01 | 33 | 2.66E+00 | 29 |
| mva1007-md | 3.70E-01 | 34 | 2.66E+00 | 31 |
| mvd10019md | 3.70E-01 | 35 | 2.66E+00 | 36 |
| mvd10018md | 3.70E-01 | 36 | 2.66E+00 | 39 |
| mha1sgd-mq | 3.08E-01 | 37 | 4.78E+00 | 16 |
| mod1018cmi | 2.26E-01 | 38 | 3.11E-02 | 60 |
| mra185e-mb | 2.14E-01 | 39 | 2.99E-02 | 61 |
| xob10044mi | 2.11E-01 | 40 | 9.69E+00 | 2 |
| 6oj1008ami | 9.31E-02 | 41 | 2.01E-01 | 53 |
| zoh1002dmi | 9.30E-02 | 42 | 2.65E+00 | 45 |
| 6oj1007ami | 7.97E-02 | 43 | 2.00E-01 | 54 |
| mha1sgc-mq | 3.64E-02 | 44 | 4.78E+00 | 13 |
| mha1sgb-mq | 3.64E-02 | 45 | 4.78E+00 | 14 |
| xoe1142-mi | 2.93E-02 | 46 | 4.29E+00 | 18 |
| rec1383ami | 2.19E-02 | 47 | 2.00E-01 | 56 |
| mva1006-md | 2.06E-02 | 48 | 2.66E+00 | 33 |
| zoq1011ami | 1.62E-02 | 49 | 2.18E-01 | 52 |
| mvd10005md | 1.29E-02 | 50 | 2.66E+00 | 41 |

Table D4 Eq Level 4 out of 6 (continued)

| | | | | |
|---|---|---|---|---|
| mod1019cmi | 1.24E-02 | 51 | 5.27E-01 | 47 |
| mhaisqa-mo | 1.23E-02 | 52 | 4.78E+00 | 15 |
| oof118b-mi | 1.20E-02 | 53 | 1.46E-01 | 57 |
| mva1520-md | 1.02E-02 | 54 | 2.66E+00 | 43 |
| xoa10178mi | 9.30E-03 | 55 | 5.80E+00 | 10 |
| mva10045md | 9.26E-03 | 56 | 2.66E+00 | 37 |
| mva1540-md | 7.81E-03 | 57 | 2.66E+00 | 40 |
| mva1005-md | 7.60E-03 | 58 | 2.66E+00 | 35 |
| 6oh1034bmi | 4.91E-03 | 59 | 2.59E-02 | 62 |
| rec1383bmi | 2.59E-03 | 60 | 2.00E-01 | 55 |
| mod1018dmi | 2.47E-03 | 61 | 1.77E-03 | 65 |
| mva185e-mb | 1.58E-03 | 62 | 1.34E-02 | 64 |
| zoi1013bmi | 9.46E-04 | 63 | 1.77E-02 | 63 |
| zzshr-wall | 2.23E-04 | 64 | 1.43E+00 | 46 |
| mod1015cmi | 8.11E-06 | 65 | 4.05E-02 | 59 |
| mra185c-mb | 4.83E-06 | 66 | 1.41E-04 | 66 |

CORRELATION 0.55

Table D5 Eq Level 5 out of 6

| NAME | V-F | RANK V-F | BRNBM | RANK BM |
|---|---|---|---|---|
| rzz01ospmp | 1.22E+02 | 1 | -1.08E+00 | 86 |
| 5tai----mi | 1.18E+02 | 2 | 1.18E+00 | 37 |
| 6oh1005ami | 8.42E+01 | 3 | -7.60E-03 | 85 |
| 6oh1004ami | 4.36E+01 | 4 | 1.09E+00 | 41 |
| zoh1001cmi | 4.28E+01 | 5 | 1.08E+00 | 42 |
| zoh1001bmi | 4.28E+01 | 6 | 1.08E+00 | 43 |
| xoc10126mi | 3.73E+01 | 7 | 1.91E+00 | 18 |
| zzch-roof- | 3.51E+01 | 8 | 5.85E-01 | 52 |
| xoa10174mi | 2.13E+01 | 9 | 6.43E-01 | 50 |
| xoc10200mi | 2.08E+01 | 10 | 1.91E+00 | 19 |
| xoa10180mi | 2.04E+01 | 11 | 6.51E-01 | 49 |
| zzuplift-- | 1.94E+01 | 12 | 5.86E-01 | 51 |
| zoi1006ami | 1.74E+01 | 13 | 1.07E+00 | 44 |
| zoh1002dmi | 1.41E+01 | 14 | 1.61E+00 | 21 |
| xob10044mi | 1.16E+01 | 15 | 5.28E+00 | 2 |
| mhaisqb-mq | 1.08E+01 | 16 | 3.59E+00 | 11 |
| mhaisqc-mq | 1.08E+01 | 17 | 3.59E+00 | 10 |
| mhaisqa-mq | 1.08E+01 | 18 | 3.59E+00 | 9 |
| mhaisqd-mq | 1.07E+01 | 19 | 3.59E+00 | 12 |
| xob10079mi | 9.89E+00 | 20 | 3.78E+00 | 4 |
| kpxircpbmq | 9.47E+00 | 21 | 3.77E+00 | 7 |
| kpxircpcmq | 9.47E+00 | 22 | 3.77E+00 | 5 |
| kpxircpamq | 9.47E+00 | 23 | 3.77E+00 | 6 |
| kpxircpdmq | 9.41E+00 | 24 | 3.76E+00 | 8 |
| xoa10010mi | 6.95E+00 | 25 | 8.22E-01 | 45 |
| xoa10173mi | 6.95E+00 | 26 | 8.22E-01 | 46 |
| xob10011mi | 4.81E+00 | 27 | 4.58E+00 | 3 |
| xoe1142-mi | 4.73E+00 | 28 | 7.59E-01 | 48 |
| xoa10178mi | 4.03E+00 | 29 | 2.02E+00 | 15 |
| mvd1002pmd | 3.63E+00 | 30 | 1.19E+00 | 32 |
| mvo1520-md | 3.63E+00 | 31 | 1.19E+00 | 22 |
| mvd10017md | 3.63E+00 | 32 | 1.19E+00 | 25 |
| mva10045md | 3.63E+00 | 33 | 1.19E+00 | 26 |
| mva1007-md | 3.63E+00 | 34 | 1.19E+00 | 29 |
| mvd10019md | 3.63E+00 | 35 | 1.19E+00 | 30 |
| mva1008-md | 3.63E+00 | 36 | 1.19E+00 | 35 |
| mva1006-md | 3.63E+00 | 37 | 1.19E+00 | 33 |
| mvd10018md | 3.63E+00 | 38 | 1.19E+00 | 28 |
| mvq1540-md | 3.63E+00 | 39 | 1.19E+00 | 34 |
| mvd10016md | 3.63E+00 | 40 | 1.19E+00 | 24 |
| mvo1510-md | 3.63E+00 | 41 | 1.19E+00 | 36 |
| mva1005-md | 3.63E+00 | 42 | 1.19E+00 | 23 |
| mvd10005md | 3.63E+00 | 43 | 1.19E+00 | 31 |
| mvq1530-md | 3.63E+00 | 44 | 1.19E+00 | 27 |
| zoh1002cmi | 3.09E+00 | 45 | 2.04E+00 | 14 |
| rec1393ami | 2.02E+00 | 46 | 9.58E-02 | 55 |
| rec1393bmi | 2.02E+00 | 47 | 9.58E-02 | 57 |
| rec1393cmi | 2.02E+00 | 48 | 9.58E-02 | 56 |
| rec1383bmi | 1.50E+00 | 49 | 6.56E-02 | 66 |
| rec1383ami | 1.50E+00 | 50 | 6.56E-02 | 67 |

Table D5 Eq Level 5 out 6 (continued)

| | | | | |
|---|---|---|---|---|
| zog1011ami | 1.26E+00 | 51 | 7.72E-02 | 59 |
| xoe1141-mi | 8.39E-01 | 52 | 7.60E-01 | 47 |
| zzshr-wall | 8.27E-01 | 53 | 2.93E-01 | 53 |
| mod1018cmi | 7.77E-01 | 54 | 1.16E-02 | 78 |
| mra11b--mo | 7.46E-01 | 55 | 5.12E-02 | 69 |
| mra11ubbmo | 7.46E-01 | 56 | 5.12E-02 | 68 |
| xob10119mi | 6.70E-01 | 57 | 1.17E+00 | 40 |
| xob10091mi | 6.70E-01 | 58 | 1.17E+00 | 38 |
| xoa10196mi | 6.70E-01 | 59 | 1.17E+00 | 39 |
| mra185e-mb | 6.55E-01 | 60 | 1.43E-02 | 74 |
| 6oi1008ami | 5.98E-01 | 61 | 6.63E-02 | 60 |
| xoc10057mi | 5.84E-01 | 62 | 1.92E+00 | 17 |
| zpbr001ame | 4.58E-01 | 63 | 6.57E-02 | 61 |
| zpbr001amo | 4.58E-01 | 64 | 6.57E-02 | 63 |
| zpbr002bmo | 4.58E-01 | 65 | 6.57E-02 | 64 |
| zpbr002bme | 4.58E-01 | 66 | 6.57E-02 | 62 |
| 6oh1005bmi | 4.12E-01 | 67 | 2.89E+00 | 13 |
| wvb1presmo | 3.78E-01 | 68 | 5.37E+00 | 1 |
| 6oh1034bmi | 2.43E-01 | 69 | 1.22E-02 | 75 |
| xoa10197mi | 1.55E-01 | 70 | 1.78E+00 | 20 |
| oof118b-mi | 1.51E-01 | 71 | 2.01E-02 | 73 |
| 6oi1007ami | 1.51E-01 | 72 | 6.56E-02 | 65 |
| xoc10023mi | 1.13E-01 | 73 | 1.92E+00 | 16 |
| 6ta1001ami | 1.73E-02 | 74 | 3.32E-02 | 70 |
| 6oh1032ami | 1.43E-02 | 75 | 2.66E-02 | 71 |
| 6oh1036ami | 1.43E-02 | 76 | 2.66E-02 | 72 |
| mod1019cmi | 1.40E-02 | 77 | 1.02E-01 | 54 |
| mvo185e-mb | 1.12E-02 | 78 | 8.96E-03 | 83 |
| 6ta1007cmi | 6.60E-03 | 79 | 1.11E-02 | 81 |
| 6ta1008dmi | 6.60E-03 | 80 | 1.11E-02 | 82 |
| 6ta1005ami | 6.60E-03 | 81 | 1.11E-02 | 79 |
| 6ta1006bmi | 6.60E-03 | 82 | 1.11E-02 | 80 |
| zoi1013bmi | 5.09E-03 | 83 | 1.16E-02 | 77 |
| 6oi1006bmi | 4.38E-03 | 84 | 1.16E-02 | 76 |
| mod1018dmi | 4.22E-03 | 85 | 2.15E-04 | 84 |
| 6oe1120ami | 8.99E-04 | 86 | 9.56E-02 | 58 |

CORRELATION 0.50

Table D6 Eq Level 6 out of 6

| NAME | V-F | V-F RANK | BRNBM | RANK BM |
|---|---|---|---|---|
| 6oh1005ami | 1.26E+02 | 1 | -3.27E-03 | 85 |
| 6oh1004ami | 1.22E+02 | 2 | 5.05E-01 | 46 |
| zoh1001cmi | 1.22E+02 | 3 | 5.03E-01 | 47 |
| rzz01ospmp | 1.15E+02 | 4 | -7.90E+01 | 86 |
| zoh1001bmi | 1.06E+02 | 5 | 5.03E-01 | 48 |
| zzch-root- | 6.05E+01 | 6 | 4.27E-01 | 50 |
| xob10011mi | 4.79E+01 | 7 | 1.87E+00 | 2 |
| zoh1002cmi | 4.74E+01 | 8 | 1.05E+00 | 15 |
| xoc10126mi | 3.97E+01 | 9 | 8.38E-01 | 22 |
| zzuolift-- | 3.89E+01 | 10 | 4.28E-01 | 49 |
| mhalsoa-ma | 3.20E+01 | 11 | 1.53E+00 | 10 |
| mhalsob-ma | 3.02E+01 | 12 | 1.53E+00 | 8 |
| xoa10180mi | 2.95E+01 | 13 | 3.97E-01 | 53 |
| xoa10174mi | 2.93E+01 | 14 | 3.90E-01 | 54 |
| xob10079mi | 2.90E+01 | 15 | 1.50E+00 | 12 |
| zoi1006ami | 2.89E+01 | 16 | 5.54E-01 | 40 |
| mhalsoc-ma | 2.88E+01 | 17 | 1.53E+00 | 9 |
| mhalsod-ma | 2.84E+01 | 18 | 1.53E+00 | 11 |
| kpxircpcma | 2.79E+01 | 19 | 1.65E+00 | 5 |
| xoa10173mi | 2.58E+01 | 20 | 5.40E-01 | 42 |
| xoc10200mi | 2.22E+01 | 21 | 8.40E-01 | 21 |
| kpxircpdma | 1.92E+01 | 22 | 1.64E+00 | 7 |
| xoa10010mi | 1.59E+01 | 23 | 5.40E-01 | 41 |
| xob10044mi | 1.07E+01 | 24 | 1.73E+00 | 3 |
| 5tal----mi | 6.78E+00 | 25 | 5.63E-01 | 39 |
| xoe1141-mi | 5.94E+00 | 26 | 4.18E-01 | 52 |
| zoh1002dmi | 5.91E+00 | 27 | 1.13E+00 | 14 |
| mva1540-md | 4.97E+00 | 28 | 5.67E-01 | 26 |
| xoa10178mi | 4.92E+00 | 29 | 8.96E-01 | 17 |
| mvd10019md | 4.78E+00 | 30 | 5.67E-01 | 28 |
| mva1006-md | 4.78E+00 | 31 | 5.67E-01 | 36 |
| mva1510-md | 4.75E+00 | 32 | 5.67E-01 | 35 |
| mvd10016md | 4.75E+00 | 33 | 5.67E-01 | 34 |
| mva10045md | 4.75E+00 | 34 | 5.67E-01 | 29 |
| mva1005-md | 4.75E+00 | 35 | 5.67E-01 | 38 |
| mvd10017md | 4.75E+00 | 36 | 5.67E-01 | 32 |
| mvd10005md | 4.75E+00 | 37 | 5.67E-01 | 30 |
| xob10091mi | 3.11E+00 | 38 | 5.34E-01 | 44 |
| kpxircpbma | 2.62E+00 | 39 | 1.65E+00 | 4 |
| kpxircpama | 2.58E+00 | 40 | 1.65E+00 | 6 |
| xoa10196mi | 2.46E+00 | 41 | 5.34E-01 | 43 |
| xoe1142-mi | 2.43E+00 | 42 | 4.18E-01 | 51 |
| wvbloresma | 2.42E+00 | 43 | 2.40E+00 | 1 |
| zpbr002bma | 1.79E+00 | 44 | 3.45E-02 | 64 |
| zpbr001ame | 1.74E+00 | 45 | 3.45E-02 | 62 |
| 6oi1007ami | 1.26E+00 | 46 | 3.45E-02 | 61 |
| zpbr002bme | 1.26E+00 | 47 | 3.45E-02 | 65 |
| rec1393cmi | 1.19E+00 | 48 | 3.63E-02 | 56 |
| zpbr001ama | 1.14E+00 | 49 | 3.45E-02 | 63 |

