A BASIS FOR STANDARDIZED SEISMIC DESIGN (SSD) FOR NUCLEAR POWER PLANTS/CRITICAL FACILITIES

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ABSTRACT

U.S. Nuclear Power Plants (NPP's) are designed, engineered and constructed to stringent standards. Their seismic adequacy is assured by compliance with regulatory standards and demonstrated by both probabilistic risk assessments (PRAs) and seismic margin studies. However, present seismic siting criteria requires improvement. Proposed changes to siting criteria discussed here will provide a predictable licensing process and a stable regulatory environment.

Two recent state-of-the-art studies evaluate the seismic design for all eastern U.S. (EUS) NPP's: a Lawrence Livermore National Labs study (LLNL, 1989) funded by the NRC and similar research by the Electric Power Research Institute (EPRI, 1989) supported by the utilities. Both confirm that Appendix A 10CFR Part 100 has not provided consistent seismic design levels for all sites.

Standardized Seismic Design (SSD) uses a probabilistic framework to accommodate alternative deterministic interpretations. It uses seismic hazard input from EPRI or LLNL to produce consistent bases for future seismic design. SSD combines deterministic and probabilistic insights to provide a comprehensive approach for determining a future site's acceptable seismic design basis.

BACKGROUND

Over the past twenty years there has been extensive funding of seismic hazard research by both the electric utility industry and the Nuclear Regulatory Commission (NRC). The impetus for this effort can be traced to historical regulatory concerns associated with the licensing process given in Appendix A, "Seismic and Geologic Siting Criteria for Nuclear Power Plants", to 10CFR, Part 100, "Reactor Site Criteria." In effect, this research has resulted in a transition from the simple deterministic assumption that the Safe Shutdown Earthquake (SSE) could not be exceeded to the realization that the annual probability of exceeding the SSE (at the peak ground acceleration (PGA)) varies considerably from site to site.

Appendix A originally addressed seismic siting criteria from a Western U. S. (WUS) perspective. This presumed that seismic activity could be assigned to structures, particularly faults exposed at the surface. In other words, given the distance to a fault and the expected rupture length, the ground shaking at some proposed site could be deterministically bounded. Of course for the eastern or central U.S. (EUS) such is not the case. Appendix A thus employed a concept of "tectonic provinces" (Hatheway and McClure, 1979) as a model to determine seismic design levels at nuclear power plant sites. The tectonic province approach is prescriptive, forcing adversaries to be placed into deterministic yes-no positions. This is particularly true with respect to determination of tectonic provinces and structures, maximum magnitude earthquake, conversion from Modified Mercalli Intensity (MMI) to Peak Ground Acceleration (PGA), and the appropriate spectral shape to anchor at the PGA. The fundamental problem with the deterministic approach (dramatically highlighted by both the LLNL (1989) and EPRI (1989) seismic hazard studies) is that there is no scientific consensus as to what are the correct provinces, structures, maximum magnitude earthquakes, etc. Furthermore, because contending viewpoints are framed in a legal context of an absolute yes-no question, the process usually ends up in court. This results in delays, increased costs, instability, and uncertainty in the overall licensing and regulatory process.

Our recent paper (O'Hara and Jacobson, 1990) discusses a method to determine acceptable site seismic design levels for future nuclear power plants or critical facilities. This paper is an application of the proposed methodology based upon seismic hazard results from both the LLNL and EPRI studies. We contend that state-of-the-art seismic hazard analyses represent a rational framework for the incorporation of the multitude of contending hypotheses concerning the cause of earthquakes, as well as for incorporation of new information. Furthermore, these analyses should be used to determine acceptable site seismic design levels. It should be noted that the SSD approach results in consistent acceptable site design levels from location to location in the EUS yet the actual design may be higher if the utility decides to adopt an enveloping 0.3g design level which is the present Advanced Light Water Reactor (ALWR) design level. The essence of this SSD approach is the calibration of a methodology (LLNL, 1989 or EPRI, 1989) to a common standard.

However, prior to describing this approach an awareness of some fundamental issues is needed to understand the basis for our approach. These issues are:

(1) Evaluation of the Deterministic Licensing Process for Existing Plants.

(2) Standardization of the Seismic Design Level or the Probability of Exceeding the Design Level.

(3) Justification of a 0.3g Standardized Design Level

(4) Justification of an Acceptable Probability of Exceeding a Design Level

The following sections discuss these issues with the objective of integrating the conclusions of each section into an overall method to standardize the seismic design licensing process.

EVALUATION OF THE DETERMINISTIC LICENSING PROCESS FOR EXISTING PLANTS

Presently, both the Electric Power Research Institute (EPRI) and Lawrence Livermore National Labs (LLNL) have mature seismic hazard methodologies and both have calculated the seismic hazard at EUS NPP sites. Because the LLNL and EPRI methodologies are internally consistent, i.e. common attenuation models, experts, and calculational procedures, the relative hazard between various NPP sites for each methodology is easily determined. In this context, the seismic hazard results from both the LLNL and EPRI studies can be used to independently evaluate the probability of exceeding the current licensing basis at existing NPPs. In particular, this comparison evaluates the consistency of the deterministic licensing process that has been used to define the current licensing basis at existing EUS NPP sites.

A fundamental licensing/engineering premise is that the seismic design basis (defined in Appendix A as the Safe Shutdown Earthquake, SSE) should be proportional to the expected seismic loadings, in other words, the higher the expected seismic loadings, the higher the seismic design basis. Figure 1 presents the SSEs determined for 61 EUS NPP sites. As can be seen these seismic design levels vary between 0.1g and 0.25g. Clearly, if the deterministic process used to determine these seismic design levels is consistent with the above premise (i.e., higher seismic loadings require a higher seismic design level) then it should follow that the probability of exceeding each plant's seismic design level should be about the same.

Figure 2 is a plot of the probability of exceeding the Safe Shutdown Earthquake (SSE) at 61 EUS NPP sites based upon median results from both LLNL and EPRI. Analyses have shown (NRC, 1990) that the median results (as compared to mean, 15th or 85th percentile results) are most consistent between LLNL and EPRI. As can be seen, the probability of exceeding the SSE from site to site is far from consistent within each methodology (LLNL or EPRI). These results cast doubt on the ability of the current deterministic approach to define consistent seismic design levels from site to site. However, what also can be seen from Figure 2, is that the trend from site to site between the LLNL and EPRI results is consistent in a relative sense, meaning that both studies consistently identify high and low hazard sites, albeit that the magnitude of the absolute probabilities vary significantly.

