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REVIEW OF SEISMIC PROBABILISTIC RISK ASSESSMENT AND THE USE OF SENSITIVITY ANALYSIS*

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ABSTRACT

This paper presents results of sensitivity reviews performed to address a range of questions which arise in the context of seismic probabilistic risk assessment (PRA). These questions are the subject of this paper. A seismic PRA involves evaluation of seismic hazard, component fragilities, and system responses. They are combined in an integrated analysis to obtain various risk measures, such as frequency of plant damage states. Calculation of these measures depends on combination of non-linear functions based on a number of parameters and assumptions used in the quantification process. Therefore, it is often difficult to examine seismic PRA results and derive useful insights from them if detailed sensitivity studies are absent.

In a seismic PRA, sensitivity evaluations can be divided into three areas: hazard, fragility, and system modeling. As a part of the review of a standard boiling water reactor seismic PRA which was performed by General Electric (GE), a reassessment of the plant damage states frequency and a detailed sensitivity analysis were conducted at Brookhaven National Laboratory. The rationale for such an undertaking is that in this case: 1) the standard plant may be sited anywhere in the eastern U.S. (i.e., in regions with safety shutdown earthquake [SSE] values equal to or less than 0.3g peak ground acceleration), 2) it may have equipment whose fragility values could vary over a wide range, 3) there are variations in system designs outside the original defined scope.

Seismic event trees and fault trees were developed to model the different system and plant accident sequences. Hazard curves which represent

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various sites on the east coast were obtained; alternate structure and equipment fragility data were postulated. Various combinations of hazard and fragility data were analyzed. In addition, system modeling was perturbed to examine the impact upon the final results. Orders of magnitude variation were observed in the plant damage state frequency among the different cases.

Several conclusions can be drawn from the results of the reassessment and the sensitivity analyses. First, it is clear that in order to gain useful insights from a seismic PRA, systematic and rigorous sensitivity studies are necessary. Back-of-the-envelope calculations or crude estimates often are found to be wrong, or at best, misleading due to the highly non-linear nature of the problem. Findings from the sensitivity studies also may not be intuitively obvious. Second, perturbation of the hazard curves yields significant changes in the final results. This is so dominant that fragility data and system model appear to be of secondary importance. Third, the percentage of contribution to plant damage state frequency from low ground accelerations can be dominated by the characterization of the left-hand-tail of the fragility curve.

INTRODUCTION

A number of seismic probabilistic risk assessment (PRA) studies for nuclear power plants have been published in the past few years.[1,2,3] All of these studies involve the evaluation of seismic hazard of a particular site location, component and structural fragilities, and system responses. Results of these considerations are presented in terms of some types of risk measures, such as core damage frequency or offsite consequences. It is a rather common practice within the nuclear industry to report these results of a single analysis. In many respects, this has limited the usefulness of the seismic PRA. Numerical results are, to some professionals, the least valuable part of the PRA. It has been suggested by others that the process of performing a seismic PRA and the insights derived by studying the effects on the power plant of the various safety related structures and equipment failure are more meaningful. It is often difficult to take the published seismic PRA results and to uncover the useful insights which are provided by the analysis without a detailed sensitivity study.

As part of the review[4] of the GESSAR-II seismic PRA[5] which was performed by General Electric Company (GE), the entire analysis was scrutinized in great detail. The justification for this effort was in part due to the fact that the GESSAR-II plant may be sited anywhere in the eastern U.S. (i.e., in regions with SSE values equal to or less than 0.3g peak ground acceleration), and only single representative analysis was performed.

New seismic event trees and fault trees were developed in the review to represent the GESSAR-II systems and plant accident sequences. Hazard curves which represent various sites on the east coast of the U.S. were obtained[6] and alternate structure and equipment fragility data were postulated. Various combinations of the hazard and fragility data were analyzed. In addition, system modeling was perturbed to examine impact on the core damage frequency.