Table D6 Eq Level 6 out 6 (Continued)

| | | | | |
|---|---|---|---|---|
| 6oi1008ami | 1.14E+00 | 50 | 3.46E-02 | 60 |
| rec1393bmi | 1.05E+00 | 51 | 3.63E-02 | 57 |
| xob10119mi | 1.02E+00 | 52 | 5.34E-01 | 45 |
| rec1393ami | 9.31E-01 | 53 | 3.63E-02 | 58 |
| rec1383bmi | 8.98E-01 | 54 | 3.45E-02 | 67 |
| zoq1011ami | 5.05E-01 | 55 | 3.58E-02 | 59 |
| 6oh1005cmi | 3.76E-01 | 56 | 1.17E+00 | 13 |
| rec1383ami | 3.70E-01 | 57 | 3.45E-02 | 66 |
| mvd10018md | 3.09E-01 | 58 | 5.67E-01 | 31 |
| 6oh1005bmi | 3.08E-01 | 59 | 9.21E-01 | 16 |
| mod1018cmi | 2.98E-01 | 60 | 1.08E-03 | 78 |
| xoc10057mi | 2.91E-01 | 61 | 8.41E-01 | 18 |
| xoc10125mi | 2.89E-01 | 62 | 8.41E-01 | 20 |
| rtr139--mk | 2.74E-01 | 63 | 3.43E-02 | 69 |
| xoc10023mi | 2.18E-01 | 64 | 8.41E-01 | 19 |
| rtr138--mk | 1.40E-01 | 65 | 3.43E-02 | 68 |
| mva1530-md | 1.35E-01 | 66 | 5.67E-01 | 33 |
| mva1008-md | 1.35E-01 | 67 | 5.67E-01 | 27 |
| mvd1002omd | 1.35E-01 | 68 | 5.67E-01 | 24 |
| mva1520-md | 1.04E-01 | 69 | 5.67E-01 | 37 |
| mva1007-md | 1.04E-01 | 70 | 5.67E-01 | 25 |
| zzshr-wall | 1.02E-01 | 71 | 2.14E-01 | 55 |
| mra185e-mb | 2.75E-02 | 72 | 1.32E-03 | 75 |
| xpa10197mi | 2.39E-02 | 73 | 7.03E-01 | 23 |
| mra11ubbmo | 2.24E-02 | 74 | 3.16E-03 | 70 |
| mra11b--ma | 1.95E-02 | 75 | 3.16E-03 | 71 |
| 6oh1034bmi | 1.18E-02 | 76 | 1.22E-03 | 77 |
| qof118b-mi | 1.08E-02 | 77 | 1.02E-03 | 83 |
| mva185e-mb | 1.06E-02 | 78 | 8.72E-04 | 84 |
| zoi1013bmi | 5.42E-03 | 79 | 1.25E-03 | 76 |
| 6ta1001ami | 5.03E-03 | 80 | 2.25E-03 | 74 |
| 6ta1006bmi | 3.92E-03 | 81 | 1.07E-03 | 80 |
| 6ta1007cmi | 3.92E-03 | 82 | 1.07E-03 | 81 |
| 6ta1008dmi | 3.92E-03 | 83 | 1.07E-03 | 82 |
| 6ta1005ami | 3.92E-03 | 84 | 1.07E-03 | 79 |
| 6oh1036ami | 3.81E-03 | 85 | 2.67E-03 | 73 |
| 6oh1032ami | 3.81E-03 | 86 | 2.67E-03 | 72 |

CORRELATION 0.46

## Analytical Derivatives Approach to Evaluation of the Birnbaum Measure

Because of the structure of the events modeled in SEISIM1 (see Section 2.1 or Ref. 13), we can develop the Birnbaum measure as a chain of analytical derivatives. The last element in the chain will be evaluation of probability of a cut set by a multivariate normal integral. Implementation in SEISIM2 will give greater accuracy than the slope approach, with potential economy in computer time and storage.

All top events (accident sequences or initiating events) are represented as a union of minimal cut sets. Their probabilities are aproximated in SEISIM1 by:

$$P\,[\text{Top Event}] = 1 - \prod_{j=1}^{n} (1-P(C_j)), \tag{D6}$$

where $C_j$ is a minimal cut set in a top event and n is the number of cut sets in the top event. The derivative of (D6) is used in approximating the derivatives of top event probabilities. The derivative of this approximation to top event probability is:

$$\sum_{\substack{j=1 \\ j \in S_i}}^{n} \delta P(C_j)/\delta P(B_i) \prod_{k \neq j} (1-P(C_k)) \tag{D7}$$

where $(B_i)$ is some basic event in at least one cut set. The set $S_i$ is the set of all cut sets $C_j$ that contain the basic event $B_i$. This derivative can then be used with the functional form of the top event probability and the chain rule to compute derivatives of top event probabilities with respect to basic event probabilities. (SEISIM2 approximates derivatives of top event probabilities with slopes, not analytical derivatives as in equation (D7).)

If $B_1$ is statistically independent of $B_2,\ldots,B_n$ then $P(B_1)$ can be factored out of the cut set probability. The derivative of cut set probability with respect to $P(B_1)$ is then the (n-1) dimensional multinormal integral:

$$\delta P(C_j)/\delta P(B_1) = P \bigcup_{i=2}^{n} B_i = \int_{-\beta_2}^{\infty} \cdots \int_{-\beta_n}^{\infty} \phi(z_2,\ldots,z_n)\, dz_2 \ldots dz_n \qquad \text{(D8)}$$

where $\phi(.)$ is the standard multinormal pdf and

$Z_i = R_i - S_i$; $R_i$ and $S_i$ are the response and fragility for component failure $B_i$;

$$\beta_i = (\mu_{R_i} - \mu_{S_i})/\sqrt{\sigma_{R_i}^2 + \sigma_{S_i}^2 - 2\,\mathrm{Cov}\,(R_i, S_i)} \qquad \text{(D9)}$$

If $B_1$ statistically depends on some other basic event in $C_j$, the derivative is similar. We can find it by the chain rule as follows. By definition [3]

$$P(C_j) = \int_{-\beta_1}^{\infty} \cdots \int_{-\beta_n}^{\infty} \phi(\underline{z})\, \underline{dz} \qquad \text{(D10)}$$

for some $\underline{\beta} = (\beta_1,\ldots,\beta_n)$ with $\underline{z} = (z_1, \ldots, z_n)$. Also by definition,

$$P(B_1) = \int_{-\beta_1}^{\infty} \phi\,(z)\, dz. \qquad \text{(D11)}$$

Consequently we can compute $\delta P(C_j)/\delta P(B_1)$ by the chain rule, because we can compute the derivative

$$\frac{\delta P(C_j)}{\delta \mu_{S_1}} = \frac{\delta P(C_j)}{\delta P(B_1)} \frac{\delta P(B_1)}{\delta \mu_{S_1}} \qquad \text{(D12)}$$

and similiar derivatives with respect to $\mu_R$, $\sigma_S^2$, $\sigma_R^2$ and $\mathrm{Cov}\,(R_1, S_1)$ and solve for $\delta P(C_j)/\delta P(B_1)$. These formulas give

$$\frac{\delta P(C_j)}{\delta P(B_1)} = \frac{\delta P(C_j)}{\delta \mu_{S_1}} \Big/ \frac{\delta P(B_1)}{\delta \mu_{S_1}} = \frac{\delta P(C_j)}{\delta \sigma_S^2} \Big/ \frac{\delta P(B_1)}{\delta \sigma_S^2} . \tag{D13}$$

The derivatives $\delta P(B_1)/\delta \mu_S$ and $\delta P(B_1)/\delta \sigma_S^2$ are computed in subroutine TRUD. The derivatives $\delta P(C_j)/\delta \mu_S$ and $\delta P(C_j)/\delta \sigma_S^2$ are approximated by slopes in subroutine DERIV. Therefore we can compute $\delta P(C_j)/\delta P(B_1)$ two ways and compare the ratios. I don't expect exact equality because of the approximation in DERIV.

TRUD uses the exact formulas (Equations A2, A3):

$$\delta P(B_j)/\delta \mu_{S_1} = \phi(-\beta_1)/\sqrt{\sigma_{S_1}^2 + \sigma_{R_1}^2 - 2\ \mathrm{Cov}(R_1, S_1)} \tag{D14}$$

and

$$\delta P(B_1)/\delta \sigma_{S_1}^2 = - \phi(-\beta_1)\ ((\mu_{R_1} - \mu_{S_1})/2)^*\ (\sigma_{R_1}^2 + \sigma_{S_1}^2 - 2\ \mathrm{Cov}(R_1, S_1))^{3/2}$$

The exact formulas for the numerators of the ratios (Ref. 11) are

$$\frac{\delta P(C_j)}{\delta \mu_{S_1}} = \frac{\int_{-\beta_2}^{\infty} \cdots \int_{-\beta_{n_j}}^{\infty} \phi(-\beta_1, z_2, \ldots z_{n_j}) dz_2 \ldots dz_{n_j}}{\sqrt{\sigma_{R_1}^2 + \sigma_{S_1}^2 - 2\ \mathrm{Cov}\ (R_1, S_1)}} \tag{D16}$$

and

$$\frac{\delta P(C_j)}{\delta \sigma_{S_1}^2} = \frac{-\frac{1}{2} \int_{-\beta_2}^{\infty} \cdots \int_{-\beta_{n_j}}^{\infty} \phi(-\beta_1, z_2, \ldots, z_{n_j}) dz_2 \ldots dz_{n_j}^*\ (\mu_{R_1} - \mu_{S_1})}{(\sigma_{R_1}^2 + \sigma_{S_1}^2 - 2\ \mathrm{Cov}(R_1, S_1))^{3/2}}$$

if all $\mu_{R_i}$, $\mu_{S_i}$, $\sigma_{R_i}^2$, $\sigma_{S_i}^2$ and $\mathrm{cov}(R_i, S_i)$ are mathematically independent of $\mu_{R_1}$ and $\sigma_{S_1}^2$. If so, tne ratios are

$$\frac{\delta P(C_j)}{\delta P(B_1)} = \frac{\int_{-\beta_2}^{\infty} \cdots \int_{-\beta_{n_j}} \phi(-\beta_1, z_2, \ldots, z_{n_j}) dz_2 \ldots dz_{n_j}}{\phi(-\beta_1)} \quad \text{(D18)}$$

from both ratios of (D13).

If the parameters of $\beta_1$ are mathematically dependent on the parameters of $\beta_2$, then, for example $\beta_1 = \beta_2$

$$\frac{\delta P(C_j)}{\delta P(B_1)} = \int_{-\beta_2}^{\infty} \cdots \int_{-\beta_{n_j}}^{\infty} \phi(-\beta_1, z_2, \ldots, z_{n_j}) dz_2 \ldots dz_{n_j} / \phi(-\beta_1)$$

$$+ \int_{-\beta_1}^{\infty} \int_{-\beta_3}^{\infty} \cdots \int_{-\beta_{n_j}}^{\infty} d(z_1, -\beta_2, z_3, \ldots, z_{n_j}) dz_1 \ldots d_{n_J} \cdot$$

$$\sqrt{\frac{\sigma_{R_1}^2 + \sigma_{S_1}^2 - 2\,\mathrm{Cov}(R_1, S_1)}{\sigma_{R_2}^2 + \sigma_{S_2}^2 - 2\,\mathrm{Cov}(R_2, S_2)}} \cdot \frac{1}{\phi(-\beta_1)} \quad \text{(D19)}$$

The first term in the formula is same as $\delta P(C_j)/\delta P(B_1)$ if all parameters in $\beta_1$ are independent of parameters in $\beta_2, \ldots, \beta_{n_j}$. Modifications of the formula for other equal variables are clear. Equal $\mu_{R_i}$, $\mu_{S_i}$, $\sigma_{R_i}^2$, $\sigma_{S_i}^2$ or $\mathrm{Cov}(R_i, S_i)$ are the only dependence we are likely to encounter and to quantify.