Figure 3 is a plot of the probability of exceeding the SSE for each of the 61 sites using the EPRI results. As can be seen, sites with an SSE of 0.15g vary by over two orders of magnitude in probability of exceedance. This figure further highlights the inability of the deterministic licensing process to define consistent design levels from site to site. Figures 2 and 3 are simply the probability of exceeding the PGA associated with the SSE at each site. Because the LLNL and EPRI results define the seismic hazard at the PGA, 25, 10, 5, 2.5, and 1hz, it is possible to convert SSE response spectra at each of these frequencies to probabilities and then plot the results. Figure 4 is such a plot and dramatically illustrates the inconsistency in probability of exceedance between sites not only at the PGA but at other frequencies as well. **We thus conclude that across the current population of NPPs the deterministic process used to define the seismic design bases at existing NPPs has not resulted in consistent seismic design levels (as defined by similar probabilities of exceedance).** However, this does not imply that those plants with the highest probability of exceeding their design basis are unsafe. PRAs and margins studies have shown that plant capacity exists well beyond the SSE and that the major contribution to seismically-induced core melt frequency for EUS plants come from earthquakes that are about 2 to 4 times the SSE (LLNL, 1985).

STANDARDIZATION OF THE SEISMIC DESIGN LEVEL OR THE PROBABILITY OF EXCEEDING THE DESIGN LEVEL

A standardized seismic design level is a design level that is the same from location to location. This implies that the envelope of future site-specific seismic hazard characteristics should be determined such that standardized design may be repetitively applied at all sites. To allow repetitive applications, the standard design must be somewhat overdesigned to envelope the seismic hazard that varies from site to site. It is believed that standardization will result in savings in engineering, licensing, equipment and procurement, construction (learning curve), start up (standard procedures), and operation (standard procedures and spare parts) (Bechtel, 1986) .

The standardized design approach is not without its inconsistencies. For example, assume that at locations A, B, and C the seismic hazard is that as shown on Figure 5, high, medium, and low respectively. Because seismic hazard is not uniform across the EUS, standardization at a fixed design level will result in the probability of exceeding the fixed value to vary from location to location. This situation is exactly what has precipitated the protracted seismic reviews by the NRC for the current generation of NPPs. To avoid this problem it must be shown that the standardized design level is acceptable at the highest hazard site and therefore is acceptable at all other sites.

An alternative to the above approach is the standardization of the probability of exceeding the design level, in other words, because the hazard varies from location to location the design level should vary from location to location. Figure 6 illustrates this approach. As can be seen, if 2.0E-4 is considered to be an acceptable probability of exceeding the design level, then the design level at locations A, B, and C would be about 0.05g, 0.15g, and 0.30g respectively. The advantage of varying the design level from location to location is that there will be a consistent probability of exceedance from site to site and also there is the potential for a reduction in cost at the low hazard sites. These acceptable site values if used as input ground motions for site geotechnical analyses such as liquefaction analyses would certainly result in cost savings. It should be noted, that if in fact site A in Figure 5 represents the site with the highest hazard, and if in fact 0.3g is acceptable at that location, then the standardized probability of exceedance is defined by site A.

As can be seen from the above discussion a standardized design value results in varying probabilities of exceedance from site to site while a standardized probability of exceedance results in varying design levels from site to site. Advantages and disadvantages are associated with both methods of standardization, however, the task at hand is to take advantage of both approaches.

In its most fundamental sense, the establishment of standardized design criteria involves the balancing of benefits and costs. For seismic design, the benefit of providing additional reinforcement to withstand earthquake motion is a reduction in risk to the public posed by a facility. The enhanced seismic capacity associated with the standardized design is believed to be relatively inexpensive compared to total plant expenditures if incorporated into the original design and construction of a new plant. A follow-up to prior studies (Stevenson, 1981) by Stevenson (Oct, 1991, personal communication) will show a 7 to 10% overall increase in cost by going from a 0.1g design to about a 0.3g design. Above about 0.3g costs increase more rapidly with design level. NPP licensing history has shown that licensing delays due to seismic design level issues and actual changes to the seismic design basis while construction is in progress have resulted in significant increases in cost and can no longer be tolerated.

Over time, as regulators require stricter and more costly so-called "safety" at newer facilities, they are assumed to be implementing the public's desire to pay more for incremental safety gains over similar previously licensed facilities. Within these arguments to standardize and increase safety, **there must be an awareness of the bottom line cost to generate electricity, otherwise future plants may only exist on paper, and may not ever be built.**

JUSTIFICATION OF THE 0.3G STANDARDIZED DESIGN LEVEL

To avoid problems associated with the deterministic licensing process it has been recommended by EPRI (1989) that the SSE be standardized to 0.3g for all future plants. The basis for this recommendation was documented by Bechtel (1986) and was primarily based upon minimizing the increase in cost due to over design. In their analysis Bechtel deterministically evaluated 21 expected future sites. For these sites the 0.3g design value is equal to or greater than each site's Preliminary Safety Analysis Review (PSAR) seismic design value. For four sites the 1.0E-4, PGA based upon EPRI hazard results, was assumed to be the PSAR seismic design value.

Two additional arguments exist which support the 0.3g standardized design level. The first is an empirical argument. It follows that because the 0.3g value bounds all currently acceptable EUS design values, and because this sample of existing sites is representative of the population of future sites (i.e. future plants will be built where present plants exist or at locations similar in hazard to existing sites), the bounding value of 0.3g should surely be acceptable.

The other argument is based on safety goals. The Advanced Light Water Reactor (ALWR) mean core damage frequency (MCDF) safety goal is 1.0E-5 (EPRI, 1989) and the goal for the seismic contribution is 1.0E-6 (i.e., 10%). The safety goal approach is based upon meeting the seismic contribution to MCDF and has been applied by EPRI (1990) using only the EPRI hazard results to justify the 0.3g design level. Fundamental to the safety goal approach is the mean hazard curve for a given site and an assumed generic plant fragility of about 1.2g for the standard 0.3g plant. It is the convolving of the mean hazard curve and the plant fragility curve that defines the seismic contribution to MCDF. As shown on Figure 7, it is not unusual to have two to three orders of magnitude difference between the LLNL and EPRI mean hazard results at acceleration levels of interest (0.5g to 1.5g). A direct consequence of this situation is that justification of the 0.3g standardized design using safety goals appear to be satisfied using the EPRI results but it will certainly not be satisfied using the LLNL results for a typical site. Due to this, efforts are being made to resolve differences between the two studies. Also, it must be understood that the quantitative safety goal approach views these probabilities in an absolute context - that is as 'true' probabilities.

