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UCID- 21829

PRINCETON PLASMA PHYSICS LABORATORY (PPPL)

SEISMIC HAZARD ANALYSIS

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October 1, 1989

Lawrence Livermore National Laboratory

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PRINCETON PLASMA PHYSICS LABORATORY (PPPL)

SEISMIC HAZARD ANALYSIS

SUMMARY

New design and evaluation guidelines for department of energy facilities subjected to natural phenomena hazard, are being finalized as UCRL-15910. Although still in draft form at this time, the document describing those guidelines should be considered to be an update of previously available guidelines. The recommendations in the guidelines document mentioned above, and simply referred to as the "guidelines" thereafter, are based on the best information at the time of its development. In particular, the seismic hazard model for the Princeton site was based on a study performed in 1981 by TERA Corp. for Lawrence Livermore National Laboratory (LLNL), which relied heavily on the results of the NRC's Systematic Evaluation Program (SEP; see Appendix C), and was based on a methodology and data sets developed in 1977 and 1978. Considerable advances have been made in the last ten years in the domain of seismic hazard modeling. Thus, it is recommended to update the estimate of the seismic hazard at the DOE sites whenever possible.

The major differences between previous estimates and the ones proposed in this study for the PPPL are in the modeling of the strong ground motion at the site, and the treatment of the total uncertainty in the estimates to include knowledge uncertainty, random uncertainty, and expert opinion diversity as well.

The results presented herein are limited to the estimates of the seismic hazard in terms of the probability of exceedance of the Peak Ground Acceleration (PGA) at the site and of the Uniform Hazard Pseudo Relative Velocity Spectra (PSRV in cm/s) for five annual probabilities of exceedance; $2.0\ 10^{-3}$, 10^{-3}, $4.0\ 10^{-4}$, 10^{-4} and 10^{-5} corresponding to 500-year, 1,000-year, 2,500-year, 10,000-year and 100,000-year return periods. It is recommended that the criteria laid down in the guidelines be used to choose a probability level for each particular facility, depending on its "performance goal" and "Facility-Use Category", as described in Table 4-1 of the guidelines. As a summary of this analysis, the table below provides the median maximum horizontal peak ground surface acceleration at several annual probability of exceedance levels.

Peak Horizontal Ground Surface Acceleration at PPPL
versus
Median Hazard Annual Probability of Exceedance
(g = 981 cm/s/s)

2×10^{-3}	1×10^{-3}	4×10^{-4}	2×10^{-4}
0.06g	0.08g	0.13g	0.19g

For the purpose of design or for a design review, the appropriate hazard models to use in this case, would be the median estimates (PGA hazard curves or PSRV uniform hazard spectra).

This study was performed by Dr. Jean Savy of LLNL, using the methodology, data bases and overall tools, developed for the Nuclear Regulatory Commission (NRC) under the project: "Seismic Hazard Characterization of the Eastern United States," whose latest results were published in NUREG/CR-5250 in 1989.

1. INTRODUCTION

The Princeton Plasma Physics Laboratory (PPPL), operated by the Princeton University, New Jersey, requested from Lawrence Livermore National Laboratory (LLNL) to estimate the seismic hazard at the Tokamak Fusion Test Reactor (TFTR) site, using the methodology recently developed by LLNL for sites in the Eastern U.S. (EUS). The development of this methodology was funded by the Nuclear Regulatory Commission (NRC) and this was applied to all the Nuclear Plant Sites located east of the Rocky mountains.

Previous seismic hazard estimates for the Princeton site were reported in UCRL 53582. These estimates were based on a study using the state-of-the-art methodology and the best available data in 1982. Since 1982, considerable research and development effort in the fields of seismo-tectonics seismicity and ground motion estimation, in large part driven by the NRC/LLNL study of the EUS and by the utility sponsored EPRI study of the EUS, have made many previous studies obsolete.

In particular, the present methodology makes extensive use of expert's opinions to account for the knowledge uncertainty. The modeling uncertainty in the ground motion models as well as in the seismicity models is represented specifically by allowing the various experts to express their opinion in the form of sets of alternate models. The response spectra models are described by attenuation models of the entire spectra rather than a spectral shape anchored on a PGA value, as it was done previously. Attenuating the entire spectrum is believed by most experts (see Bernreuter et al. 1988) at the present time, to be the appropriate approach.

The current state-of-the-art study for NRC was specifically designed to provide a set of tools with which the hazard at all the plant sites in the EUS could be estimated. However, it must be noted that the very specific characteristics of each plant site are only accounted for in generic fashion. The specificity of each plant site was accounted for by defining eight different types of soil conditions. The seismicity information as well as the ground motion prediction models were allowed to take different forms in four major tectonic regions of the EUS. This approach allows to make the most site specific type of analysis for sites at which the complete details of the site characteristics are not completely known, such as is the case of most NRC plant sites, and the Princeton site. In very elaborate studies concentrating on a single plant, enormous efforts are spent only to characterize the site. This could involve extensive geophysical and soil mechanics testing to define the geology, topography and mechanical properties of the underground at the site and can cost enormous amount of money. A good current example is the effort done at the Diablo Canyon Nuclear Power Plant. This is clearly not the scope of this study for which at best generic and scanty information is available.

A summary of the method is given in Appendix C, with a list of the experts used in Appendix D, and a complete description of the methodology and of the data used here is presented in detail in Bernreuter et al., l989 volumes 1, 6 and 7, provided in Appendix E of this letter report. The results provided by the NRC/LLNL method with the present data banks are accurate enough to be used as the basis for choosing seismic parameters for facility and equipment design and for design reviews of the type envisioned at the Princeton site.

The present document reports the results of calculations performed with the existing set of codes and data applied to the PPPL-TFTR site.

The parameters of interest in the present study are:

1. The peak ground acceleration (PGA), considered to be at the site location in the free-field.

2. The pseudo relative velocity response spectrum (PSRV) of the free-field motion for 5% critical damping and at five frequencies (lHz, 2.5Hz, 5Hz, 10.0Hz, and 25Hz).

In this analysis, only the earthquakes of magnitude 5.0 or above are assumed to contribute to the hazard.

2. METHODOLOGY

The hazard model used here is based on the now well accepted model developed by C.A. Cornell (1968).

The important aspects of the NRC/LLNL methodology consist of:

- using many experts opinions to include the knowledge uncertainty, as well as the physical uncertainty which is already included in the hazard model itself.

- propagating all uncertainties, in the seismicity modeling and ground motion modeling, through the use of a Monte Carlo simulation process.

A summary of the methodology is given in Appendix C and the details, including the hazard model and the process of elicitation of the experts' opinion, are given in Bernreuter et al. 1989 vol. 1, 6, and 7 (given in Appendix E). In particular, Volume 7 details all the questionnaires used in the experts opinion elicitations.

3. INPUT DATA

The input data used for the PPPL-TFTR study, is exhaustively described in Bernreuter et al. 1989 Vol. I. The minimum magnitude of the earthquakes contributions to the hazard in the base case, is magnitude 5.0, the input of 11 seismicity and tectonics experts (the S-experts), and five ground motion experts (the G-experts) inputs are used, the list of whom is given in Appendix D.

At the present time, there is still some controversy as to the need to account for the effect of earthquakes of magnitude lower than 5. However, most Nuclear Power Utilities and their engineering consultants believe that such smaller earthquakes are not likely to cause damage in a well-engineered facility. Consequently, the NRC/LLNL methodology, for consistency, has limited itself to earthquakes greater than a magnitude of 5.0. The effect of the lower magnitude earthquakes is analyzed as a sensitivity analysis in Bernretuer et al., 1989. (See Appendix E).

4. SEISMIC HAZARD ESTIMATES AT THE PPPL-TFTR SITE

4.1 Site Description

The PPPL site is located in Princeton, New Jersey, its coordinates are:

Latitude	Longitude
N 40° 20' 55"	W 74° 36' 0"

The description of the soil underground at the site is given to us in a letter report by Melick-Tully and Associates, Inc., dated December 8, 1987, addressed to Mr. Charles Montana.

Careful study of the above report, coupled with input from the TFTR-PSAR (Section 2.5.1.4) lead us to assign the PPPL-TFTR site to the LLNL classification of rock (see Bernreuter et al., vol 1 and 7).

4.2 Dominant Zonal Contributions

The dominant zonal contributions table (Tables 1.1 to 1.11) identifies which of the seismic zones given by the seismicity experts (S-Experts) contribute the most to creating the seismic hazard at the PPPL-TFTR site. The percentages given in Table 1.1 through 1.11 are the ratios of the hazard provided by a zone, to the total hazard at the site, given only for the four highest contributing zones. The total number of S-experts used in this study was 11, with identification numbers 1, 2, 3, 4, 5, 6, 7, 10, 11, 12, and 13. The experts number 8 and 9 initially participated in the study and later resigned. Consequently, no results exist for experts 8 and 9. (See Bernreuter et al. 1989 Vol 1, Appendix C).

One needs to be careful in interpreting the results presented here since the calculations are made <u>only with the Best Estimate Hazard Curves</u> (BEHC) and not with the Constant Percentile Hazard Curves (CPHC).

The BEHC for a given S-Expert is obtained by setting each of the uncertain parameters equal to what each S-Expert had defined as the most likely value of the parameter (*zonation, seismicity* parameters) and the most likely models of the ground motion experts (G-experts). Thus, the table of zonal contributions is only indicative of the relative contributions but it does not always represent accurately the relative contribution as it would be if all possible alternatives, and all uncertainties were included.

The zones' identification given in Tables 1.1 to 1.11 refer to the zones shown in Appendix B for each of the 11 S-Experts. In these tables, the seismic zone in which the PPPL-TFTR site is located is called the "Host Zone". Note that since the Tables of zonal contribution are based on best estimate zonation, only zones shown in the best estimation zonation map appear in Tables 1.1 to 1.11. The zones appearing in the alternative zonation maps were only used to estimate the uncertainty in the hazard (See Bernreuter et al., Volume 1, 1989 in Appendix C). Note that the figure B6.3 only displays a large zone covering the entire EUS. In this particular interpretation, to which the experts number 6 gave a low weight, the entire EUS is assumed to have a constant uniform seismicity.

4.3 Hazard Estimates with all Seismicity and Ground Motion Experts

Figs. 1 through 13 show the results of the analysis for the PPPL-TFTR site when all the seismicity and ground motion experts' inputs are used and when the contributions of all earthquakes greater than magnitude 5 are accounted for.

Fig. I shows the hazard curves in terms of arithmetic mean and Best Estimate (BE). The use of the expression Best Estimate may be confusing and must be clarified again to avoid misinterpretation.

The BE is obtained as a single, deterministic calculation of the hazard where all the uncertain models and parameters are set equal to their most likely value. For example, the random uncertainty (σ) in the ground motion models is set to its most likely value, as given by each ground motion expert. The curves in fig I are obtained by averaging the results over the 11 S-experts.

Fig. 2 displays the total uncertainty, including random and modeling uncertainty, for the PGA. Figs. 3 to 7 display the same as in fig. 2 for the 5 frequencies of the PSRV., (ie., 1Hz, 2.5Hz, 5Hz, 10Hz, and 25Hz.)

Fig. 8 shows the Uniform Hazard Spectra for 5 return periods, namely 500, 1,000, 2,500, 10,000 and 100,000 year return periods. These spectra are obtained from the arithmetic average hazard curves of the PSRV at the 5 frequencies. And finally, figs. 9 through 13 show the uncertainty in the Uniform Hazard Spectra obtained from the corresponding uncertainty analyses performed at each of the 5 frequencies.

5. USE OF THE RESULTS

The body of results presented in this report is intended to make as complete as possible the description of the seismic hazard at the site, for the purpose of possible sensitivity analyses and to better describe the complex interaction of the seismic zonation, ground-motion and choice of strong motion parameter. Consequently, only few selected curves presented here are of direct interest to the designer or to the design-reviewer. Specifically, the appropriate curves to be used for design or for review would be the median estimates, i.e., the 50% hazard curves. In fig 2, that would be the middle curve. The same would be true for any of the various uniform hazard response spectra curves, such as in fig 9, for example.

Once the proper curve, or set of curves is selected, the analyst will select the appropriate hazard value (i.e. the appropriate probability of exceedance, or equivalently the appropriate return period), from the guidelines (UCRL-15910). The end result for the analyst will be a PGA value corresponding to the estimate of the free-field peak ground acceleration at the site with a given probability of exceedance. similarly with velocity for the PSRV.

Table 1.1
Seismic Hazard at the PPPL-TFTR DOE Site
Most Important Zones Contributing to the Hazard

Seismicity Expert Number: 1

Host Zone: Zone 4

	PGA = 0.125G			PGA = 0.55g	
Zone ranking	A Zone	B %		C Zone	D %
First	Zone 4	60.		Zone 4	68.
Second	Zone 1	14.		Zone 1	27.
Third	Zone 20	14.		Zone 20	3.
Fourth	Zone 22	6.		Zone 22	1.

Key:

A: Identification of zones contributing the most to be "Best Estimate" of the seismic hazard (BEH) for low PGA (.125g).

B: Percent contribution to the total BEH, for zones identified in A.

C: Same as A, for high PGA (0.55g).

D: Same as B, for zones identified in C.

Note: The percent contributions are rounded off, and only the four highest contributions are gi
As a result the percentage numbers do not necessarily add up to exactly I.0.

Table 1.2
Seismic Hazard at the PPPL-TFTR DOE Site
Most Important Zones Contributing to the Hazard

Seismicity Expert Number: 2

Host Zone: Zone 28

	PGA = 0.125G			PGA = 0.55g	
Zone ranking	A Zone	B %		C Zone	D %
First	Zone 28	82.		Zone 28	93.
Second	Zone 31	8.		Zone 31	3.
Third	Zone 32	8.		Zone 32	3.
Fourth	Comp. Zone	2.		Comp Zone	1.

Key:

A: Identification of zones contributing the most to be "Best Estimate" of the seismic hazard (BEH) for low PGA (.125g).

B: Percent contribution to the total BEH, for zones identified in A.

C: Same as A, for high PGA (0.55g).

D: Same as B, for zones identified in C.

Note: The percent contributions are rounded off, and only the four highest contributions are given. As a result the percentage numbers do not necessarily add up to exactly 1.0.

Table 1.3
Seismic Hazard at the PPPL-TFTR DOE Site
Most Important Zones Contributing to the Hazard

Seismicity Expert Number: 3

Host Zone: Zone 5

	PGA = 0.125G			PGA = 0.55g	
Zone ranking	A Zone	B %		C Zone	D %
First	Zone 5	72.		Zone 5	87.
Second	Zone 4	13.		Zone 8a	8.
Third	Zone 8a	10.		Zone 4	4.
Fourth	Zone 2	2.			

Key:

A: Identification of zones contributing the most to be "Best Estimate" of the seismic hazard (BEH) for low PGA (.125g).

B: Percent contribution to the total BEH, for zones identified in A.

C: Same as A, for high PGA (0.55g).

D: Same as B, for zones identified in C.

Note: The percent contributions are rounded off, and only the four highest contributions are given. As a result the percentage numbers do not necessarily add up to exactly 1.0.

Table 1.4
Seismic Hazard at the PPPL-TFTR DOE Site
Most Important Zones Contributing to the Hazard

Seismicity Expert Number: 4

Host Zone: Zone 11

	PGA = 0.125G			PGA = 0.55g	
Zone ranking	A Zone	B %		C Zone	D %
First	Zone 11	49.		Zone 11	95.
Second	Zone 16	19.		Zone 12	2.
Third	Zone 12	10.		Zone 16	2.
Fourth	Zone 18	7.			

Key:

A: Identification of zones contributing the most to be "Best Estimate" of the seismic hazard (BEH) for low PGA (.125g).

B: Percent contribution to the total BEH, for zones identified in A.

C: Same as A, for high PGA (0.55g).

D: Same as B, for zones identified in C.

Note: The percent contributions are rounded off, and only the four highest contributions are given. As a result the percentage numbers do not necessarily add up to exactly I.0.

Table 1.5
Seismic Hazard at the PPPL-TFTR DOE Site
Most Important Zones Contributing to the Hazard

Seismicity Expert Number: 5

Host Zone: Zone 1

	PGA = 0.125G			PGA = 0.55g	
Zone ranking	A Zone	B %		C Zone	D %
First	Zone 1	50.		Zone 1	99.
Second	Zone 6	43.		Zone 8	1.
Third	Zone 8	3.		Zone 3	0.+
Fourth	Zone 3	2.			

Key:

A: Identification of zones contributing the most to be "Best Estimate" of the seismic hazard (BEH) for low PGA (.125g).

B: Percent contribution to the total BEH, for zones identified in A.

C: Same as A, for high PGA (0.55g).

D: Same as B, for zones identified in C.

Note: The percent contributions are rounded off, and only the four highest contributions are given. As a result the percentage numbers do not necessarily add up to exactly l.0.

Table 1.6
Seismic Hazard at the PPPL-TFTR DOE Site
Most Important Zones Contributing to the Hazard

Seismicity Expert Number: 6

Host Zone: Zone 6

	PGA = 0.125G			PGA = 0.55g	
Zone ranking	A Zone	B %		C Zone	D %
First	Zone 6	86.		Zone 6	98.
Second	Zone 7	6.		Zone 7	1.
Third	Zone 3	4.			
Fourth	Zone 5	1.			

Key:

A: Identification of zones contributing the most to be "Best Estimate" of the seismic hazard (BEH) for low PGA (.125g).

B: Percent contribution to the total BEH, for zones identified in A.

C: Same as A, for high PGA (0.55g).

D: Same as B, for zones identified in C.

Note: The percent contributions are rounded off, and only the four highest contributions are given. As a result the percentage numbers do not necessarily add up to exactly 1.0.

Table 1.7
Seismic Hazard at the PPPL-TFTR DOE Site
Most Important Zones Contributing to the Hazard

Seismicity Expert Number: 7

Host Zone: Zone 13

	PGA = 0.125G			PGA = 0.55g	
Zone ranking	A Zone	B %		C Zone	D %
First	Zone 13	63.		Zone 13	78.
Second	Zone 14	16.		Zone 14	11.
Third	Zone 29	10.		Zone 29	7.
Fourth	Zone 7	7.		Zone 7	4.

Key:

A: Identification of zones contributing the most to be "Best Estimate" of the seismic hazard (BEH) for low PGA (.125g).

B: Percent contribution to the total BEH, for zones identified in A.

C: Same as A, for high PGA (0.55g).

D: Same as B, for zones identified in C.

Note: The percent contributions are rounded off, and only the four highest contributions are given. As a result the percentage numbers do not necessarily add up to exactly I.0.

Table 1.8
Seismic Hazard at the PPPL-TFTR DOE Site
Most Important Zones Contributing to the Hazard

Seismicity Expert Number: 10

Host Zone: Zone 4

	PGA = 0.125G			PGA = 0.55g	
Zone ranking	A Zone	B %		C Zone	D %
First	Zone 4	46.		Zone 4	75.
Second	Zone 5	36.		Zone 5	24.
Third	Comp Zone	4.		Comp Zone	1.
Fourth	Zone 6	4.			

Key:

A: Identification of zones contributing the most to be "Best Estimate" of the seismic hazard (BEH) for low PGA (.125g).

B: Percent contribution to the total BEH, for zones identified in A.

C: Same as A, for high PGA (0.55g).

D: Same as B, for zones identified in C.

Note: The percent contributions are rounded off, and only the four highest contributions are given. As a result the percentage numbers do not necessarily add up to exactly I.0.

Table 1.9
Seismic Hazard at the PPPL-TFTR DOE Site
Most Important Zones Contributing to the Hazard

Seismicity Expert Number: 11

Host Zone: Zone 5

	PGA = 0.125G			PGA = 0.55g	
Zone ranking	A Zone	B %		C Zone	D %
First	Zone 5	79.		Zone 5	98.
Second	Zone 3	10.		Zone 3	1.
Third	CZ	5.		CZ	1.
Fourth	Zone 8	1.		Zone 4	0.+

Key:

A: Identification of zones contributing the most to be "Best Estimate" of the seismic hazard (BEH) for low PGA (.125g).

B: Percent contribution to the total BEH, for zones identified in A.

C: Same as A, for high PGA (0.55g).

D: Same as B, for zones identified in C.

Note: The percent contributions are rounded off, and only the four highest contributions are given. As a result the percentage numbers do not necessarily add up to exactly 1.0.