The integrands factor if basic events $B_1$ or $B_2$ are statistically independent of $B_3, \ldots B_{n_j}$.

Programming the derivatives is not as difficult as it appears. SEISIM part 2 already computes $\Delta P(C_j)/\Delta\mu_{S_k}$ and $\Delta P(C_j)/\Delta\sigma_{S_k}^2$ for dominant basic events $B_k$ in subroutine DERIV. It also computes $\delta P(B_k)/\delta\mu_{S_k}$ and $\delta P(B_k)\delta\sigma^2_{S_k}$ in subroutine TRUD for all response dependent basic events.

So we can get $\delta P(C_j)/\delta P(B_k)$ from the ratios, (D13). We can also compute $\delta P(C_j)/\delta P(B_k)$ directly from (D8), (D18) or (D19) which are exact. See figure D1 for flow chart. We program all three and compare for some cut sets before we resort to approximate ratios.

Just as DERIV now computes slopes only for important top events and basic events, it should be programmed to do BIRNIMP and BIRNBAM only for the same top events and basic events.

Do for initiating events, system failures, accident sequences, terminal event sequences and radioactive releases

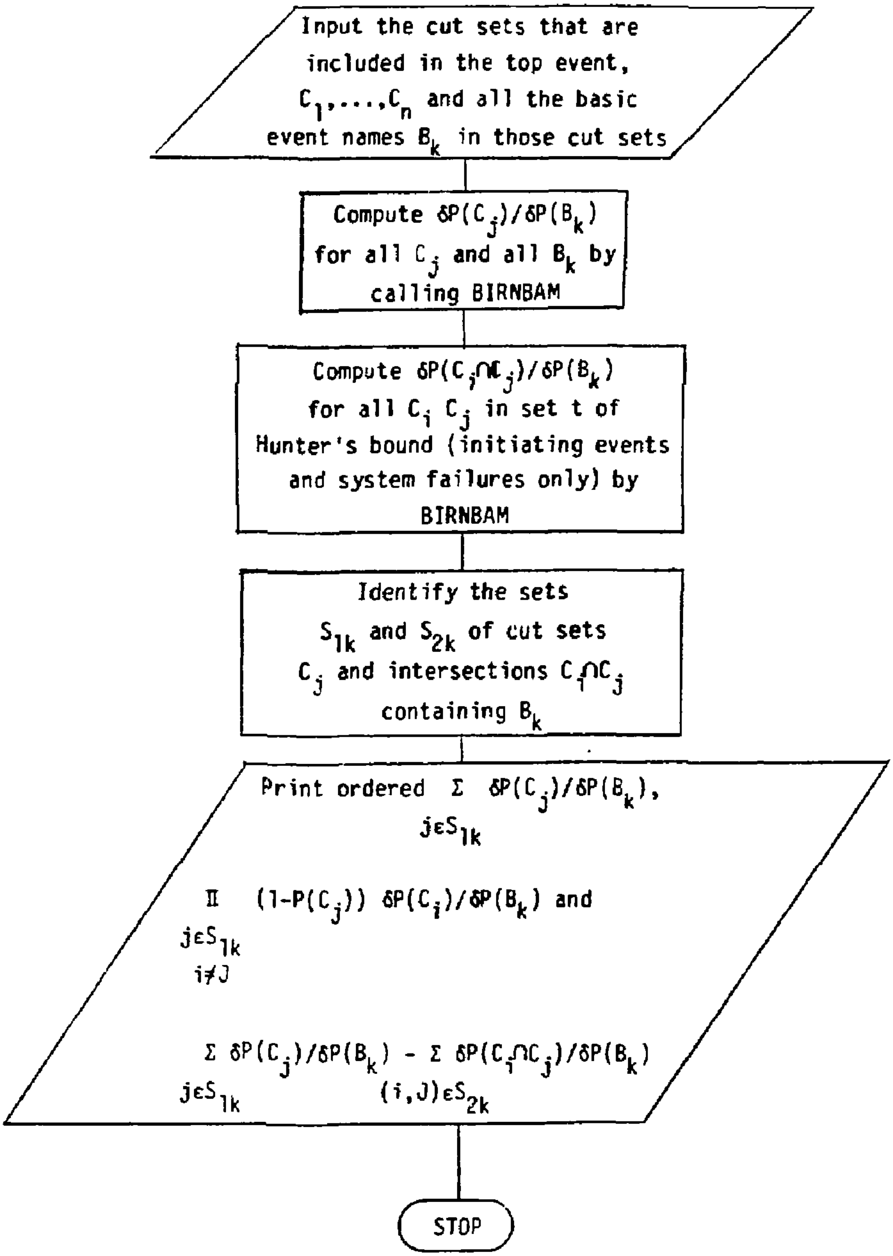


Figure D1. Subroutine BIRNIMP to replace or be Incorporated in DCAG

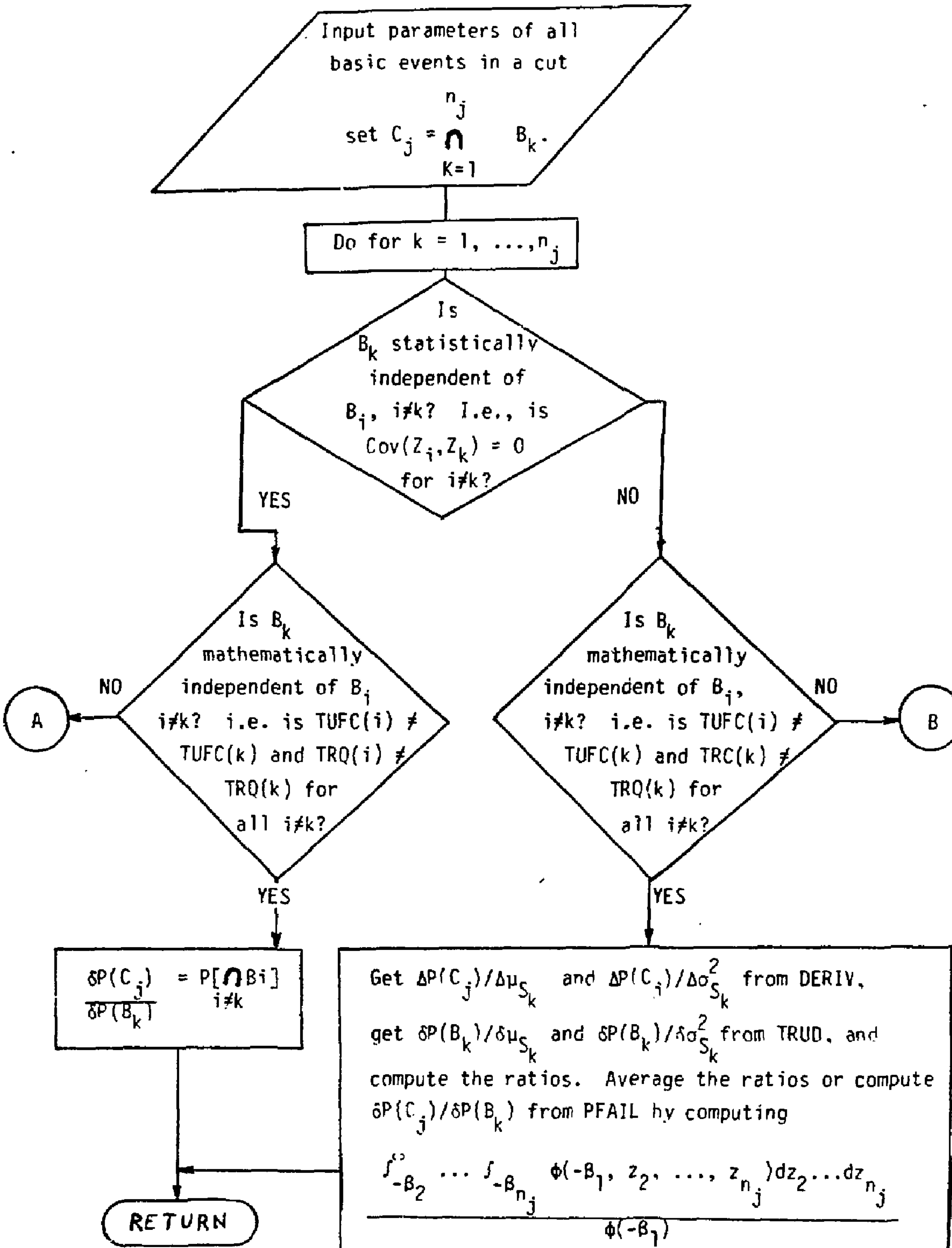


Figure D2. Subroutine BIRNBAM to compute $\delta P(C_j)/\delta P(B_k)$

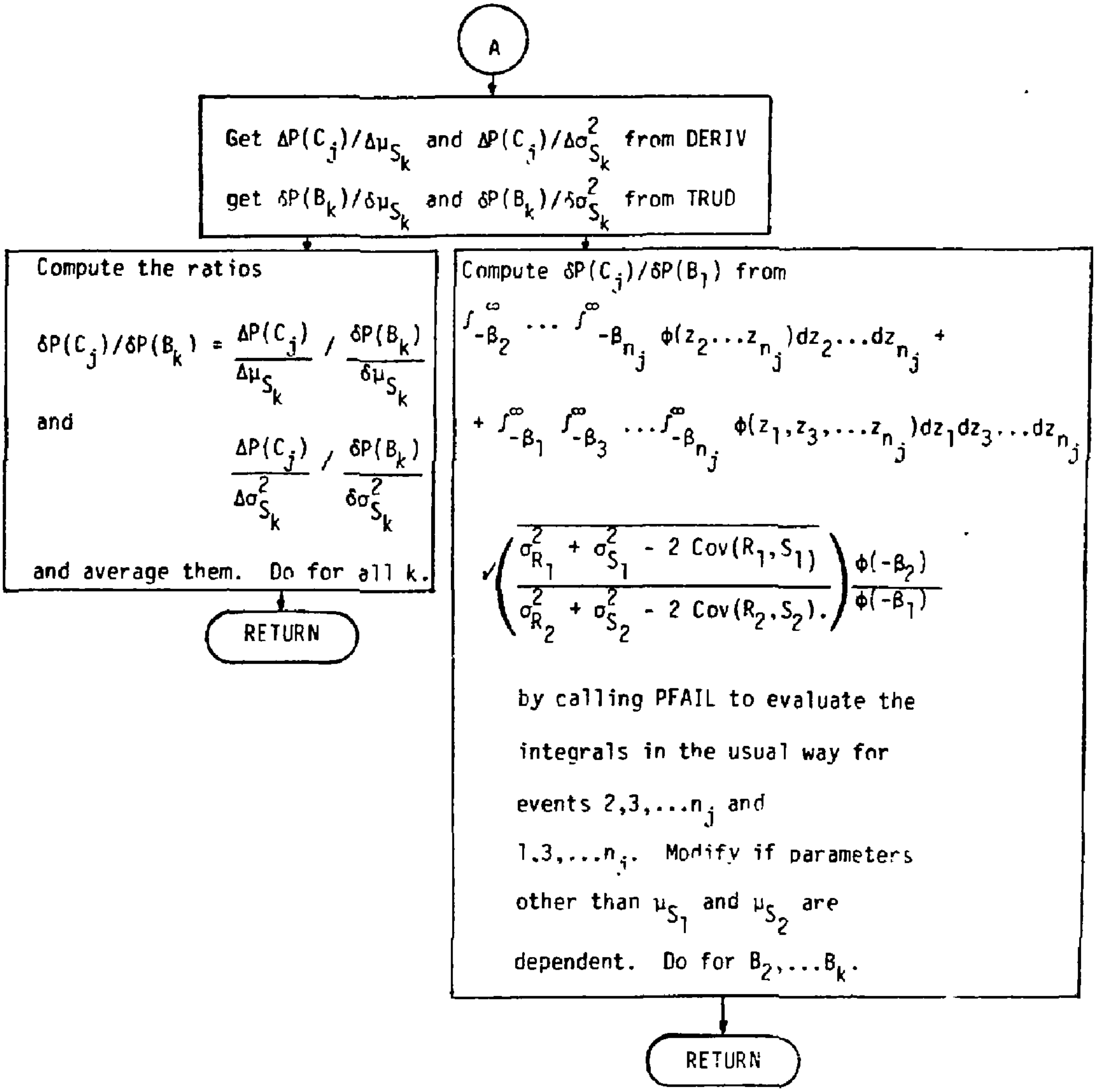


Figure D2, sheet 2 of 3.