True probabilities, such as the probability of tossing a six in one throw of a fair die, are based on one's ability to define the sample space and the likelihood of each outcome. In seismic hazard analyses the process is not quite as simple. Figure 8 shows a logic tree which would typically be used to define the sample space (all possible outcomes) for a seismic hazard analysis. The figure illustrates how the "degree of belief" of each hypothesis (outcome) is calculated. First, weights are assigned to each parameter of the tree. The weights of the different zonations add to one, those of the different attenuation models add to one, and so on. These weights are typically subjective expert opinion. Second, the likelihood of each hypothesis (outcome) is obtained as the product of the weights of the various components that define that hypothesis. The point to be made here is that the sample space may be adequately covered but the likelihood of each outcome in the sample space is based upon subjective opinion unlike the classic die tossing problem. Because there are divergent opinions on all of the parameters that typically go into a seismic hazard analysis, use of these results in an absolute fashion (safety goal approach) will not prove to be feasible until all the significant differences are resolved.

The safety goals method is appealing because the acceptance criterion is apparently quantifiable. But, because the calculation to determine MCDF is based upon the convolving of both a mean hazard curve and an assumed generic plant fragility curve, and the half life of the hypotheses presented in seismic hazard analyses may be on the order of a few years (i.e. the length of time before new theories replace older ones), a meeting of the safety goals now may show otherwise in a few years. In addition, nothing prevents the safety goals or the value of the future-plant fragility curve from changing. Because of these issues, a safety goal approach, at present, cannot satisfactorily justify a 0.3g standardized design level. Conversely, deterministic arguments strongly support 0.3g as an acceptable value.

JUSTIFICATION OF AN ACCEPTABLE PROBABILITY OF EXCEEDING THE DESIGN LEVEL

Acceptable probabilities must be defined relative to a methodology. The relative use of subjective probabilistic results contrasts with the absolute safety goal approach. The relative approach is used because absolute approaches fail to recognize the inherent limitations in current EUS seismic hazard results. As stated above, it is not unusual to find differences between EPRI and LLNL results of two orders of magnitude or more at a given acceleration. Because of these differences, there is a question as to whether these estimates of seismic hazard can be used in an absolute (safety goal) sense.

Justification of acceptable probabilities is empirical. The major problem associated with this approach is obviously that of calibrating the results from a seismic hazard methodology (LLNL or EPRI) to some realistic acceptance level. Design levels for currently operating NPPs are by definition acceptable and therefore the probabilities associated with these design levels must be acceptable. Thus, for future plants a fundamental premise is that acceptable site seismic design levels shall be consistent with current seismic designs. The basis for this premise is that results of PRAs and Margins studies at existing plants show that current design levels are acceptable. Consistent can be defined such that the population of future plants will have a higher seismic resistance than the current population of plants. Acceptable probabilities of exceedance can thus be determined as follows:

(1) Using the median seismic hazard results calculated by LLNL or EPRI for all existing EUS sites convert the existing SSEs (Figure 9) into probabilities at various frequencies (PGA, 25, 10, 5, 2.5, and 1 hz). Figure 10 illustrates this process.

(2) Define some target levels for future plants, and compute the acceptable probabilities. The acceptable probabilities could be, for example, the mean or median values of the probabilities of exceedance associated with current design spectra at the above defined frequencies.

An alternative and more objectively justifiable approach is based on use of the standardized 0.3g R.G. 1.60 spectrum. Because this spectrum exceeds all existing design spectra for EUS NPPs it can certainly be considered acceptable, if not excessive. Given this premise, an analysis similar to that described above can be performed except that rather than using existing SSEs, the 0.3g standardized spectrum is assumed to be the SSE at each site. Probabilities of exceeding the 0.3g spectrum can be calculated for each site and the enveloping probabilities are defined as acceptable. Using these approaches, interpretations of acceptable probabilities have been calculated consistent with both the LLNL and EPRI methodologies. Figure 11 shows the Figure 9 spectra converted to probabilities using the LLNL results. The dashed line defines acceptable probabilities based upon the assumption that the 0.3g spectrum is acceptable. Results of both approaches are shown on Figure 12. As can be seen, even though the 0.3g spectrum approach envelopes all existing EUS spectra, its acceptable probabilities are consistent with the median probabilities for the current generation of NPPs.

Figure 12 also illustrates the basis for confusion that has typically been associated with the concept of acceptable probabilities. For example, in the Systematic Evaluation Program (SEP) the 1000 year spectra developed by LLNL were applied to the SEP sites. Given this information utilities assumed 1.0E-3 was acceptable and would then calculate seismic hazard at their sites using a different seismic hazard methodology and determine the PGA associated with the 1.0E-3 'acceptable' probability. As expected the 1.0E-3 PGA determined by the utility was significantly lower than the LLNL value. Obviously, the point to be made here is that the above defined acceptable probabilities are acceptable relative to the methodology. What will be shown in the next section is an application of the above defined acceptable probabilities and the use of these probabilities in a relative sense to define acceptable and consistent site seismic design values.

STANDARDIZED SEISMIC DESIGN PROCESS

This approach results in an acceptable site design level of less than 0.3g at typical EUS sites (excepting New Madrid, Missouri and Charleston, South Carolina) and a default standardized plant design level of 0.3g. A fundamental premise of this approach is that a utility should be given the option of building a plant to some standardized design (0.3g) or to some acceptable site design level less than or equal to 0.3g. Furthermore, using this approach, the probability of exceeding the acceptable site design level will be the same from site to site, while the probability of exceeding the actual plant design value will always be equal to or less than the acceptable site design value.

