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COMPARISON OF THE EFFECT OF HAZARD AND RESPONSE/FRAGILITY UNCERTAINTIES ON CORE MELT PROBABILITY UNCERTAINTY

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ABSTRACT

This report proposes a method for comparing the effects of the uncertainty in probabilistic risk analysis (PRA) input parameters on the uncertainty in the predicted risks.

The proposed method is applied to compare the effect of uncertainties in the descriptions of 1) the seismic hazard at a nuclear power plant site and 2) random variations in plant subsystem responses and component fragility on the uncertainty in the predicted probability of core melt. The PRA used is that developed by the Seismic Safety Margins Research Program.

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Executive Summary

The risks associated with complex systems such as a nuclear power plant have been analyzed using probability modeling or probability risk analysis (PRA). Necessary inputs into a PRA are probability distributions which describe the random variation of many of the parameters, e.g., subsystem stresses and strengths, which influence risk. Unfortunately, these probability distributions are unknown and sufficient data does not always exist to get good estimates. Thus, limited data and/or subjective judgements and opinions frequently form the basis for the probability inputs into a PRA. It follows that there is considerable uncertainty associated with the predicted risks, e.g., probability of a core melt due to an earthquake.

A point of interest is to compare how the uncertainties in the various inputs affect the uncertainty in the predicted risk. A goal might be to identify the single input which contributes most significantly to the uncertainty in the predicted risk. A method for comparing the effects on the uncertainty in the predicted risk of the uncertainty in two inputs is proposed in this report. The method is based on an analysis of the variance of the predicted risk. Uncertainty in the probabilistic inputs into a PRA are usually described by associating an 'uncertainty' distribution with the characteristics of the probability inputs into a PRA. Thus, the predicted risk can be treated as a random variable and the variance is a natural measure of variation or uncertainty.

The proposed method is applied to compare the effect of uncertainties in the descriptions of the

- seismic hazard
- random variations in subsystem responses and component fragility

on the uncertainty in the predicted probability of core melt using the SSMRP probability risk analysis. Although the data available does not satisfy the requirements of a valid analysis, application of the methodology suggests that the effect on the uncertainty in the risk prediction of seismic hazard uncertainty and fragility/response uncertainty are comparable.

SECTION 1: Introduction

Risk of a nuclear power plant, as quantified by the probability of core melt, is a function of many parameters; e.g., the magnitude of an earthquake and the resulting peak ground acceleration at the base, soil/structure damping; which are subject to inherent or physical random variation. Probability Risk Analysis (PRA) is an analysis method used to estimate the risk or probability of core melt in which the physical randomness is described by associating probability distributions with the various parameters. In the SSMRP a PRA was used to estimate the risk of an earthquake-induced core melt and radioactive release from a commercial nuclear power plant.

Core melt will occur only if several safety related subsystems fail simultaneously with the occurrence of an earthquake. Failure of large, expensive components and subsystems, as well as the occurrence of earthquakes, are rare events. Thus, there is a limited data base available to develop the necessary probability distributions needed for a PRA and it is often necessary to base the probability distributions on engineering judgments and subjective opinions. In addition, models describing the sequence of events, including initiating events and accident sequences, leading to a core melt are based on knowledgeable judgments about the operation and interrelationships between appropriate subsystems within the plant. In the SSMRP study of the Zion nuclear power plant the following areas relied on subjective inputs in developing distributions for the PRA:

- the seismic hazard curves were developed from an elicitation of expert opinions about the zonation and seismicity of the Eastern United States which could form the source of earthquakes affecting Zion.

- the fragility distribution for many of the components and subsystems were based on a combination of opinions of knowledgeable individuals from industry and private consultants, governmental laboratories and universities along with some experimental data.
- the nominal values for many of the soil and structural parameters affecting component and subsystem responses were chosen by engineering judgment based on information in the professional literature.

Use of judgment, opinion and experimental data to characterize the probability distributions of the random parameters introduces a degree of uncertainty into the PRA. This uncertainty is called modeling uncertainty in SSMRP. Thus, rather than evaluating the probability of core melt deterministically, as would be the case if all the models and probability distributions were known, a PRA provides an estimate of the risk or probability of core melt.

Following the practice of statistics, in which estimates of unknown paramters are based on sampled data, the output of PRA can be either

- a point estimate (single value) of the risk or probability of core melt.
- an interval estimate (called an uncertainty interval) of risk which attempts to quantify all the modeling uncertainties associated with the analysis process.

A question of frequent interest, when assessing the significance of the uncertainties in estimating risk, is 'what modeling uncertainties have a significant effect on the uncertainty in the estimate of risk?'

This report attempts to address this question with respect to the estimation of the risk of an earthquake-induced core melt at the Zion nuclear power plant. Specifically, the report centers on comparing the contributions to uncertainty in estimating risk due to uncertainty in describing the seismic hazard and in describing the random variations in response and fragility parameters.

Section 2 discusses the different sources of modeling uncertainties that were considered in the Zion risk analysis. Comparison of the contribution to uncertainty in risk due to uncertainties in hazard versus uncertainties in response/fragility parameters is based on an analysis of the variance of the probability of core melt estimated in a simulation study. The basis of a comparison is discussed in Section 3. Results of the uncertainty simulation experiment are summarized in Section 4. The report concludes with a discussion of the results and some recommendations in Section 5.