Table 1 Alternate Fragility Parameter Values

Structure/Component	Alternate Parameter Values			
	Case 1		Case 2	
	Median (g)	β_c	Median (g)	β_c
Ceramic Insulator	0.20	0.32	0.20	0.32
Pump	1.81	0.61	1.81	0.61
Piping	(1)	(1)	(1)	(1)
Heat Exchanger	1.09	0.47	1.09	0.47
Valve (Hydraulic or Air)	(1)	(1)	(1)	(1)
Valve (Check or Spring)	(1)	(1)	(1)	(1)
Shroud Support	0.67	0.43	0.67	0.49
CRD Guide Tube	1.37	0.45	1.37	0.48
Hydraulic Control Unit	1.24	0.63	1.24	0.63
SLC Tank	1.33	0.33	1.33	0.33
RPV	1.25	0.40	1.25	0.59
Auxiliary Building	1.50	0.50	1.50	0.41
Drywell	1.50	0.50	1.50	0.50
Containment	1.50	0.50	1.50	0.50
Shield Building	1.50	0.50	1.50	0.50
Control Building	1.50	0.50	1.50	0.40
Diesel Generator Building	1.50	0.50	1.50	0.50
Diesel Generator Panel	1.56	0.52	1.50	0.67
125-V DC Bus	1.49	0.56	1.49	0.56
Diesel Generator Heat & Vent	1.55	0.51	1.50	0.65
480-V Transformer	1.49	0.56	1.39	0.66
480-V Switchgear	1.46	0.58	1.46	0.58
4-kV Switchgear	1.46	0.58	1.46	0.58
Water Service System	1.50	0.45	1.50	0.79
Condensate Storage Tank	0.80	0.39	0.24	0.39
Relay Chatter	0.60	0.67	0.60	0.67
Diesel Generator Structural	1.50	0.50	0.91	0.49

(1) Not included in systems analysis since capacities are relatively high.

As a result of this exercise, two areas have been identified from the results of this assessment and of the sensitivity analyses which warrant some discussion. The first area pertains to the effects of the hazard curve on core damage frequency. The second area deals with the contribution to core damage frequency from low ground acceleration earthquakes.

Impact of Hazard Curves and Fragility Curves

Owing to the fact that the GESSAR-II plant may be located anywhere in the Eastern U.S. where the SSE value does not exceed 0.3 pga, various hazard curves for different sites were obtained from a study sponsored by the U.S. NRC.[5] A selection of these curves are presented in Figure 1. A general observation of these curves is that there is a large variation in the annual frequency of exceedance for all the curves in general and even for those curves characterizing the same site; for instance, curves 2, 3, and 4 are generated by different experts for the Zion site, whereas curves 8 and 9 are for the Limerick site. The GESSAR-II curve has been omitted from the figure because of GE's claim of proprietary information. It lies approximately in the middle of these curves. In the sensitivity analyses, three hazard curves were selected; they are curve 14 for the Watts Bar site calculated by Lawrence Livermore National Laboratory, curve 4 of the Zion site by Dames and Moore, and the GESSAR-II curve. The GESSAR-II curve was chosen because it lies between the two extreme cases.

Using the BNL system model and the fragility values tabulated in Table 1, core damage frequency for the different cases was calculated; results are presented in Table 2.

Table 2 Core Damage Frequency
(Events/year)

Hazard Curve	Case 1	Case 2
Zion	9.29(-6)	1.35(-5)*
GESSAR-II	6.64(-5)	9.68(-5)
Watt Bar	7.31(-4)	1.00(-3)

*1.35(-5) = 1.35×10^{-5}

It can be seen from Table 1 that the changes in median capacity values from Case 1 to Case 2 occur mainly with the electrical components, and the changes are typically a few percent. The two major changes come from the condensate storage tank and the diesel generator structural. In addition to the median capacity values, the β_c are also changed. By and large, β_c values are those used for Case 1 with a slight increase for some components and structures. The most significant ones are the diesel generator panel and the diesel generator heat and vent.