The essence of this approach is the normalization of a seismic hazard methodology relative to a standard (0.3g R.G. 1.60 spectrum) to determine acceptable probabilities, and then the use of these probabilities in an internally consistent manner. Figure 2 shows there is reasonable consistency between the LLNL and EPRI results in a relative sense but not in terms of the absolute value of the numbers. Given that the relative rankings of the hazard are consistent from site to site, it is only a matter of defining acceptable probabilities consistent with a methodology to determine acceptable site design levels.

As stated earlier, " consistent " is defined in terms of probabilities specific to a given methodology. Using these acceptable probabilities, standardized probabilistic methods (such as LLNL, EPRI, USGS, or the results of a resolution between LLNL and EPRI) can be used to determine acceptable site design levels that will be consistent in terms of probability of exceedance from location to location. The philosophy of this approach is similar to that of Short et al (1990) except that in their paper they advocate the use of the mean probability of exceeding current SSE values. Based upon arguments stated earlier, we conclude that the enveloping probabilities of exceeding the 0.3g spectrum at existing EUS sites can be used to define acceptable probabilities for future sites. Using the LLNL or EPRI hazard results for existing sites and these acceptable probabilities, it is possible to determine <u>acceptable site seismic design spectra</u> for future plants at these existing sites. The process is simply the reverse of the Figure 10 process. Figures 13 shows these proposed spectra relative to the 0.3g R. G. 1.60 spectrum. As can be seen Figure 13 looks very similar to Figure 9, however the significant difference is that all of these spectra have exactly the same probability of exceedance which is defined by the dashed line on Figure 11. In other words, the probability of exceeding the spectra would be consistent across all sites. Similar results would be obtained if the EPRI hazard results were used. An important result of this approach is that it assures that a 0.3g standardized design is acceptable at any existing EUS site regardless of seismic hazard methodology.

Given an acceptable site design spectrum, it is extremely important that well defined, close in, seismological and geological evidence around the proposed site be gathered to confirm the adequacy of the spectra.

CONCLUSIONS

Based upon a review of the issues associated with the determination of a seismic design basis for NPPs, the SSD methodology has been developed to stabilize the licensing and regulatory process. The SSD approach results in an acceptable site design level of less than 0.3g at typical EUS sites and a default standardized plant design level of 0.3g.

Three fundamental assumptions are used in this methodology. They are:

1. Multiple-hypothesis seismic hazard methodologies, such as LLNL or EPRI, represent rational methods to incorporate the diversity of expert opinion concerning earthquake prediction.

2. A conservative deterministic standard (0.3g R. G. 1.60 spectrum) should be used to define acceptable probabilities consistent with a seismic hazard methodology.

3. Relative probabilities, based upon acceptable probabilities within a given methodology, will be stable and predictable.

The SSD methodology is important because the current seismic licensing process, as defined in Appendix A 10CFR Part 100, is now being re-written. Given the methodology presented here there is little reason as to why seismic design issues cannot be treated similar to meteorology and hydrology, in other words maps could be made defining acceptable site design levels for essentially all of the EUS for future plants. Even those utilities that choose to bound the acceptable site value with a 0.3g standardized value may find it beneficial to use the acceptable site values when performing liquefaction and other geotechnical analyses.

Lastly, there are those that see the existence of two or more seismic hazard methodologies as destabilizing to the licensing process for future NPPs or critical facilities. This concern merely becomes a distinction without a difference when our proposed SSD approach is used. Based upon use of the SSD approach in conjunction with conservative and consistent design standards, adequate seismic resistance will be provided at all future NPPs and critical facilities.

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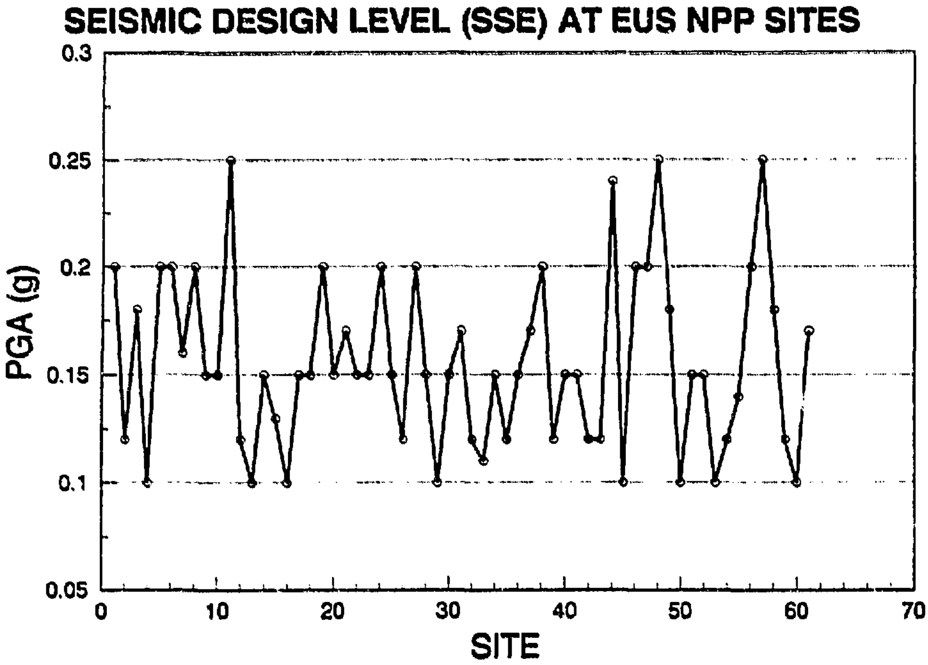

Figure 1. Distribution of seismic design levels (SSE) for EUS NPP's by sites.