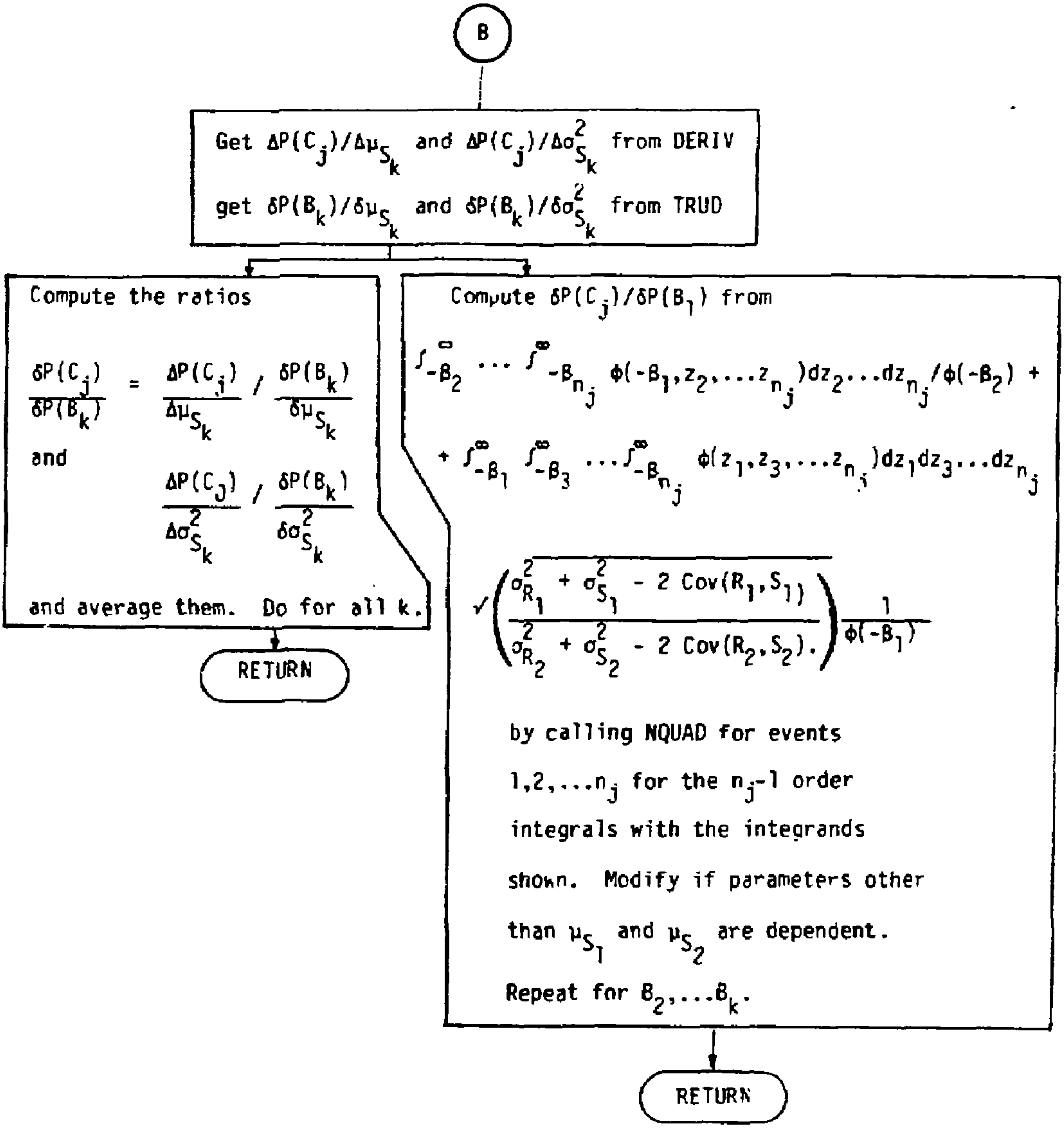


Figure D2, sheet 3 of 3.

Analytical Derivatives Approach with Random Basic Events

SEISIM2 could analytically compute derivatives of all events with respect to probabilities of important random basic events. This is how:

1. Cut Sets

$$\delta P[C_j]/\delta P(BE(i)) = P[\cap_{k \neq i} BE(k)]$$

$$= P[C_j]/P(BE(i))$$

where $\{BE(k)\}$ are basic events in cut set $C_j$.

2. Systems and Accident Sequences

$$\delta P(UC_j)/\delta P(BE(i)) = \frac{\delta(1 - \Pi(1 - P(C_j)))}{\delta P[BE(i)]}$$

$$= \sum_{j \in J} \left[ \prod_{k \neq j} (1-P(C_k)) \right] \delta P(C_j)/\delta P(BE(i))$$

where J is the set of indexes of cut sets that contain BE(i). The product can be computed as

$$\prod_{k \neq j} (1 - P(C_k)) = (1 - P(UC_k))/(1-P(C_j))$$

in SEISIM2 the derivative $\delta P(C_j)/\delta P(BE(i))$ comes from Step 1. The formula above assumes BE(i) appears explicitly in a system or accident sequence cut set. If BE(i) appears implicitly in a system that appears explicitly in an accident sequence cut set, compute the derivative of system failure probability first and use the chain rule to get

$$\frac{\delta P[\text{Acc. Seq.}]}{\delta P(BE(i))} = \frac{\delta P[\text{Acc. Seq.}]}{\delta P[\text{System}]} \frac{\delta P[\text{System}]}{\delta P(BE(i))}$$

No basic events should appear explicitly and implicitly in accident sequence cut sets!

### 3. Initiating Events

Derivatives of initiating events must be computed according to our hierarchy of which initiating events are more dominant if they occur. Let $P(IE(k); initial] = P[UC_j(k)]$ be the initiating event probability computed by SEISIM before the hierarchy is imposed. Then:

a. $P[RPV; final] = P[RPV; initial]$,

b. $$P[IE(k); final] = P[IE(k); initial] \prod_{j=1}^{k-1} (1-P[IE(k); final])$$

where $k \in \{2,3,\ldots,6\}$ are the indexes corresponding to {LLOCA, MLOCA, SLOCA, SSLOCA, IET2}, and

c. $$P(IET1; final) = 1 - \sum_{k=1}^{6} P(IE(k); final)$$

if the sum is less than 1.0, and 0.0 otherwise.

If the sum $\sum_{k=1}^{6} P(IE(k); final)$ is greater than 1.0, all $P(IE(k); final)$ are normalized to sum to 1.0.

Then $$\frac{\delta P[IE(k); final]}{\delta P(BE(i))} = \prod_{j=1}^{k-1} (1 - P[IE(k); initial]) \frac{\delta P[UC_j(k)]}{\delta P((BE(i))}$$ unless normalized or unless BE(i) appears in more than one initiating event. The derivative can be computed as in Step 2.

4. Terminal Event Sequences

$$\frac{\delta P(TES)}{\delta P(BE(i))} = P(Eq)\, \frac{\delta P(IE)}{\delta BE(i)}\; P(Acc.\ Seq.\ |\, IE)\; P(Ctnmt)$$

$$+\; P(Eq)\; P(IE)\; \frac{\delta P(Ac.\ Seq.\, |\, IE)}{\delta BE(i)}\; P(Ctnmt)$$

The two derivatives can be obtained from Steps 2 and 3.

# APPENDIX E. BIRNBAUM MEASURES OF COMPONENTS FOR EACH RELEASE CATEGORY

The response-and fragility-related component failures important to release in each of six earthquake intervals and their Birnbaum measures for each release category are listed in Table E.1. Component failures* are ranked by their importance according to their Vesely-Fussell importance measures. Their Birnbaum measures are the partial derivatives of the probability of earthquake in an interval and a release category, with respect to the conditional probabilities of the component failures given an earthquake in an interval. The component failures appear in either initiating event or accident sequence cut sets. The pipe failures listed are mostly from the primary coolant system (important to LOCA initiating events) and residual heat removal (RHR) and safety injection (SI) system pipes (important to accident sequences).

These component failures identify important cut sets which can be used to evaluate sensitivities -- the effect of changes in probability of release due to changes in parameters of fragilities, responses, or primary input variables.

The Birnbaum measures of components for risk (summed over all release categories) have been presented in Appendix D.

The first fifteen components have been forced into Table E.1 for all six earthquake levels even though their importance is negligible at some earthquake levels. This is necessary for computing derivatives with respect to parameters of primary input variables.

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* The component names are in a ten-character code detailed in Appendix E of Ref. 13.

Table E.1a. Components important to release category probabilities and their Birnbaum measures at .06-.1g earthquake.

| Component Perturbed | Cat 1 | Cat 2 | Cat 3 | Cat 4 | Cat 5 | Cat 6 | Cat 7 |
|---|---|---|---|---|---|---|---|
| zzuplift-- | 9.6e-09 | 1.2e-07 | 5.4e-06 | 0. | 0. | 2.2e-11 | 5.4e-04 |
| zzch-roof- | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| rzz01ospmp | 0. | 0. | 1.7e-10 | 0. | 1.4e-18 | 0. | 1.7e-08 |
| ftalscstmj | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| 5tal----mj | 0. | 0. | 1.7e-10 | 0. | 1.4e-18 | 0. | 1.7e-08 |
| rec1393amj | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| rec1393bmj | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| rec1393cmj | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| 6oh1005amj | 0. | 0. | 1.1e-22 | 0. | 1.9e-21 | 0. | 9.8e-21 |
| zoi1006amj | 0. | 0. | 1.2e-17 | 0. | 1.9e-16 | 0. | 9.9e-16 |
| zoh1001bmj | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| zoh1001cmj | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| 6oh1004amj | 0. | 0. | 2.7e-18 | 0. | 4.3e-17 | 0. | 2.2e-16 |
| qof118b-mj | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| zzshr-wall | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| xoe1142-mj | 1.7e-10 | 0. | 1.7e-06 | 0. | 0. | 0. | 1.7e-04 |
| xoc10126mj | 1.7e-10 | 0. | 4.4e-08 | 0. | 0. | 0. | 4.3e-06 |
| xoe1141-mj | 1.7e-10 | 0. | 1.7e-06 | 0. | 0. | 0. | 1.7e-04 |
| xoa10174mj | 1.7e-10 | 2.8e-09 | 4.3e-10 | 0. | 2.6e-09 | 5.0e-13 | 5.4e-08 |
| xob10079mj | 1.9e-10 | 2.8e-09 | 4.9e-09 | 0. | 2.6e-09 | 5.0e-13 | 5.0e-07 |
| xoc10200mj | 1.7e-10 | 0. | 4.4e-08 | 0. | 0. | 0. | 4.3e-06 |
| 6oh1034bmj | 0. | 0. | 4.3e-10 | 0. | 0. | 0. | 4.3e-08 |
| xoa10180mj | 1.7e-10 | 2.8e-09 | 3.6e-10 | 0. | 2.6e-09 | 5.0e-13 | 4.8e-08 |
| xob10011mj | 1.8e-10 | 2.8e-09 | 2.2e-09 | 0. | 2.6e-09 | 5.0e-13 | 2.3e-07 |
| xoa10010mj | 1.7e-10 | 2.8e-09 | 3.3e-10 | 0. | 2.6e-09 | 5.0e-13 | 4.4e-08 |
| xoa10173mj | 1.7e-10 | 2.8e-09 | 3.3e-10 | 0. | 2.6e-09 | 5.0e-13 | 4.4e-08 |

Table E.1b. Components important to release category probabilities and their Birnbaum measures at .1-.2g earthquake.

| Component Perturbed | Cat 1 | Cat 2 | Cat 3 | Cat 4 | Cat 5 | Cat 6 | Cat 7 |
|---|---|---|---|---|---|---|---|
| zzuplift-- | 3.1e-08 | 4.6e-07 | 2.6e-06 | 0. | 0. | 8.3e-11 | 2.6e-04 |
| zzch-roof- | 3.1e-08 | 4.6e-07 | 2.6e-06 | 0. | 0. | 8.3e-11 | 2.6e-04 |
| rzz01ospmp | 0. | 0. | 3.5e-09 | 0. | 1.7e-17 | 0. | 3.5e-07 |
| ftalscstmj | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| 5tal----mj | 0. | 0. | 3.5e-09 | 0. | 1.7e-17 | 0. | 3.5e-07 |
| rec1393amj | 0. | 0. | 4.0e-14 | 0. | 0. | 0. | 4.0e-12 |
| rec1393bmj | 0. | 0. | 4.0e-14 | 0. | 0. | 0. | 4.0e-12 |
| rec1393cmj | 0. | 0. | 4.0e-14 | 0. | 0. | 0. | 4.0e-12 |
| 6oh1005amj | 0. | 0. | 5.5e-11 | 0. | 2.7e-19 | 0. | 5.5e-09 |
| zoi1006amj | 0. | 0. | 5.8e-11 | 0. | 2.6e-16 | 0. | 5.7e-09 |