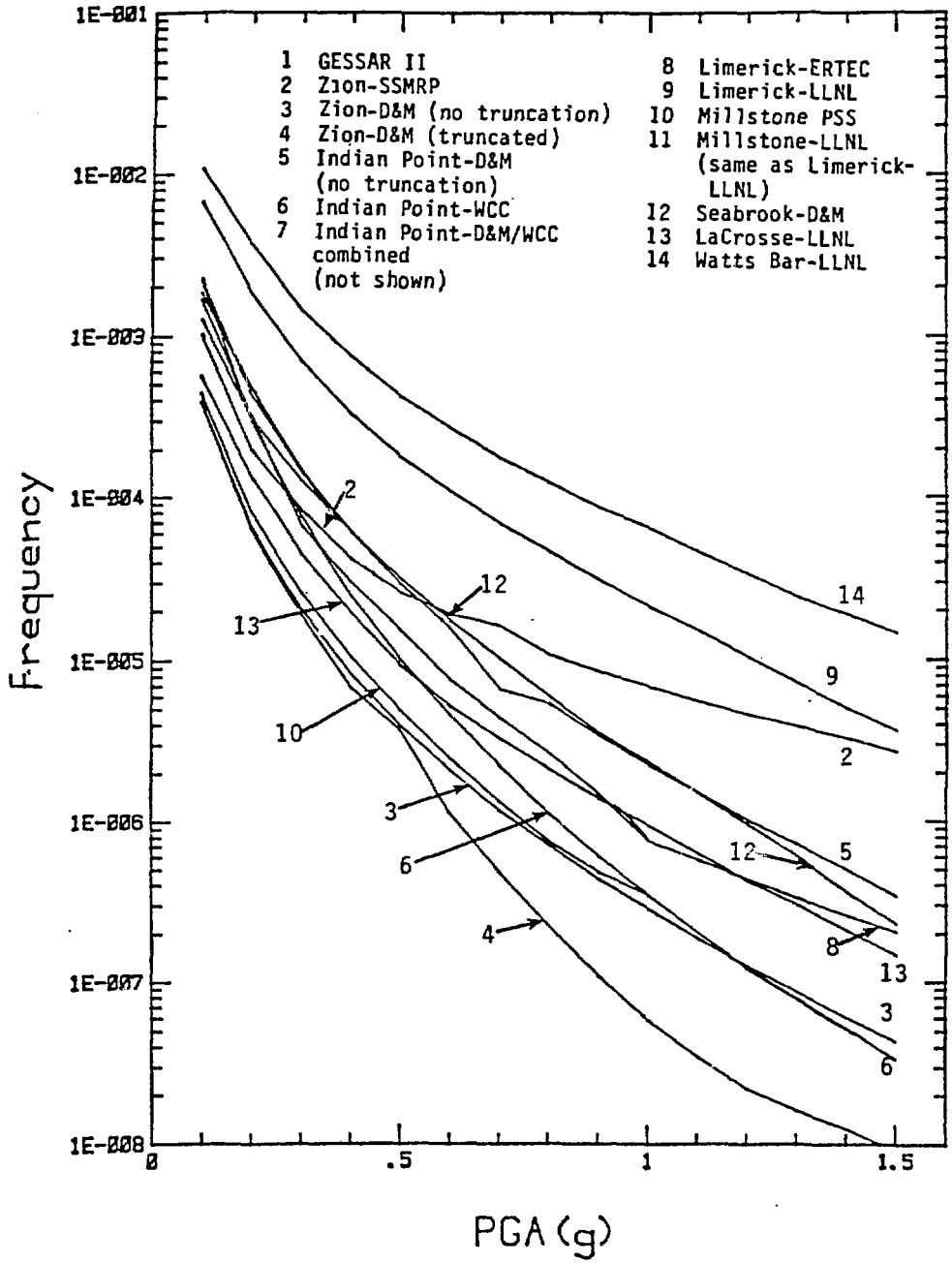

Figure 1 Annual frequency of exceedance versus peak ground accelerations for different sites.

Results from Table 2 indicate that if one keeps the fragility values and the system model constant, changing the hazard curves yields an order of magnitude change in core damage frequency. This is evident from either Case 1 or Case 2 results. For instance, the core damage frequency calculated for Case 1 using the Zion curve is 9.29(-6); if the GESSAR-II hazard curve is used instead, the core damage frequency is increased to 6.64(-5). Examination of the three hazard curves shows that they differ from each other by about an order of magnitude, especially in the low acceleration region. This sensitivity analysis shows that the core damage frequency is sensitive to the hazard curve definition, and in this example the change in core damage frequency is approximately proportional to the change in hazard frequency.

If one examines the results from Case 1 and Case 2, the core damage frequency is seen to change by less than a factor of 2. On one hand, this reveals that the final results are also sensitive to fragility changes; however, component fragilities do not vary by orders of magnitude, whereas hazard curves do. Therefore, the effect of the fragility variation is substantially less significant than the effect of the hazard frequency variation.

Contribution from Low Ground Acceleration

A cumulative core damage curve as a function of peak ground acceleration for Case 1 is depicted in Figure 2. It represents the conditional probability of core damage given that an earthquake of a particular peak ground acceleration occurs. For instance, given the occurrence of a seismic event of 0.5g peak ground acceleration, there is a 60 percent probability that there would be a core damage event. Similarly, 1.0g, the conditional probability of core damage given an earthquake of that magnitude is unity. It is interesting to note that the left hand tail of this curve slowly approaches zero at low acceleration. At 0.3g, which is the SSE value for the GESSAR-II plant, the conditional probability of core damage is about 10%.