Section 2: Sources of Uncertainty

In a complex PRA such as the study of the risk of an earthquake-induced core melt at the Zion nuclear power plant there are many inputs into the analysis, e.g., descriptions of the seismic hazard, component/subsystem fragilities, subsystem models, which are potential sources of uncertainty in the estimation of risk. The two principle sources of uncertainty of interest in the SSMRP seismic risk analysis of Zion are:

- uncertainties associated with development of the seismic hazard curve.
- uncertainties in describing the random variation associated with the component/subsystem response and fragility parameters.

To make a comparison of the significnace of these two sources of uncertainty to the uncertainty in estimating risk, ideally, these two sources of uncertainty would affect the estimate of risk 'independently.' Unfortunately, this is not true for the PRA methods used in the Zion seismic risk analysis. Why? The reason is that the risk estimation process involves a preliminary estimation of the parameters (mean, standard deviation and correlations of the logarithms of the responses) of the distribution of responses at several PGA levels. That is, for fixed values of the hazard parameters and response/fragility parameters, instead of estimating risk based on a specified response distribution an estimated response distribution is used. Estimates of the characteristics of the response distribution are based on simulations of response parameters and earthquake time histories. The simulated time histories are related to the hazard curve. This simulation of response parameters and time histories introduces a sampling variation in the risk estimator which exists if both or only one of the two sources of uncertainty are varied.

This phenomenon complicates any attempt to separate the effects of the two sources of uncertainty on the uncertainty in the probability of core melt. Further, if the sampling variation is a significant contributor to the uncertainty in the estimate of risk, differences in the effects of the two sources of uncertainty may not be identifiable.

2.1 Seismic Hazard Uncertainties

Seismic hazard is described by a seismic hazard curve which is a plot of probability $P(A_{max}>a)$ that the maximum peak ground acceleration (PGA) at the site exceeds level a versus the value a. The value of $P(A_{max}>a)$ depends on:

- Zonation of the region surrounding the site.
- Seismicity, i.e., range and distribution of magnitudes, for each zone.
- Ground motion models including a measure of the random variation in ground motion and the possible effects of local site soil conditions.

Information for the Zion study regarding these factors, particularly zonation and seismicity, were based on opinions of a panel of experts. Each expert's uncertainty in his/her description of the location and shape of a zone and in his/her estimate of the seismicity within a zone contribute to uncertainty in the hazard curve. Ground motion models describe the transfer of ground motion at the source (location of the earthquake) to the site (location of the power plant). Such transfer will be affected by the soil type and condition between the source and the site. Numerous ground motion models have been developed to describe this transfer. Most of the models are based on data from a variety of events and locations, hence soil conditions. Many of them are based on data from the western United States where the propagation or attenuation of ground motion may be quite different from that in the eastern United States. Overall, development of the ground motion models are based on limited data, thus will be a factor in the uncertainty of the seismic hazard. Further, application of the ground motion models to Zion and the implementation of local site corrections are based on subjective judgments which adds additional uncertainty to the description of the seismic hazard.

Uncertainty in the seismic hazard was modeled by a catalog of seismic hazard curves. The variation in the seismic hazard curves in the catalog reflected the uncertainties in the inputs; zonation, seismicity, ground motion model, local site effect; involved in the construction of the seismic hazard curves.

2.2 Response/Fragility Uncertainties

Component and subsystem responses, as quantified by accelerations or moments, are subject to random variation, hence were modeled as multidimensional lognormal random variables in the SSMRP studies. The parameters of the multivariate lognormal distribution:

μ - means of the logarithm of responses

β - standard deviations of the logarithm of responses

ρ - correlations of the logarithm of responses

depend on the soil and structural properties of the Zion plant. Although many soil and structural properties affect response, the following properties were considered to have a significant effect and hence were the parameters identified in SSMRP:

- soil shear modulus and damping
- structure damping and frequency

The precise values of these parameters are unknowns. Hence, these parameters were considered to be random variables, i.e., Zion was considered to be a sample plant from the collection of all possible plants that might have been constructed using the same design as the Zion plant. Variations in structural properties between these (conceptual) plants would be due to construction variables (materials, construction practices, quality control). The realized or nominal values of these parameters were based on either design or the best information available for the Zion plant.

Because the nominal value itself is not known definitively there is modeling uncertainty associated with specification of the nominal soil and structure properties. Thus, the nominal value of each parameter was considered to be a lognormal variable for which the coefficient of variation, β, described the uncertainty in specifying the nominal values.

Because the soil/structure parameters have both a random and modeling component of variation, the risk analysis estimation involved a two-stage simulation process:

- Stage 1: given fixed nominal values of the soil/structure parameters, a sample of time histories and soil/structure parameter values were used to estimate the charactersitics (μ,β,ρ) of the multivariate lognormal distribution of responses.
- Stage 2: a sample of nominal values of the soil/structure parameters were selected for the uncertainty analysis.