(Continued)

| Component Perturbed | Cat 1 | Cat 2 | Cat 3 | Cat 4 | Cat 5 | Cat 6 | Cat 7 |
|---|---|---|---|---|---|---|---|
| zoh1001bmj | 0. | 0. | 5.7e-11 | 0. | 0. | 0. | 5.7e-09 |
| zoh1001cmj | 0. | 0. | 5.7e-11 | 0. | 0. | 0. | 5.7e-09 |
| 6oh1004amj | 0. | 0. | 1.1e-10 | 0. | 4.3e-16 | 0. | 1.1e-08 |
| qof118b-mj | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| zzshr-wall | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| xoel142-mj | 3.5e-09 | 0. | 8.7e-07 | 0. | 0. | 0. | 8.6e-05 |
| xoa10174mj | 3.5e-09 | 5.6e-08 | 7.1e-10 | 0. | 1.2e-09 | 1.0e-11 | 3.6e-07 |
| xoc10126mj | 3.5e-09 | 0. | 2.1e-08 | 0. | 0. | 0. | 2.4e-06 |
| kpxlrcpamq | 6.1e-09 | 4.0e-08 | 2.2e-06 | 0. | 0. | 0. | 2.2e-04 |
| kpxlrcpbmq | 6.1e-09 | 4.0e-08 | 2.2e-06 | 0. | 0. | 0. | 2.2e-04 |
| kpxlrcpcmq | 6.1e-09 | 4.0e-08 | 2.2e-06 | 0. | 0. | 0. | 2.2e-04 |
| kpxlrcpdmq | 6.1e-09 | 4.0e-08 | 2.2e-06 | 0. | 0. | 0. | 2.2e-04 |
| mhalsga-mq | 5.2e-09 | 2.6e-08 | 2.1e-06 | 0. | 0. | 0. | 2.1e-04 |
| mhalsgb-mq | 5.2e-09 | 2.6e-08 | 2.1e-06 | 0. | 0. | 0. | 2.1e-04 |
| mhalsgc-mq | 5.2e-09 | 2.6e-08 | 2.1e-06 | 0. | 0. | 0. | 2.1e-04 |
| mhalsgd-mq | 5.2e-09 | 2.6e-08 | 2.1e-06 | 0. | 0. | 0. | 2.1e-04 |
| xoa10180mj | 3.5e-09 | 5.6e-08 | 7.4e-10 | 0. | 1.2e-09 | 1.0e-11 | 3.6e-07 |
| xob10044mj | 6.5e-09 | 5.6e-08 | 1.8e-08 | 0. | 1.2e-09 | 1.0e-11 | 2.4e-06 |
| xob10079mj | 4.8e-09 | 5.6e-08 | 8.4e-09 | 0. | 1.2e-09 | 1.0e-11 | 1.2e-06 |
| xoa10178mj | 5.2e-09 | 5.6e-08 | 1.0e-08 | 0. | 1.2e-09 | 1.0e-11 | 1.5e-06 |
| xoa10010mj | 3.5e-09 | 5.6e-08 | 9.0e-10 | 0. | 1.2e-09 | 1.0e-11 | 3.8e-07 |
| xoa10173mj | 3.5e-09 | 5.6e-08 | 9.0e-10 | 0. | 1.2e-09 | 1.0e-11 | 3.8e-07 |
| xoc10200mj | 3.5e-09 | 0. | 2.1e-08 | 0. | 0. | 0. | 2.4e-06 |

Table E.1c. Components important to release category probabilities and their Birnbaum measures at .2-.32g earthquake.

| Component Perturbed | Cat 1 | Cat 2 | Cat 3 | Cat 4 | Cat 5 | Cat 6 | Cat 7 |
|---|---|---|---|---|---|---|---|
| zzuplift-- | 4.0e-08 | 4.0e-07 | 9.6e-08 | 3.1e-19 | 1.2e-17 | 5.5e-11 | 1.2e-05 |
| zzch-roof- | 4.0e-08 | 4.0e-07 | 9.6e-08 | 3.1e-19 | 1.2e-17 | 5.5e-11 | 1.2e-05 |
| rzz01ospmp | 0. | 0. | 1.0e-08 | 0. | 2.0e-15 | 0. | 9.9e-07 |
| ftalscstmj | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| 5tal----mj | 0. | 0. | 1.0e-08 | 0. | 2.0e-15 | 0. | 9.9e-07 |
| recl393amj | 8.0e-13 | 1.5e-12 | 8.6e-11 | 9.3e-24 | 6.9e-22 | 0. | 5.4e-10 |
| recl393bmj | 8.0e-13 | 1.5e-12 | 8.6e-11 | 9.3e-24 | 6.9e-22 | 0. | 5.4e-10 |
| recl393cmj | 8.0e-13 | 1.5e-12 | 8.6e-11 | 9.3e-24 | 6.9e-22 | 0. | 5.4e-10 |
| 6oh1005amj | 1.0e-12 | 1.9e-12 | 1.8e-09 | 9.3e-24 | 4.2e-19 | 0. | 1.7e-07 |
| zoi1006amj | 1.2e-11 | 2.4e-11 | 3.8e-09 | 1.5e-22 | 1.4e-14 | 0. | 2.5e-07 |
| zoh1001bmj | 1.3e-11 | 2.5e-11 | 3.8e-09 | 9.4e-24 | 3.2e-19 | 0. | 2.5e-07 |
| zoh1001cmj | 1.3e-11 | 2.5e-11 | 3.8e-09 | 9.4e-24 | 3.2e-19 | 0. | 2.5e-07 |
| 6oh1004amj | 1.3e-11 | 2.5e-11 | 5.8e-09 | 9.4e-24 | -3.4e-15 | 0. | 4.4e-07 |
| qof118b-mj | 0. | 0. | 0. | 0. | 0. | 0. | 0. |

(Continued)

| Component Perturbed | Cat 1 | Cat 2 | Cat 3 | Cat 4 | Cat 5 | Cat 6 | Cat 7 |
|---|---|---|---|---|---|---|---|
| zzshr-wall | 2.0e-08 | 2.0e-07 | 4.8e-08 | 1.5e-19 | 6.1e-18 | 2.7e-11 | 6.3e-06 |
| kpxlrcpamq | 7.2e-08 | 9.8e-07 | 2.6e-07 | 1.2e-18 | 1.6e-17 | 0. | 2.7e-05 |
| kpxlrcpbmq | 7.2e-08 | 9.8e-07 | 2.6e-07 | 1.2e-18 | 1.6e-17 | 0. | 2.7e-05 |
| kpxlrcpcmq | 7.2e-08 | 9.8e-07 | 2.6e-07 | 1.2e-18 | 1.6e-17 | 0. | 2.7e-05 |
| kpxlrcpdmq | 7.2e-08 | 9.8e-07 | 2.6e-07 | 1.2e-18 | 1.6e-17 | 0. | 2.7e-05 |
| xoal0174mj | 1.0e-08 | 1.6e-07 | 2.4e-09 | 1.2e-24 | 6.3e-11 | 2.9e-11 | 9.0e-07 |
| xocl0126mj | 1.0e-08 | 0. | 3.8e-09 | 3.9e-23 | 0. | 0. | 1.1e-06 |
| xoel142-mj | 1.0e-08 | 0. | 4.7e-08 | 3.9e-23 | 1.2e-27 | 0. | 5.4e-06 |
| xoal0180mj | 1.0e-08 | 1.6e-07 | 2.4e-09 | 1.1e-24 | 6.3e-11 | 2.9e-11 | 9.0e-07 |
| xobl0079mj | 1.7e-08 | 1.6e-07 | 5.3e-09 | 3.0e-23 | 6.3e-11 | 2.9e-11 | 1.7e-06 |
| xocl0200mj | 1.0e-08 | 0. | 3.8e-09 | 3.9e-23 | 0. | 0. | 1.1e-06 |
| xoal0010mj | 1.0e-08 | 1.6e-07 | 2.5e-09 | 2.0e-24 | 6.3e-11 | 2.9e-11 | 9.2e-07 |
| xoal0173mj | 1.0e-08 | 1.6e-07 | 2.5e-09 | 2.0e-24 | 6.3e-11 | 2.9e-11 | 9.2e-07 |
| 6ohl034bmj | 0. | 0. | 2.8e-09 | 0. | 2.3e-19 | 0. | 2.8e-07 |
| mhalsga-mq | 2.8e-08 | 2.9e-07 | 1.7e-07 | 1.2e-18 | 1.6e-17 | 0. | 1.7e-05 |
| mhalsgb-mq | 2.8e-08 | 2.9e-07 | 1.7e-07 | 1.2e-18 | 1.6e-17 | 0. | 1.7e-05 |
| mhalsgc-mq | 2.8e-08 | 2.9e-07 | 1.7e-07 | 1.2e-18 | 1.6e-17 | 0. | 1.7e-05 |
| mhalsgd-mq | 2.8e-08 | 2.9e-07 | 1.7e-07 | 1.2e-18 | 1.6e-17 | 0. | 1.7e-05 |
| zogl01lamj | 7.9e-13 | 1.5e-12 | 2.5e-09 | 9.3e-24 | 3.1e-19 | 0. | 2.4e-07 |
| mval0045md | 0. | 0. | 1.0e-08 | 0. | 2.0e-15 | 0. | 1.0e-06 |
| mval005-md | 0. | 0. | 1.0e-08 | 0. | 2.0e-15 | 0. | 1.0e-06 |
| mval006-md | 0. | 0. | 1.0e-08 | 0. | 2.0e-15 | 0. | 1.0e-06 |
| mval007-md | 0. | 0. | 1.0e-08 | 0. | 2.0e-15 | 0. | 1.0e-06 |
| mval008-md | 0. | 0. | 1.0e-08 | 0. | 2.0e-15 | 0. | 1.0e-06 |
| mvdl0005md | 0. | 0. | 1.0e-08 | 0. | 2.0e-15 | 0. | 1.0e-06 |
| mvdl0016md | 0. | 0. | 1.0e-08 | 0. | 2.0e-15 | 0. | 1.0e-06 |
| mvdl0017md | 0. | 0. | 1.0e-08 | 0. | 2.0e-15 | 0. | 1.0e-06 |
| mvdl0018md | 0. | 0. | 1.0e-08 | 0. | 2.0e-15 | 0. | 1.0e-06 |
| mvdl0019md | 0. | 0. | 1.0e-08 | 0. | 2.0e-15 | 0. | 1.0e-06 |
| mvdl002omd | 0. | 0. | 1.0e-08 | 0. | 2.0e-15 | 0. | 1.0e-06 |
| mvgl510-md | 0. | 0. | 1.0e-08 | 0. | 2.0e-15 | 0. | 1.0e-06 |
| mvgl520-md | 0. | 0. | 1.0e-08 | 0. | 2.0e-15 | 0. | 1.0e-06 |
| mvgl530-md | 0. | 0. | 1.0e-08 | 0. | 2.0e-15 | 0. | 1.0e-06 |
| mvgl540-md | 0. | 0. | 1.0e-08 | 0. | 2.0e-15 | 0. | 1.0e-06 |
| zoil013bmj | 0. | 0. | 2.4e-09 | 0. | 3.1e-19 | 0. | 2.4e-07 |
| zohl002dmj | 4.6e-12 | 8.7e-12 | 1.2e-09 | 9.4e-24 | 9.6e-20 | 0. | 7.5e-08 |
| xoal0196mj | 1.0e-08 | 1.6e-07 | 2.4e-09 | 5.3e-25 | 6.3e-11 | 2.9e-11 | 8.8e-07 |
| xobl0091mj | 1.0e-08 | 1.6e-07 | 2.4e-09 | 5.3e-25 | 6.3e-11 | 2.9e-11 | 8.8e-07 |
| xobl0119mj | 1.0e-08 | 1.6e-07 | 2.4e-09 | 5.3e-25 | 6.3e-11 | 2.9e-11 | 8.8e-07 |
| xobl0044mj | 2.7e-08 | 1.6e-07 | 8.8e-09 | 6.7e-23 | 6.3e-11 | 2.9e-11 | 2.7e-06 |
| xocl0057mj | 1.0e-08 | 0. | 3.8e-09 | 3.9e-23 | 0. | 0. | 1.1e-06 |

Table E.1d. Components important to release category probabilities and their Birnbaum measures at .32-.42g earthquake.

