

Seismic margin reviews of nuclear power plants: Identification of important functions and systems*

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1 INTRODUCTION

In 1984, the NRC initiated the Seismic Margins Program to study the inherent seismic capacity of nuclear power plants because of regulatory needs and the changing perception of seismic hazards. The NRC formed an "Expert Panel on the Quantification of Seismic Margins" to conduct the study and charged them with the development of a methodology and application guidelines to quantitatively assess how much larger must an earthquake be above the safe shutdown earthquake (SSE) before it compromises the safety of the plant (Cummings, et al. (1984). Their studies were used to develop a screening approach that combined both systems insights and fragility information to simplify the margin review process.

The seismic margin review approach has been documented in the report, "An Approach to the Quantification of Seismic Margins in Nuclear Power Plants" (R. J. Budnitz, et al. 1985) and draft guidelines for the implementation of seismic margin reviews are given in "Recommendation to the Nuclear Regulatory Commission on Trail Guidelines for Seismic Margin Reviews of Nuclear Power Plants, Draft Report for Comment" (Prassinos, et al. 1986).

The purpose of this paper is to present the basis and method used for the development of the systems screening portion of the seismic margin review methodology.

2 REVIEW OF SEISMIC PRA RESULTS

Insights gained from the results of eight published seismic Probabilistic Risk Assessments (PRAs) were used in the development of the screening approach. These were the utility-sponsored PRAs of Zion, Indian Point 2 and 3, Millstone 3, Limerick, Seabrook, and Oconee and the NRC-sponsored SSMRP study of Zion.

These seismic PRA results include dominant plant damage states, accident sequences and dominant components to seismic core melt for

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six PWR plants and only one BWR plant. Because of this, the generic functional statements and comparisons can only be made, at this time, for PWRs.

One thing to note in these results, which applies to all of the plants, is that loss of offsite power is effectively assumed to occur for all earthquakes studied as a result of the low capacity of switchyard components. Thus, the dominant contributors always include this event.

3 FUNCTIONAL INSIGHTS ON SEISMIC MARGINS BASED ON SEISMIC PRA RESULTS

Some key insights useful in developing seismic margin review criteria can be observed by examining the results of the available seismic PRAs. A list of the plant safety functions generally considered in PRAs (seismic or otherwise) is as follows:

- (1) Reactor Subcriticality
- (2) Normal Cooldown
- (3) Emergency Core Cooling (Early)
- (4) Emergency Core Cooling (Late)
- (5) Containment Heat Removal
- (6) Containment Overpressure Protection (Early)
- (7) Containment Overpressure Protection (Late)

An examination the seismic PRA results indicates the following trend. The dominant core melt plant damage states for seismic events are generally early core melt with early containment failure. They generally involve core melt induced by combinations of failure of the first three functions listed above followed by loss of containment integrity early in the accident progression. This insight leads us to consider the seven functions listed above in two distinct groups, as follows:

Group A - Functions 1-3

Group B - Functions 4-7

Core melt for the dominant plant damage states is caused by functional failure of Group A and also characterized by functional failure of Group B. This insight indicates that the dominant cause of core melt results from some combination of failures of the systems which provide the initial shut down of the nuclear reaction and cooling of the core followed by the failure of systems which provide the Group B functions. These Group B failures can be defined as actual failure of the functions or failure of containment integrity which makes the Group B functions useless. This statement can be represented by the following equation:

$$P(B|EQ,A) = 1 \quad (1)$$

The conditional failure probability of Group B given that an earthquake has occurred and Group A has failed is, essentially equal to 1 (a certainty). Core melt for the dominant plant damage states is generally not caused by a functional failure of Group B following success of Group A. In fact, if Group A survives the earthquake, the probability of Group B surviving the earthquake is basically unchanged as compared to the non-earthquake case. This can be represented by the following equation:

$$P(B|EQ, \bar{A}) = P(B|\bar{EQ}, \bar{A}) \quad (2)$$

The conditional failure probability of Group B given that an earthquake has occurred and Group A has succeeded (not failed) is approximately equal to the conditional failure probability of Group B given that an earthquake has not occurred and Group A has succeeded. This insight could be tested and justified by comparing the conditional failure rates from seismic and non-seismic events of the systems which provide the Group B functions given that the systems which provide the Group A functions have succeeded.