Fragilities of components and subsystems were modeled by considering the failure threshold, in terms of the appropriate response variable, acceleration or moment, was a lognormal random variable. The characteristics of these distributions were derived primarily from the opinions of experts. When estimates of these characteristics, based on test data, were available, these were combined with the opinions of the experts. Uncertainties associated with estimating these characteristics were due to

- uncertainty in an expert's opinion
- variations in opinions among experts
- sampling variation associated with test data.

These uncertainties were combined and described by treating μ, the mean of the logarithm of failure threshold, as a lognormal variable in which the coefficient of variation quantified the uncertainties.

Section 3: Measurement of the Effect of Modeling Uncertainties

Introducing modeling uncertainty in 1) the seismic hazard by treating the hazard curve as variable, and 2) the distributions of the response/fragility parameters by treating the distribution characteristics as random variables means that the estimator of the probability of core melt is also a random variable. One measure of the variability in the distribution of values of a random variable is the variance. In this case, since the variability in the estimator of the probability of core melt is due to modeling uncertainties, the variance is a quantification of these uncertainties. An analysis of the variance of the estimator of the probability of core melt is the basis for comparing the effects of the two primary sources of modeling uncertainty.

It must be noted, however, that there is an additional source of variation - sampling variation - which has been neglected in making this analysis. Since simulation, i.e., sampling, is used in both the estimation phase and uncertainty analysis phase of the risk estimation, sampling variation will have an effect on the realized results of the study and may influence the comparative study which is the basis of this report. However, given the complexity of the Zion analysis, an analysis of the variation in the estimates due to sampling variation has not been done and it was not possible, given time and resources, to do a simulation study of sampling variation. Since the conclusions of the comparative study can only be suggestive and not definitive we have neglected the effect of sampling variation at this stage. It must be recognized that if sampling variation is large so that the relative importance of the hazard and response/fragility uncertainties cannot be identified, then the uncertainty due to sampling variation must be considered a significant contributor to the uncertainty in the estimator of risk.

3.1 Variance of the Estimator of Probability of Core Melt

If the hazard curve and the nominal values of all response/fragility parameters were known, as well as all other parameters such as the systems models and unmodeled random events, the probability of core melt would be evaluated exactly - it would not be estimated. The identity for the probability assessment is

$$P(CM \mid \underline{\theta}_H, \underline{\theta}_R) = \int_a P(CM \mid a; \underline{\theta}_H, \underline{\theta}_R)\, g(a \mid \underline{\theta}_H)\, da \tag{3.1}$$

where $\underline{\theta}_H$, $\underline{\theta}_R$ are symbols used to recognize that the probability assessment depends on the parameters $\underline{\theta}_H$ of the hazard curve and the nominal values $\underline{\theta}_R$ of the characteristics of the response and fragility distributions.

Since $\underline{\theta}_H$, $\underline{\theta}_R$ are unknown, estimators $(\tilde{\underline{\theta}}_H, \tilde{\underline{\theta}}_R)$ of these characteristics based on opinions, judgments or data (or combinations of these sources of information) are used in place of the unknown $(\underline{\theta}_H, \underline{\theta}_R)$. The estimator of risk, labeled $\tilde{P}(CM)$, is

$$\tilde{P}(CM) = \int_a P(CM \mid a; \tilde{\underline{\theta}}_H, \tilde{\underline{\theta}}_R)\, g(a \mid \tilde{\underline{\theta}}_H)\, da \tag{3.2}$$

Uncertainty in the estimates of these characteristics is handled by treating $(\tilde{\underline{\theta}}_H, \tilde{\underline{\theta}}_R)$ as random variables. Then $\tilde{P}(CM)$ can be treated as a random variable which is a function of $\tilde{\underline{\theta}}_H$ and $\tilde{\underline{\theta}}_R$. The variance, $\mathrm{Var}[\tilde{P}(CM)]$, of $\tilde{P}(CM)$ can be expressed in the following way

$$\mathrm{Var}[\tilde{P}(CM)] = E_{\tilde{\underline{\theta}}_H}\{\mathrm{Var}_{\tilde{\underline{\theta}}_R}[\tilde{P}(CM) \mid \tilde{\underline{\theta}}_H]\} + \mathrm{Var}_{\tilde{\underline{\theta}}_H}\{E_{\tilde{\underline{\theta}}_R}[\tilde{P}(CM) \mid \tilde{\underline{\theta}}_H]\} \tag{3.3}$$

$$= E_{\tilde{\underline{\theta}}_R}\{\mathrm{Var}_{\tilde{\underline{\theta}}_H}[\tilde{P}(CM) \mid \tilde{\underline{\theta}}_R]\} + \mathrm{Var}_{\tilde{\underline{\theta}}_R}\{E_{\tilde{\underline{\theta}}_H}[\tilde{P}(CM) \mid \tilde{\underline{\theta}}_R]\} \tag{3.4}$$

To provide some motivation for the proposed statistics to be used to compare the relative effects of two sources of uncertainty, we consider the terms in Equations (3.3) and (3.4) in more detail.