Furthermore, if this cumulative curve is combined with the hazard curve, the following will result (see Table 3). This table shows that for the Zion hazard curve, 25 percent of the core damage frequency comes from peak ground acceleration below 0.19g, 50 percent from below 0.28g, and 75 percent from below 0.41g. Similarly, if the Watts Bar hazard curve is used, 25 percent of the core damage frequency can be ascribed to accelerations below 0.29g. The GESSAR-II hazard curve yields results that are between the two cases.

The major reason that the core damage results show a much higher contribution from low acceleration events than the conditional probability curve of Figure 2 is the shape of the hazard curves. Low acceleration frequency of exceedance (< 0.15g) is one to two orders of magnitude greater than that of higher accelerations (> 0.3g). This tends to amplify the sensitive portion of the fragility curve (i.e., the left hand tail) where not a great deal of data is available. For example, for the Zion-Dames and Moore hazard curve about 50 percent of the core damage frequency is accumulated between 0 and 0.3g; however, from Figure 2 the conditional core damage probability is only 10 percent at 0.3g acceleration.

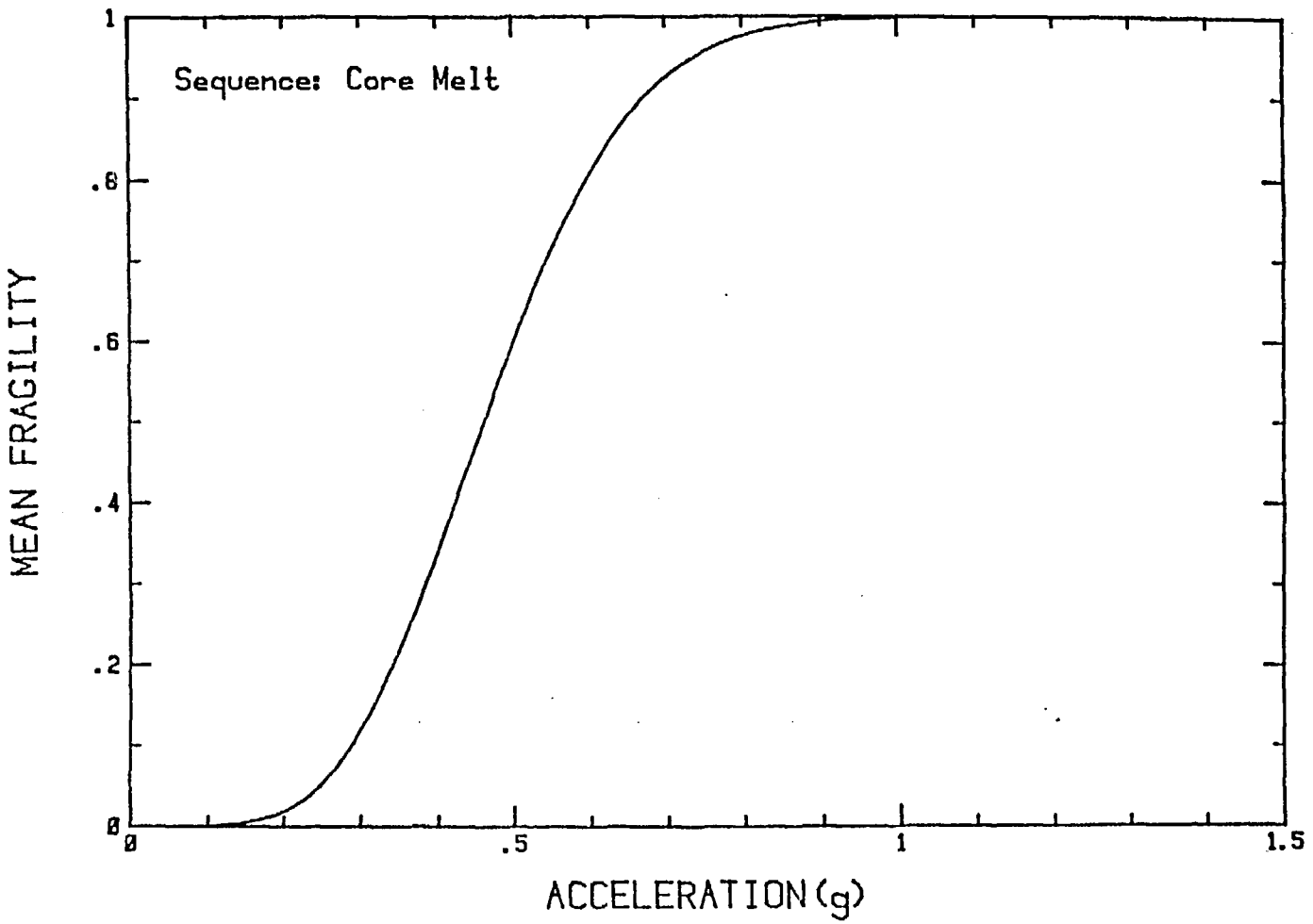

Figure 2 Conditional probability of core damage given the occurrence of an earthquake.

Table 3 Accelerations Contributing to the Mean Frequency of Core Melt for the Case 1 Alternate Fragilities

Hazard Curve	Percent of Total Core Melt		
	25	50	75
Zion - Dames & Moore (truncated)	0.19g	0.28g	0.41g
GESSAR-II	0.22g	0.31g	0.44g
Watts Bar--LLNL	0.29g	0.45g	0.66g

This type of results raises one important question: How credible is the seismic core damage result in view of the contributions from low ground accelerations? If the results are reasonable, what is the ramification for the current SSE requirement for nuclear power plants?

In general, it is believed that within the context of PRA for earthquakes below the SSE, there is a non-zero probability that a core damage accident may occur; however, a 25 to 30 percent contribution violates expectations based on deterministic review. The intricacy of this question lies with the definition of component or structural fragility curves at low ground acceleration and the amplifying effect of the hazard curve. Little can be done about the latter effect, but with regard to the former one, it is questioned whether fragility curves should be defined in such a way that the left hand tail extends to zero at zero acceleration. It has been suggested that at low ground accelerations component failure mode may become different and other considerations, such as fatigue failure, may become important. Others have suggested that below a certain ground acceleration, no failure would occur. In other words, a slight vibration is not expected to fail a component. In this case, the fragility curve would be truncated at the left hand tail to describe the threshold effect. However, the question still remains: if indeed there is a threshold, how can it be determined?