| Component Perturbed | Cat 1 | Cat 2 | Cat 3 | Cat 4 | Cat 5 | Cat 6 | Cat 7 |
|---|---|---|---|---|---|---|---|
| zzuplift-- | 1.6e-08 | 5.6e-07 | 0. | 1.9e-18 | 0. | 1.1e-07 | 9.1e-07 |
| zzch-roof- | 1.6e-08 | 5.6e-07 | 0. | 1.9e-18 | 0. | 1.1e-07 | 9.1e-07 |
| rzz01ospmp | 1.3e-08 | 1.0e-06 | 3.5e-16 | 0. | 5.6e-15 | 2.4e-07 | 2.9e-14 |
| ftalscstmj | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| 5tal----mj | 6.7e-09 | 5.4e-07 | 1.8e-16 | 0. | 2.9e-15 | 1.2e-07 | 1.5e-14 |
| rec1393amj | 2.2e-09 | 3.0e-08 | 3.5e-08 | 1.1e-10 | 9.3e-10 | 1.2e-07 | 4.0e-08 |
| rec1393bmj | 2.2e-09 | 3.0e-08 | 3.5e-08 | 1.1e-10 | 9.3e-10 | 1.2e-07 | 4.0e-08 |
| rec1393cmj | 2.2e-09 | 3.0e-08 | 3.5e-08 | 1.1e-10 | 9.3e-10 | 1.2e-07 | 4.0e-08 |
| 6oh1005amj | 4.1e-10 | 2.7e-09 | 1.6e-08 | -3.5e-13 | -5.0e-17 | 1.2e-08 | 7.5e-09 |
| zoi1006amj | 7.9e-09 | 2.1e-08 | 5.7e-07 | 7.8e-11 | 1.7e-14 | 1.5e-08 | 9.9e-08 |
| zoh1001bmj | 7.2e-09 | 1.8e-08 | 5.9e-07 | 7.4e-19 | 9.6e-21 | 1.5e-08 | 7.7e-09 |
| zoh1001cmj | 7.2e-09 | 1.8e-08 | 5.9e-07 | 7.4e-19 | 9.6e-21 | 1.5e-08 | 7.7e-09 |
| 6oh1004amj | 7.4e-09 | 2.1e-08 | 5.9e-07 | 5.0e-11 | 9.7e-15 | 2.8e-08 | 9.4e-09 |
| qof118b-mj | 1.4e-09 | 2.4e-08 | 1.5e-10 | 6.7e-12 | 8.9e-10 | 1.2e-07 | 7.7e-09 |
| zzshr-wall | 8.5e-09 | 2.8e-07 | 0. | 9.8e-19 | 0. | 5.7e-08 | 4.5e-07 |
| xoa10174mj | 1.3e-08 | 1.4e-07 | 4.7e-07 | 2.1e-10 | 1.1e-09 | 1.5e-07 | 6.3e-07 |
| xoa10180mj | 1.3e-08 | 1.4e-07 | 4.7e-07 | 2.1e-10 | 1.1e-09 | 1.5e-07 | 6.3e-07 |
| xoc10126mj | 1.7e-08 | 7.1e-10 | 1.1e-06 | 2.3e-21 | 0. | 3.6e-09 | 6.7e-07 |
| xoc10200mj | 1.7e-08 | 7.1e-10 | 1.1e-06 | 2.3e-21 | 0. | 3.6e-09 | 6.7e-07 |
| xob10011mj | 3.1e-08 | 1.4e-07 | 1.5e-06 | 2.1e-10 | 1.1e-09 | 1.5e-07 | 1.2e-06 |
| xoa10010mj | 1.4e-08 | 1.4e-07 | 5.1e-07 | 2.1e-10 | 1.1e-09 | 1.5e-07 | 6.5e-07 |
| xoa10173mj | 1.4e-08 | 1.4e-07 | 5.1e-07 | 2.1e-10 | 1.1e-09 | 1.5e-07 | 6.5e-07 |
| xob10079mj | 3.2e-08 | 1.4e-07 | 1.6e-06 | 2.1e-10 | 1.1e-09 | 1.5e-07 | 1.3e-06 |
| xoe1141-mj | 1.8e-08 | 3.3e-08 | 7.3e-07 | 2.4e-21 | 0. | 1.7e-07 | 8.3e-07 |
| mrallubbmg | 2.7e-09 | 4.7e-08 | 2.6e-10 | 1.9e-10 | 1.4e-09 | 1.9e-07 | 5.3e-08 |
| mrallb--mg | 2.7e-09 | 4.7e-08 | 2.6e-10 | 1.9e-10 | 1.4e-09 | 1.9e-07 | 5.3e-08 |
| xoe1142-mj | 1.8e-08 | 3.3e-08 | 7.3e-07 | 2.4e-21 | 0. | 1.7e-07 | 8.3e-07 |
| zoh1002cmj | 1.0e-08 | 2.6e-08 | 8.5e-07 | 1.0e-18 | 1.3e-20 | 2.2e-08 | 7.8e-09 |
| kpxlrcpamq | 9.9e-08 | 1.4e-06 | 7.6e-11 | 5.8e-17 | 2.4e-19 | 7.8e-07 | 8.7e-07 |
| kpxlrcpbmq | 9.9e-08 | 1.4e-06 | 7.6e-11 | 5.8e-17 | 2.4e-19 | 7.8e-07 | 8.7e-07 |
| kpxlrcpcmq | 9.9e-08 | 1.4e-06 | 7.6e-11 | 5.8e-17 | 2.4e-19 | 7.8e-07 | 8.7e-07 |
| kpxlrcpdmq | 9.9e-08 | 1.4e-06 | 7.6e-11 | 5.8e-17 | 2.4e-19 | 7.8e-07 | 8.7e-07 |
| mod1018cmj | 3.2e-10 | 5.3e-09 | 2.7e-11 | 9.6e-11 | 1.3e-10 | 1.8e-08 | 1.1e-08 |
| zoh1002dmj | 5.7e-09 | 1.4e-08 | 4.7e-07 | 5.8e-19 | 7.3e-21 | 1.1e-08 | 7.6e-09 |
| mhalsga-mq | 6.5e-08 | 8.9e-07 | 7.7e-11 | 5.8e-17 | 2.4e-19 | 7.8e-07 | 8.7e-07 |
| mhalsgb-mq | 6.5e-08 | 8.9e-07 | 7.7e-11 | 5.8e-17 | 2.4e-19 | 7.8e-07 | 8.7e-07 |
| mhalsgc-mq | 6.5e-08 | 8.9e-07 | 7.7e-11 | 5.8e-17 | 2.4e-19 | 7.8e-07 | 8.7e-07 |
| mhalsgd-mq | 6.5e-08 | 8.9e-07 | 7.7e-11 | 5.8e-17 | 2.4e-19 | 7.8e-07 | 8.7e-07 |
| mral85e-mb | 3.1e-10 | 5.1e-09 | 2.4e-11 | 3.9e-11 | 1.3e-10 | 1.8e-08 | 9.7e-09 |
| rec1383amj | 4.9e-10 | 9.2e-10 | 3.5e-08 | 1.2e-19 | 5.5e-22 | 8.2e-13 | 7.4e-09 |
| rec1383bmj | 4.9e-10 | 9.2e-10 | 3.5e-08 | 1.2e-19 | 5.5e-22 | 8.2e-13 | 7.4e-09 |
| mva10045md | 6.7e-09 | 5.4e-07 | 1.8e-16 | 0. | 2.9e-15 | 1.2e-07 | 1.5e-14 |
| mva1005-md | 6.7e-09 | 5.4e-07 | 1.8e-16 | 0. | 2.9e-15 | 1.2e-07 | 1.5e-14 |
| mva1006-md | 6.7e-09 | 5.4e-07 | 1.8e-16 | 0. | 2.9e-15 | 1.2e-07 | 1.5e-14 |
| mva1007-md | 6.7e-09 | 5.4e-07 | 1.8e-16 | 0. | 2.9e-15 | 1.2e-07 | 1.5e-14 |

*(Continued)*

| Component Perturbed | Cat 1 | Cat 2 | Cat 3 | Cat 4 | Cat 5 | Cat 6 | Cat 7 |
|---|---|---|---|---|---|---|---|
| mval008-md | 6.7e-09 | 5.4e-07 | 1.8e-16 | 0. | 2.9e-15 | 1.2e-07 | 1.5e-14 |
| mvd10005md | 6.7e-09 | 5.4e-07 | 1.8e-16 | 0. | 2.9e-15 | 1.2e-07 | 1.5e-14 |
| mvd10016md | 6.7e-09 | 5.4e-07 | 1.8e-16 | 0. | 2.9e-15 | 1.2e-07 | 1.5e-14 |
| mvd10017md | 6.7e-09 | 5.4e-07 | 1.8e-16 | 0. | 2.9e-15 | 1.2e-07 | 1.5e-14 |
| mvd10018md | 6.7e-09 | 5.4e-07 | 1.8e-16 | 0. | 2.9e-15 | 1.2e-07 | 1.5e-14 |
| mvd10019md | 6.7e-09 | 5.4e-07 | 1.8e-16 | 0. | 2.9e-15 | 1.2e-07 | 1.5e-14 |
| mvd1002omd | 6.7e-09 | 5.4e-07 | 1.8e-16 | 0. | 2.9e-15 | 1.2e-07 | 1.5e-14 |
| mvg1510-md | 6.7e-09 | 5.4e-07 | 1.8e-16 | 0. | 2.9e-15 | 1.2e-07 | 1.5e-14 |
| mvg1520-md | 6.7e-09 | 5.4e-07 | 1.8e-16 | 0. | 2.9e-15 | 1.2e-07 | 1.5e-14 |
| mvg1530-md | 6.7e-09 | 5.4e-07 | 1.8e-16 | 0. | 2.9e-15 | 1.2e-07 | 1.5e-14 |
| mvg1540-md | 6.7e-09 | 5.4e-07 | 1.8e-16 | 0. | 2.9e-15 | 1.2e-07 | 1.5e-14 |
| zog1011amj | 6.8e-10 | 3.9e-09 | 3.5e-08 | 7.2e-19 | 5.5e-22 | 1.5e-08 | 7.4e-09 |
| mod1019cmj | 5.8e-09 | 9.5e-08 | 2.9e-10 | 2.1e-09 | 9.5e-10 | 1.3e-07 | 3.8e-07 |
| 6oj1008amj | 5.1e-10 | 1.1e-09 | 3.5e-08 | 6.4e-12 | 6.6e-15 | 8.2e-13 | 8.9e-09 |
| 6oh1034bmj | 2.7e-10 | 4.3e-09 | 0. | 4.4e-19 | 0. | 2.2e-08 | 0. |
| xob10044mj | 3.2e-08 | 1.4e-07 | 1.6e-06 | 2.1e-10 | 1.1e-09 | 1.5e-07 | 1.3e-06 |
| mod1018dmj | 1.9e-11 | 3.1e-10 | 1.2e-12 | 8.9e-12 | 3.9e-12 | 5.4e-10 | 1.1e-09 |
| mvg185e-mb | 1.4e-10 | 2.3e-09 | 1.1e-11 | 5.4e-11 | 4.8e-11 | 6.6e-09 | 5.9e-09 |
| xoa10178mj | 2.1e-08 | 1.4e-07 | 9.1e-07 | 2.1e-10 | 1.1e-09 | 1.5e-07 | 9.0e-07 |
| 6oj1007amj | 4.9e-10 | 9.2e-10 | 3.5e-08 | 1.2e-19 | 5.5e-22 | 8.2e-13 | 7.4e-09 |
| zoi1013bmj | 1.8e-10 | 2.9e-09 | 0. | 6.0e-19 | 0. | 1.5e-08 | 0. |
| mod1015cmj | 4.2e-10 | 7.0e-09 | 3.2e-11 | 8.7e-11 | 1.6e-10 | 2.2e-08 | 1.5e-08 |
| mra185c-mb | 1.4e-12 | 2.4e-11 | 1.3e-13 | 4.9e-13 | 6.1e-13 | 8.4e-11 | 4.7e-11 |

Table E.1e. Components important to release category probabilities and their Birnbaum measures at .42-.53g earthquake.

| Component Perturbed | Cat 1 | Cat 2 | Cat 3 | Cat 4 | Cat 5 | Cat 6 | Cat 7 |
|---|---|---|---|---|---|---|---|
| zzuplift-- | 7.8e-09 | 1.1e-07 | 0. | 2.7e-14 | 0. | 7.3e-09 | 2.9e-07 |
| zzch-roof- | 7.8e-09 | 1.1e-07 | 0. | 2.7e-14 | 0. | 7.3e-09 | 2.9e-07 |
| rzz01ospmp | -2.7e-09 | -2.1e-07 | -1.4e-16 | 0. | -2.3e-15 | -5.2e-08 | -1.2e-14 |
| ftalscstmj | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| 5tal----mj | 3.0e-09 | 2.4e-07 | 1.6e-16 | 0. | 2.5e-15 | 5.7e-08 | 1.3e-14 |
| recl393amj | 6.2e-10 | 9.2e-09 | 8.0e-09 | 1.0e-10 | 9.7e-10 | 1.8e-08 | 1.9e-08 |
| recl393bmj | 6.2e-10 | 9.2e-09 | 8.0e-09 | 1.0e-10 | 9.7e-10 | 1.8e-08 | 1.9e-08 |
| recl393cmj | 6.2e-10 | 9.2e-09 | 8.0e-09 | 1.0e-10 | 9.7e-10 | 1.8e-08 | 1.9e-08 |
| 6oh1005amj | 1.1e-10 | 1.0e-09 | -1.2e-09 | -2.8e-09 | -1.4e-14 | 8.0e-09 | -7.9e-09 |
| zoi1006amj | 6.7e-09 | 7.1e-08 | 1.2e-07 | 1.5e-10 | 4.2e-13 | 1.0e-08 | 9.7e-08 |
| zoh1001bmj | 5.9e-09 | 7.1e-08 | 1.2e-07 | 6.0e-15 | 2.1e-17 | 1.0e-08 | 6.5e-09 |
| zoh1001cmj | 5.9e-09 | 7.1e-08 | 1.2e-07 | 6.0e-15 | 2.1e-17 | 1.0e-08 | 6.5e-09 |
| 6oh1004amj | 6.0e-09 | 7.3e-08 | 1.2e-07 | 1.4e-10 | 3.8e-13 | 1.9e-08 | 7.7e-09 |