Since $\tilde{P}(CM)$ is a function of 2 sets of random variables $\underline{\tilde{\theta}}_H$ and $\underline{\tilde{\theta}}_R$ it is appropriate to consider the conditional expected value and variance holding one of the variables fixed. That is, we can consider

- the conditional mean of $\tilde{P}(CM)$
  - with $\underline{\tilde{\theta}}_H$ fixed, labeled $E_{\underline{\tilde{\theta}}_R}[\tilde{P}(CM) \mid \underline{\tilde{\theta}}_H]$
  - with $\underline{\tilde{\theta}}_R$ fixed, labeled $E_{\underline{\tilde{\theta}}_H}[\tilde{P}(CM) \mid \underline{\tilde{\theta}}_R]$

Since the expected value is a measure of central tendency or location each of the expected values is an 'estimate' of the P(CM) given the value of the fixed variable. This 'estimate' varies as the value of the fixed variable changes. How variable this 'estimate' is as the fixed variable varies over its range of values provides a measure of the effect of uncertainty in the fixed variable on the estimate of P(CM).

- the conditional variance of $\tilde{P}(CM)$
  - with $\underline{\tilde{\theta}}_H$ fixed, labeled $\mathrm{Var}_{\underline{\tilde{\theta}}_R}[\tilde{P}(CM) \mid \underline{\tilde{\theta}}_H]$
  - with $\underline{\tilde{\theta}}_R$ fixed, labeled $\mathrm{Var}_{\underline{\tilde{\theta}}_H}[\tilde{P}(CM) \mid \underline{\tilde{\theta}}_R]$

The conditional variance is a measure of the variability in P(CM) due to the uncertainty in the non-fixed variable at each value of the fixed variable. A measure of the effect of the uncertainty in the non-fixed variable on the estimate of P(CM) would be the average of the conditional variances, averaged over the range of values of the fixed variable.

The conditional means and variances are functions of the fixed variables, i.e., are functions of random variables. Thus, the conditional means and variances are random variables also. It is appropriate to consider the mean and variance of these random variables also. Four of these are important to our analysis:

- the variance, over $\underline{\Theta}_H$, of the conditional mean given $\underline{\Theta}_H$, labeled

  $$\mathrm{Var}_{\tilde{\underline{\Theta}}_H} \{E_{\tilde{\underline{\Theta}}_R} [\tilde{P}(CM) \mid \tilde{\underline{\Theta}}_H]\}$$

- the variance, over $\tilde{\underline{\Theta}}_R$, of the conditional mean given $\tilde{\underline{\Theta}}_R$, labeled

  $$\mathrm{Var}_{\tilde{\underline{\Theta}}_R} \{E_{\tilde{\underline{\Theta}}_H} [\tilde{P}(CM) \mid \tilde{\underline{\Theta}}_R]\}$$

- the expected value or average of the conditional variance given $\tilde{\underline{\Theta}}_H$, labeled

  $$E_{\tilde{\underline{\Theta}}_H} \{\mathrm{Var}_{\tilde{\underline{\Theta}}_R} [\tilde{P}(CM) \mid \tilde{\underline{\Theta}}_H]\}$$

- the expected value or average of the conditional variance given $\tilde{\underline{\Theta}}_R$, labeled

  $$E_{\tilde{\underline{\Theta}}_R} \{\mathrm{Var}_{\tilde{\underline{\Theta}}_H} [\tilde{P}(CM) \mid \tilde{\underline{\Theta}}_R]\}$$

The proposed indices for measuring the effect of uncertainty in $\underline{\Theta}_R$ and $\underline{\Theta}_H$ respectively are based on combining appropriate subsets of these four distributional characteristics. That is, the variability or uncertainty in P(CM) due to the uncertainty in either set of inputs, e.g., $\underline{\Theta}_R$, can be measured by combining

- the average value of the $\mathrm{Var}_{\tilde{\underline{\Theta}}_R}$ { $\tilde{P}$(CM) | $\tilde{\underline{\Theta}}_H$}

and

- the $\mathrm{Var}_{\tilde{\underline{\Theta}}_R}$ {conditional mean of $\tilde{P}$(CM) | $\tilde{\underline{\Theta}}_R$}

Mathematically, the proposed measure of variation in $\tilde{P}(CM)$ due to the uncertainty in $\underline{\theta}_R$ is

$$\gamma(\underline{\theta}_R) = 0.5 \left(E_{\tilde{\underline{\theta}}_H} \{ \mathrm{Var}_{\tilde{\underline{\theta}}_R} [\tilde{P}(CM) | \tilde{\underline{\theta}}_H] \} + \mathrm{Var}_{\tilde{\underline{\theta}}_R} \{ E_{\tilde{\underline{\theta}}_H} [\tilde{P}(CM) | \tilde{\underline{\theta}}_R] \} \right)$$

Similarly, the measure of variation in $\tilde{P}(CM)$ due to the uncertainty is $\underline{\theta}_H$ is

$$\gamma(\underline{\theta}_H) = 0.5 \left(E_{\tilde{\underline{\theta}}_R} \{ \mathrm{Var}_{\tilde{\underline{\theta}}_H} [\tilde{P}(CM) | \tilde{\underline{\theta}}_R] \} + \mathrm{Var}_{\tilde{\underline{\theta}}_H} \{ E_{\tilde{\underline{\theta}}_R} [\tilde{P}(CM) | \tilde{\underline{\theta}}_H] \} \right)$$

Of course, it will be necessary to estimate these indices since it will not be *possible to analytically calculate the values, at least for complex PRA's such* as the SSMRP model. This is discussed in the next section.