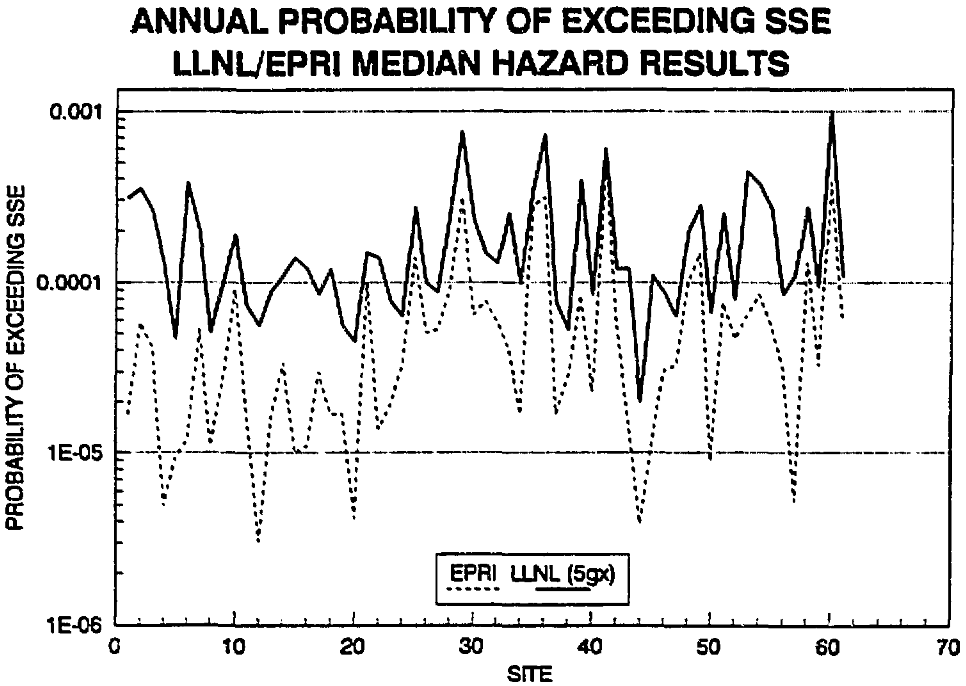

Figure 2. Annual probability of exceeding seismic design levels (SSE) based on median hazard results from EPRI (1989) and LLNL (1989).

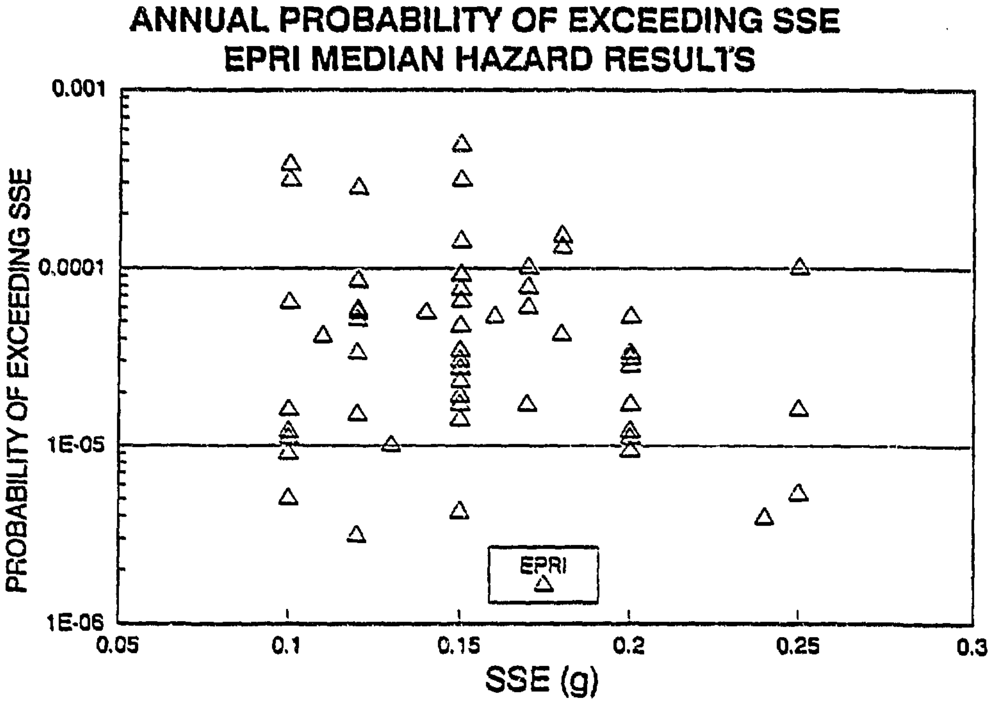

Figure 3. Annual probability of exceeding SSE by seismic design level.

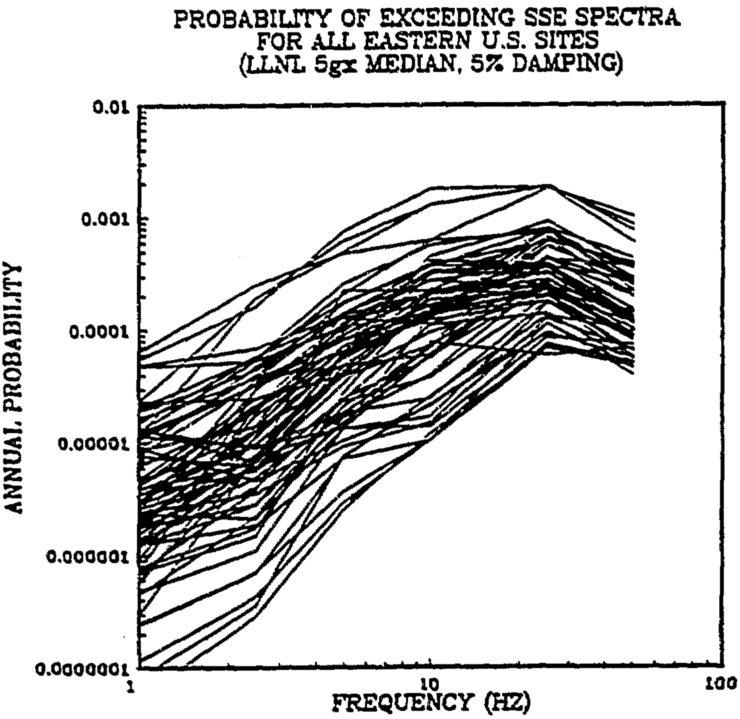

Figure 4. Probbability of exceeding SSE for all EUS sites based on LLNL (1989).