It is the belief of the authors that a lower bound cut-off exists for structure and component capacities; however, additional data is required to quantify this belief. For the case considered in this paper, the relay chatter capacity is an important contributor to the core damage fragility curve. Relay chatter has generally been considered to be recoverable in past seismic PRAs, and thus has not dominated the results. For the results reported in this paper, a 50 percent chance of recovery was used.

FUTURE RESEARCH

This paper reports the findings of a seismic PRA review and the sensitivity analyses. Two particular areas are discussed where further refinements would enable better quantification of core damage frequency for nuclear power plants.

First, the definition of hazard curves is found to greatly effect the results of a seismic PRA. It is an area where expert opinion plays an important role and consequently large differences may exist in the hazard results. This difference in the definition of the hazard curve could significantly alter and influence how the risk measure, such as core damage frequency, is calculated, and hence it would affect the interpretation of the PRA results. It has become more evident that there is an increased tendency to use seismic PRA to support nuclear power plant design modification decisions. Therefore, efforts to improve the definition of hazard curves, especially at low ground acceleration, should be conducted.

The second point pertains to the definition of fragility for components. The final results are also sensitive to them. There is in general a lack of realistic information for the different power plant components. It is important to acquire actual test data for these components if seismic PRA is to be meaningful. Moreover, additional work is required to better define the left hand tail of the fragility curves in order to provide a more realistic model of component failures for PRA analysis.

CONCLUSION

Several conclusions can be drawn from the results of the reassessment and the sensitivity analyses. First, it is clear that in order to gain useful insights from a seismic PRA, systematic and rigorous sensitivity studies are necessary. Back-of-the-envelope calculations or crude estimates often are found to be wrong, or at best, misleading due to the highly non-linear nature of the problem. Findings from the sensitivity studies also may not be intuitively obvious. Second, perturbation of the hazard curves yields significant changes in the final results. This is so dominant that fragility data and system model appear to be of secondary importance. Third, the percentage of contribution to plant damage state frequency from low ground accelerations can be dominated by the characterization of the left-hand-tail of the fragility curve.

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