3.2 Estimation of the Effect of Uncertainties in Response/Fragility and Hazard Characterizations

To use $\gamma(\underline{\theta}_R)$ and $\gamma(\underline{\theta}_H)$ as measures of the effect of uncertainty in response/fragility and hazard characterizations on uncertainty in the estimator of the probability of core melt it is necessary to estimate the various expected values and variances in Equations (3.5) and (3.2). Estimates of these parameters can be derived by running an experiment involving random samples of the response/fragility and hazard parameters. An outline of such an experiment is given in Fig. 3.1.

Notationally,

- $\tilde{P}_i\ (CM | a_\ell ; \underline{\theta}_{Ri})$ is the estimated conditional probability of core melt, given PGA a_ℓ, based on the random sample of response parameters for response/fragility nominal values $\underline{\theta}_{Ri}$.
- $P_j(a_\ell | \underline{\theta}_{Hj})$ are probabilities derived from hazard curve $\underline{\theta}_{Hj}$

- $\overline{P}_{i\bullet}$ is the sample mean

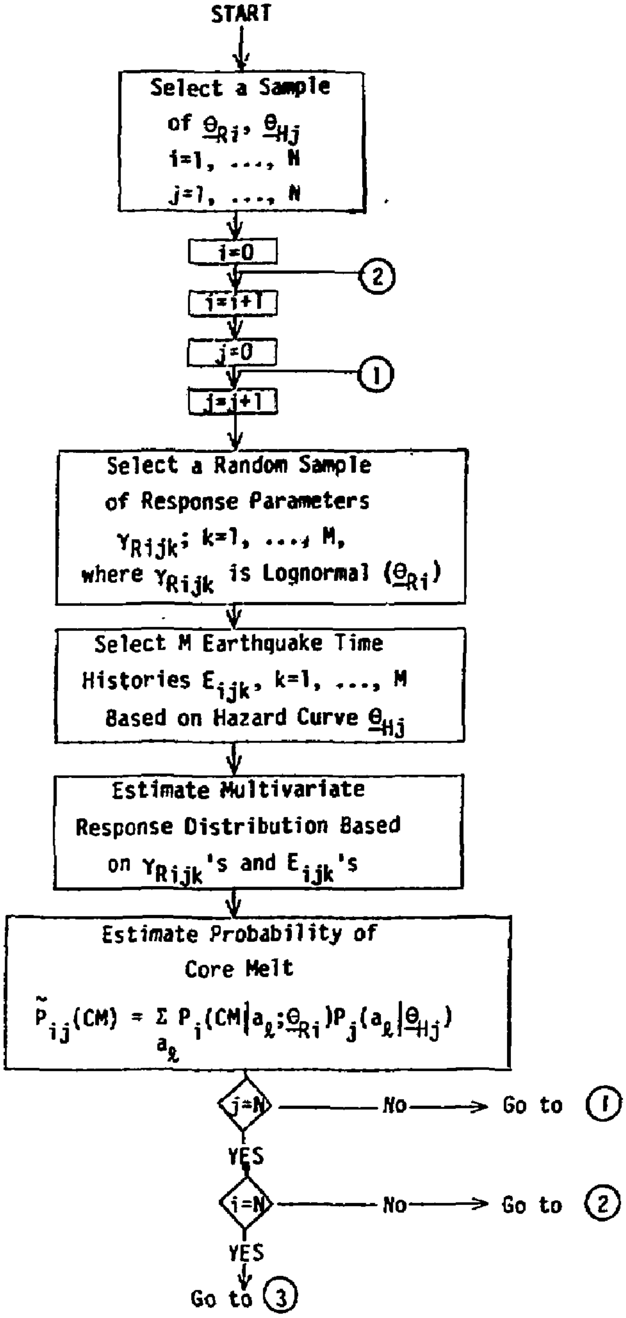
  $$\frac{1}{N} \sum_{j=1}^{N} \tilde{P}_{ij}(CM)$$

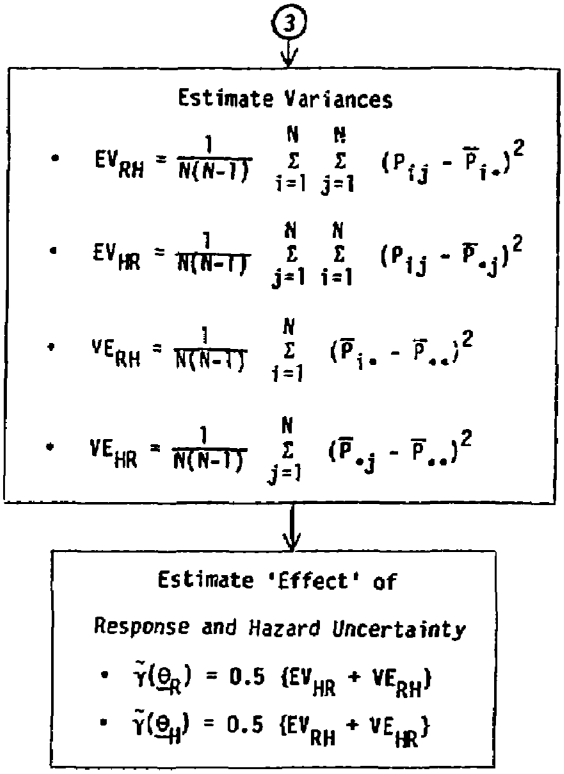
- $\overline{P}_{\bullet j}$ is the sample mean