Both of these statements are supported by the results of the seismic PRAs studied. For the transient and small LOCA cases, the limiting failures which lead to core melt are support system failures or structural failures which are global in nature and would cause failure of both Groups A and B. For the large LOCA/vessel rupture cases, combined functional group failures occur because of the inherent strength of the piping, supports, and vessel that require high accelerations to induce failure. These high accelerations cause failures of both functional groups because the seismic capacities of the safety systems, their supporting systems and the structural "weak links" are not sufficient to withstand accelerations of this level.

At this point, it is important to consider two apparent exceptions to the statements made above which could lead one to believe these insights to be invalid. The first is the Seabrook PRA, which has as one of its dominant plant damage states a late melt with containment failure caused by earthquake effects. The assumptions used in the development of this plant damage state resulted in it being placed into a late damage state. These assumptions are not consistent with other PRAs. Even if it were a late melt by virtue of the assumptions made in the Seabrook PRA, the cause of the melt is still the functional failure of Group A (in this case, emergency core cooling early).

The second contradictory result is the occurrence of a late melt caused by dam failure at Oconee. This late melt is the result of a very unique, site-specific condition, a dam failure. This implies that it will always be necessary to perform some kind of walk-through to look for unique features which will have to be evaluated in a seismic margins study.

Having dealt with the insights from the PRA results, we can reach some conclusions regarding the development of seismic margins screening criteria. The results have shown that failure of Group B is virtually assured if failure of Group A occurs and that failure of Group B is unlikely to contribute to dominant plant damage states given success of Group A. Thus, we can declare as one of our screening criteria that it is only necessary to consider the functions in Group A. That is, we can get an idea of the seismic margin if we perform analysis only on those systems associated with Group A and simply assume that if a core melt results from failure of Group A that failure of Group B is assured and an appropriate early melt, early release plant damage state results. This greatly simplifies the analysis by eliminating a large number of systems and parts of systems.

4 DETAILED DISCUSSION OF SCREENING INSIGHTS AND LIMITATIONS

By dividing the plant functions into two groups, it is possible to express the totality of possible occurrences in the form of a Boolean expression of four combinations of success and failure of the two functional groups.

$$\bar{A}\bar{B} + \bar{A}B + A\bar{B} + AB \quad (3)$$

That is, either both Group A and Group B succeed (do not fail), or Group A succeeds and Group B fails, or Group A fails and Group B succeeds, or both Groups A and B fail. The first term, where both succeed, does not result in a core melt. Each of the other three terms could result in core melt.

The probability of core melt (and non-core melt) can be expressed by converting the Boolean terms into probability terms and putting them in equation form. In doing this, it is important to consider that the probability of Group B being in any given state is conditional upon the state of Group A, since the state of Group A is determined first and there are certain commonalities between the two functional groups. Thus, the following equation represent the probabilities of core melt.

$$P(\text{CM}) = P(\bar{A}) P(B|\bar{A}) + P(A) P(\bar{B}|A) + P(A)P(B|A) \quad (4)$$

The probability of core damage is equal to the probability of Group A succeeding times the probability of Group B failing (given Group A has succeeded) plus the probability of Group A failing times the probability of Group B succeeding (given Group A has failed) plus the probability of Group A failing times the probability of Group B failing (given Group A has failed).