Table 1.10
Seismic Hazard at the PPPL-TFTR DOE Site
Most Important Zones Contributing to the Hazard

Seismicity Expert Number: 12

Host Zone: Zone 32

	PGA = 0.125G			PGA = 0.55g	
Zone ranking	A Zone	B %		C Zone	D %
First	Zone 32	86.		Zone 32	100.
Second	Zone 31	6.			
Third	Zone 34	4.			
Fourth	Zone 27	2.			

Key:

A: Identification of zones contributing the most to be "Best Estimate" of the seismic hazard (BEH) for low PGA (.125g).

B: Percent contribution to the total BEH, for zones identified in A.

C: *Same as A, for high PGA (0.55g).*

D: Same as B, for zones identified in C.

Note: The percent contributions are rounded off, and only the four highest contributions are given. As a result the percentage numbers do not necessarily add up to exactly 1.0.

Table 1.11
Seismic Hazard at the PPPL-TFTR DOE Site
Most Important Zones Contributing to the Hazard

Seismicity Expert Number: 13

Host Zone: Comp Zone (CZ17)

	PGA = 0.125G			PGA = 0.55g	
Zone ranking	A Zone	B %		C Zone	D %
First	Zone 10	54.		Zone 10	59.
Second	CZ17	28.		CZ17	33.
Third	CZ15	10.		CZ15	8.
Fourth	Zone 12	6.			

Key:

A: Identification of zones contributing the most to be "Best Estimate" of the seismic hazard (BEH) for low PGA (.125g).

B: Percent contribution to the total BEH, for zones identified in A.

C: Same as A, for high PGA (0.55g).

D: Same as B, for zones identified in C.

Note: The percent contributions are rounded off, and only the four highest contributions are given. As a result the percentage numbers do not necessarily add up to exactly l.0.

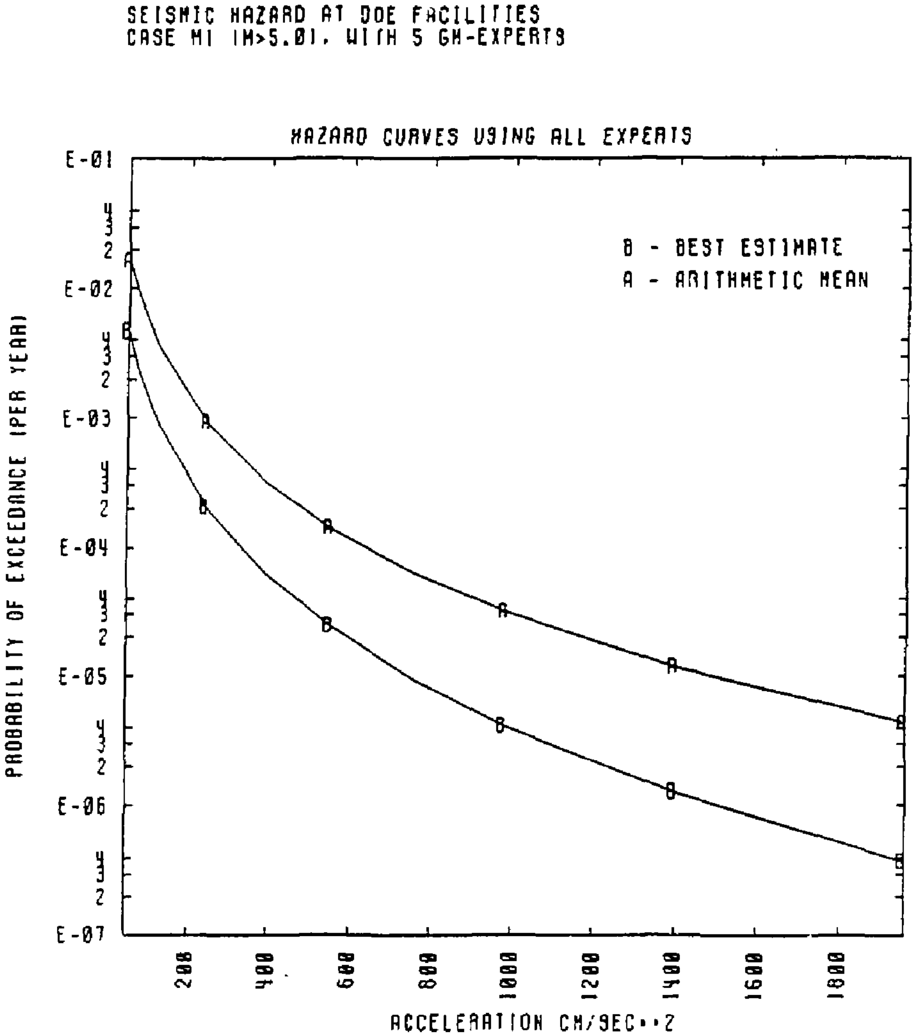

Fig 1: **Best estimate and arithmetic average hazard curves (Minimum contributing magnitude = 5.0) of the PGA for the PPPL-TFTR.**

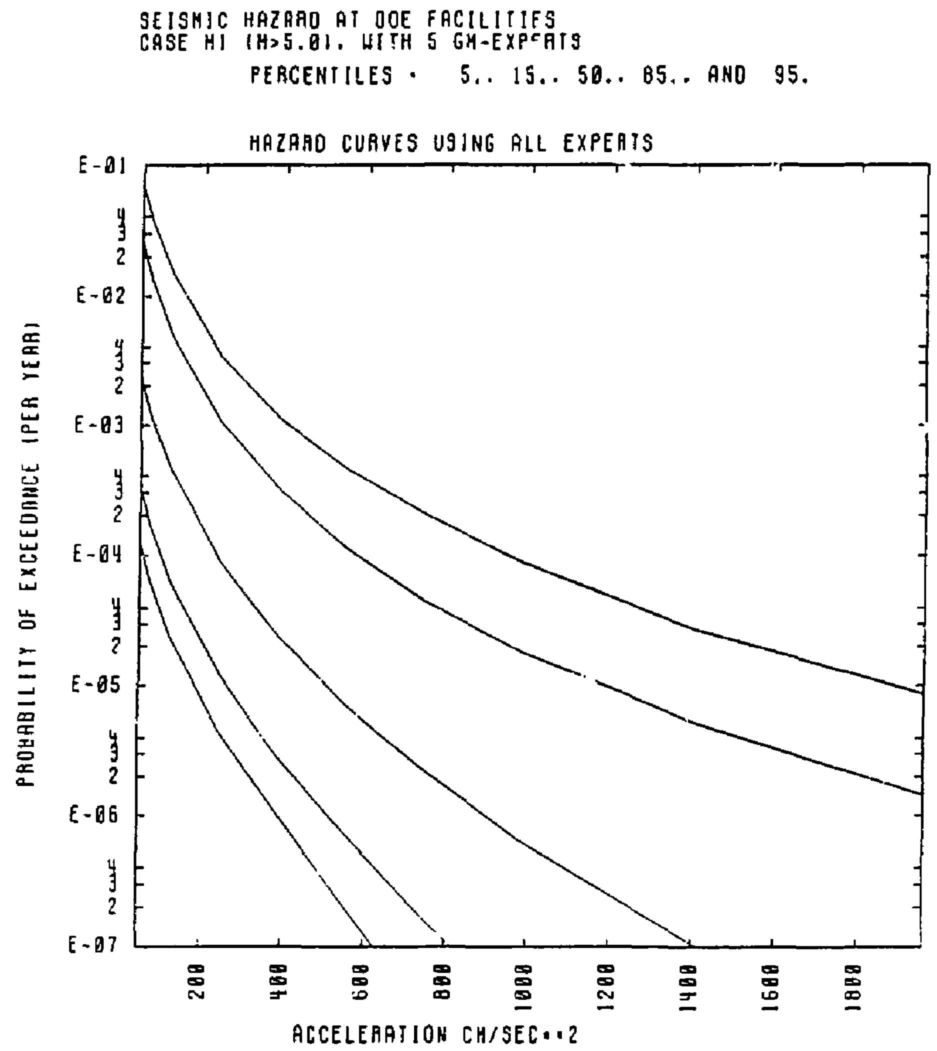

Fig 2: **5, 15, 50, 85, and 95 percent constant percentile hazard curves (Minimum contributing magnitude = 5.0) of the PGA for the PPPL-TFTR site.**

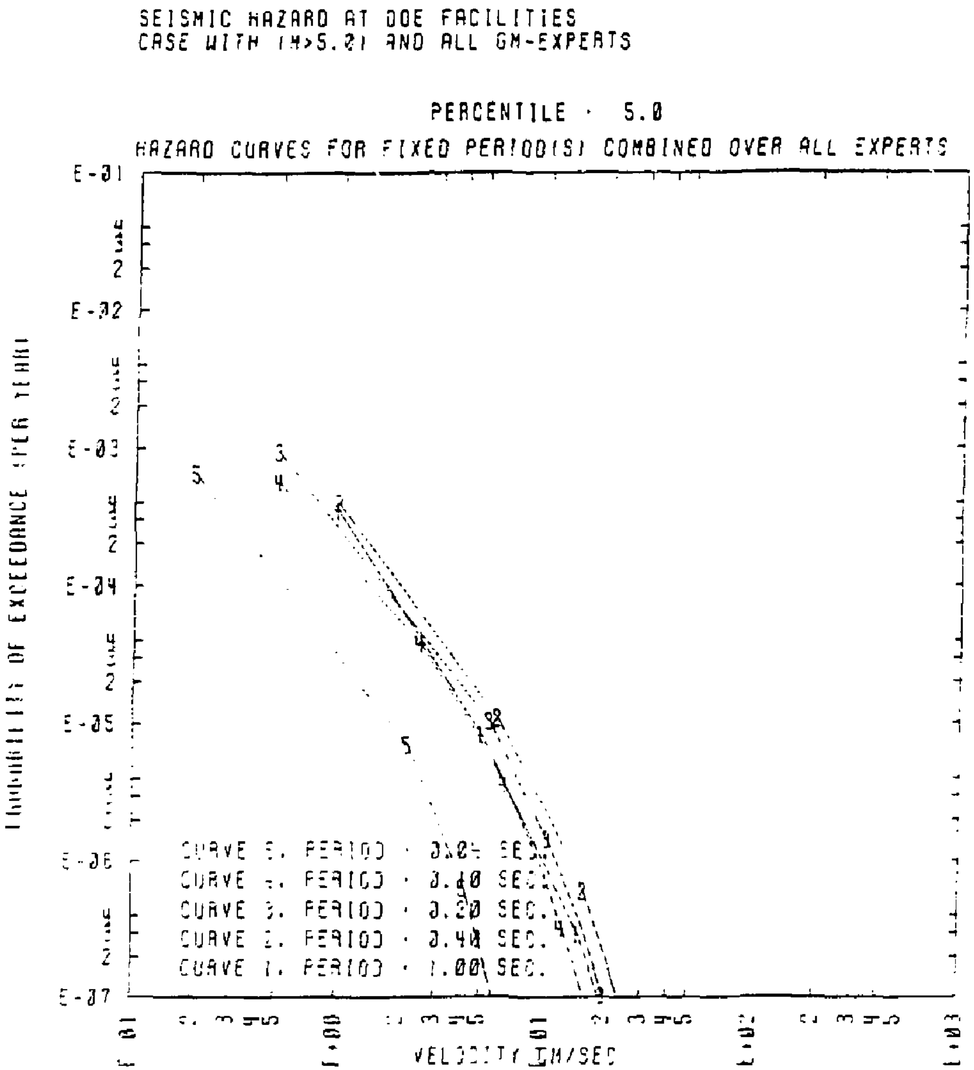

Fig. 3: 5 percent constant percentile hazard curves (Minimum contributing magnitude = 5.0) of the PSRV at 5 frequencies for the PPPL-TFTR site.

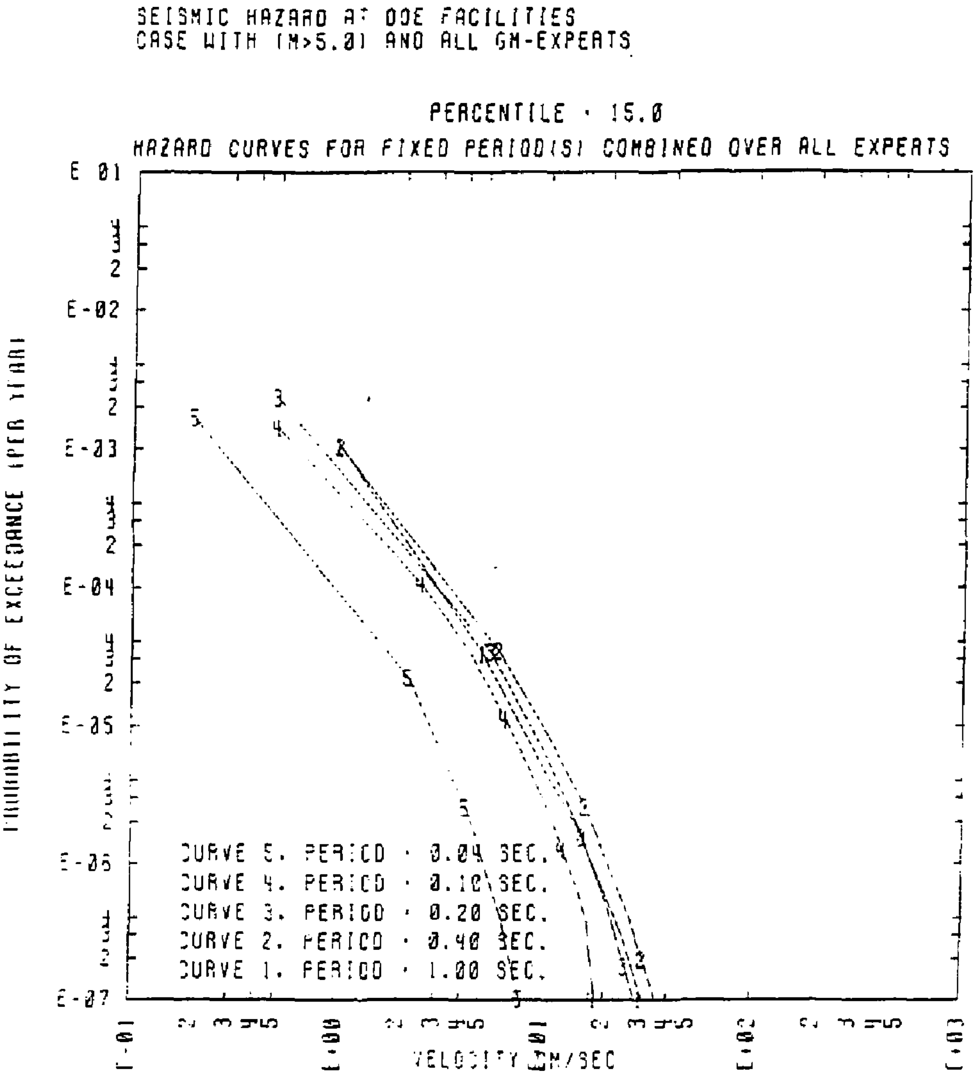

Fig 4: **15 percent constant percentile hazard curves (Minimum contributing magnitude = 5.0) of the PSRV at *5 frequencies for the PPPL-TFTR site.***

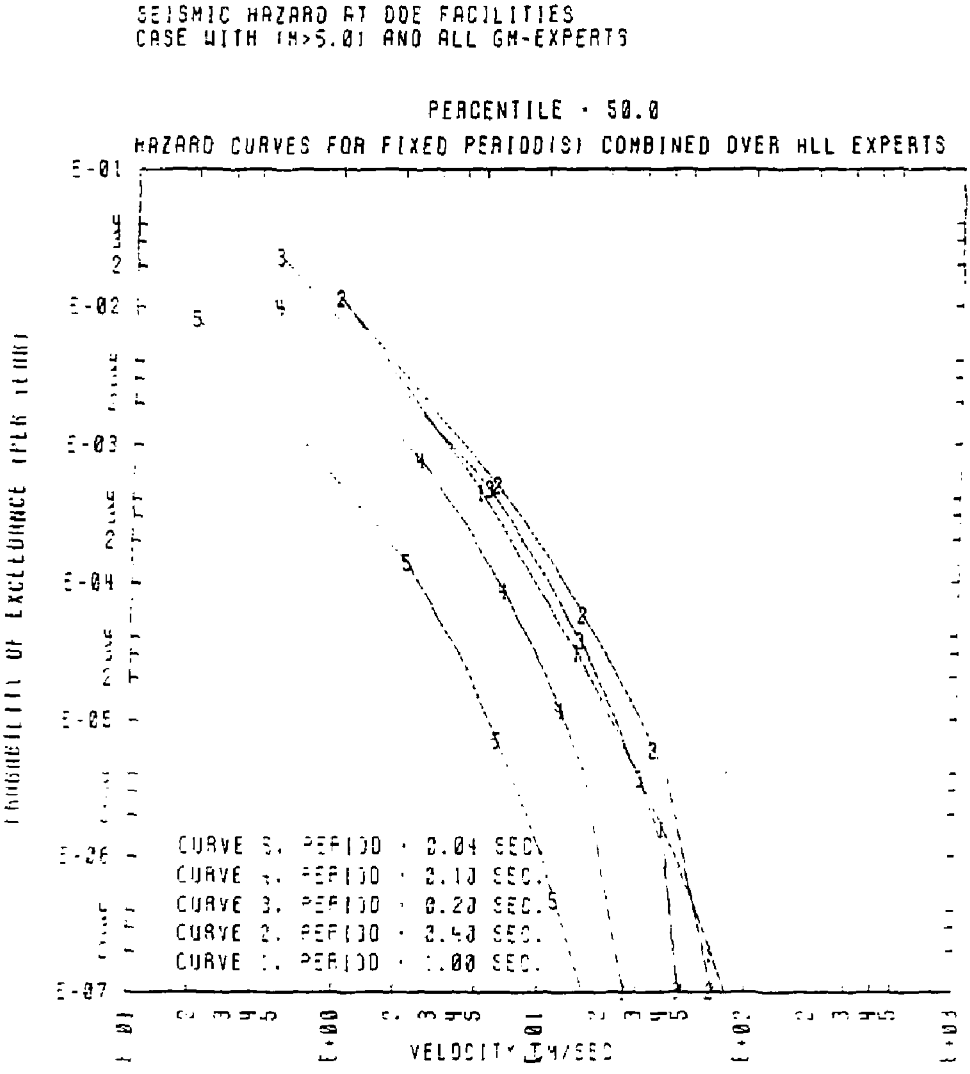

Fig 5: **50 percent constant percentile hazard curves (Minimum contributing magnitude = 5.0) of the PSRV at 5 frequencies for the PPPL-TFTR site.**

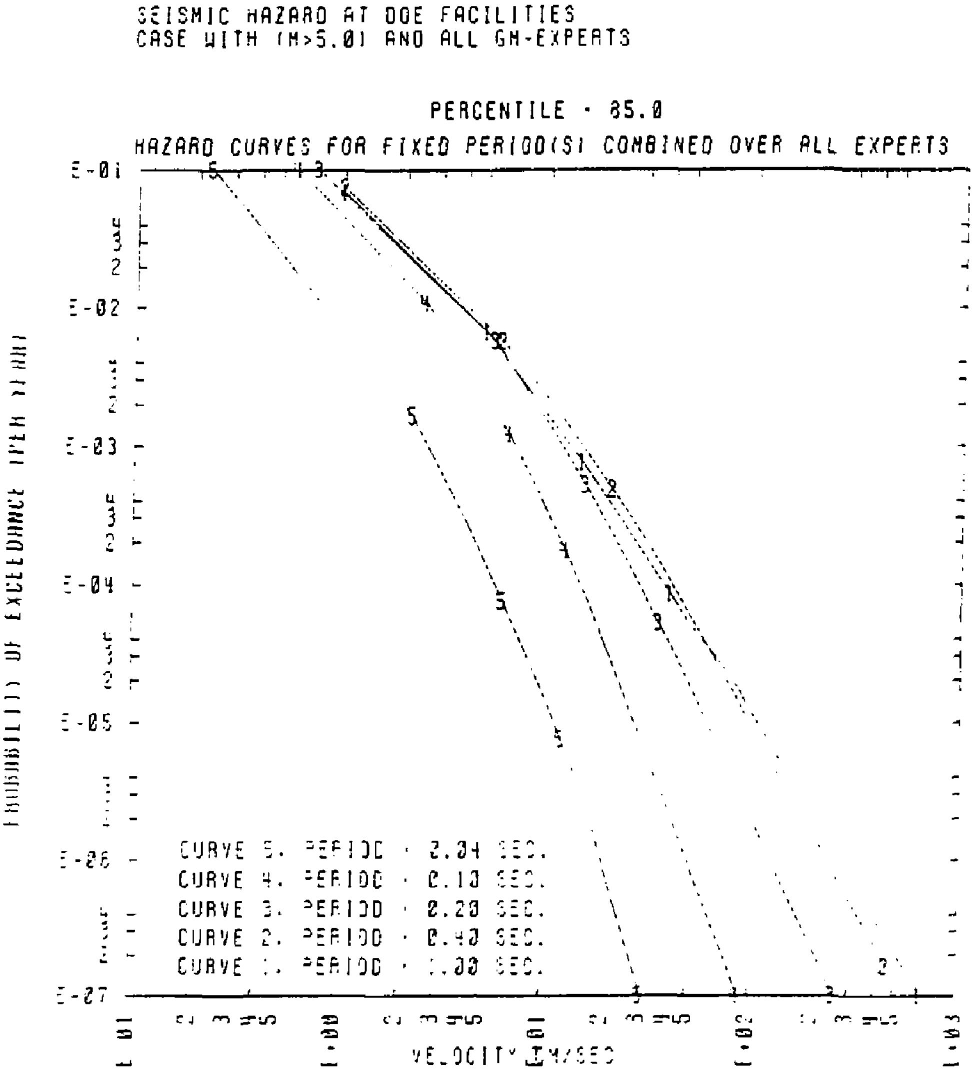

Fig 6: **85 percent constant percentile hazard curves (Minimum contributing magnitude = 5.0) of the PSRV at 5 frequencies for the PPPL-TFTR site.**