  $$\frac{1}{N} \sum_{i=1}^{N} \tilde{P}_{ij}(CM)$$

- $\overline{P}_{\bullet\bullet}$ is the sample mean

  $$\frac{1}{N^2} \sum_{i=1}^{N} \sum_{j=1}^{N} \tilde{P}_{ij}(CM)$$


START
Select a Sample of $\underline{\theta}_{Ri}$, $\underline{\theta}_{Hj}$ $i=1, \ldots, N$ $j=1, \ldots, N$
$i=0$
②
$i=i+1$
$j=0$
①
$j=j+1$
Select a Random Sample of Response Parameters Y_{Rijk}; $k=1, \ldots, M$, where Y_{Rijk} is Lognormal ($\underline{\theta}_{Ri}$)
Select M Earthquake Time Histories E_{ijk}, $k=1, \ldots, M$ Based on Hazard Curve $\underline{\theta}_{Hj}$
Estimate Multivariate Response Distribution Based on Y_{Rijk}'s and E_{ijk}'s
Estimate Probability of Core Melt
$\tilde{P}_{ij}(CM) = \sum_{a_\ell} P_i(CM|a_\ell;\underline{\theta}_{Ri})P_j(a_\ell|\underline{\theta}_{Hj})$
$j=N$
No
Go to ①
YES
$i=N$
No
Go to ②
YES
Go to ③



Estimate Variances

- $EV_{RH} = \frac{1}{N(N-1)} \sum_{i=1}^{N} \sum_{j=1}^{N} (P_{ij} - \bar{P}_{i\cdot})^2$
- $EV_{HR} = \frac{1}{N(N-1)} \sum_{j=1}^{N} \sum_{i=1}^{N} (P_{ij} - \bar{P}_{\cdot j})^2$
- $VE_{RH} = \frac{1}{N(N-1)} \sum_{i=1}^{N} (\bar{P}_{i\cdot} - \bar{P}_{\cdot\cdot})^2$
- $VE_{HR} = \frac{1}{N(N-1)} \sum_{j=1}^{N} (\bar{P}_{\cdot j} - \bar{P}_{\cdot\cdot})^2$

Estimate 'Effect' of

Response and Hazard Uncertainty

- $\tilde{\gamma}(\underline{\theta}_R) = 0.5 \{EV_{HR} + VE_{RH}\}$
- $\tilde{\gamma}(\underline{\theta}_H) = 0.5 \{EV_{RH} + VE_{HR}\}$

Figure 3.1: Outline of Experiment to Estimate Expected Values and Variances.

Although the methods of sampling $\underline{\theta}_R$ *and* $\underline{\theta}_H$ *are unspecified, it* would be appropriate to reduce the sample size by using latin hypercube sampling.

Section 4: Experimental Results

The experimental design outlined in Section 3.2 involves many random samples and a lot of simulations. For example, if $N = 50$ and $M = 10$, then $MxN^2 = 25{,}000$ response calculations would be made based on 25,000 time histories and values of the response parameters. The resulting 2,500 estimates of the multivariate response means, standard deviations and correlations would be used to evaluate 2,500 estimates $\tilde{P}_{ij}(CM)$ of the probability of core melt. The rather large number of replications is necessary to insure that the $\tilde{P}_{ij}(CM)$ can be considered to be realizations of independent random variables which can be used to evaluate the estimates EV_{RH}, EV_{HR}, VE_{RH}, VE_{HR}.

The basic concept in considering $\gamma(\underline{\Theta}_R)$ and $\gamma(\underline{\Theta}_H)$ as measures of the effect of uncertainty in response/fragility and seismic hazard respectively is to vary the response/fragility and hazard parameters and quantify the resulting variation in the estimate of the probability of core melt by the variance. Although the uncertainty analysis in the SSMRP study of Zion was not designed for estimating $\gamma(\underline{\Theta}_R)$ and $\gamma(\underline{\Theta}_H)$, making some additional calculations with the results of the 14 replications from that study provides some data which can be used to draw, perhaps, some inferences about the relative effect of uncertainties in response/fragility and seismic hazard characterizations. Specifically, for each of the 14 combinations of $\underline{\Theta}_R$ and $\underline{\Theta}_H$ in the Zion uncertainty

- $P(CM|a;\underline{\Theta}_R, \underline{\Theta}_H)$
- $g(a|\underline{\Theta}_H)$

are derived. Note that the former estimate $P(CM|a;\underline{\Theta}_R, \underline{\Theta}_H)$ depends on the hazard curve only through the time histories, associated with the given hazard curve, used in the response calculations. Actually, the same ten time histories, adjusted for the different hazard curves, were used in all 14 replications. This is likely to have the effect of reducing sampling variation. A preferred analysis would have used a different random sample of time histories for each of the 14 replications.