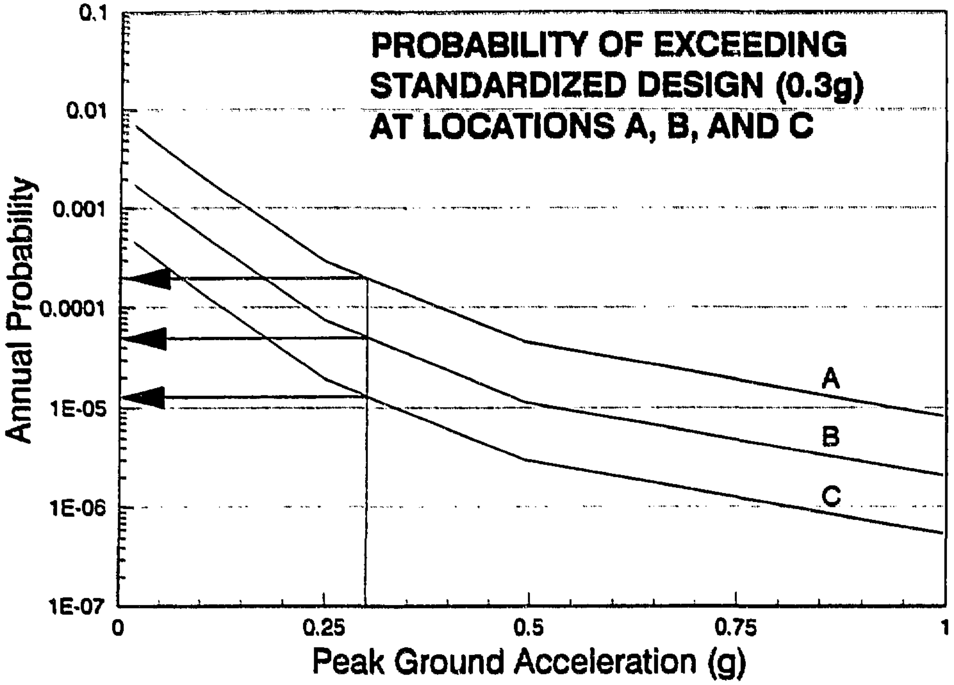

Figure 5. Probability of exceeding standardized design (0.3g) for hypothetical locations A, B and C. Choice of PGA is made to determine DBE.

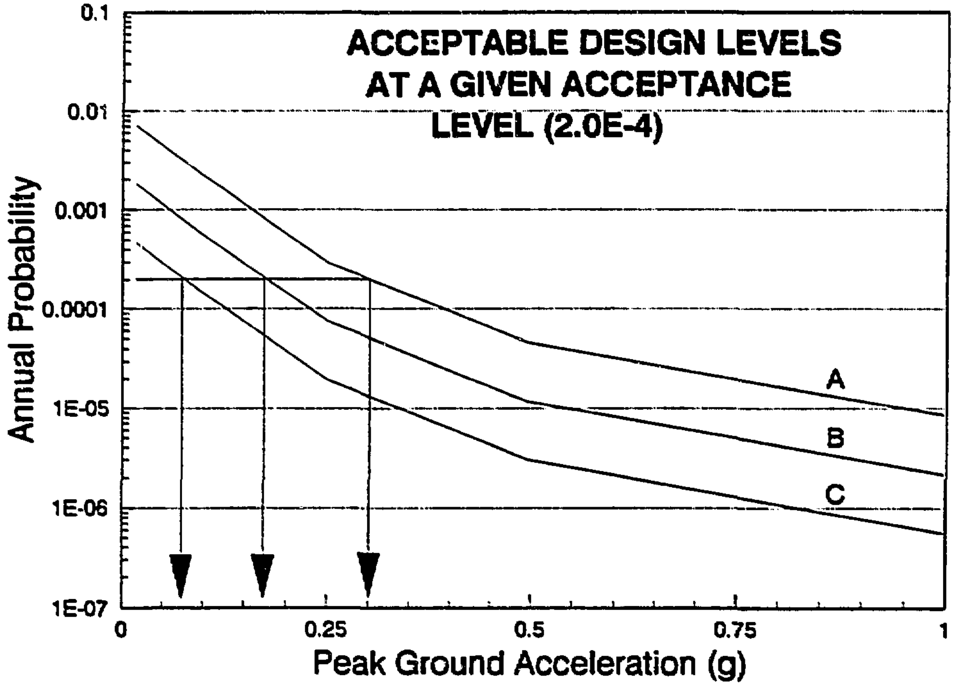

Figure 6. Acceptable design levels for a given acceptance level (2.0e-4). Choice of annual probability of exceedance is made to determine DBE.

COMPARISON OF MEAN HAZARD CURVES FOR TYPICAL NEW ENGLAND SITE

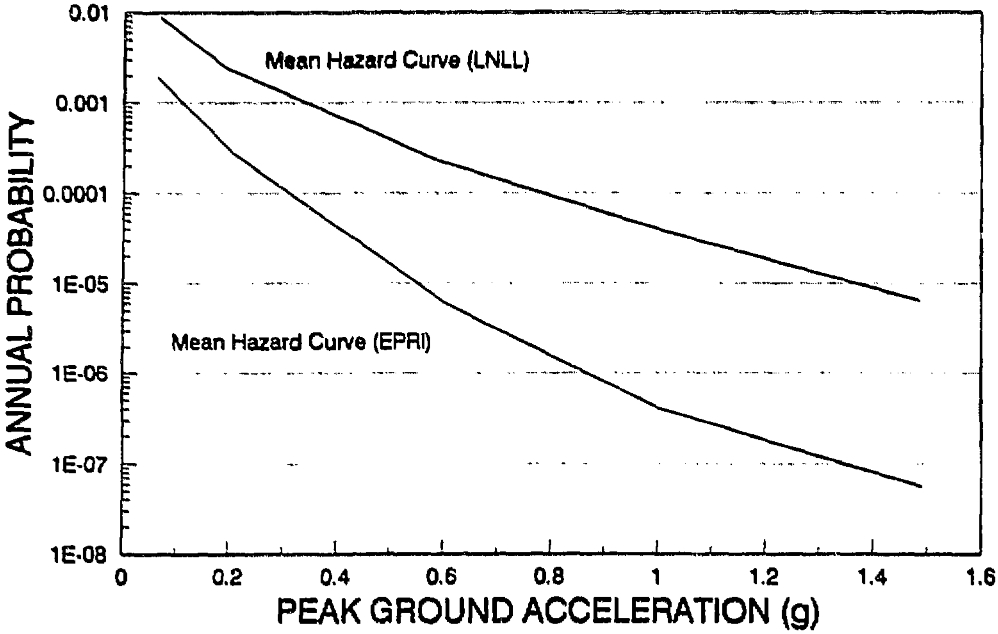

Figure 7. Mean hazard curves for data from EPRI (1989) and LLNL (1989) for an EUS site. Mean values are used for any "Safety Goals" approach.