SEISMIC HAZARD AT DOE FACILITIES
CASE WITH (M>5.0) AND ALL GM-EXPERTS

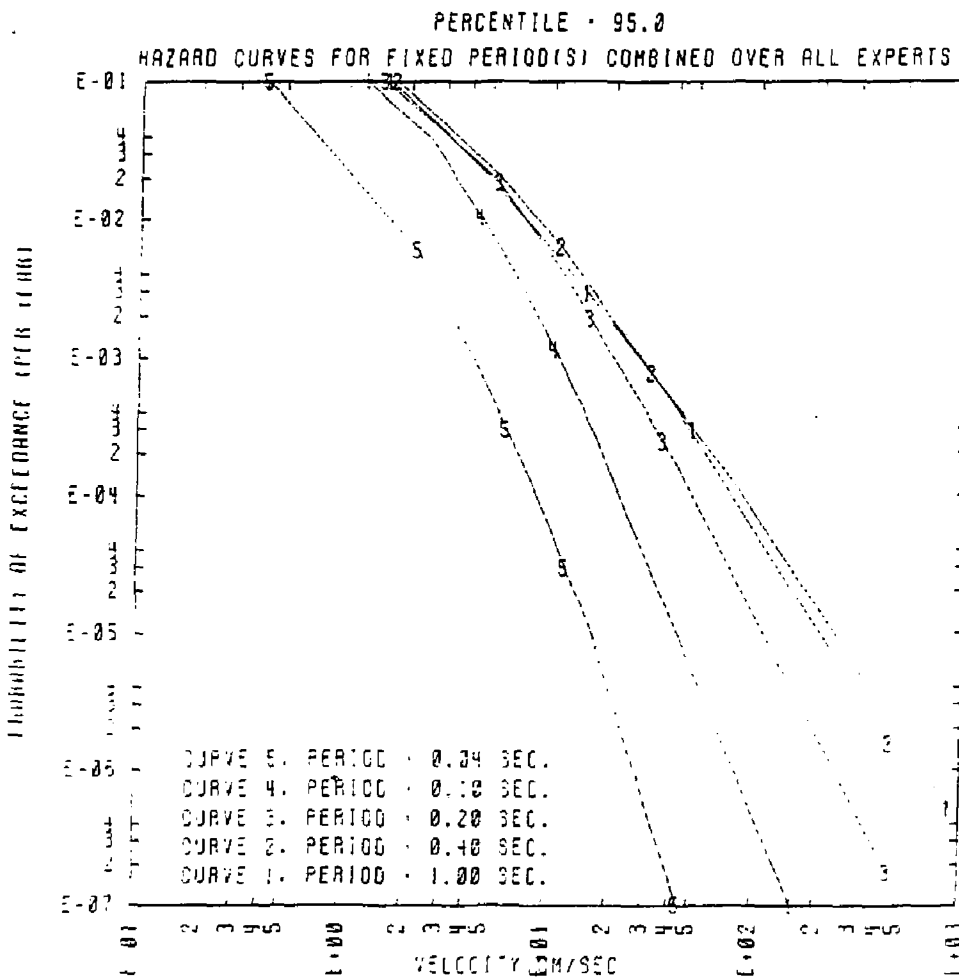

Fig 7: **95 percent constant percentile hazard curves (Minimum contributing magnitude = 5.0) of the PSRV at 5 frequencies for the PPPL-TFTR site.**

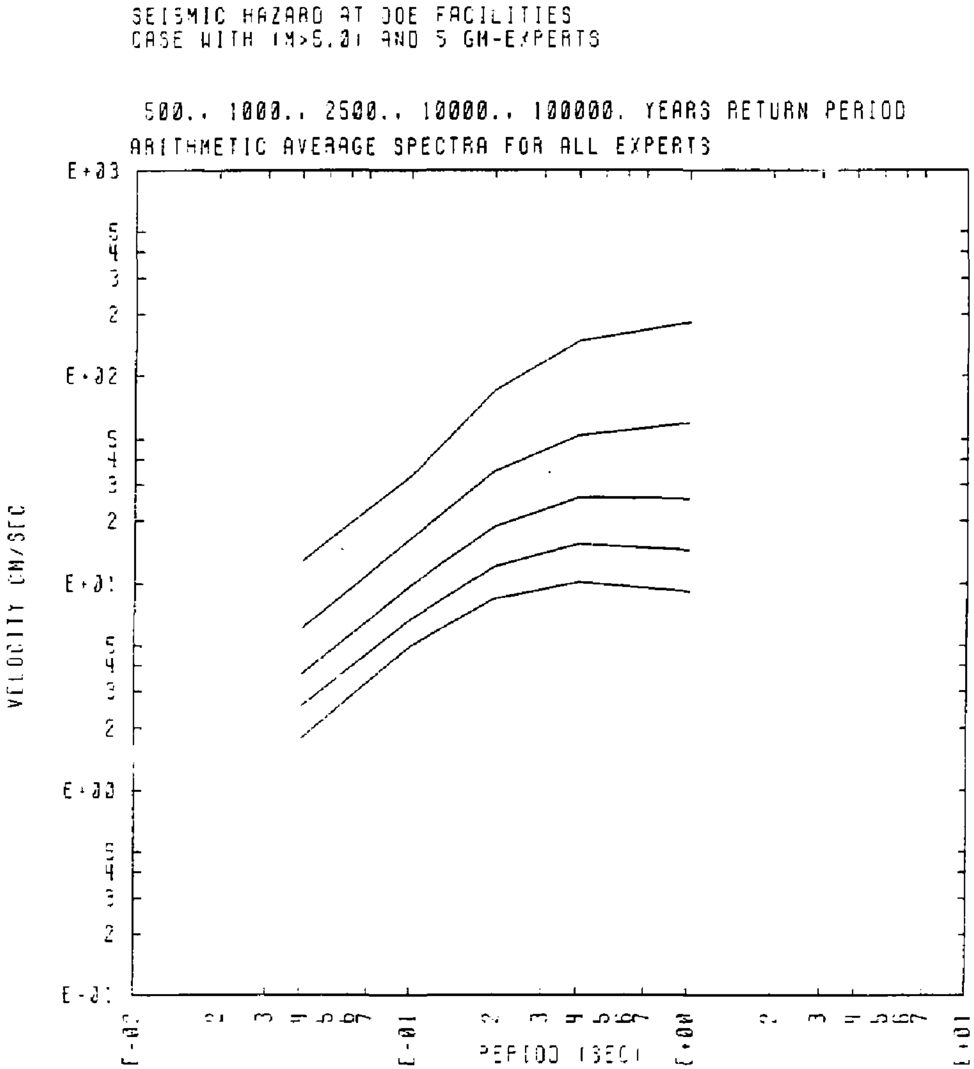

Fig 8: **Arithmetic average Uniform Hazard Spectra for five return periods (Minimum contributing magnitude = 5.0) for the PPPL-TFTR site.**

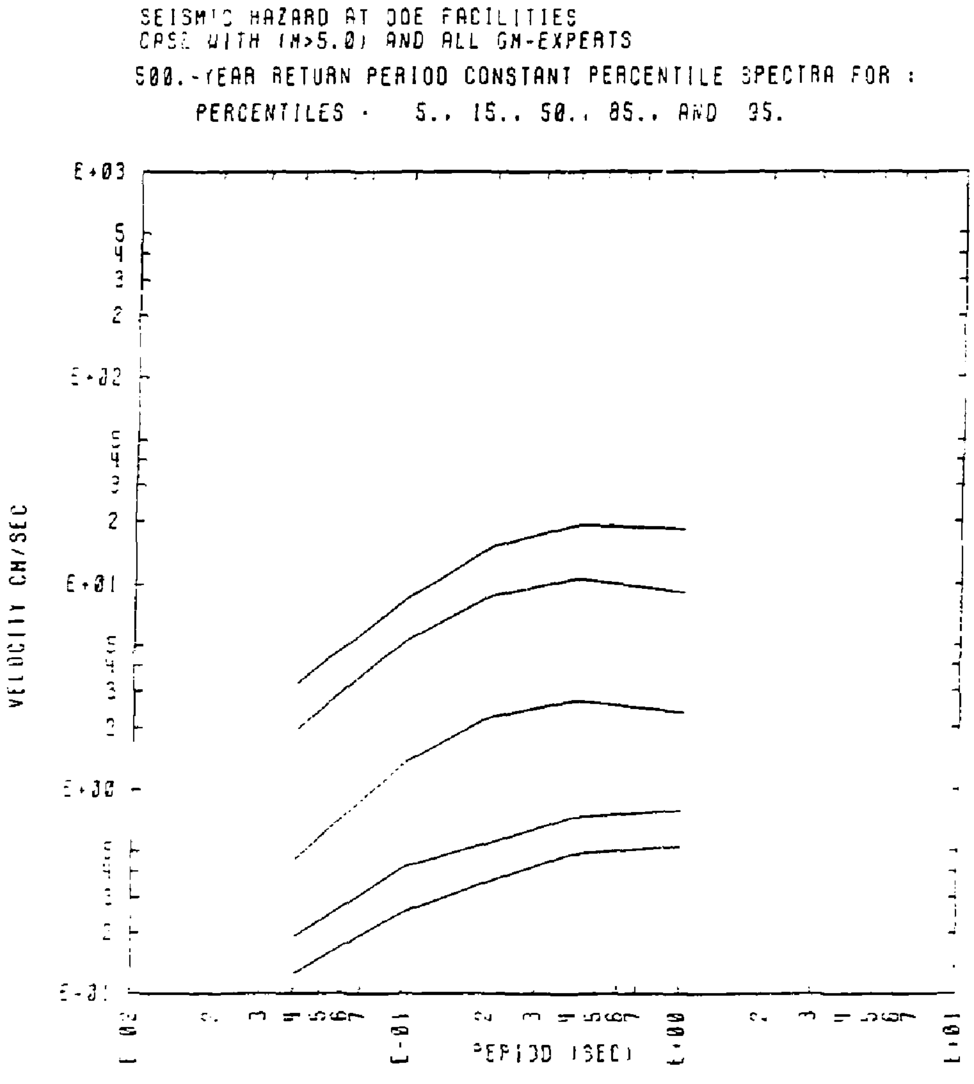

Fig 9: ***5, 15, 50, 85*** **and** ***95*** **percent** ***constant percentile 500 year*** **return period Uniform Hazard Spectra (Minimum contributing magnitude = 5.0) for the PPPL-TFTR site.**

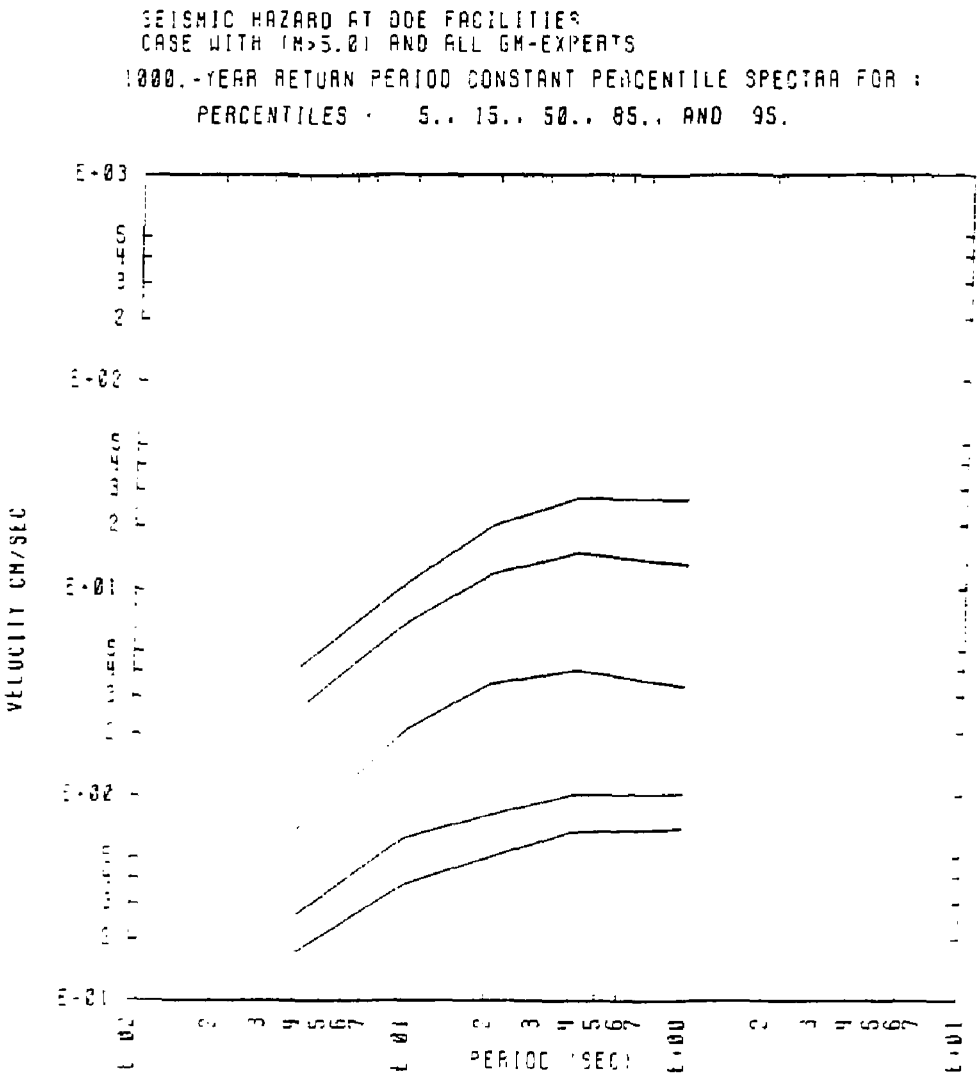

Fig 10: ***5, 15, 50, 85* and *95* percent *constant* percentile *1,000* year *return period Uniform* Hazard *Spectra* (*Minimum* contributing magnitude = 5.0) for the PPPL-TFTR site.**

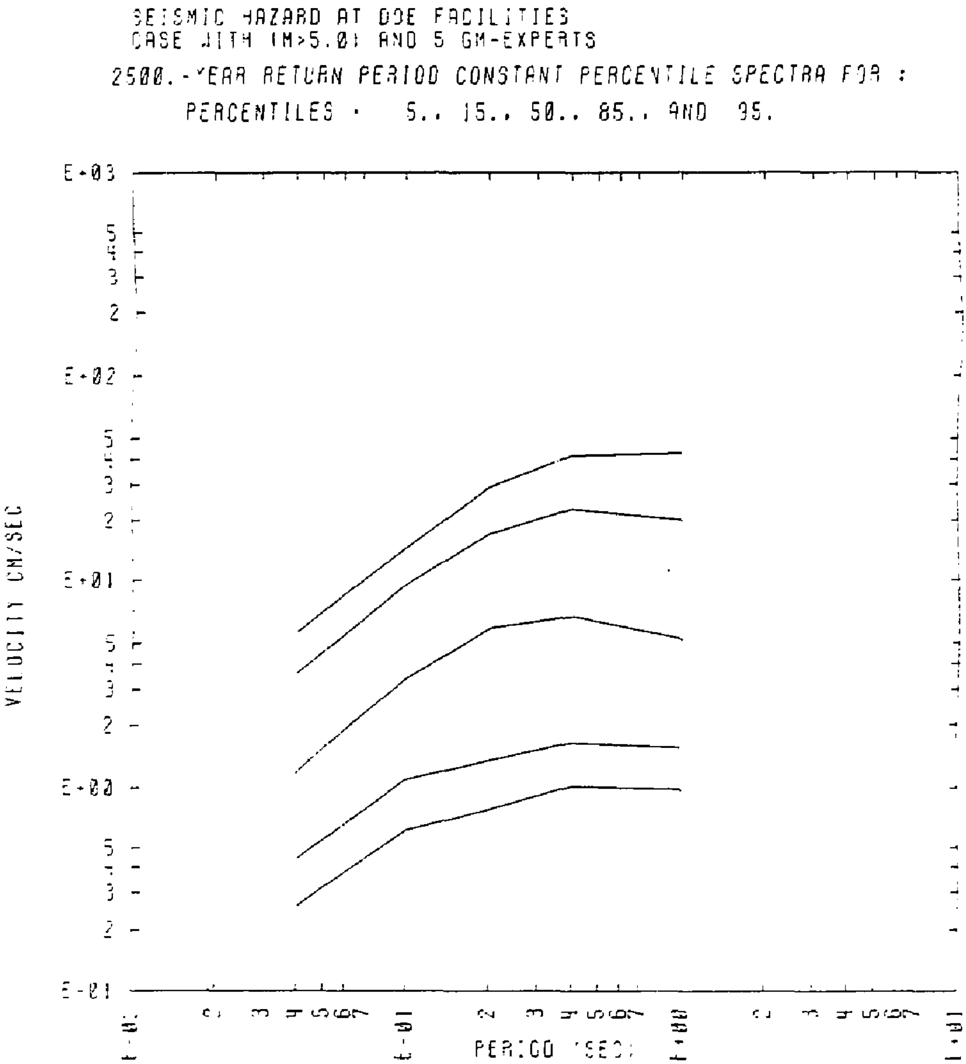

Fig 11: 5, 15, 50, 85 and 95 percent constant percentile 2,500 year return period Uniform Hazard Spectra (Minimum contributing magnitude = 5.0) for the PPPL-TFTR site.