If we ignore the effect of the time histories being associated with the hazard curve, the 14 estimates of $P(CM|a; \underline{\Theta}_R, \underline{\Theta}_H)$ can be combined with each of the 14 hazard curves $g(a|\underline{\Theta}_H)$ to give 14 x 14 = 196 estimates of $P(CM)$. These are listed in Table 4.1. Using the notation of the estimates of variances in Fig. 3.1, the entrees in Table 4.1 are

$$P_{ij} = \tilde{P}_{ij}(CM) \qquad \begin{array}{l} i=1, \ldots, 14 \\ j=1, \ldots, 14 \end{array}$$

which depend on the ith set of response parameters and jth hazard curve. The results of the 14 runs for the Zion uncertainty analysis are the diagonal entrees in Table 4.1. These are the only estimates which can be considered independent. It must be recognized that the P_{ij}'s are not independent since the same values of $\tilde{P}(CM|a; \underline{\Theta}_{Ri}, \underline{\Theta}_{Hj})$ are used for each hazard curve $g(a|\underline{\Theta}_{Hj})$. Lack of independence of the P_{ij}'s primarily affects the variance calculations, e.g., any sample mean is still an unbiased estimator whereas the sample variance is not. This is a recognized deficiency in the data and the analysis and results based on this data. The estimated conditional means and variances were nevertheless evaluated. These, along with the coefficients of variation, are summarized in Tables 4.2 and 4.3 for fixed response/fragility and hazard parameters respectively. For a fixed set of response parameters $\underline{\Theta}_{Ri}$, the estimates P_{ij}, j=1, ..., 14

i/j	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	.4188-5	.1833-5	.2335-5	.1628-4	.2870-4	.6645-4	.5853-4	.7194-5	.1660-4	.2584-5	.2028-5	.3132-5	.1198-4	.3044-3
2	.2960-3	.9104-4	.1025-3	.4721-3	.1198-2	.1098-2	.5408-3	.3056-3	.4381-3	.1542-3	.1377-3	.1658-3	.3633-3	.4157-2
3	.1036-5	.5635-6	.7327-6	.6312-5	.1001-4	.3179-4	.3224-4	.1875-5	.6680-5	.7712-6	.4768-5	.9187-6	.4785-5	.1654-3
4	.4781-5	.2135-5	.2797-5	.1990-4	.3407-4	.7998-4	.6873-4	.9508-5	.2020-4	.2750-5	.2212-5	.3589-5	.1451-4	.3565-3
5	.3908-4	.1406-4	.1676-4	.9160-4	.1933-3	.2671-3	.1775-3	.5795-4	.8812-4	.2125-4	.1909-4	.2502-4	.6864-4	.1060-2
6	.3376-4	.1592-5	.2054-5	.1489-4	.2532-4	.6264-4	.5636-4	.6410-5	.1530-4	.2183-5	.1679-5	.2699-5	.1095-4	.2903-3
7	.9660-5	.3987-5	.4979-5	.3138-4	.5834-4	.1095-3	.8613-4	.1780-4	.3111-4	.5515-4	.4796-5	.6916-5	.2321-4	.4673-3
8	.1967-5	.9789-6	.1255-5	.9699-5	.1609-4	.4420-4	.4247-4	.3519-5	.1011-4	.1367-5	.9772-6	.1645-5	.7237-5	.2184-3
9	.7649-5	.2282-5	.2814-5	.1697-4	.3578-4	.5965-4	.4606-4	.8840-5	.1640-4	.3175-5	.2696-5	.3849-5	.1272-4	.2701-3
10	.1144-3	.3369-4	.3888-4	.1881-3	.4633-3	.4689-3	.2457-3	.1209-3	.1743-3	.5376-4	.4833-4	.6008-4	.1431-3	.1811-2
11	.3745-4	.1320-4	.1562-4	.8397-4	.1808-3	.2427-3	.1602-3	.5249-4	.8065-4	.2034-4	.1817-4	.2365-4	.6310-4	.9674-3
12	.2780-6	.1542-6	.1939-6	.1779-5	.2807-5	.9508-5	.1017-4	.4517-6	.1898-5	.2154-6	.1220-6	.2481-6	.1394-5	.5293-4
13	.8279-3	.2947-3	.3157-3	.1333-2	.3508-2	.2802-2	.1390-2	.8420-3	.1263-2	.5611-3	.4910-3	.5612-3	.1052-2	.1044-1
14	.3681-4	.1232-4	.1495-4	.8342-2	.1761-3	.2473.3	.1625-3	.5274-4	.7969-4	.1761-4	.1595-4	.2149-4	.6214-4	.9864-3

Table 4.1 Estimates of Probability of Core Melt

Response Set, i	Conditional Mean $\overline{P}_{i\cdot}$ Over Hazard Curves	Conditional Variance Over Hazard Curves	Coefficient of Variation
1	.3759-4	.6334-8	2.11
2	.6800-3	.1120-5	1.56
3	.1883-4	.1896-8	2.31
4	.4440-4	.8686-8	2.10
5	.1526-3	.7421-7	1.78
6	.3541-4	.5777-8	2.15
7	.6148-4	.1472-7	1.97
8	.2571-4	.3287-8	2.23
9	.3493-4	.4904-8	2.00
10	.2832-3	.2137-6	1.63
11	.1400-3	.6171-7	1.77
12	.5868-5	.1947-9	2.38
13	.1835-2	.6998-5	1.44
14	.1407-3	.6440-7	1.80