PROCEDURE FOR GENERATION OF SEISMIC HAZARD HYPOTHESES AND THEIR PROBABILITIES

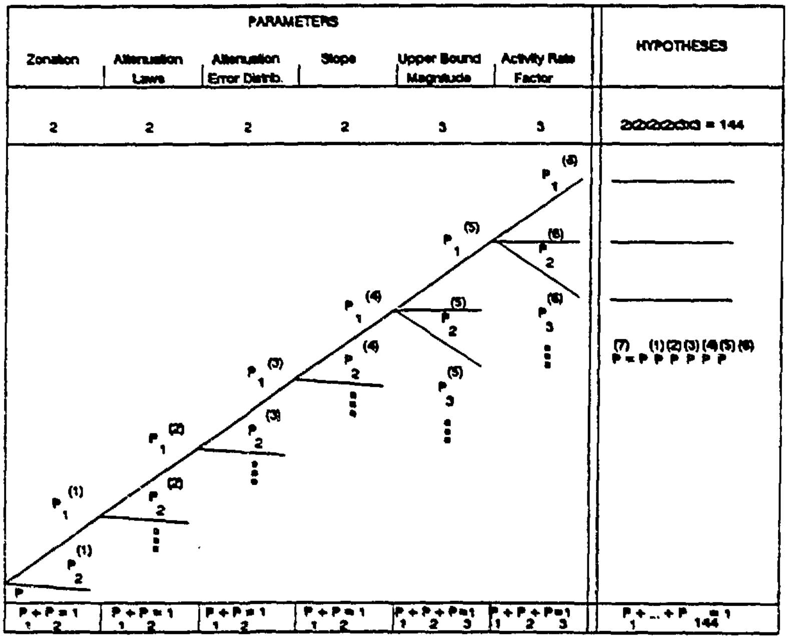

Figure 8. Illustration of procedures used to generate hypotheses and their probabilities for methodologies such as LLNL (1989) and EPRI (1989).

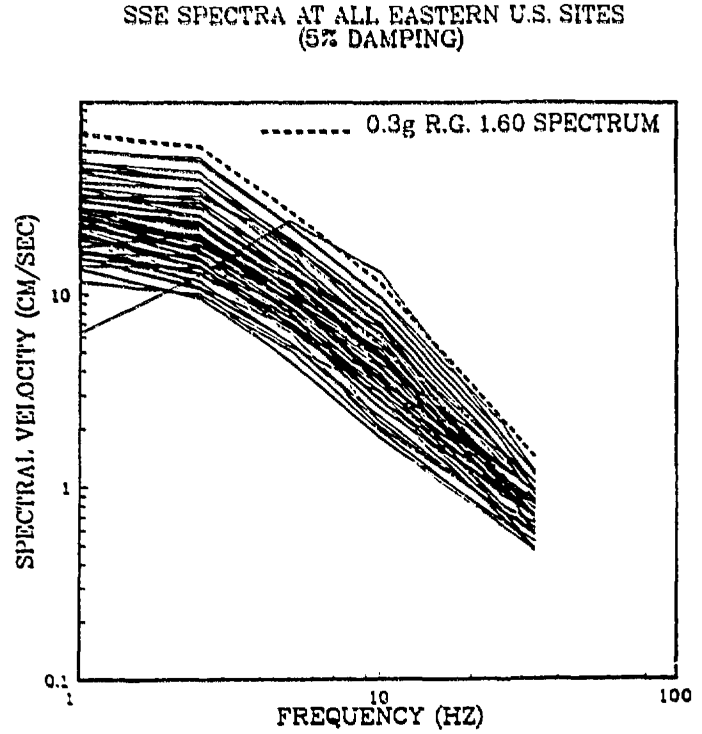

Figure 9. SSE design spectra for all EUS NPP's, and 0.3g R.G. 1.60 spectrum

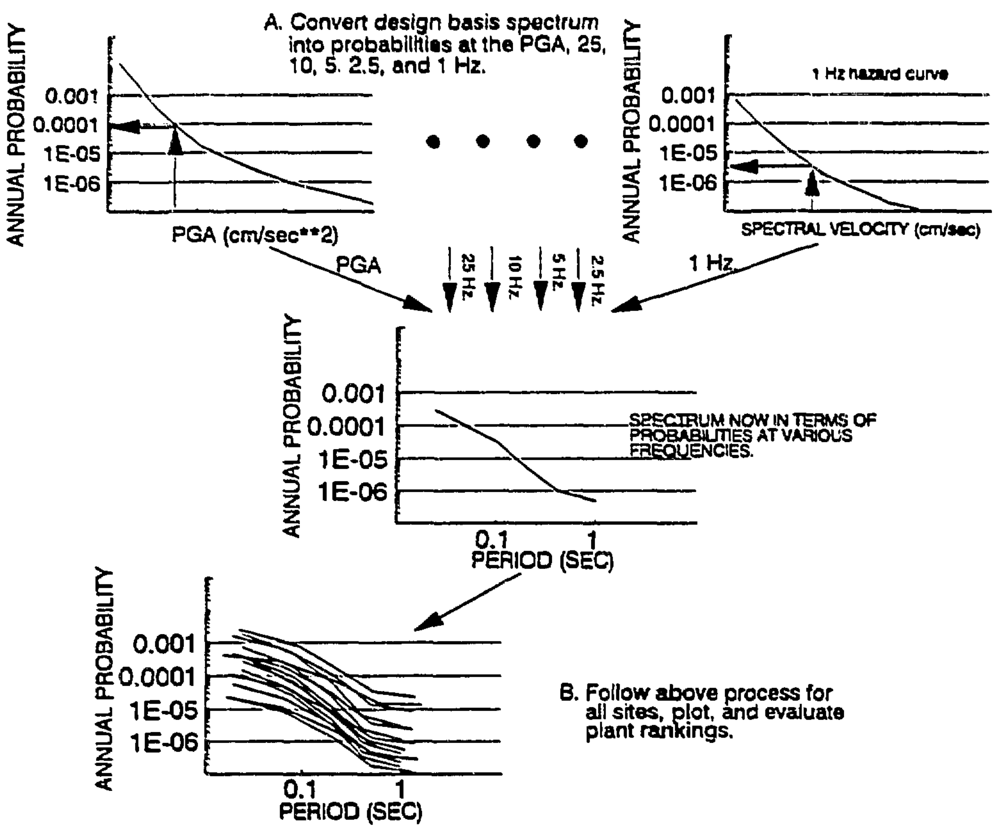

Figure 10. Procedure to illustrate relative comparisons among plants using design basis spectra and seismic hazard curves.