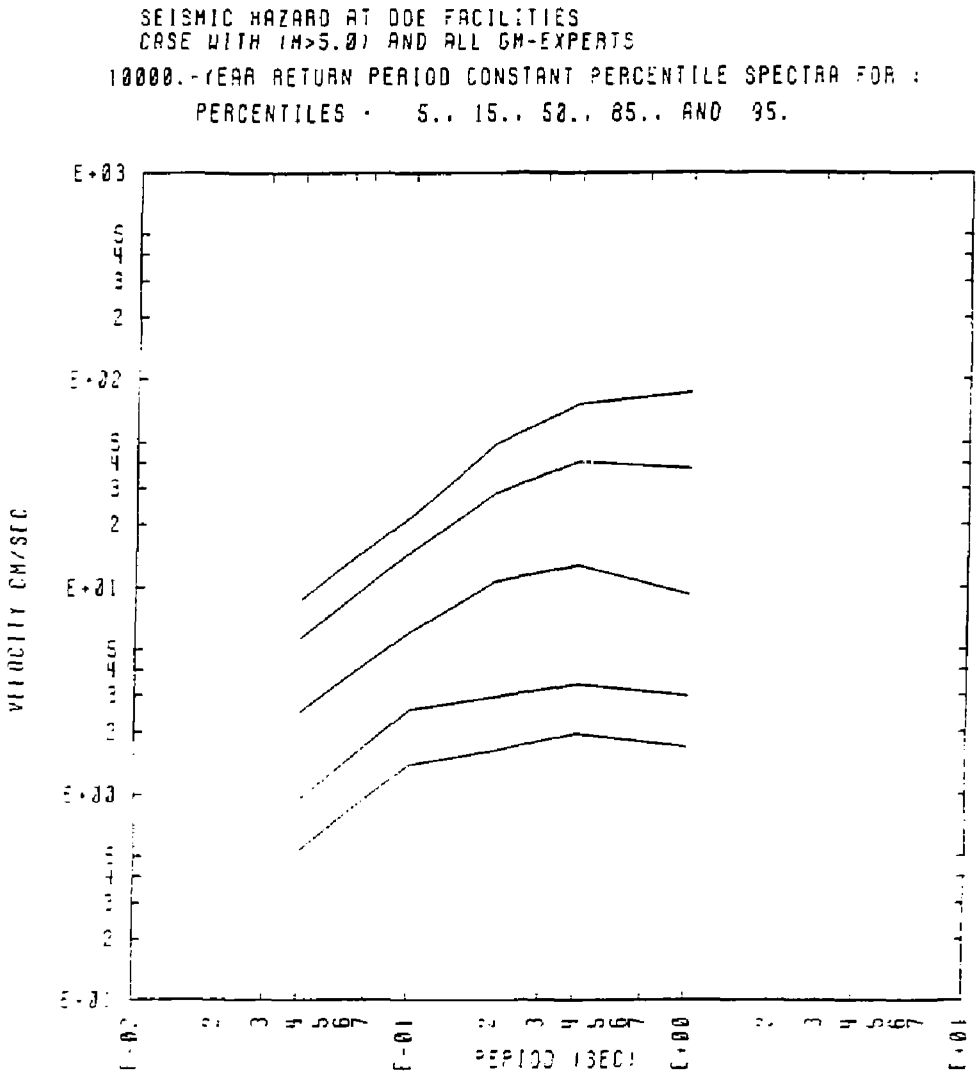

Fig 12: 5, 15, 50, 85 and 95 percent constant percentile 10,000 year return period Uniform Hazard Spectra (Minimum contributing magnitude = 5.0) for the PPPL-TFTR site.

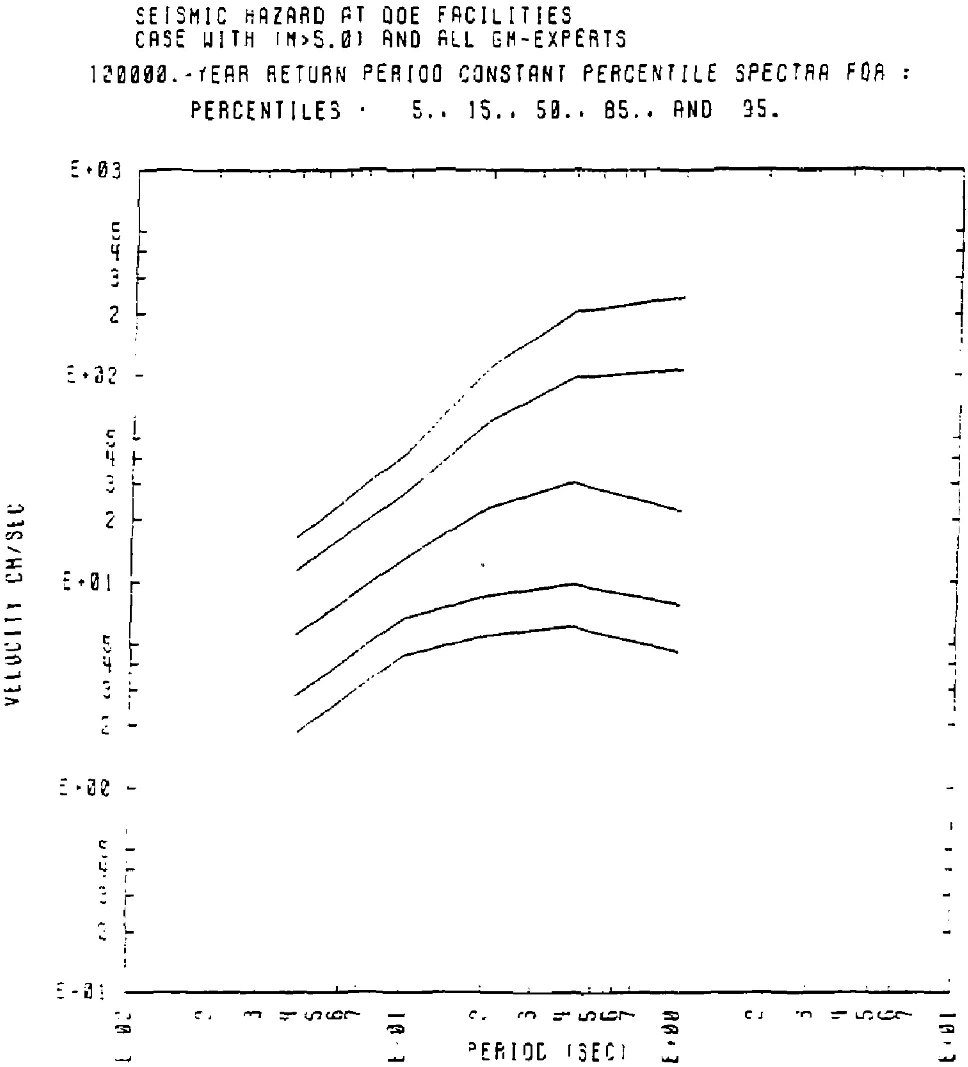

Fig 13: 5, 15, 50, 85 and 95 percent constant percentile 100,000 year return period *Uniform* Hazard Spectra (Minimum contributing magnitude = 5.0) for the PPPL-TFTR site.

APPENDIX A

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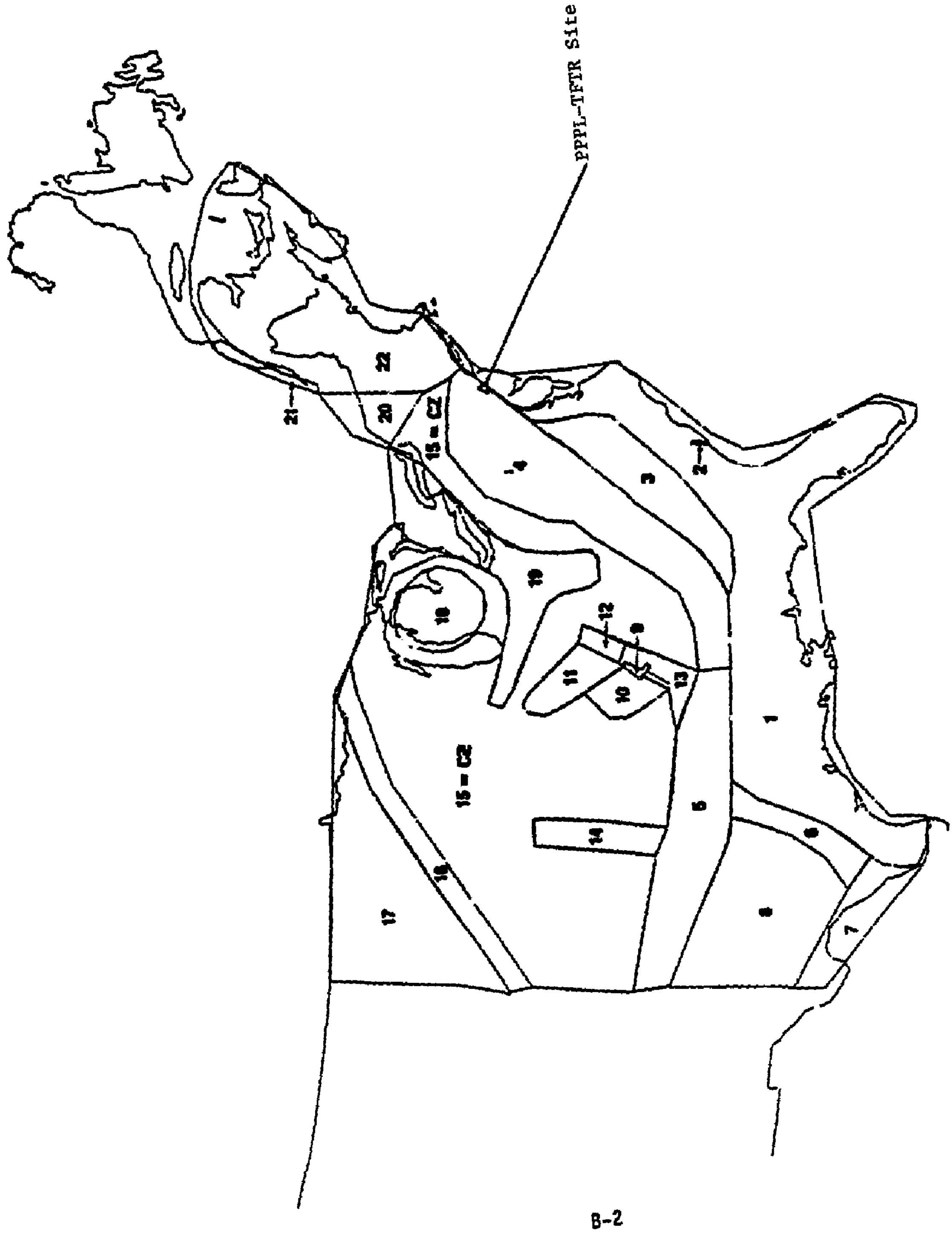
APPENDIX B

Maps of the Seismic Zonation for Each of the 11 S-Experts


PPPL-TFTR Site
15 = C2
15 = C2

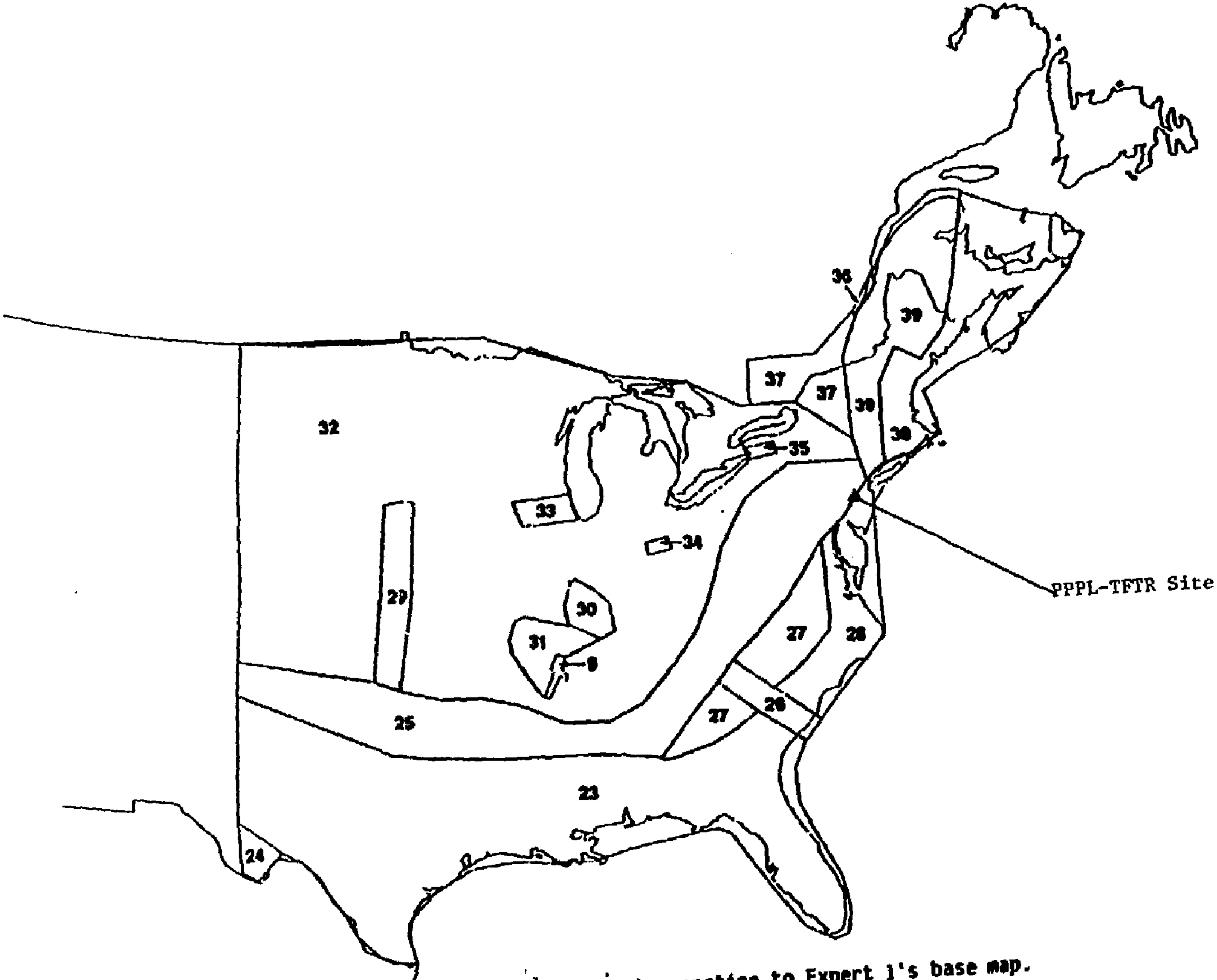


Figure B1.2 Map of alternative seismic zonation to Expert 1's base map.

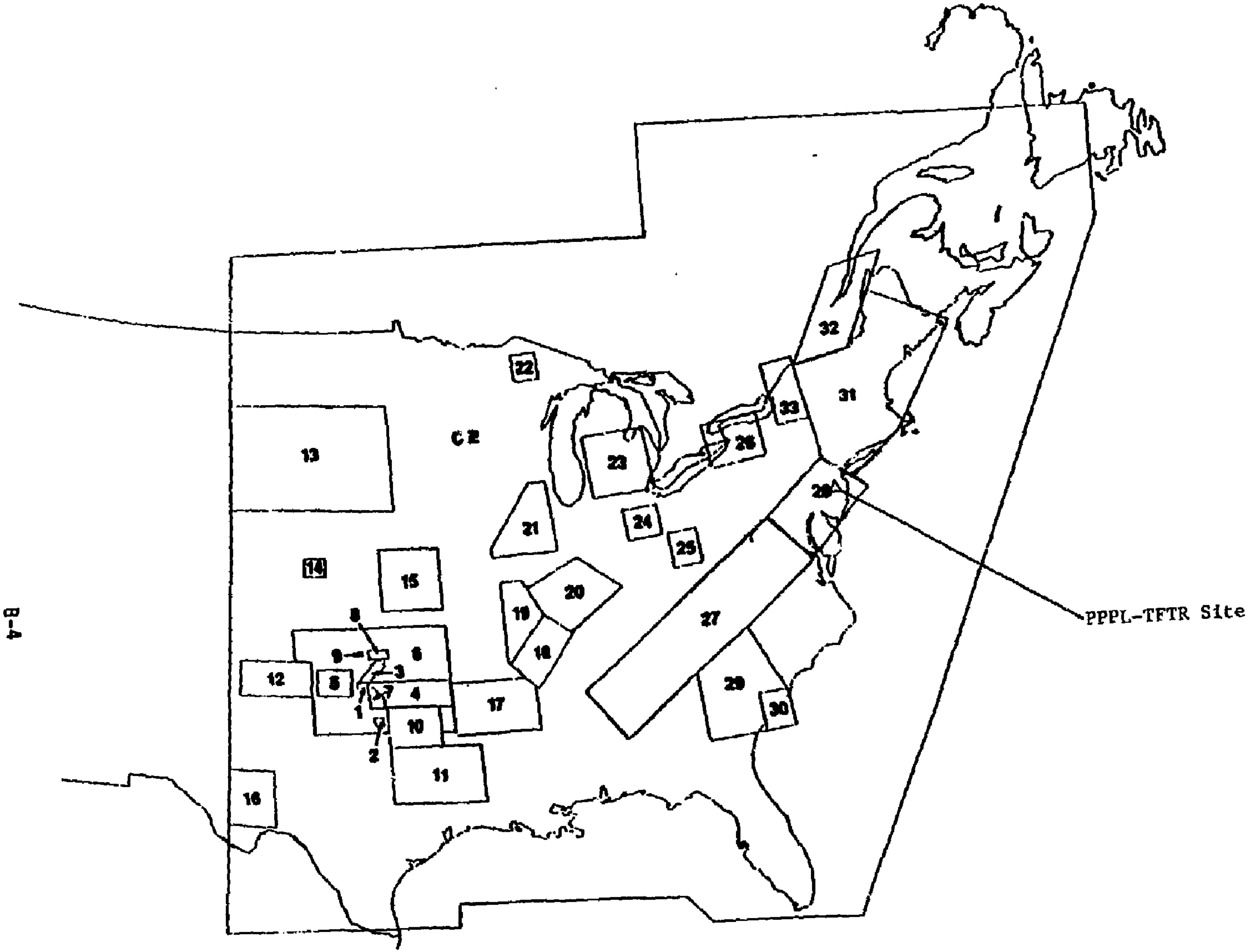


Figure B2.1 Seismic zonation base map for Expert 2.

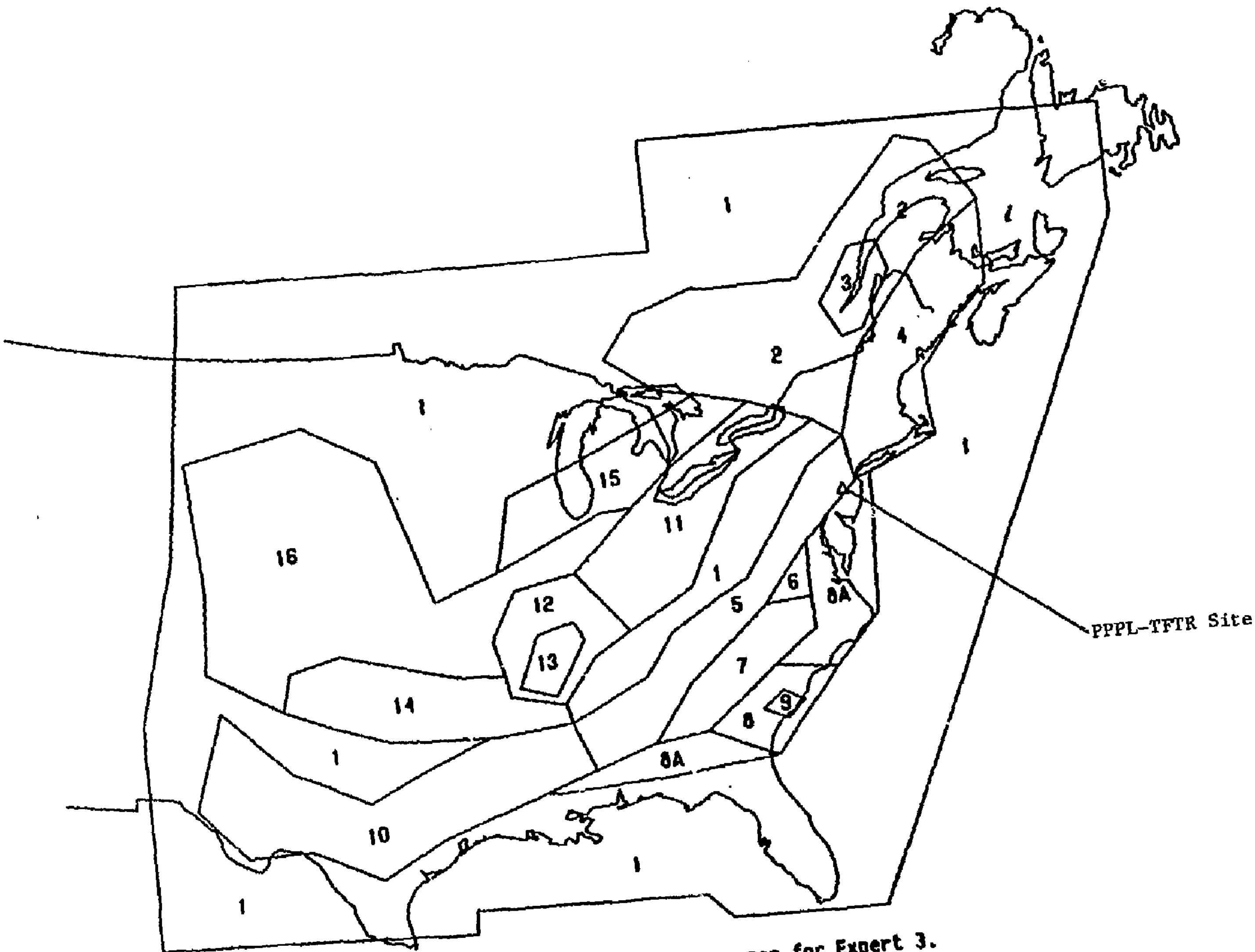


Figure B3.1 Seismic zonation base map for Expert 3.