Table 4.2 Conditional Means, Variances and Coefficients of Variation Given the Response Parameters

Hazard Curve j	Conditional Mean $\bar{P}_{\cdot j}$ Over Response Parameters	Conditional Variance Over Response Parameters	Coefficient of Variation
1	.9890-4	.5029-7	2.27
2	.3375-4	.6221-8	2.34
3	.3726-4	.7159-8	2.27
4	.1692-3	.1276-6	2.11
5	.4236-3	.8884-6	2.23
6	.3993-3	.5591-6	1.87
7	.2198-3	.1319-6	1.65
8	.1062-3	.5142-7	2.13
9	.1601-3	.1139-6	2.11
10	.6049-4	.2242-7	2.48
11	.5323-4	.1721-7	2.46
12	.6287-4	.2250-7	2.39
13	.1314-3	.7935-7	2.14
14	.1539-2	.7706-5	1.80

Table 4.3 Conditional Means, Variance and Coefficients of Variation Given the Hazard Curves

of the probability of core melt, *given* $\underline{\Theta}_{Ri}$, *involve* the same *random* Latin hypercube sample of response parameters and time histories in the estimates $\tilde{P}(CM|a;\underline{\Theta}_{Ri}, \underline{\Theta}_{Hj})$. Even so, the sample conditional means $\bar{P}_{i\cdot}$ are still unbiased estimators of the conditional expected value of probability of core melt given the response parameters $\underline{\Theta}_{Ri}$. However, since the same hazard curves contribute to all the $\bar{P}_{i\cdot}$'s, these estimates are not independent over the responses. Thus, the estimated variance VE_{RH} would not be an unbiased estimate of the variance of the conditional means. The same is true for the estimated variance VE_{HR}. However, to possibly get some information about the relative effects of response/fragility versus seismic hazard uncertainty, we consider these estimates. Using the data in Tables 4.2 and 4.3,

$$EV_{RH} = .6127\text{-}6$$

$$EV_{HR} = .6988\text{-}6$$

$$VE_{RH} = .2393\text{-}6$$

$$VE_{HR} = .1529\text{-}6$$

and

$$\tilde{\gamma}(\underline{\Theta}_R) = 0.5\ [VE_{RH} + EV_{HR}] = 0.4691\text{-}6$$

$$\tilde{\gamma}(\underline{\Theta}_H) = 0.5\ [VE_{HR} + EV_{RH}] = 0.3828\text{-}6$$

For comparison, consider the ratio of the $\tilde{\gamma}$'s,

$$\tilde{\gamma}(\underline{\Theta}_R)/\gamma(\underline{\Theta}_H) = 1.225$$

which suggests the inference that the effects of uncertainty in the response/fragility parameters and in the seismic hazard parameters are comparable. The results, taken literally, might suggest more. However, given the inadequate data base it does not seem reasonable to suggest more than that they are comparable.

SECTION 5: Discussion

Uncertainties in the probabilistic descriptions in a PRA affect the quality of the estimates derived from the analysis. Thus, it is of interest to compare how uncertainties in various descriptive input parameters, e.g., response/fragility parameters vs. seismic hazard parameters, affect the uncertainty in the measure of risk, e.g., probability of core melt.

One way to describe the uncertainties associated with the probabilistic input parameters, i.e., nominal values of the soil/structure parameters and hazard curves, is to treat these probabilistic descriptors as random variables themselves. Since the estimator of risk is a function of these descriptors, it is a random variable. One measure of the uncertainty or variability of a random variable is its variance or standard deviation.

An analysis of the variance of the estimator of risk is suggested in this report as a means of comparing the effects of the uncertainties in two groups, response/fragility and seismic hazard, of inputs. Specifically, it is shown that the variance of the estimator of risk can be partitioned into two components:

- the average value of the conditional variances,
- the variance of conditional means.

A combination of these sources of variation provides a means of measuring the relative effects of the uncertainties in the two groups of inputs.

An experiment is suggested which would provide unbiased estimators of the two components of variance. Although such an experiment has not been run in the SSMRP study of the Zion nuclear power plant, data from the Zion uncertainty analysis is used to

- illustrate how the proposed measures can be estimated
- suggest, recognizing the limitations of the sample data, that the effects of response/fragility and seismic hazard uncertainties on the estimate of risk are comparable.

Although the data from the Zion uncertainty analysis has serious limitations to make definitive conclusions, both the

- average conditional variance

and

- variance of conditional means

of the probability of core melt are comparable when comparing the effects of uncertainties in response/fragility and seismic hazard parameters. Because the variance of the estimate of risk involves an 'averaging' and because the magnitudes of the probabilities are 'small', differences in the levels of uncertainties of the two groups of inputs may be mitigated in the estimation process. Also, there is the possibility that sampling variation may be so large that the true differences between the two sources of uncertainty of interest are not recognizable.

Again it must be emphasized that limitations on the data available for analysis do not allow one to make definitive conclusions. An experiment designed especially for this type of analysis is needed to

- further consider the proposed measures
- make definitive conclusions about the relative effects of response/fragility versus seismic hazard uncertainties on the uncertainty in the estimator of the probability of core melt.