PROBABILITY OF EXCEEDING SSE SPECTRA
FOR ALL EASTERN U.S. SITES
(LLNL 5gx MEDIAN, 5% DAMPING)

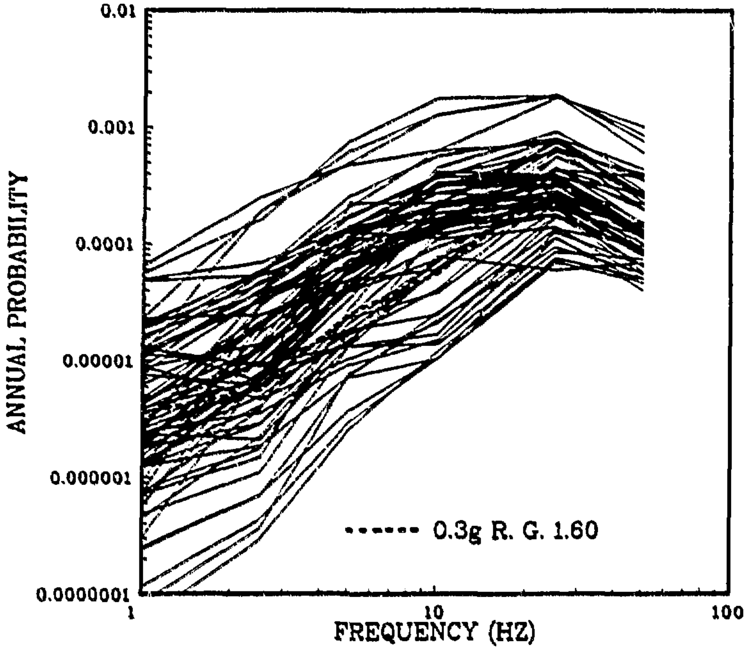

Figure 11. Probability of exceeding SSE spectra for all EUS NPP sites based on LLNL (1989) results, and the probability of exceeding spectrum from R.G. 1.60.

PROBABILITY OF EXCEEDING 0.3g R.G. 1.60 SPECTRUM AND THE MEDIAN PROBABILITY OF EXCEEDING EUS SPECTRA BASED ON EPRI AND LLNL RESULTS

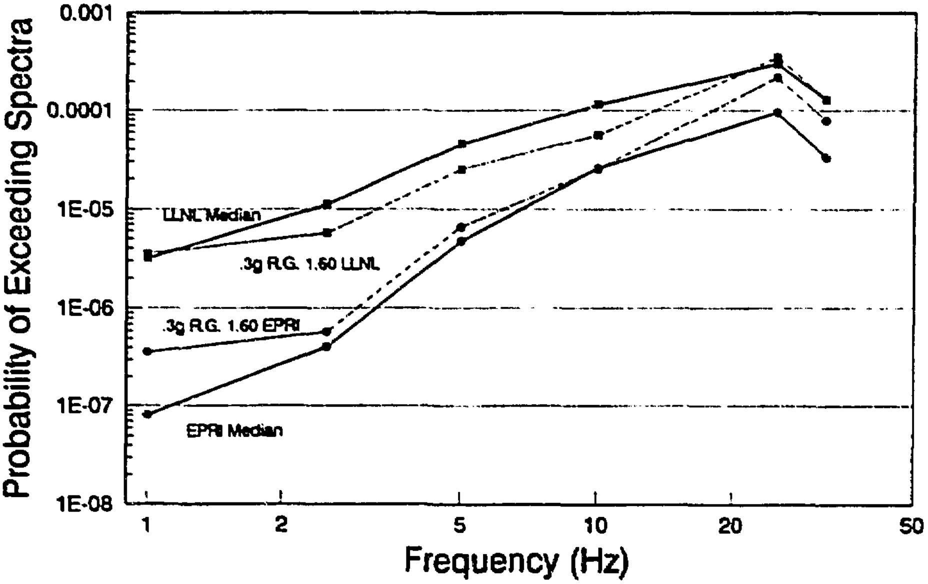

Figure 12. Probability of exceeding SSE spectra for all EUS NPP sites based on LLNL (1989) results, and the probability of exceeding spectrum from R.G. 1.60.

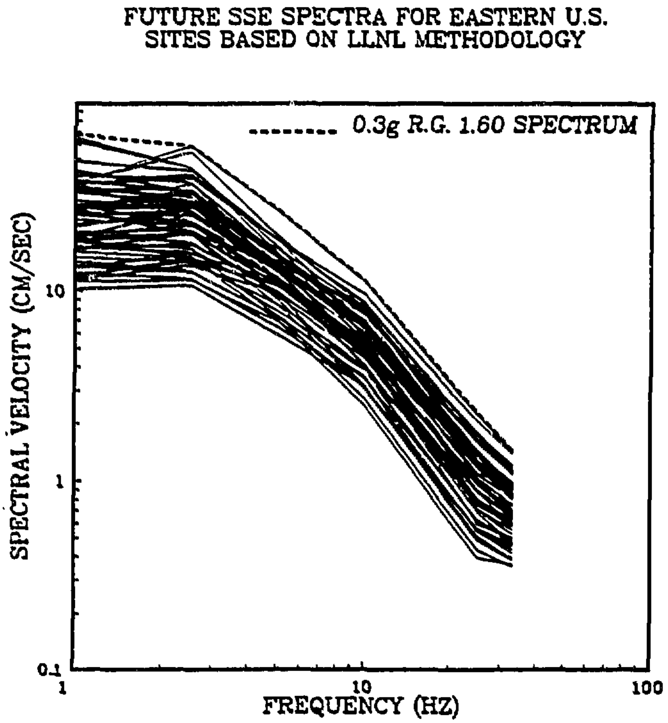

Figure 13. SSE spectra for future EUS NPP sites based on LLNL (1989).