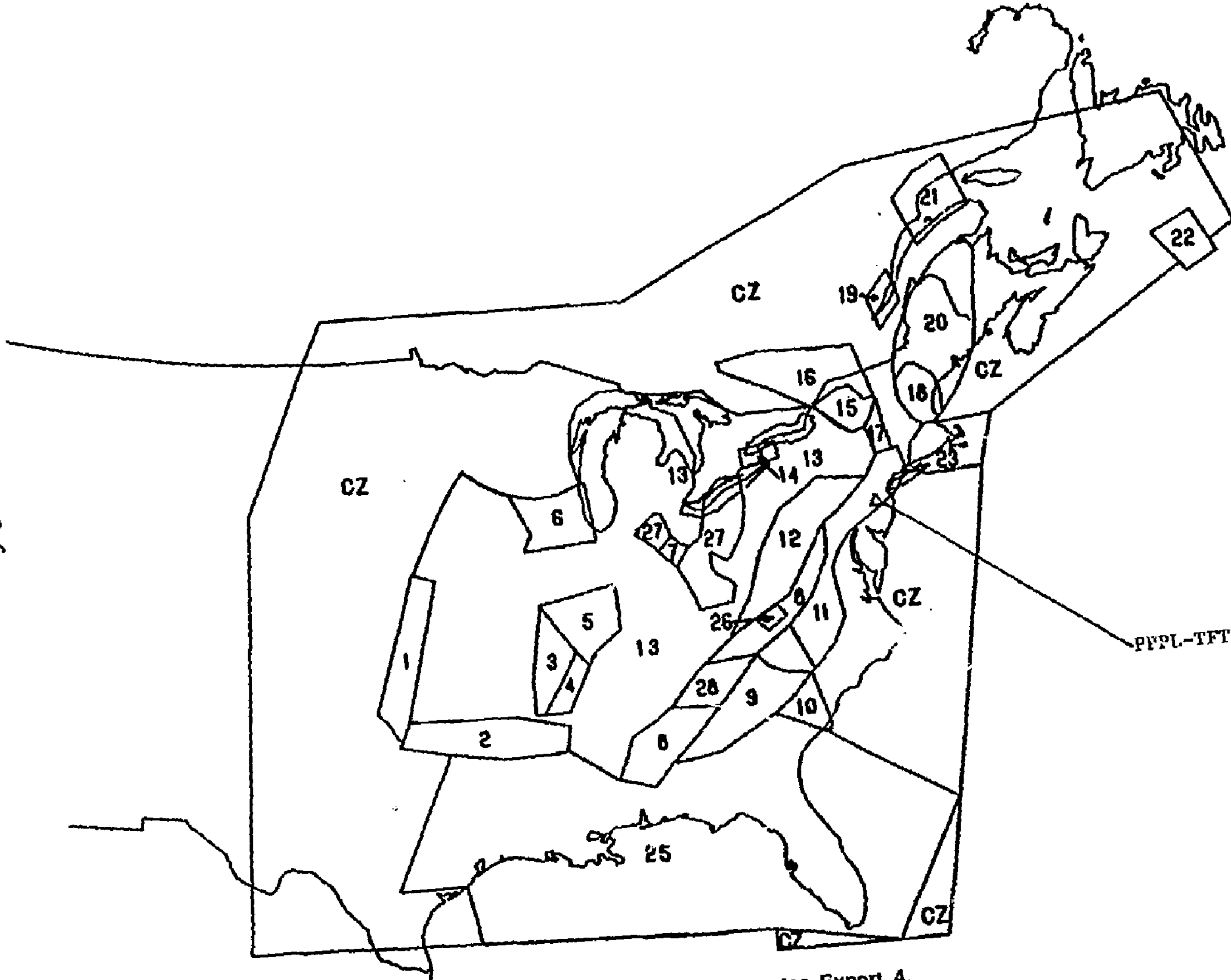


Figure B4.1 Seismic zonation base map for Expert 4.

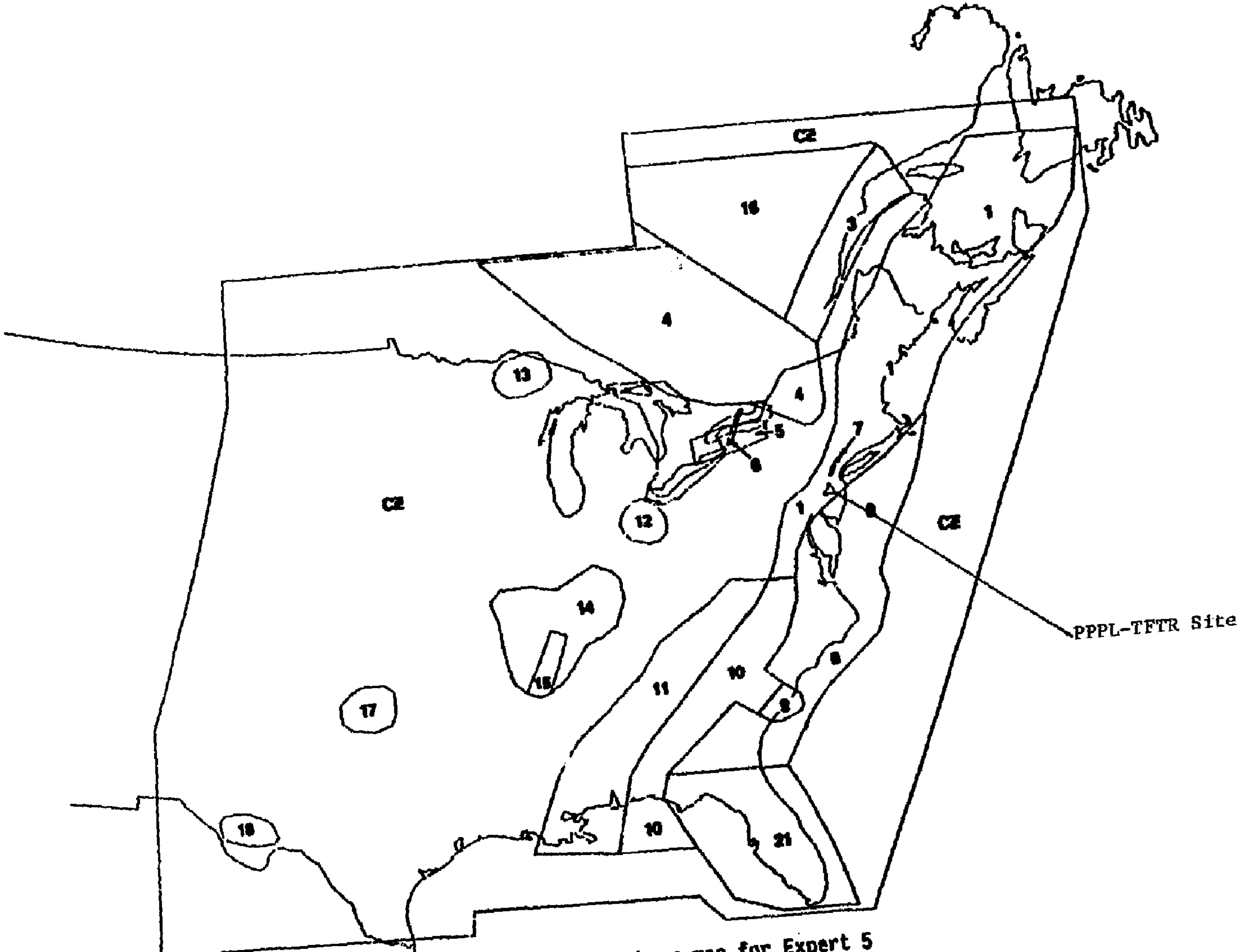


Figure B5.1 Seismic zonation base map for Expert 5

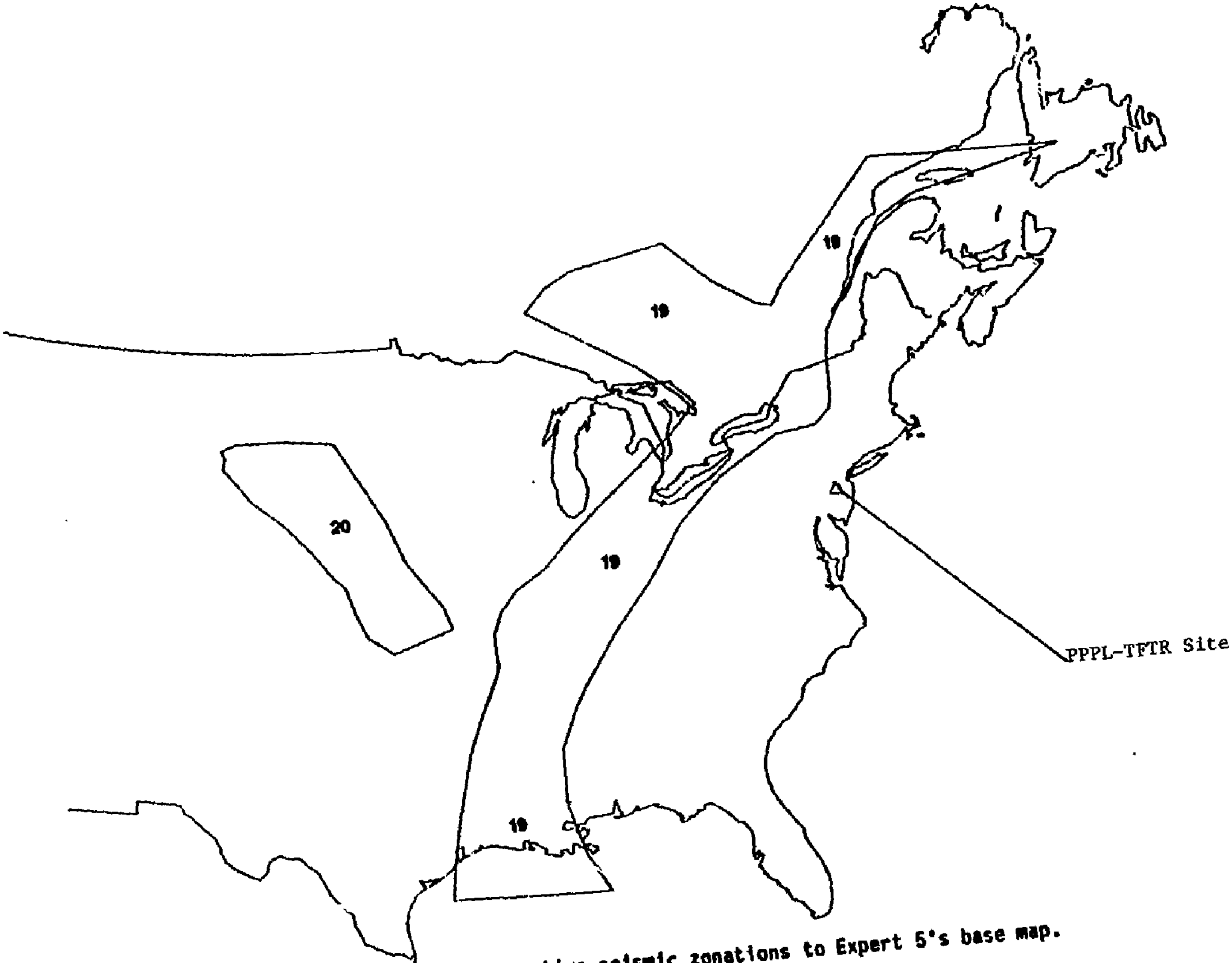


Figure B5.2 Map of alternative seismic zonations to Expert 5's base map.

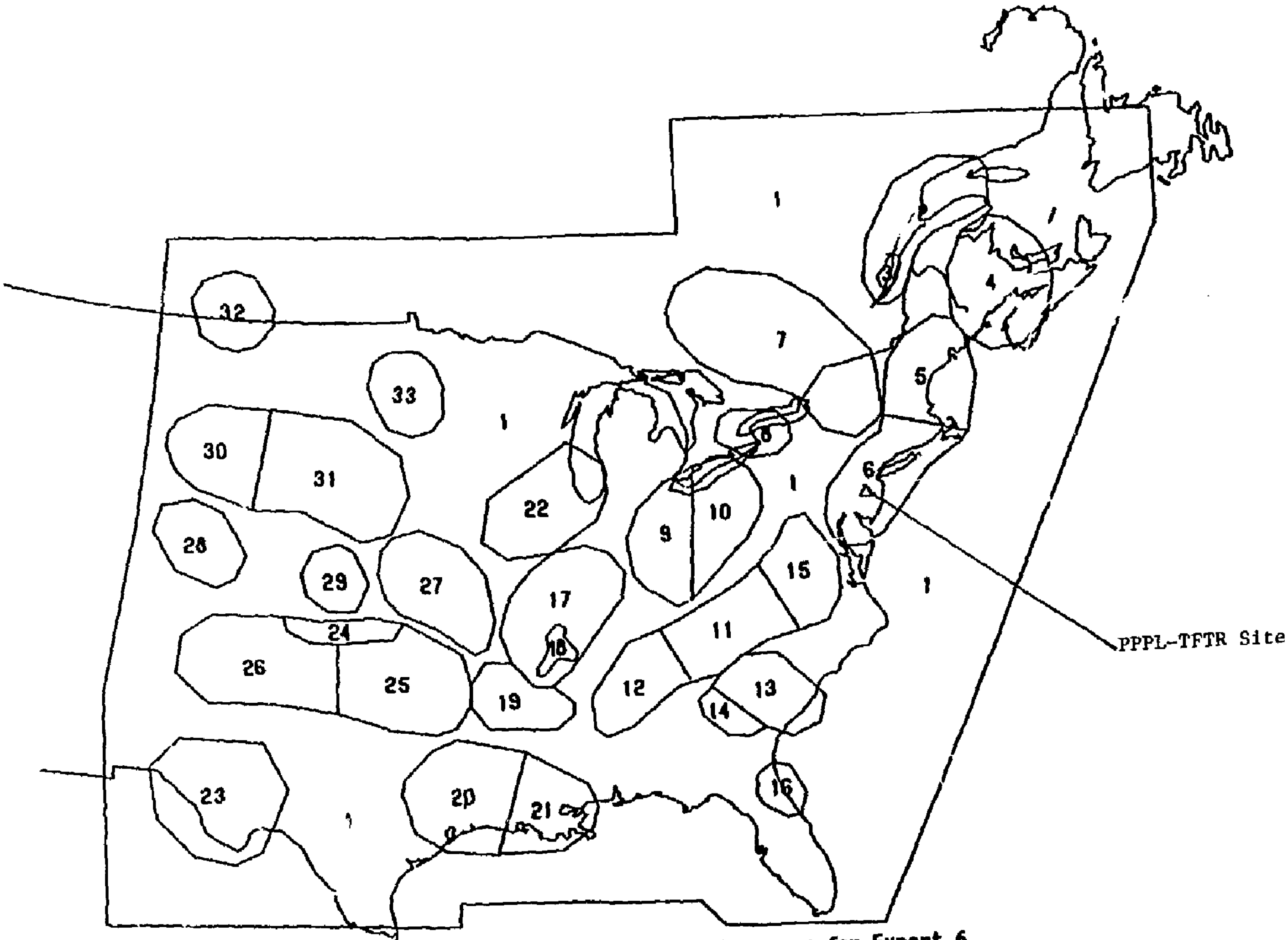


Figure B6.1 Seismic zonation base map for Expert 6

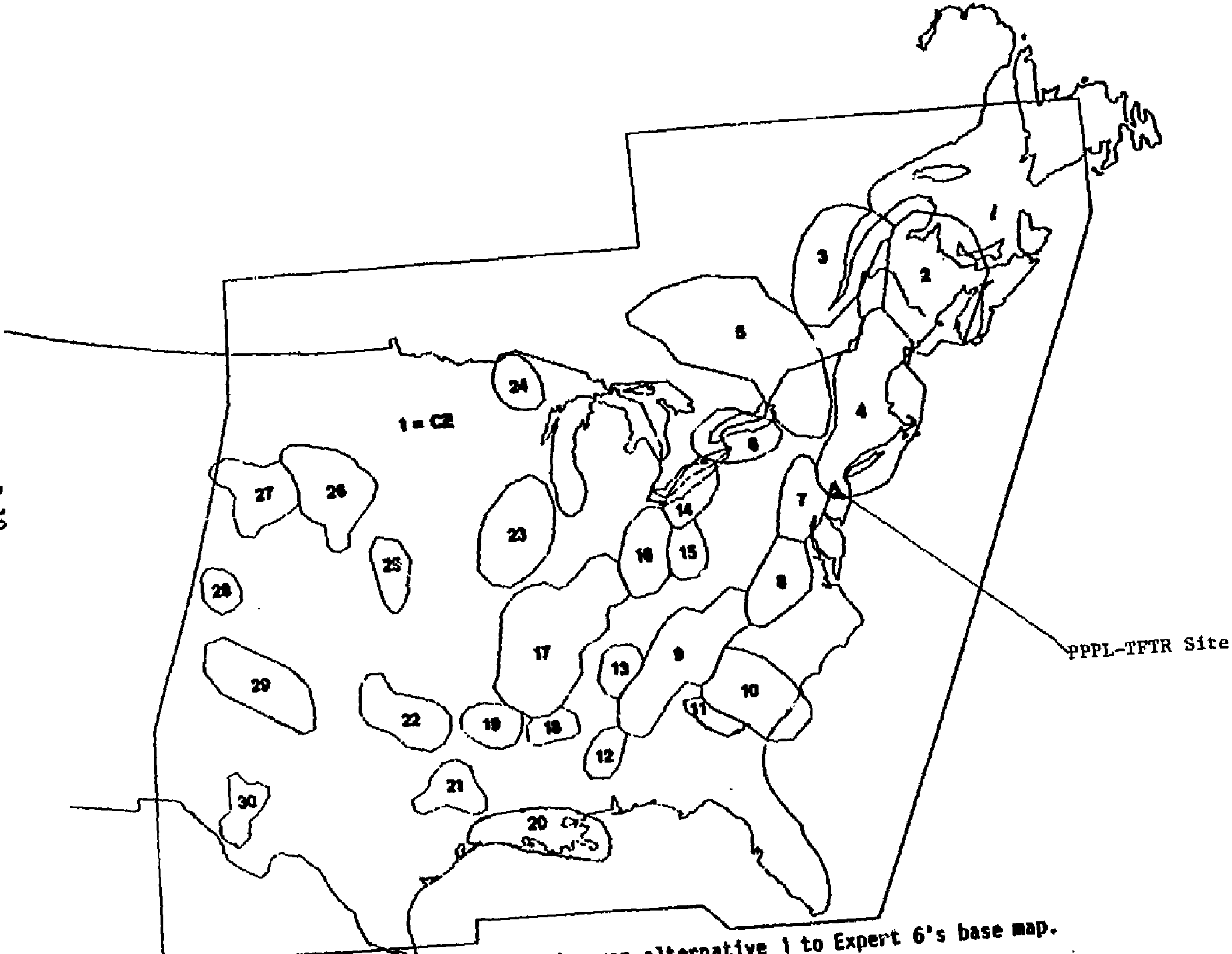


Figure B6.2 Seismic zonation map alternative 1 to Expert 6's base map.