The probability of non-core damage is equal to the probability of Group A succeeding times the probability of Group B succeeding (given that Group A has succeeded) and represented by the following equation:

$$P(\bar{\text{CM}}) = P(\bar{A}) P(\bar{B}|\bar{A}) \quad (5)$$

For the earthquake case, our screening insight has led us to the simplification of these equations. Given an earthquake, we have concluded that Groups A and B are highly dependent. This implies that the first two terms in the core damage probability equation are essentially zero. The third term of the core damage equation is essentially equal to the probability of Group A failing, since our screening insight states that the probability of Group B failing given that Group A has failed is essentially 1.0 (a certainty). The complement to this argument is that the non-core damage equation can be simplified to just the probability of Group A succeeding. The equations therefore become:

$$P(\text{CM}|EQ) = P(A|EQ) \quad (6)$$

$$P(\bar{\text{CM}}|EQ) = P(\bar{A}|EQ) \quad (7)$$

that is, for the case in which one assumes that a large enough earthquake has occurred, the probability of core damage is approximately equal to the probability of Group A failing. Further, the probability on non-core damage is approximately equal to the probability of Group A succeeding.

There are two distinct types of errors which are possible when making use of the screening insight (only considering Group A functions) when compared with a detailed seismic PRA. These errors are as follows:

Type I Error - This error involves seismic core damage sequences which would result from the success of Group A functions and failure of Group B functions. These sequences will be missed since the core melt is caused by failure of Group B and the screening insight assumes that if Group A succeeds then Group B succeeds, which is a non-core damage. This type of error would be non-conservative.

Type II Error - This error involves seismic core damage sequences which result from failure of Group A functions but which are followed by success of Group B functions. These sequences would not be missed since the core damage results from failure of Group A. This type of error would be conservative, since these Group A failure/Group B success sequence would be placed into Group A failure/Group B failure plant damage states, which have higher consequences.

Given that these two error types exist, the real question becomes whether these errors are significant when attempting to estimate seismic margins. We can gain some insight into this by examining the results of the available seismic PRAs and extrapolating the effect the screening insights would have had if they had been used.

We reexamined the dominant seismic core damage contributors for the six published PRAs of the PWRs. In addition, we examined the dominant sequences from the Zion SSMRP study and the result from three unpublished seismic PRAs, which were not used during the development of the screening insights, as a check on their validity. The unpublished results were obtained on the condition that plant identities would be concealed.

A review of the dominant seismic core damage and risk contributors involved a total of 60 seismic sequences or plant damage states. The conclusion of that review is that 54 of those contributors would have been identified using our screening insight of only evaluating Group A functions. Of those, all but five of them would have been correctly identified as involving failure of both Group A and Group B. The five erroneously identified sequences would have been conservatively identified as being more serious (in terms of consequences) than they actually were. This would not have affected the estimates of core damage frequency. Six sequences would not have been identified at all because they involved core damage due only to failure of Group B. Missing these sequences would have resulted in a measurable but unimportant underestimation of core damage frequency.

Based on the above discussions, the screening criterion shows itself to be generally insensitive to both Type I and Type II errors and

should yield a reasonable estimate of seismic vulnerabilities at pressurized water reactors.

5 CONCLUSION

The results from the review of the seven utility-sponsored seismic PRAs plus the Zion SSMRP have been used to develop some insights regarding the importance of various systems and functions to seismic margins. By taking this information and combining it with the fragility insights we can develop some functional/systemic screening guideline for margin studies. This screening approach will greatly reduce the scope of the analysis.

There are a number of conclusions regarding the use of functional/systemic insights to simplify the seismic margin review process. These are as follows:

- o It is possible only to come to conclusions regarding the importance of plant systems and safety functions for PWRs, for which six plants were studied (one by two different methods). No functional/systemic conclusions can be made about BWRs because the results of only one study are available at this time.
- o For PWRs, it is possible to categorize plant safety functions as belonging to one of two groups, one of which is important to the assessment of seismic margins and one of which is not.
- o The important functional group involves only two functions that must be considered for estimating seismic margin. These two functions are shutting down the nuclear reaction and providing cooling to the reactor core in the time period immediately following the seismic event (that is, the injection phase or pre-residual heat removal time period).
- o It is possible to reasonably estimate the seismic margin of the plant by performing a study only involving the analysis of the plant systems and structures which are required in order to perform the two functions. Such analysis must include an assessment of a complete set of seismic initiating events.

The approach for the quantification of seismic margin at nuclear power plants presents a method for screening a plant to determine important functions, systems and components to seismic plant safety.

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