(Continued)

| Component Perturbed | Cat 1 | Cat 2 | Cat 3 | Cat 4 | Cat 5 | Cat 6 | Cat 7 |
|---|---|---|---|---|---|---|---|
| qofl18b-mj | 1.2e-10 | 3.2e-09 | 1.3e-10 | 4.8e-12 | 7.8e-10 | 1.5e-08 | 5.6e-09 |
| zzshr-wall | 3.9e-09 | 5.5e-08 | 0. | 1.3e-14 | 0. | 3.6e-09 | 1.4e-07 |
| xoal0174mj | 4.4e-09 | 6.3e-08 | 5.3e-08 | 8.8e-10 | 3.2e-09 | 6.1e-08 | 3.1e-07 |
| xoal0180mj | 4.4e-09 | 6.3e-08 | 5.5e-08 | 8.8e-10 | 3.2e-09 | 6.1e-08 | 3.1e-07 |
| xocl0126mj | 6.5e-09 | 5.2e-10 | 3.4e-07 | 1.0e-17 | 0. | 2.0e-09 | 2.9e-07 |
| xocl0200mj | 6.5e-09 | 5.2e-10 | 3.4e-07 | 1.0e-17 | 0. | 2.0e-09 | 2.9e-07 |
| xoal0010mj | 5.0e-09 | 6.3e-08 | 8.6e-08 | 8.8e-10 | 3.2e-09 | 6.2e-08 | 3.4e-07 |
| xoal0173mj | 5.0e-09 | 6.3e-08 | 8.6e-08 | 8.8e-10 | 3.2e-09 | 6.2e-08 | 3.4e-07 |
| xobl0044mj | 2.0e-08 | 6.5e-08 | 8.9e-07 | 8.8e-10 | 3.2e-09 | 6.6e-08 | 1.0e-06 |
| xobl0079mj | 1.5e-08 | 6.4e-08 | 6.2e-07 | 8.8e-10 | 3.2e-09 | 6.5e-08 | 8.0e-07 |
| mhalsga-mq | 4.7e-08 | 6.8e-07 | 4.7e-12 | 1.7e-13 | 1.5e-16 | 1.5e-07 | 3.4e-07 |
| mhalsgb-mq | 4.7e-08 | 6.8e-07 | 4.7e-12 | 1.7e-13 | 1.5e-16 | 1.5e-07 | 3.4e-07 |
| mhalsgc-mq | 4.7e-08 | 6.8e-07 | 4.7e-12 | 1.7e-13 | 1.5e-16 | 1.5e-07 | 3.4e-07 |
| mhalsgd-mq | 4.7e-08 | 6.8e-07 | 4.7e-12 | 1.7e-13 | 1.5e-16 | 1.5e-07 | 3.4e-07 |
| xoel142-mj | 5.0e-09 | 7.3e-09 | 1.2e-07 | 1.0e-17 | 0. | 3.8e-08 | 3.3e-07 |
| kpxlrcpamq | 4.9e-08 | 7.2e-07 | 4.7e-12 | 1.7e-13 | 1.5e-16 | 1.5e-07 | 3.4e-07 |
| kpxlrcpbmq | 4.9e-08 | 7.2e-07 | 4.7e-12 | 1.7e-13 | 1.5e-16 | 1.5e-07 | 3.4e-07 |
| kpxlrcpcmq | 4.9e-08 | 7.2e-07 | 4.7e-12 | 1.7e-13 | 1.5e-16 | 1.5e-07 | 3.4e-07 |
| kpxlrcpdmq | 4.9e-08 | 7.2e-07 | 4.7e-12 | 1.7e-13 | 1.5e-16 | 1.5e-07 | 3.4e-07 |
| zohl002dmj | 8.8e-09 | 1.0e-07 | 1.9e-07 | 8.1e-15 | 3.1e-17 | 1.6e-08 | 6.5e-09 |
| xoal0178mj | 9.1e-09 | 6.4e-08 | 3.0e-07 | 8.8e-10 | 3.2e-09 | 6.3e-08 | 5.2e-07 |
| xobl0011mj | 1.7e-08 | 6.5e-08 | 7.6e-07 | 8.9e-10 | 3.2e-09 | 6.6e-08 | 9.2e-07 |
| modl018cmj | 9.6e-11 | 1.9e-09 | 5.0e-11 | 2.1e-10 | 2.2e-10 | 4.2e-09 | 7.9e-09 |
| mrallubbmg | 3.5e-10 | 8.4e-09 | 2.8e-10 | 1.7e-10 | 1.6e-09 | 3.1e-08 | 2.1e-08 |
| mrallb--mg | 3.5e-10 | 8.4e-09 | 2.8e-10 | 1.7e-10 | 1.6e-09 | 3.1e-08 | 2.1e-08 |
| mval0045md | 3.0e-09 | 2.4e-07 | 1.6e-16 | 0. | 2.5e-15 | 5.7e-08 | 1.3e-14 |
| mval005-md | 3.0e-09 | 2.4e-07 | 1.6e-16 | 0. | 2.5e-15 | 5.7e-08 | 1.3e-14 |
| mval006-md | 3.0e-09 | 2.4e-07 | 1.6e-16 | 0. | 2.5e-15 | 5.7e-08 | 1.3e-14 |
| mval007-md | 3.0e-09 | 2.4e-07 | 1.6e-16 | 0. | 2.5e-15 | 5.7e-08 | 1.3e-14 |
| mval008-md | 3.0e-09 | 2.4e-07 | 1.6e-16 | 0. | 2.5e-15 | 5.7e-08 | 1.3e-14 |
| mvdl0005md | 3.0e-09 | 2.4e-07 | 1.6e-16 | 0. | 2.5e-15 | 5.7e-08 | 1.3e-14 |
| mvdl0016md | 3.0e-09 | 2.4e-07 | 1.6e-16 | 0. | 2.5e-15 | 5.7e-08 | 1.3e-14 |
| zzuplift-- | 7.8e-09 | 1.1e-07 | 0. | 2.7e-14 | 0. | 7.3e-09 | 2.9e-07 |
| mvdl0017md | 3.0e-09 | 2.4e-07 | 1.6e-16 | 0. | 2.5e-15 | 5.7e-08 | 1.3e-14 |
| mvdl0018md | 3.0e-09 | 2.4e-07 | 1.6e-16 | 0. | 2.5e-15 | 5.7e-08 | 1.3e-14 |
| mvdl0019md | 3.0e-09 | 2.4e-07 | 1.6e-16 | 0. | 2.5e-15 | 5.7e-08 | 1.3e-14 |
| mvdl002omd | 3.0e-09 | 2.4e-07 | 1.6e-16 | 0. | 2.5e-15 | 5.7e-08 | 1.3e-14 |
| mvgl510-md | 3.0e-09 | 2.4e-07 | 1.6e-16 | 0. | 2.5e-15 | 5.7e-08 | 1.3e-14 |
| mvgl520-md | 3.0e-09 | 2.4e-07 | 1.6e-16 | 0. | 2.5e-15 | 5.7e-08 | 1.3e-14 |
| mvgl530-md | 3.0e-09 | 2.4e-07 | 1.6e-16 | 0. | 2.5e-15 | 5.7e-08 | 1.3e-14 |
| mvgl540-md | 3.0e-09 | 2.4e-07 | 1.6e-16 | 0. | 2.5e-15 | 5.7e-08 | 1.3e-14 |
| mral85e-mb | 1.2e-10 | 2.4e-09 | 5.1e-11 | 1.4e-10 | 2.6e-10 | 4.8e-09 | 9.9e-09 |
| zohl002cmj | 1.1e-08 | 1.3e-07 | 2.4e-07 | 9.4e-15 | 3.7e-17 | 1.9e-08 | 6.5e-09 |
| xoel141-mj | 5.0e-09 | 7.4e-09 | 1.2e-07 | 1.0e-17 | 0. | 3.8e-08 | 3.3e-07 |
| zogl011amj | 5.3e-10 | 6.2e-09 | 7.9e-09 | 5.7e-15 | 1.1e-18 | 1.0e-08 | 6.4e-09 |
| recl383amj | 4.1e-10 | 4.2e-09 | 7.9e-09 | 1.6e-15 | 1.1e-18 | 1.3e-13 | 6.4e-09 |

(Continued)

| Component Perturbed | Cat 1 | Cat 2 | Cat 3 | Cat 4 | Cat 5 | Cat 6 | Cat 7 |
|---|---|---|---|---|---|---|---|
| rec1383bmj | 4.1e-10 | 4.2e-09 | 7.9e-09 | 1.6e-15 | 1.1e-18 | 1.3e-13 | 6.4e-09 |
| xoa10196mj | 6.2e-09 | 6.4e-08 | 1.4e-07 | 8.9e-10 | 3.2e-09 | 6.2e-08 | 3.9e-07 |
| xob10091mj | 6.2e-09 | 6.4e-08 | 1.4e-07 | 8.9e-10 | 3.2e-09 | 6.2e-08 | 3.9e-07 |
| xob10119mj | 6.2e-09 | 6.4e-08 | 1.4e-07 | 8.9e-10 | 3.2e-09 | 6.2e-08 | 3.9e-07 |
| 6oh1034bmj | 1.2e-10 | 2.0e-09 | 0. | 3.3e-15 | 0. | 1.0e-08 | 0. |
| xoc10057mj | 6.5e-09 | 5.2e-10 | 3.4e-07 | 1.0e-17 | 0. | 2.1e-09 | 3.0e-07 |
| 6oj1008amj | 4.2e-10 | 4.3e-09 | 7.9e-09 | 1.0e-11 | 1.4e-11 | 1.3e-13 | 7.1e-09 |
| zpbr001ame | 4.1e-10 | 4.2e-09 | 7.9e-09 | 1.6e-15 | 1.1e-18 | 1.3e-13 | 6.4e-09 |
| zpbr001amg | 4.1e-10 | 4.2e-09 | 7.9e-09 | 1.6e-15 | 1.1e-18 | 1.3e-13 | 6.4e-09 |
| zpbr002bme | 4.1e-10 | 4.2e-09 | 7.9e-09 | 1.6e-15 | 1.1e-18 | 1.3e-13 | 6.4e-09 |
| zpbr002bmg | 4.1e-10 | 4.2e-09 | 7.9e-09 | 1.6e-15 | 1.1e-18 | 1.3e-13 | 6.4e-09 |
| mod1019cmj | 9.2e-10 | 1.6e-08 | 3.7e-10 | 2.6e-09 | 1.2e-09 | 2.3e-08 | 8.3e-08 |
| wyblpresmq | 6.9e-08 | 1.0e-06 | 4.7e-12 | 1.7e-13 | 1.5e-16 | 1.5e-07 | 3.4e-07 |
| xoa10197mj | 8.3e-09 | 6.4e-08 | 2.5e-07 | 8.9e-10 | 3.2e-09 | 6.3e-08 | 4.9e-07 |
| mvg185e-mb | 8.2e-11 | 1.5e-09 | 2.9e-11 | 9.6e-11 | 1.3e-10 | 2.6e-09 | 6.5e-09 |
| 6ta1001amj | 3.5e-10 | 5.5e-09 | 0. | 4.0e-15 | 0. | 2.9e-08 | 4.8e-10 |
| 6oh1005bmj | 1.6e-08 | 1.9e-07 | 3.4e-07 | 8.1e-10 | 2.1e-12 | 3.6e-08 | 5.3e-08 |
| 6oh1032amj | 2.8e-10 | 4.5e-09 | 0. | 7.2e-15 | 0. | 2.3e-08 | 0. |
| 6oh1036amj | 2.8e-10 | 4.5e-09 | 0. | 7.2e-15 | 0. | 2.3e-08 | 0. |
| mod1018dmj | 1.9e-12 | 3.6e-11 | 7.1e-13 | 2.4e-12 | 4.0e-12 | 5.7e-11 | 1.6e-10 |
| 6oj1007amj | 4.1e-10 | 4.2e-09 | 7.9e-09 | 1.6e-15 | 1.1e-18 | 1.3e-13 | 6.4e-09 |
| 6ta1005amj | 1.1e-10 | 1.8e-09 | 0. | 3.0e-15 | 0. | 9.7e-09 | 0. |
| 6ta1006bmj | 1.1e-10 | 1.8e-09 | 0. | 3.0e-15 | 0. | 9.7e-09 | 0. |
| 6ta1007cmj | 1.1e-10 | 1.8e-09 | 0. | 3.0e-15 | 0. | 9.7e-09 | 0. |
| 6ta1008dmj | 1.1e-10 | 1.8e-09 | 0. | 3.0e-15 | 0. | 9.7e-09 | 0. |
| xoc10023mj | 6.5e-09 | 5.2e-10 | 3.4e-07 | 1.0e-17 | 0. | 2.1e-09 | 3.0e-07 |
| zoi1013bmj | 1.2e-10 | 1.9e-09 | 0. | 4.0e-15 | 0. | 1.0e-08 | 0. |
| 6oi1006bmj | 1.2e-10 | 1.9e-09 | 0. | 4.0e-15 | 0. | 1.0e-08 | 0. |
| 6oe1120amj | 4.9e-10 | 1.8e-08 | 8.2e-11 | 0. | 0. | 2.2e-08 | 1.6e-08 |

Table E.1f. Components important to release category probabilities and their Birnbaum measures at .53-.69g earthquake.

| Component Perturbed | Cat 1 | Cat 2 | Cat 3 | Cat 4 | Cat 5 | Cat 6 | Cat 7 |
|---|---|---|---|---|---|---|---|
| zzuplift-- | 5.9e-09 | 8.2e-08 | 0. | 6.8e-14 | 0. | 8.5e-11 | 7.3e-08 |
| zzch-roof- | 5.9e-09 | 8.1e-08 | 0. | 6.8e-14 | 0. | 8.5e-11 | 7.3e-08 |
| rzz01ospmp | -2.0e-07 | -1.6e-05 | -1.3e-14 | 0. | -2.1e-13 | -3.8e-06 | -1.0e-12 |
| fta1scstmj | 0. | 0. | 0. | 0. | 0. | 0. | 0. |
| 5ta1----mj | 1.4e-09 | 1.1e-07 | 9.4e-17 | 0. | 1.5e-15 | 2.7e-08 | 7.8e-15 |
| rec1393amj | 3.7e-10 | 5.3e-09 | 1.5e-09 | 1.0e-11 | 1.1e-10 | 9.4e-10 | 3.9e-09 |
| rec1393bmj | 3.7e-10 | 5.3e-09 | 1.5e-09 | 1.0e-11 | 1.1e-10 | 9.4e-10 | 3.9e-09 |