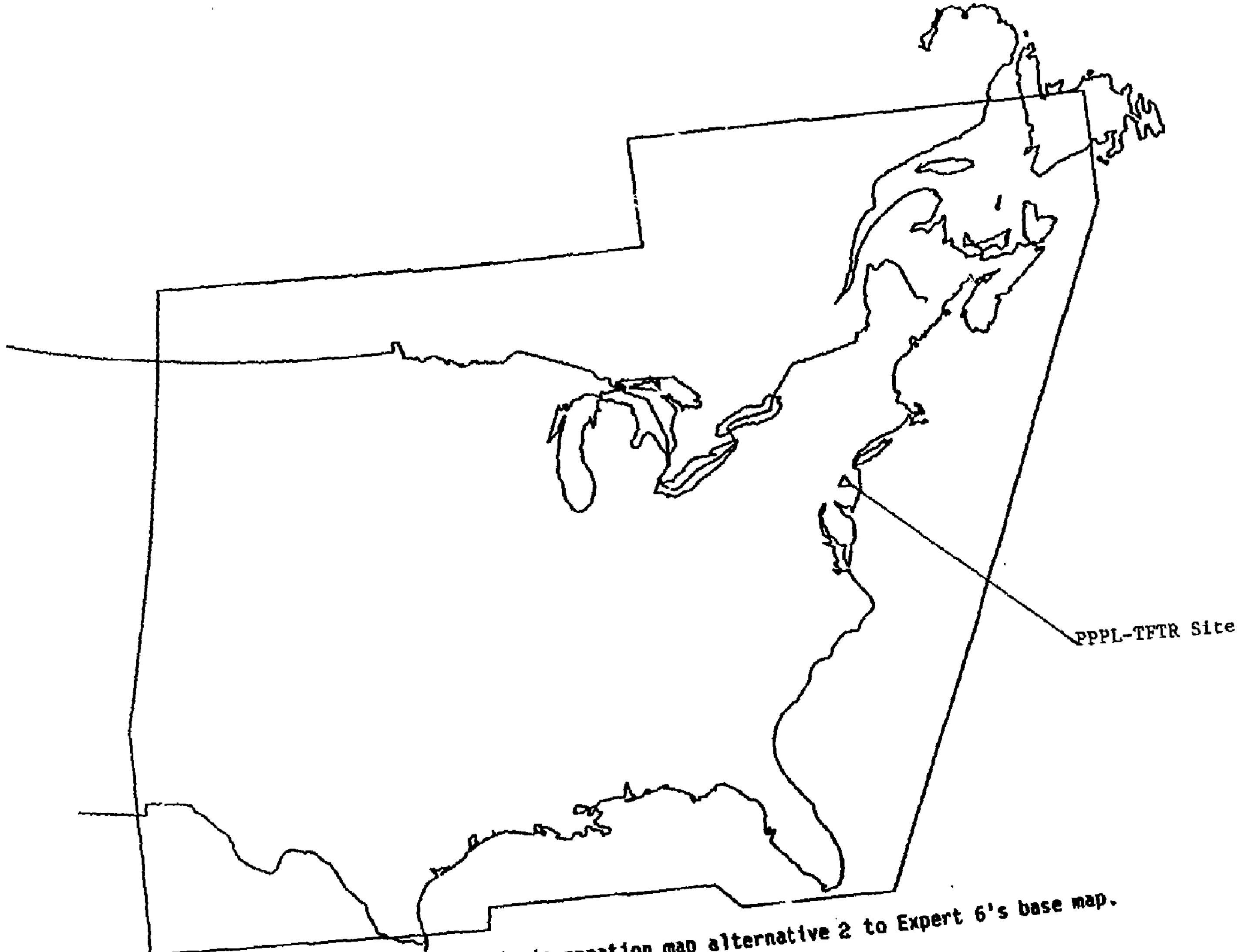


Figure B6.3 Seismic zonation map alternative 2 to Expert 6's base map.

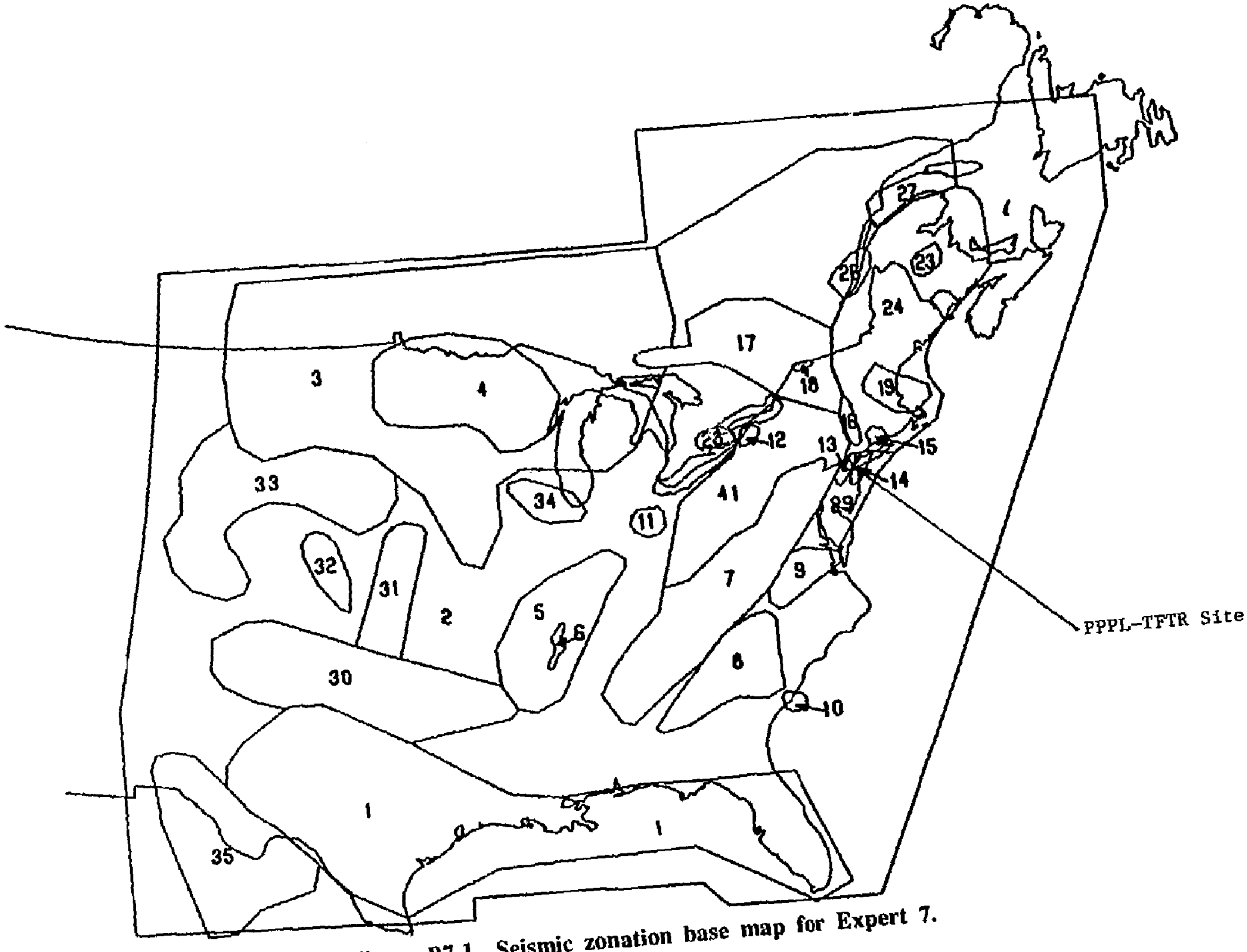


Figure B7.1 Seismic zonation base map for Expert 7.

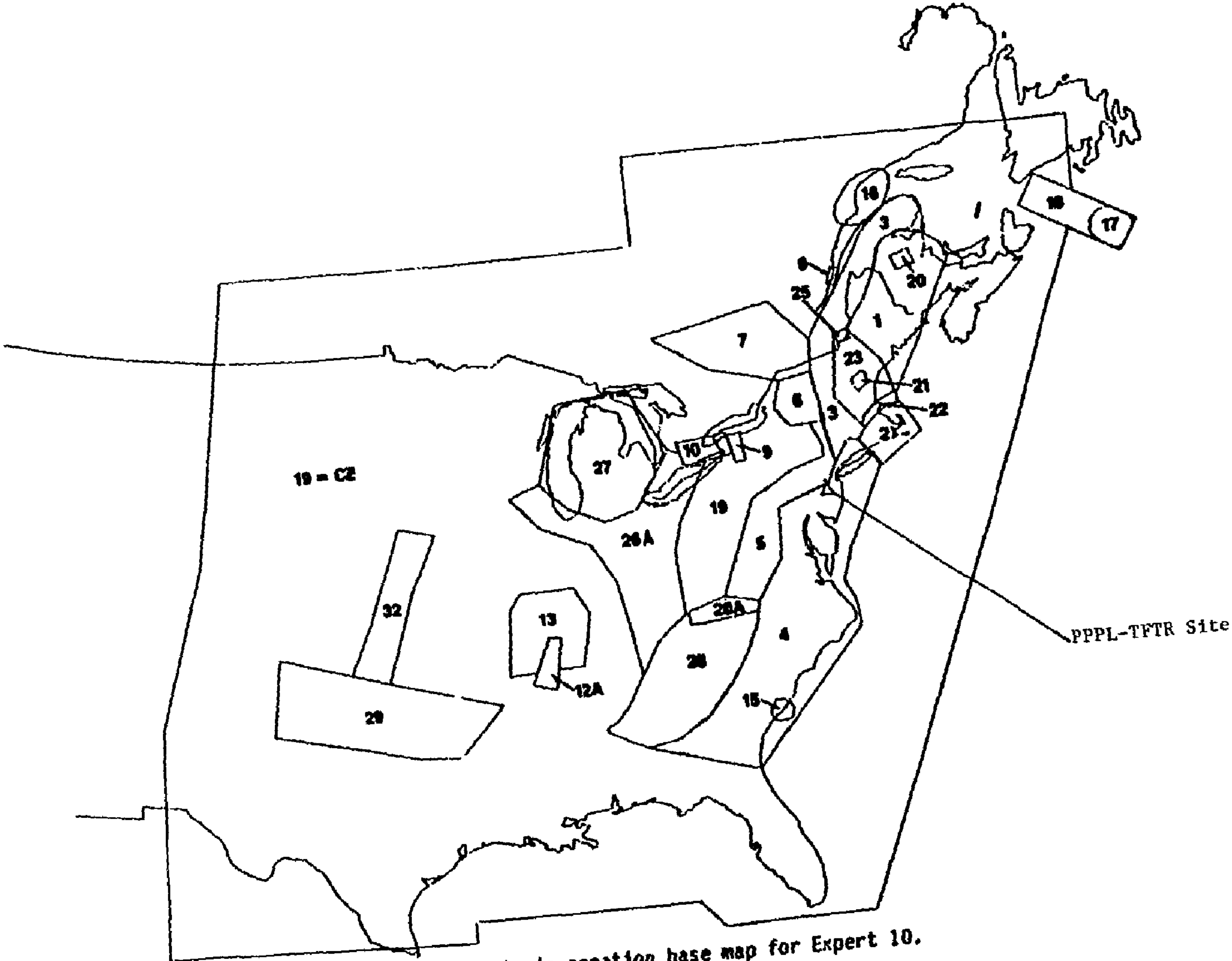


Figure B10.1 Seismic zonation base map for Expert 10.

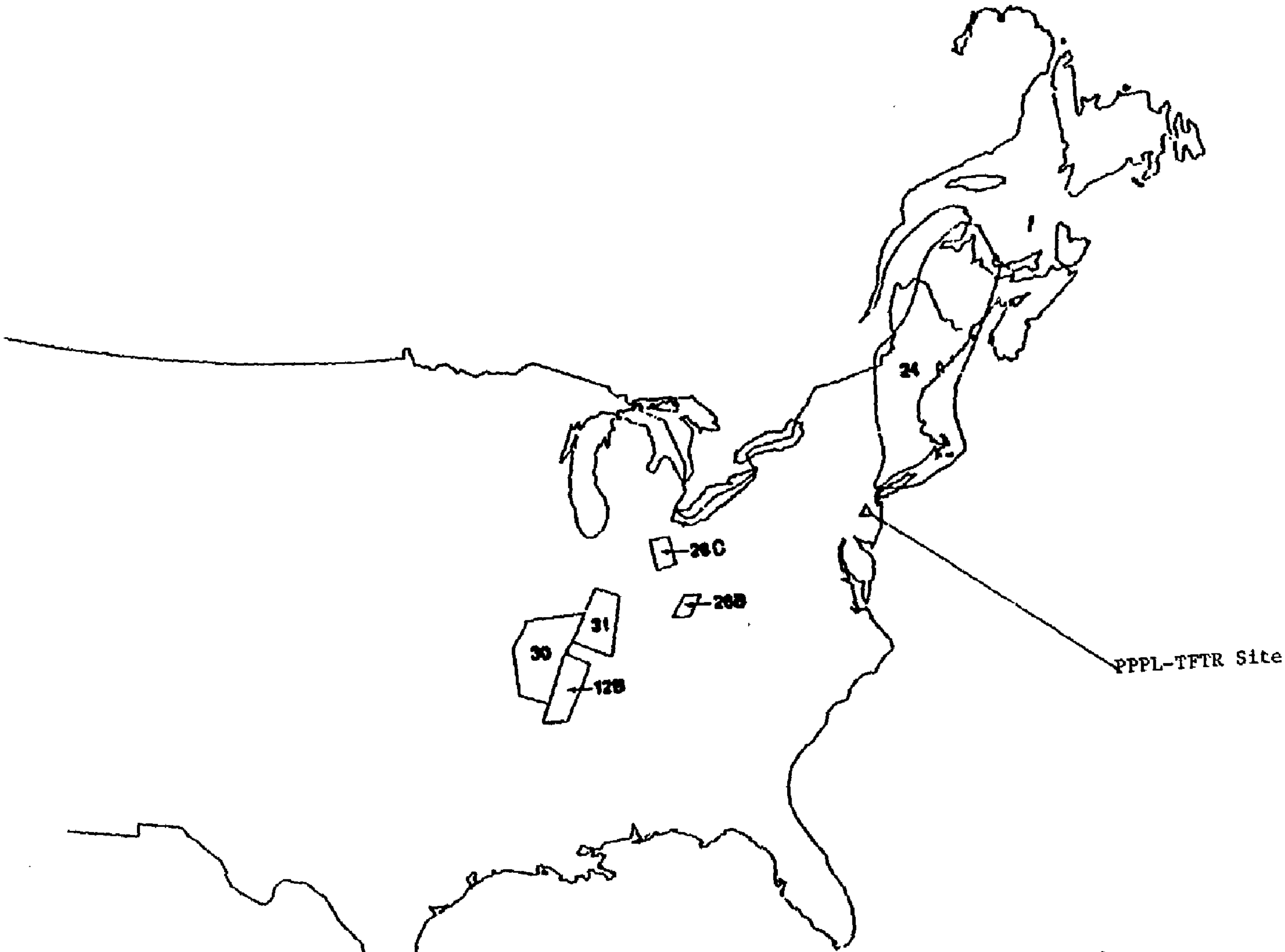


Figure B10.2 Map of alternative seismic zonations to Expert 10's base map.

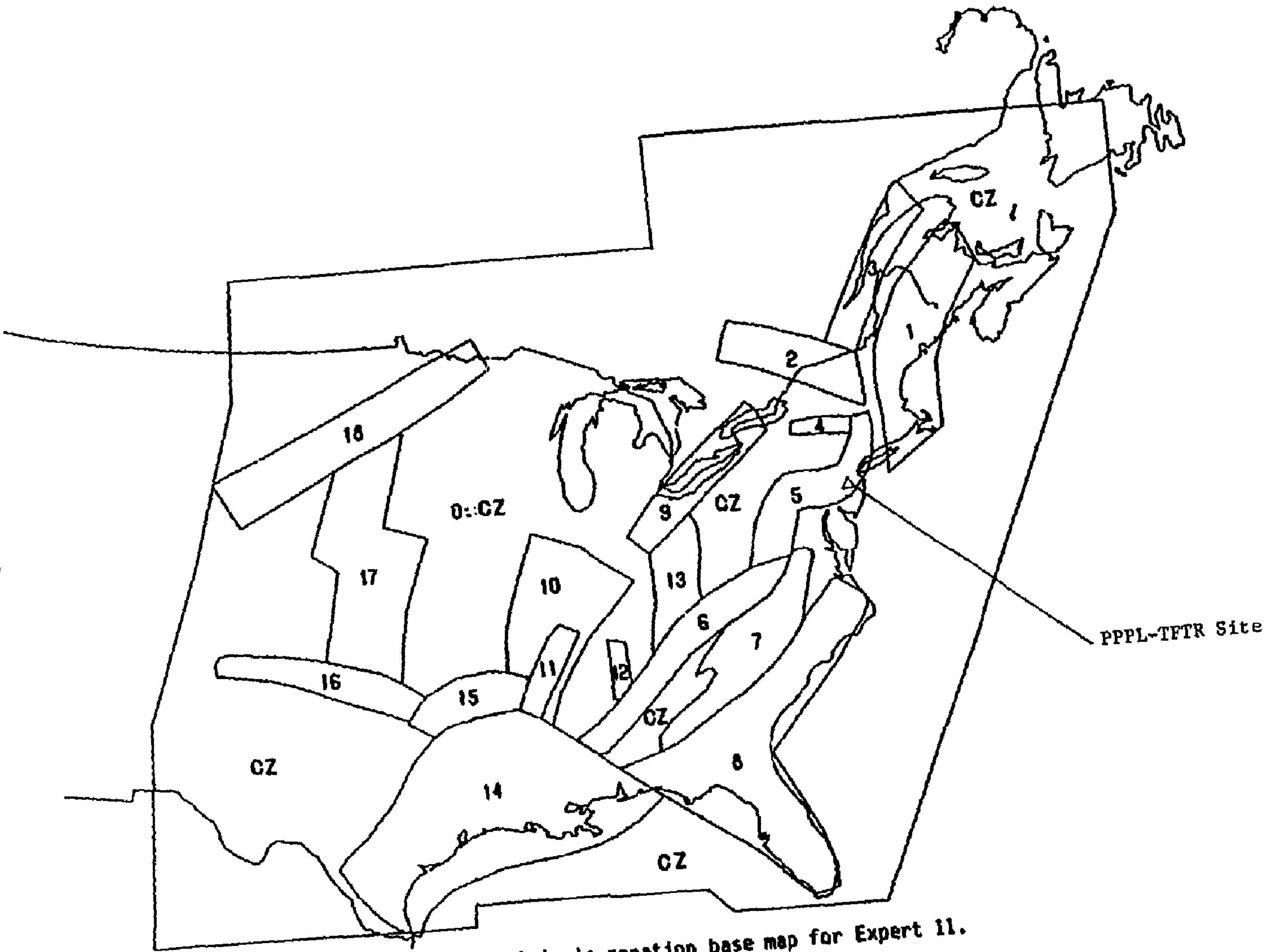


Figure B11.1 Seismic zonation base map for Expert 11.

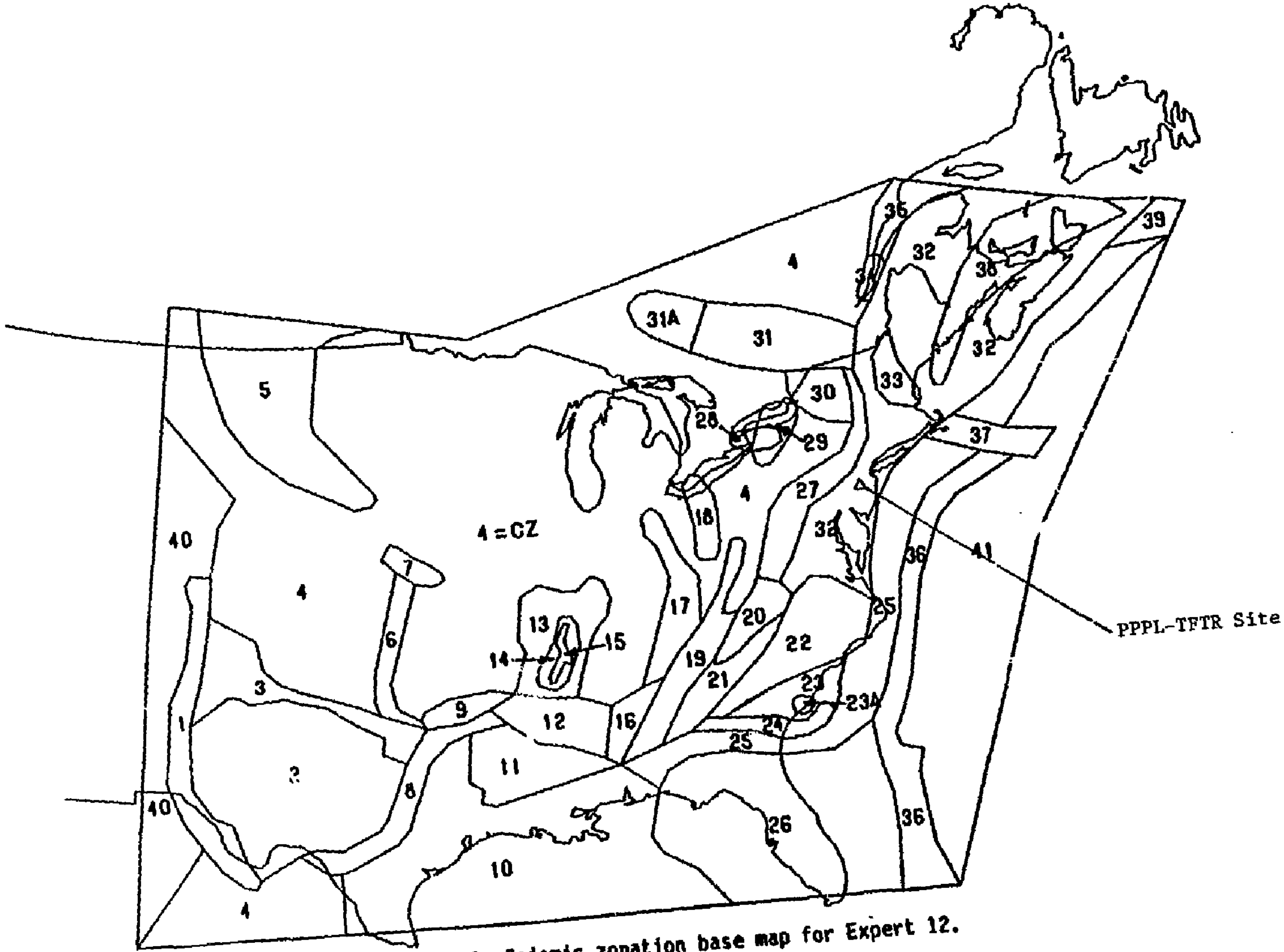


Figure B12.1 Seismic zonation base map for Expert 12.