(Continued)

| Component Perturbed | Cat 1 | Cat 2 | Cat 3 | Cat 4 | Cat 5 | Cat 6 | Cat 7 |
|---|---|---|---|---|---|---|---|
| recl393cmj | 3.7e-10 | 5.3e-09 | 1.5e-09 | 1.0e-11 | 1.1e-10 | 9.4e-10 | 3.9e-09 |
| 6ohl005amj | -8.8e-12 | -5.5e-10 | -1.4e-10 | 2.5e-12 | 5.6e-16 | 9.4e-10 | 2.8e-09 |
| zoil006amj | 5.8e-09 | 8.1e-08 | 2.4e-08 | 2.5e-11 | 2.8e-14 | 1.0e-09 | 4.2e-08 |
| zohl001bmj | 4.9e-09 | 7.3e-08 | 2.2e-08 | 6.8e-15 | 2.3e-18 | 1.2e-09 | 2.8e-09 |
| zohl001cmj | 4.9e-09 | 7.3e-08 | 2.2e-08 | 6.8e-15 | 2.3e-18 | 1.2e-09 | 2.8e-09 |
| 6ohl004amj | 4.9e-09 | 7.3e-08 | 2.2e-08 | 2.1e-11 | 5.3e-15 | 2.2e-09 | 2.9e-09 |
| qofl18b-mj | 1.4e-12 | 1.5e-10 | 1.3e-11 | 4.2e-13 | 7.9e-11 | 6.5e-10 | 5.6e-10 |
| zzshr-wall | 2.9e-09 | 4.1e-08 | 0. | 3.4e-14 | 0. | 4.2e-11 | 3.6e-08 |
| xoal0180mj | 2.3e-09 | 3.2e-08 | 3.9e-08 | 1.4e-09 | 4.3e-09 | 3.6e-08 | 1.9e-07 |
| xoal0174mj | 2.2e-09 | 3.2e-08 | 3.7e-08 | 1.4e-09 | 4.3e-09 | 3.6e-08 | 1.9e-07 |
| xocl0126mj | 2.9e-09 | 9.3e-11 | 1.5e-07 | 3.3e-17 | 0. | 4.6e-10 | 1.4e-07 |
| xobl0079mj | 6.2e-09 | 3.2e-08 | 2.3e-07 | 1.4e-09 | 4.3e-09 | 3.7e-08 | 3.8e-07 |
| xobl0011mj | 7.5e-09 | 3.2e-08 | 3.0e-07 | 1.4e-09 | 4.3e-09 | 3.7e-08 | 4.4e-07 |
| xocl0200mj | 2.9e-09 | 9.4e-11 | 1.5e-07 | 3.3e-17 | 0. | 4.6e-10 | 1.4e-07 |
| xoal0010mj | 2.8e-09 | 3.2e-08 | 6.4e-08 | 1.4e-09 | 4.3e-09 | 3.6e-08 | 2.2e-07 |
| xoal0173mj | 2.8e-09 | 3.2e-08 | 6.4e-0[illegible] | 1.4e-09 | 4.3e-09 | 3.6e-08 | 2.2e-07 |
| kpxlrcpamq | 2.1e-08 | 3.1e-07 | 1.2e-13 | 3.1e-13 | 2.1e-17 | 2.3e-08 | 1.5e-07 |
| kpxlrcpbmq | 2.1e-08 | 3.1e-07 | 1.2e-13 | 3.1e-13 | 2.1e-17 | 2.3e-08 | 1.5e-07 |
| kpxlrcpcmq | 2.1e-08 | 3.1e-07 | 1.2e-13 | 3.1e-13 | 2.1e-17 | 2.3e-08 | 1.5e-07 |
| kpxlrcpdmq | 2.1e-08 | 3.1e-07 | 1.2e-13 | 3.1e-13 | 2.1e-17 | 2.3e-08 | 1.5e-07 |
| mhalsga-mq | 2.0e-08 | 2.9e-07 | 1.2e-13 | 3.1e-13 | 2.1e-17 | 2.3e-08 | 1.5e-07 |
| mhalsgb-mq | 2.0e-08 | 2.9e-07 | 1.2e-13 | 3.1e-13 | 2.1e-17 | 2.3e-08 | 1.5e-07 |
| mhalsgc-mq | 2.0e-08 | 2.9e-07 | 1.2e-13 | 3.1e-13 | 2.1e-17 | 2.3e-08 | 1.5e-07 |
| mhalsgd-mq | 2.0e-08 | 2.9e-07 | 1.2e-13 | 3.1e-13 | 2.1e-17 | 2.3e-08 | 1.5e-07 |
| zohl002cmj | 1.0e-08 | 1.5e-07 | 4.6e-08 | 9.4e-15 | 4.6e-18 | 2.4e-09 | 2.8e-09 |
| xobl0044mj | 7.0e-09 | 3.2e-08 | 2.8e-07 | 1.4e-09 | 4.3e-09 | 3.7e-08 | 4.2e-07 |
| xoel141-mj | 2.3e-09 | 1.1e-09 | 7.3e-08 | 3.3e-17 | 0. | 5.9e-09 | 1.4e-07 |
| xoal0178mj | 4.0e-09 | 3.2e-08 | 1.2e-07 | 1.4e-09 | 4.3e-09 | 3.6e-08 | 2.8e-07 |
| zohl002dmj | 1.1e-08 | 1.6e-07 | 5.0e-08 | 9.2e-15 | 4.5e-18 | 2.3e-09 | 2.8e-09 |
| xoal0196mj | 2.8e-09 | 3.2e-08 | 6.3e-08 | 1.4e-09 | 4.3e-09 | 3.6e-08 | 2.2e-07 |
| xobl0091mj | 2.8e-09 | 3.2e-08 | 6.3e-08 | 1.4e-09 | 4.3e-09 | 3.6e-08 | 2.2e-07 |
| xobl0119mj | 2.8e-09 | 3.2e-08 | 6.3e-08 | 1.4e-09 | 4.3e-09 | 3.6e-08 | 2.2e-07 |
| xoel142-mj | 2.3e-09 | 1.1e-09 | 7.3e-08 | 3.3e-17 | 0. | 5.9e-09 | 1.4e-07 |
| mval0045md | 1.4e-09 | 1.1e-07 | 9.5e-17 | 0. | 1.5e-15 | 2.7e-08 | 7.8e-15 |
| mval005-md | 1.4e-09 | 1.1e-07 | 9.5e-17 | 0. | 1.5e-15 | 2.7e-08 | 7.8e-15 |
| mval006-md | 1.4e-09 | 1.1e-07 | 9.5e-17 | 0. | 1.5e-15 | 2.7e-08 | 7.8e-15 |
| mval007-md | 1.4e-09 | 1.1e-07 | 9.5e-17 | 0. | 1.5e-15 | 2.7e-08 | 7.8e-15 |
| mval008-md | 1.4e-09 | 1.1e-07 | 9.5e-17 | 0. | 1.5e-15 | 2.7e-08 | 7.8e-15 |
| mvdl0005md | 1.4e-09 | 1.1e-07 | 9.5e-17 | 0. | 1.5e-15 | 2.7e-08 | 7.8e-15 |
| mvdl0016md | 1.4e-09 | 1.1e-07 | 9.5e-17 | 0. | 1.5e-15 | 2.7e-08 | 7.8e-15 |
| mvdl0017md | 1.4e-09 | 1.1e-07 | 9.5e-17 | 0. | 1.5e-15 | 2.7e-08 | 7.8e-15 |
| mvdl0018md | 1.4e-09 | 1.1e-07 | 9.5e-17 | 0. | 1.5e-15 | 2.7e-08 | 7.8e-15 |
| mvdl0019md | 1.4e-09 | 1.1e-07 | 9.5e-17 | 0. | 1.5e-15 | 2.7e-08 | 7.8e-15 |
| mvdl002omd | 1.4e-09 | 1.1e-07 | 9.5e-17 | 0. | 1.5e-15 | 2.7e-08 | 7.8e-15 |
| mvgl510-md | 1.4e-09 | 1.1e-07 | 9.5e-17 | 0. | 1.5e-15 | 2.7e-08 | 7.8e-15 |
| mvgl520-md | 1.4e-09 | 1.1e-07 | 9.5e-17 | 0. | 1.5e-15 | 2.7e-08 | 7.8e-15 |

(Continued)

| Component Perturbed | Cat 1 | Cat 2 | Cat 3 | Cat 4 | Cat 5 | Cat 6 | Cat 7 |
|---|---|---|---|---|---|---|---|
| mvg1530-md | 1.4e-09 | 1.1e-07 | 9.5e-17 | 0. | 1.5e-15 | 2.7e-08 | 7.8e-15 |
| mvg1540-md | 1.4e-09 | 1.1e-07 | 9.5e-17 | 0. | 1.5e-15 | 2.7e-08 | 7.8e-15 |
| wyblpresmq | 3.1e-08 | 4.6e-07 | 1.2e-13 | 3.1e-13 | 2.1e-17 | 2.3e-08 | 1.5e-07 |
| recl383amj | 3.6e-10 | 5.0e-09 | 1.5e-09 | 4.3e-15 | 1.2e-19 | 7.0e-15 | 2.7e-09 |
| recl383bmj | 3.6e-10 | 5.0e-09 | 1.5e-09 | 4.3e-15 | 1.2e-19 | 7.0e-15 | 2.7e-09 |
| zogl011amj | 3.8e-10 | 5.2e-09 | 1.5e-09 | 6.6e-15 | 1.2e-19 | 1.0e-09 | 2.8e-09 |
| 6oj1008amj | 3.6e-10 | 5.0e-09 | 1.5e-09 | 1.8e-12 | 2.7e-12 | 7.0e-15 | 2.8e-09 |
| xoc10057mj | 2.9e-09 | 9.4e-11 | 1.5e-07 | 3.3e-17 | 0. | 4.6e-10 | 1.4e-07 |
| 6oj1007amj | 3.6e-10 | 5.0e-09 | 1.5e-09 | 4.3e-15 | 1.2e-19 | 7.0e-15 | 2.8e-09 |
| zpbr001ame | 3.6e-10 | 5.0e-09 | 1.5e-09 | 4.3e-15 | 1.2e-19 | 7.0e-15 | 2.8e-09 |
| zpbr001amg | 3.6e-10 | 5.0e-09 | 1.5e-09 | 4.3e-15 | 1.2e-19 | 7.0e-15 | 2.8e-09 |
| zpbr002bme | 3.6e-10 | 5.0e-09 | 1.5e-09 | 4.3e-15 | 1.2e-19 | 7.0e-15 | 2.8e-09 |
| zpbr002bmg | 3.6e-10 | 5.0e-09 | 1.5e-09 | 4.3e-15 | 1.2e-19 | 7.0e-15 | 2.8e-09 |
| mod1018cmj | 6.6e-12 | 1.7e-10 | 8.2e-12 | 2.7e-11 | 4.0e-11 | 3.1e-10 | 9.2e-10 |
| mra185e-mb | 9.4e-12 | 2.1e-10 | 8.3e-12 | 2.4e-11 | 4.2e-11 | 3.2e-10 | 1.1e-09 |
| mra11ubbmg | 1.0e-11 | 4.9e-10 | 3.4e-11 | 1.9e-11 | 1.9e-10 | 1.6e-09 | 2.0e-09 |
| mra11b--mg | 1.0e-11 | 4.9e-10 | 3.4e-11 | 1.9e-11 | 1.9e-10 | 1.6e-09 | 2.0e-09 |
| xoc10125mj | 2.9e-09 | 9.4e-11 | 1.5e-07 | 3.3e-17 | 0. | 4.6e-10 | 1.4e-07 |
| xoa10197mj | 3.4e-09 | 3.2e-08 | 9.4e-08 | 1.4e-09 | 4.3e-09 | 3.6e-08 | 2.4e-07 |
| 6oh1005cmj | 1.1e-08 | 1.7e-07 | 5.1e-08 | 4.8e-11 | 5.2e-14 | 3.3e-09 | 4.6e-09 |
| 6oh1034bmj | 1.2e-11 | 2.0e-10 | 0. | 1.9e-15 | 0. | 1.0e-09 | 0. |
| xoc10023mj | 2.9e-09 | 9.4e-11 | 1.5e-07 | 3.3e-17 | 0. | 4.6e-10 | 1.4e-07 |
| 6oh1005bmj | 9.1e-09 | 1.3e-07 | 4.0e-08 | 3.5e-11 | 3.8e-14 | 2.8e-09 | 4.0e-09 |
| mvg185e-mb | 6.2e-12 | 1.4e-10 | 5.4e-12 | 1.6e-11 | 2.7e-11 | 2.1e-10 | 7.5e-10 |
| rtr138--mk | 3.3e-10 | 5.0e-09 | 1.5e-09 | 1.0e-19 | 1.2e-19 | 7.0e-15 | 1.3e-13 |
| rtr139--mk | 3.3e-10 | 5.0e-09 | 1.5e-09 | 1.0e-19 | 1.2e-19 | 7.0e-15 | 1.3e-13 |
| zoi1013bmj | 1.3e-11 | 2.1e-10 | 0. | 2.2e-15 | 0. | 1.0e-09 | 0. |
| 6ta1001amj | 2.4e-11 | 3.7e-10 | 0. | 2.2e-15 | 0. | 1.9e-09 | 1.0e-10 |
| 6ta1005amj | 1.1e-11 | 1.8e-10 | 0. | 1.7e-15 | 0. | 9.3e-10 | 0. |
| 6ta1006bmj | 1.1e-11 | 1.8e-10 | 0. | 1.7e-15 | 0. | 9.3e-10 | 0. |
| 6ta1007cmj | 1.1e-11 | 1.8e-10 | 0. | 1.7e-15 | 0. | 9.3e-10 | 0. |
| 6ta1008dmj | 1.1e-11 | 1.8e-10 | 0. | 1.7e-15 | 0. | 9.3e-10 | 0. |
| 6oh1032amj | 2.8e-11 | 4.5e-10 | 0. | 4.2e-15 | 0. | 2.3e-09 | 0. |
| 6oh1036amj | 2.8e-11 | 4.5e-10 | 0. | 4.2e-15 | 0. | 2.3e-09 | 0. |

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