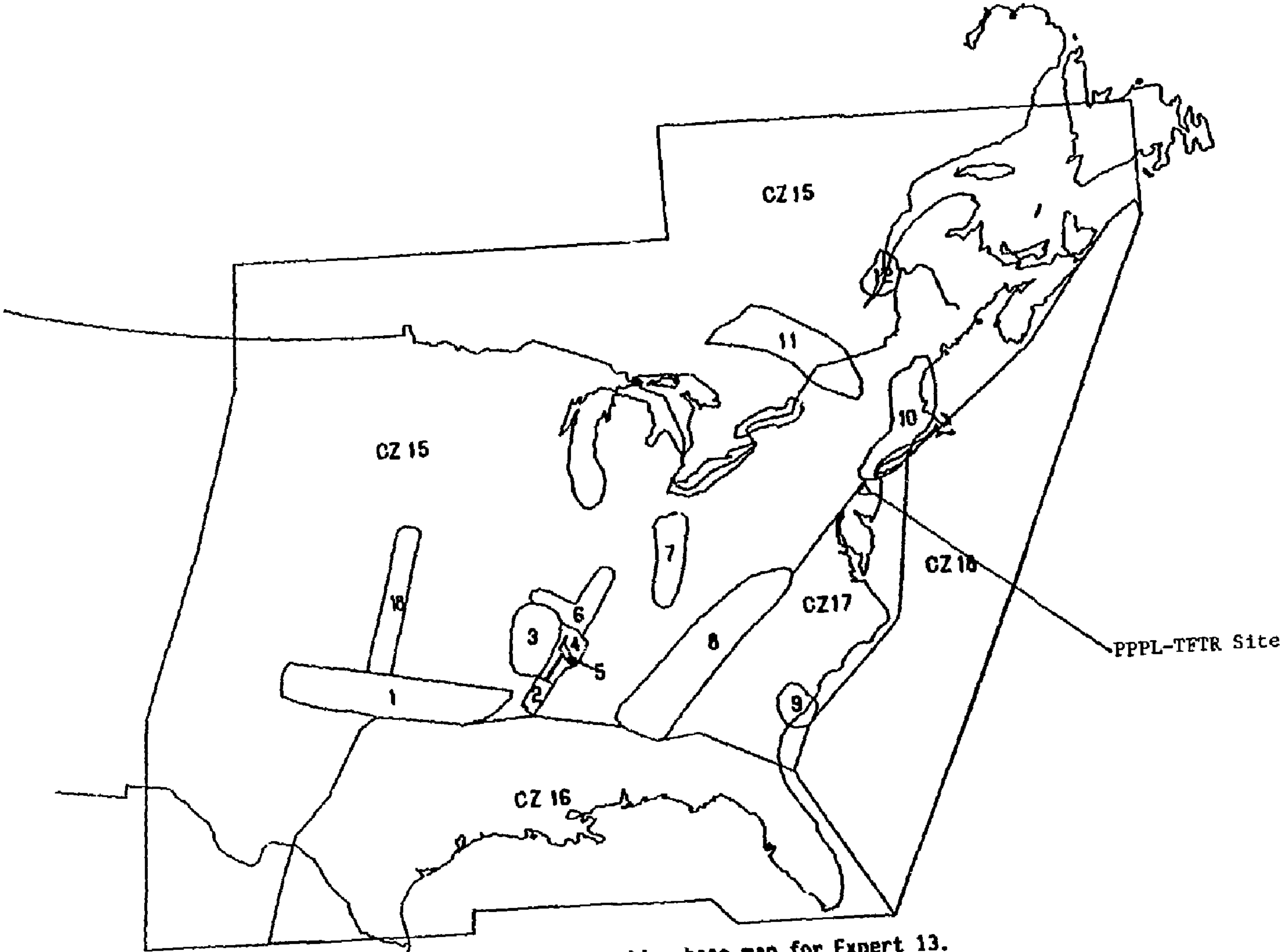


Figure B13.1 Seismic zonation base map for Expert 13.

Figure B13.2 Map of alternative seismic zonations to Expert 13's base map.

APPENDIX C

Published papers summarizing the methodology.

APPENDIX C.1

Seismic Hazard Characterization for the Eastern United States
by J. B. Savy, D. L. Bernreuter and R. W. Mensing
***Nuclear Safety*, Vol. 27, No. 4, Oct-Dec 1986.**

SEISMIC HAZARD CHARACTERIZATION FOR THE EASTERN UNITED STATES*

By Jean B. Savy, Don L. Bernreuter, and Richard W. Mensing
P.O. Box 808, Livermore, CA

Abstract

The purpose of the Eastern United States seismic hazard characterization project was to develop a methodology and a data base to calculate the hazard at any site east of the Rocky Mountains. The basic characteristic of the methodology is the use of experts' opinions to supplement the sparse and often low quality seismicity and ground motion data available.

The methodology also recognizes the uncertainties associated with a hazard analyses. A simulation technique is used to develop a probability distribution of the hazard. It describes the uncertainty in the hazard due to uncertainty in the source zonation maps, the ground motion models, the earthquake recurrence modeling, and the maximum magnitude possible in each source zone. The uncertainty is presented in terms of envelopes of percentile curves for the peak ground acceleration and for 5% damping spectral values.

The emphasis of this paper is on the use of experts' opinions, comparison with other existing studies. It is concluded that the largest contributor to the uncertainty in the final hazard is caused by the uncertainty in the ground motion predictions. The diversity of opinions between the experts was the next largest contributor and source zonation and seismicity parameters, respectively, followed in importance.

*This work was supported by the United States Nuclear Regulatory Commission under a Memorandum of Understanding with the United States Department of Energy.

INTRODUCTION

Knowledge of the seismic hazard at the site is an important element in the design of a nuclear power plant. It is an essential ingredient in the selection of design parameters as well as an important input into probabilistic risk analyses (PRA's). These PRA's can be used to estimate the probability of core melt and the total risk to the population and environment in terms of predicted loss of lives, delayed effects on humans, and damage to the environment.

Seismic hazard analysis has been limited by the poor quality and sparsity of the available seismicity and strong motion data, particularly in the Eastern United States (EUS). The purpose of this study was to develop a methodology and a data base so that the seismic hazard could be estimated at any site in the EUS.

The Systematic Evaluation Program (SEP) study[1] proposed the use of experts' opinions to supplement the sparse data. The results of the SEP study were point estimates of the seismic hazard. The Seismic Hazard Characterization (SHC) project[2] incorporated several modifications of the SEP methodology. An important extension was recognition and inclusion of uncertainties in the analysis and its inputs. Thus, the results of the study include an estimate of the hazard with uncertainty bounds. Other methodologies now exist to perform the same tasks. The Parametric Historic Analysis is based on using the data without identification of the seismic sources. A recent study, sponsored by the utility companies,[3] is similar in many respects to the SHC study. It, like SHC, combines experts' opinions with historical data and includes uncertainties in the analysis.

This article describes the SHC study in some detail. Emphasis is placed on eliciting the experts' opinions and the treatment of uncertainty.

References are made to other state-of-the-art studies, and the differences with SHC are outlined.

DESCRIPTION OF THE HAZARD CALCULATION METHODOLOGIES

HAZARD MODEL AND CALCULATION

The Hazard Model

In the SHC study, the seismic hazard is quantified by a seismic hazard curve which describes the relation between the value of a ground motion parameter and the probability it is exceeded, at a site, in one year. The methodology used in SHC is similar, in many ways, to the well-established methods developed by Cornell,[4,5] McGuire,[6] Algermissen et al.,[7] Mortgat and Shah,[8] and Der Kuireghian and Ang.[9] All these studies involved four basic elements as described in Fig. 1:

- Identification of seismic source zones (Fig. 1a).
- A model describing the expected frequency as a function of magnitude (Fig. 1b).
- A model describing the expected value of a ground motion parameter (e.g., peak acceleration) as a function of the magnitude and distance of the source (Fig. 1c).
- Integration into a seismic hazard curve (Fig. 1d).

In the SHC, the ground motion parameters considered are the peak ground acceleration (PGA) and the pseudo-relative velocity (PSV) of a 5% damping response spectrum . We assume that the region affecting the ground motion at the site can be partitioned into distinct areas of constant seismic characteristics (referred to as source zones). This partition is partly based on geophysical information accumulated by each expert (such as tectonic stresses, plate motions, geology) and partly on observed seismicity developed by the individual expert's analysis of earthquake catalogs.

The following assumptions about the occurrence of earthquakes throughout the EUS form the basis for the probability calculations.

- Earthquakes occur randomly over time and space within a source zone.
- Earthquakes are point sources, thus the fact that they are created by rupture of tectonic faults is neglected.
- The occurrence of earthquakes is independent between source zones.
- The occurrence rate of earthquakes within a source zone is constant; its value describes the seismic and tectonic conditions that presently exist within the zone.
- The expected number of earthquakes of magnitude m or greater, $\Lambda(m)$, per unit of area occurring within a zone is described by the magnitude recurrence relation

$$\log \Lambda(m) = H(m) \qquad M_0 \leq m \leq M_U \quad , \tag{1}$$

where M_0 is the minimum magnitude of interest and M_U (upper magnitude cutoff) is the maximum magnitude possible in the zone under the present tectonic conditions. M_U and the functional form H(m) are elicited from each of the experts.

Given these assumptions, the number $N_t(m)$ of earthquakes with magnitude greater than M, $m > M_0$, occurring within a zone in a time period of t years is a

Poisson random variable with intensity parameter $\Lambda(m)$. Thus, the probability of exactly n earthquakes with magnitude greater than m in t years is:

$$P\left[N_t(m) = n\right] = \frac{\left[t\Lambda(m)\right]^n}{n!} e^{-t} \qquad ,n = 0,1,2,3,\cdots\} \qquad (2)$$

Using the assumption that earthquakes are point sources which occur uniformly through a zone, if $N_t(r,m)$ is the number of earthquakes in t years of magnitude greater than m occurring at points which are a distance r to r+dr (kilometers) from the site, then $N_t(r,m)$ is a Poisson random variable with intensity parameter

$$\lambda_{m,t} = t\ \Lambda(m)\ f_R(r)\ dr \quad , \qquad (3)$$

where $f_R(r)$ is the density function for the distribution of the distance from the site to points within a source zone.

Given an earthquake of magnitude $M > m$ at a distance $(r,r+dr)$ from the site, the ground motion parameter, e.g. ,PGA, at the site depends on the attenuation of the source energy between the source and the site. This is modeled as a random process. The expected value of PGA is described by a ground motion model depending on m and r. Since a multitude of such models exists, a panel of ground motion experts was used in the SHC project to select appropriate models. The conditional probability of PGA exceeding the value a, given m,r, is denoted $P(A>a|m,r)$, where A represents the peak ground acceleration.

Let $N_t(a)$ be the random variable, the number of earthquakes occurring in a zone in t years such that the PGA at the site is greater than a. The probability that one or more earthquakes occur in t years resulting in the PGA at the site exceeding a, denoted $P(A_t > a)$, is given by

$$P(A_t > a) = P(N_t(a) > 0). \tag{4}$$

Given the range of magnitudes (M_0, M_U), where M_U is the upper magnitude cutoff for the specific zone, and distances $r>0$, $N_t(a)$ is a Poisson random variable w[illegible] intensity parameter $\lambda_a t$ where

$$\lambda_a = \int_{M_0}^{M_U} \int_{r>0} P(A>a|m,r)\ f_R(r)\ dr\ d\Lambda(m) \quad , \tag{5}$$

such that $d\Lambda(m) = \lambda_0\ dF_M(m|M_0,M_U)$ and λ_0 is the expected frequency, per unit time and area, of earthquakes with magnitude exceeding M_0, and $F_M(m|M_0,M_U)$ denotes the distribution function of magnitudes given an earthquake, conditional on minimum magnitude M_0 and upper magnitude cutoff M_U.

The probability that the maximum PGA at the site exceeds a, in a time period of length t, due to earthquakes occurring in zone q, is given by the complement to the probability of no such events, i.e., using the Poisson distribution,

$$\begin{aligned} P_q(A_t>a) &= P_q(N_t(a) > 0) \\ &= 1 - \exp(-\lambda_{aq} t) \quad , \end{aligned} \tag{6}$$

where λ_{aq} , given by Eq. (5), is the expected number of earthquakes per year causing a PGA greater than a at the site from earthquakes occurring in zone q. The distance density $f_R(\cdot)$ and magnitude distribution $F(\cdot|M_0,M_U)$ are dependent on the zone.

Finally, under the assumption that events between zones are independent, the seismic hazard in t years at a site caused by earthquakes occurring in all zones is given by:

$$P(A_t>a) = 1 - \prod_q [1-P_q(A_t>a)] = 1-\prod_q \exp(-\lambda_{aq}t). \qquad (7)$$

In the SHC analysis, the ranges of magnitude and distance were discretized and Eq. (5) was approximated numerically by a series of summations. Several ground motion models and distributions were selected by the experts to model the conditional probability $P(A>a|m,r)$. Also the magnitude recurrence relationship, Eq. (1), was modeled by either a linear or bilinear truncated exponential relation, where the truncation was based on the model of Weichert,[10] or a relationship developed in the SHC project.

Uncertainty in the Hazard

The limited historical data, empirical models, and uses of experts' opinions cause the resulting hazard estimates to be uncertain. This uncertainty needs to be identified and included in the description of the seismic hazard. Thus, the hazard can be described not by a single curve, as in Fig. 1d, but typically by envelopes of percentiles of the hazard as shown in Fig. 7. In one method[3,11] the uncertainty in each of the uncertain input parameters is expressed by a discrete probability distribution with a few values (typically 2 or 3 values for each parameter). Using a logic tree, all possible combinations of parameter values are identified and the hazard is calculated, using a technique analogous to that described in The Hazard Model section, for each combination. Each end branch of the logic tree (i.e., combination of parameter values) has a probability and a hazard curve associated with it. From this set of weighted hazard curves describing the distribution on the hazard, a set of percentile values are derived.

A second method, developed for the SHC, is based on simul tion to develop a probability distribution of the hazard. Using a Monte Carlo proach, each of the uncertain parameters is sampled a large number of times from its respective probability distribution describing the uncertainty in the parameter. For each pair of seismicity and ground motion experts (respectively S- and G-expert) (described in the section on Use of Experts' Opinion), a typical simulation is as follows:

- Draw a map from the distribution of maps for this S-expert.
- For each one of the seismic sources in a sample map, draw a set of seismicity parameters from their respective distribution, i.e.,:
  - a value for the a parameter of the recurrence law
  - a value for the b parameter of the recurrence law (b is allowed to have three levels of correlation with a, as specified by the S-expert)
  - the value of the upper magnitude (or intensity) cutoff
- Draw a ground motion model from the distribution of models.
- Draw a value for the random uncertainty parameter, which is associated with the selected ground motion, for the appropriate EUS region (NE, SE, NC or SC).
- Draw a site correction method.

The hazard is calculated for each of the seismic sources and combined for all sources. Each simulation gives a possible hazard curve. For each site 2750 such curves (50 simulations per G-expert times 5 G-experts times 11 S-experts) were developed. Percentiles, usually the 15, 50 and 85th, are then used to describe the uncertainty in the hazard.

This method, relative to the discrete approach, provides more flexibility by allowing for a wider range of distributions to describe the uncertainties in the parameters. It also has the advantage of better sampling the tails of the distributions.

USE OF EXPERTS' OPINION

The calculation of the hazard, described in the section on Hazard Model and Calculation relies on the availability of data to develop the seismicity and ground motion models used in Eq. (5) i.e., the functions $f_R(r)$, $\Lambda(m)$ and $P(A>a|m,r)$. Only limited historical data are available for the EUS. Specifically, the earthquake catalogs cover only 200 to 300 years at the most, and must be used to make predictions in the range of 1000 to 10,000 years. Consequently, various interpretations are possible and the scientific community offers a diversity of opinion with respect to seismicity and ground motion prediction for the EUS. An important aspect of the SHC was to recognize this diversity which exists in the scientific community and to incorporate it in the uncertainty of the hazard.

Thus, in the SHC the inputs, i.e., parameter values and models, for the hazard analysis were derived by eliciting experts' opinions in the fields of seismicity modeling and ground motion prediction modeling. To this end, two panels were formed. The S-panel included 11 eminent experts on seismicity and zonation. Five eminent experts on ground motion prediction formed the G-panel. The individuality of the experts was emphasized by encouraging them to use their own information and data bases. The intent was to avoid the screening of nonclassical interpretations which might be achieved by favoring any kind of consensus among the experts including a consensus in the raw data or in the modeling. The opinions of the experts were elicited through a series of written questionnaires, feedback meetings, and feedback questionnaires.

AGGREGATION OF EXPERTS' OPINIONS

When the opinions of several individuals are to be elicited, it is frequently necessary to consider ways of combining the information provided by the individuals into a single statement which represents, in some way, the "average" or consensus opinion of the group of individuals.

Basically, there are two classes of methods of aggregating experts' opinions. One class of methods is based on pooling some normalized quantification of the experts' opinions. In this case the experts are queried individually, are not expected to interact, and no attempt is made to reach a consensus through dialogue. Consensus is represented by the pooled quantification of opinions. The emphasis is placed on independence and free expression. The second class of methods attempts to reach a consensus. It is based on group interaction in which the experts are allowed to interact, with or without feedback, and through dialogue. In this case the free exchange of information is expected to result in a reduction in the range of views[12,13,14], thus, seemingly, to imply a greater state of knowledge. However, unrestricted dialogue can be misleading since agreement may have been a result of strategic manipulation, intimidation, and other factors which could lead to biased results. To be effective the interaction must be well-planned and carefully directed.

The method used in the SHC is based on the former method, pooling of opinions. However, feedback, group interaction, extensive analysis of the responses, checks for consistency and gross errors, and a peer review were part of the overall elicitation process to alleviate some of the drawbacks associated with complete anonymity of the experts (e.g., lack of responsibility, arbitrary answers).

Retention of the diversity of opinions between experts was an important consideration in the SHC project. Thus, individual hazard curves were estimated for each expert and the diversity of opinion between experts was included in the description of uncertainty.

In the case of the SHC the hazard is calculated for every pair of experts (i.e., S-expert and G-expert) and these are subsequently combined. The combination rule is based on a normalized weighted average of the hazard curves or individual hazards in the uncertainty analysis. The weights for the G-experts were normalized values of self-weights the experts provided. The weights for the S-experts were themselves a weighted average of four regional self-weights provided by the S-experts, i.e.,

$$w_s = \sum_w w_{sw} \, P(A=A_w), \qquad (8)$$

where w_s is the single weight for the s-th expert, w_{sw} is the self-rating of the s-th expert for region w, and $P(A=A_w)$ is the probability that the maximum PGA at the site results from an earthquake originating in the w-th region. An appealing property of Eq. (3) is that it will provide a "high" value for w_s if the self-weight is highest in the region with highest probability of producing the maximum PGA. Conversely, it will be low if the weight is highest in the region with the lowest probability of producing the maximum PGA.

DEVELOPMENT OF THE HAZARD ANALYSIS INPUTS

SEISMIC ZONATION MAPS

A fundamental step in hazard analysis for the SHC project is partitioning the EUS into seismic source zones. Several approaches are possible in the elaboration of a spacial model of earthquake occurrences. The most common approach used in the western U.S. is based on identifying prominent features (such as fault traces) to which historic earthquakes can be associated. Thus it is relatively straightforward to build a spacial model of earthquake occurrences by delineating the areas where the events associated with a given feature will occur in the future. Unfortunately, it is difficult to associate historic events to specific geologic or tectonic features in the EUS. An elaborate technique recently applied to the EUS by EPRI[3] consisted of analyzing the available geophysical, tectonic, geologic, and historic data to identify existing features which are potential sources of earthquakes and associating some degree of belief that each one represents the actual source. In this technique, the contribution of every observable parameter (such as the direction and value of tectonic stresses, gravity anomalies, magnetic flux, geologic features, seismicity) is subjectively evaluated in terms of how much support it provides to the hypothesis of a given feature being a potential source of earthquakes in the future.

The source zones of the SHC are assumed to be areas of diffuse seismicity such that all potential earthquakes occurring within an area have the same characteristics such as constant spacial and temporal occurrences and identical maximum magnitudes. It differs from the EPRI approach in that it does not necessarily associate the historic seismicity with existing features (some historical events cannot be associated with features). Furthermore, the mode of distribution of events within an EPRI zone is not necessarily constant within each zone (as in SHC) and the option of having a nonuniform density of events, when chosen by a team of experts, is controlled by the existence of features and historic data.

The S-experts of the SHC were asked to identify the source zones. In a first step, they were asked to provide a map of the source zones which they believed were the most probable ones, referred to as their best estimate map, based on all the information available to them. Figure 2 is an example of such a best estimate map given by one of the S-experts in the SHC. In a second step they were asked to express their uncertainty in the zonation by assigning degrees of belief to the need to identify (i.e. ,on the existence of) each zone in their best estimate map. They also could provide alternative source zone boundaries, again with appropriate degrees of belief. Such a set of alternative boundaries for Fig. 2 is shown in Fig. 3. Based on this information, all the possible combinations of zonations were generated for each S-expert. The degrees of belief were combined to compute a probability for each map. This probability distribution represented the experts uncertainty in the zonation of the EUS. For each S-expert the set of all possible maps with their associated probabilities formed the basis for a discrete probability distribution of the maps used in the Monte Carlo simulation.

SEISMICITY AND UPPER MAGNITUDE CUTOFF

In most hazard analyses, the seismicity of a zone is described in terms of the number N of earthquakes per unit of area greater than a given magnitude (or intensity). The number N is customarily related to magnitude by an empirical magnitude recurrence model such as

$$\mathrm{Log}_{10}\, N = a - b\, m \text{ (or } I\text{)}, \tag{9}$$

where the seismicity parameters a and b are constant for a given seismic zone, m denotes magnitude, and I is the epicentral intensity. Generally, Eq. (9) is modified to account for the fact that every seismic zone is believed to be only capable of producing earthquakes with magnitudes (or intensities) bounded above by some maximum value[4,10] (called the upper magnitude cutoff, M_U).

In the SHC, the experts were asked to model the seismicity of the EUS by providing the a, b, and M_U values for each of the zones they identified in their maps. They were asked to provide a best estimate value (the value which they believe is the most likely to represent the true state of nature) and a range of values which represented their uncertainty in estimating the values of these parameters. This information was used to develop probability distributions which were used in the Monte Carlo simulations.

An expert's estimates of a and b depended on the catalog of events the expert used. In a previous study using experts' opinions,[15] a-,b- values were estimated by the analyst using a uniform technique to account for the incompleteness of the catalog and for the occurrence of aftershocks. These a-and b-values were given to the experts for their review and modification. In the SHC, the experts were expected to choose their own catalog of earthquakes and estimate a and b using whatever technique they deemed most appropriate. The experts were also asked to decide on the type of correction to apply for incompleteness and aftershocks.

GROUND MOTION MODELS

The purpose of a ground motion model is to estimate the ground motion at a site caused by an earthquake at a given location and of a known magnitude. It is very difficult, if not impossible, to develop such a model only on the basis of theoretical principles of physics, mechanics, and a knowledge of the geology and tectonics because many aspects of earthquakes and wave propagation through the earth crust still remain poorly understood. Also, the earthquake energy path is determined by the nature and geometry of the various media (whose properties are very erratic in general) between the source and the site. In addition, the local site characteristics (topography and nature of the soil layers immediately under the site) can have a considerable effect on the level of ground motion observed at a site. Some of the ground motion models rely entirely on the available strong motion data and are empirical in nature. The more recent models combine a geophysical formulation with the available strong motion data, e.g., Joyner and Boore,[16] Campbell,[17] and Atkinson.[18]

The approach used in SHC was to present the experts of the G-panel with a description of the models available and to ask them to select a set of ground motion models for each of the four regions (Northeast, Southeast, North

Central and South Central) of the EUS.[2] For each region, the experts were asked to provide the model which they believed best related the ground motion to the earthquake characteristics, e.g., location and magnitude (their best estimate models) and as many as six alternative models. To each model they selected they associated a degree of belief. The collection of models plus degrees of belief represented the uncertainty in choosing the most appropriate model. For each of the five G-experts, the set of ground motion models with their associated normalized degrees of belief were used as a discrete probability distribution of ground motion models in the Monte Carlo simulation. The G-experts selected 33 ground motion models of PGA and 18 models of response spectra. Figure 4 shows the best estimate ground motion models selected by one of the G-experts for the Northeast Region of the U.S.

Some hazard analyses use a simple multiplicative factor to adjust for the local site condition effects in the estimate of the hazard at a site. Other analyses use a more sophisticated technique which assumes that the strong motion is predicted at a point sitting on hard rock near the site. Then the theory of wave propagation is used to calculate the motion at the site, accounting for the topography and the quality of the soil under the site. These latter analyses use, for example, a linear technique such as the one developed by Schnabel, et al.[19]

The method used in SHC used this linear technique to develop a set of correction factors applicable to eight generic classes of sites, including thick soil sites (the base case), hard rock, and three depths of soil deposits, either sandlike or till-like. A probabilistic description of the correction factors was developed and used in the Monte Carlo simulation of the hazard analysis. In each simulation the correction was applied by scaling the selected ground motion model.

COMPARISON OF THE SHC METHODOLOGY WITH OTHER TECHNIQUES

INTRODUCTION

The various techniques of estimating the hazard at a site can be different in their concepts as well as in their methods of application. For example, they may be nonparametric by not assuming any parametric model and relying entirely on the historic earthquake data,[20,1] or they may rely on physical and empirical models as well as on the data in various degrees of mixes. Also, some techniques provide "point estimates" of the hazard,[4,6,21] while others provide information on the uncertainty in the estimates.[1,22,3]

All these techniques may also show differences in the way the data is derived. For example, some analyses[1,20] are based on the historical data alone, or are based on information derived from a single team developing a consensus set of input data.[11,23,24] Other analyses rely on the subjective opinions of experts with diverse backgrounds.[1,3] The SHC methodology, as described in the section on Description of the Hazard Calculation Methodologies, involved parametric models and relied on the opinions of experts in both seismicity and ground motion modeling.

COMPARISON WITH HISTORIC ANALYSES

The characteristic feature of historic analyses is that they do not require the identification of seismic sources and their seismicity. In place of this information they use catalogs of past earthquakes (historic catalogs). The concept of these techniques is based on estimating the strong motion at the site, due to the past earthquakes, by using ground motion models to "attenuate" each event to the site. The catalog of calculated ground motions at the site is used to estimate the seismic hazard. In the "non-parametric" historic method[20] no <u>a priori</u> assumption is made about the occurrence rate or location of events that produce site acceleration greater than a certain value. In the "parametric" historic method,[22] the occurrence of earthquakes is assumed to follow a functional form, e.g. a Poisson process. Figure 5 shows a comparison of the hazard calculations for a site in the Southeast U.S. using the SHC methodology (unlabeled curves in Fig. 5) and the nonparametric historic (labeled H in Fig. 5) method. The curves without labels refer to the 11 seismicity experts of the SHC study and the curve labeled H refers to the historic analysis. In the same range of site intensities, the nonparametric method is biased in the sense that most of the times it produces hazard estimates below the true values.[22] Thus, it is often used as an estimate of a lower bound of the hazard.

COMPARISON WITH THE USGS ZONATION

In the study sponsored by the United States Geological Survey,[1] zonations were developed in regional workshops. As a result, the experts' opinions on zonation were aggregated at the initial stage and a single zonation map was developed for the entire EUS. Based on the USGS zonation and seismicity data, the hazard using the SHC methodology, including the SHC set of ground motion models, is shown by the curve labeled (X) in Fig. 5. The hazard is within the range of values obtained by using the information from the experts in the SHC study.

COMPARISON WITH THE SEP STUDY

The SHC borrowed some of its main characteristics, such as the use of experts' opinions, from the SEP study.[1] Since 6 of the 11 S-experts of the SHC also participated in the SEP study, it is instructive to compare hazard curves based on the responses of these 6 experts. Several years have passed between the dates for finalizing the SEP and the SHC inputs during which time several important earthquake events and studies took place:

- The joint NRC/USGS Charleston, New Madrid, and New England studies have been ongoing for several years see, for example, Hays[25] and Gori and Hays.[26]

- Several earthquakes have occurred. The New Brunswick series in 1982 and the New Hampshire 1982 events provide new data for the Northeast.

- A large group of utilities have instituted, through EPRI, a major seismic hazard research program which emphasizes the modeling of the seismicity for the EUS. Eight of the S-experts in the SHC project were involved in the EPRI study.[3]

The hazard was calculated at four sites in the North Central region and New England for the purpose of comparing the results of the SEP and the SHC studies. The results were consistent and, in general, in good agreement between the two studies in spite of some fundamental differences in the two methodologies.

COMPARISONS TO OTHER STUDIES

Seismic hazard analyses have been developed for the Maine Yankee site,[23,24] the Limerick site[27] and the Millstone site.[28] The ERTEC[27] and the Dames and Moore[28] studies were performed to provide seismic hazard estimates for Probabilistic Risk Assessment (PRA) studies for the Limerick and Millstone nuclear power plants, respectively. The Yankee Atomic study is the most complete, including a full uncertainty analysis, and constant percentile hazard curves (CPHC) were developed. Thus, it is possible to directly compare Yankee Atomic's results[23,24] to the results of the SHC. Yankee Atomic's CPHC for the Maine Yankee site and the CPHC from the SHC study are compared in Fig. 6. It is observed that the two median hazard curves are in reasonable agreement although the bounds based on the SHC results are much wider than Yankee Atomic's bounds.

RESULTS AND CONCLUSIONS

The methodology developed in the SHC study was demonstrated by calculating the seismic hazard at 10 sites distributed throughout the entire EUS. The ground motion parameters of interest were the peak ground acceleration (PGA) and the pseudo relative velocity (PSV) in the form of 5% damping response spectra. The uncertainty in the hazard was expressed in the form of the 15th, 50th, and 85th percentile curves. The constant percentile uniform hazard spectra (CPUHS) were obtained by calculating the hazard at nine frequencies (using 2750 simulations for each frequency) and joining the points with equal percentiles. Figure 7 shows the 15th, 50th, and 85th percentile hazard curves for the Braidwood site in the North Central U.S.

The percentile curves do not represent any particular actual hazard curve obtained in the simulation process. Rather, they represent a joining of constant percentiles over the range of ground motion values and are only descriptive of the probability distribution of the hazard value for a given ground motion. It is not recommended, for instance, to use these specific curves in a Probabilistic Risk Analysis (PRA). Instead, all the data and curves generated in the simulation with their associated weight or a small number of curves representative of the clusters of similar curves obtained by clustering should be used.[22] A summary of the best estimate hazard curves (BEHC) at the 10 sites is shown in Fig. 8. The BEHC does not contain any uncertainty information. It is obtained by setting all the uncertain parameters of the analysis equal to the best estimate values provided by the experts.

The SEP study had already shown that experts' opinions could be used as a viable alternative to sparse data. Recent methodologies, including the SHC study and the EPRI study, have expanded on this concept and have included the uncertainty in the estimated seismic hazard at a site due to using opinions and limited data. An important aspect of the SHC study was to identify the relative amount of uncertainty introduced by each of the uncertain parameters. It was found that the uncertainty associated with the ground motion models dominates the final uncertainty in the hazard estimate. The diversity of opinions among the experts was the next largest contributor to the uncertainty, then the uncertainty in the zonation maps and seismicity parameters followed in importance.

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BIOGRAPHY

Jean B. Savy

A native of Paris, France, where he obtained an Engineer's degree in civil engineering, Mr. Savy came to the United States in 1970. He obtained an M.S. in nuclear civil engineering, an Engineer's degree in soil mechanics, and a Ph.D. in structures, all from Stanford University. His thesis investigated the use of geophysical modeling in seismic hazard analyses. He worked with Dames and Moore in geotechnical and hazard analyses and with E.D.S. Nuclear in soil-water-structure interaction. He was a research associate for three years at M.I.T. prior to joining Lawrence Livermore National Laboratory in 1982 where he is involved in seismic hazard analyses, as well as other types of engineering development, principally for the Nuclear Regulatory Commission.

BIOGRAPHY

Richard W. Mensing

Richard W. Mensing received his Ph.D. in Statistics from Iowa State University in 1969. From 1968 through 1977 he was a member of the Department of Statistics at Iowa State University. Since 1977 he has been a consulting statistician at Lawrence Livermore National Laboratory. Dr. Mensing's principle areas of interest include probabilistic risk analysis, eliciting and combining expert opinions, statistical methodology and experimental design. He is a member of the American Statistical Association and the Society of Risk Analysis.

BIOGRAPHY

Don L. Bernreuter

Don L. Bernreuter received his BS (1958) and MS (1959) in Engineering at the Georgia Institute of Technology. He was an NSF Faculty Fellow at Stanford University from 1967 to 1968. He was a member of the Department of Engineering Mechanics at Louisiana State University from 1962 through 1966. Since 1968 he has been at the Lawrence Livermore National Laboratory. From 1972 through 1974 he was on loan to the Geosciences Branch of the U.S. Nuclear Regulatory Commission. Currently, he is the leader of the Engineering Geosciences Group. He has directed a number of projects for NRC and DOE developing seismic hazard estimates for sites in the eastern United States.

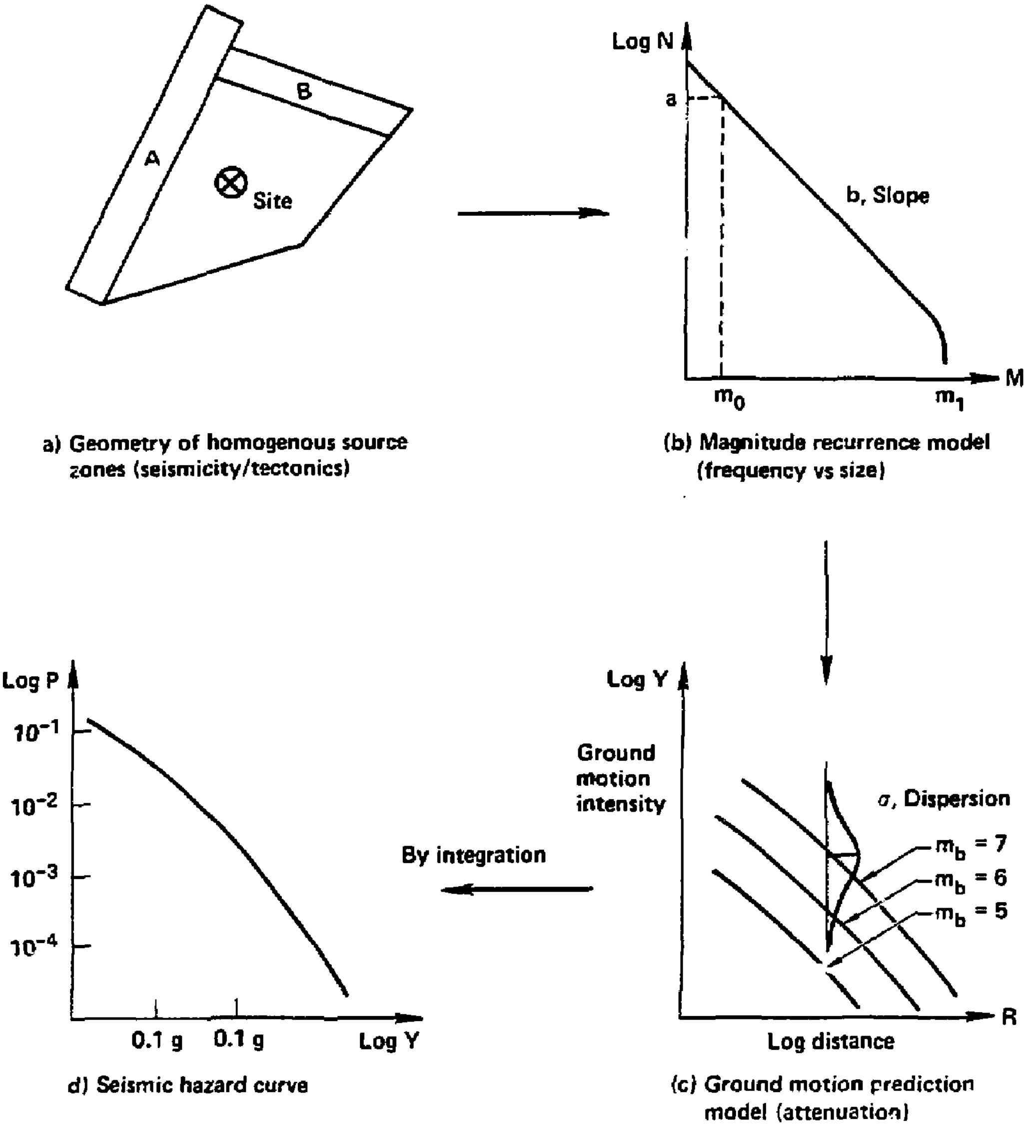

Fig. 1. Steps involved in seismic source hazard calculations.

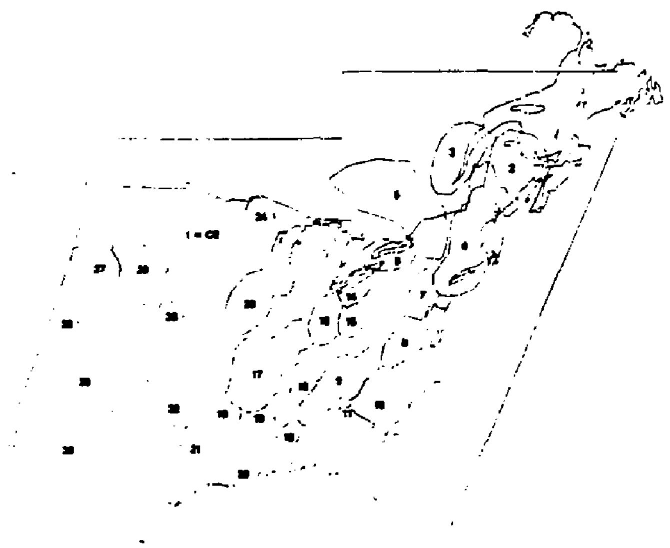

Fig. 2. Seismic zonation base map for Expert 6.

Fig. 3. Map of alternative seismic zonations to Expert 6's base map.

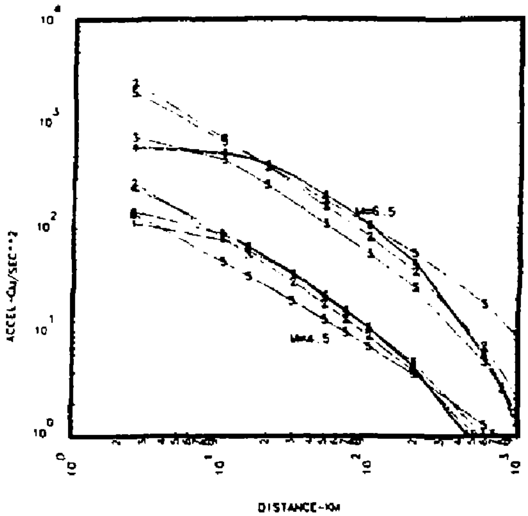

Fig. 4. Best estimate PGA models for the five G-experts, for the Northeast U.S. Each of the five experts selected a best estimate model for each region and as many as six alternative models to represent their uncertainty. Over the entire Eastern U.S. a total of 33 ground motion models were selected. Each model had a weight. The models and this weight (normalized) constituted the probability distribution of the ground motion models used in the simulation.

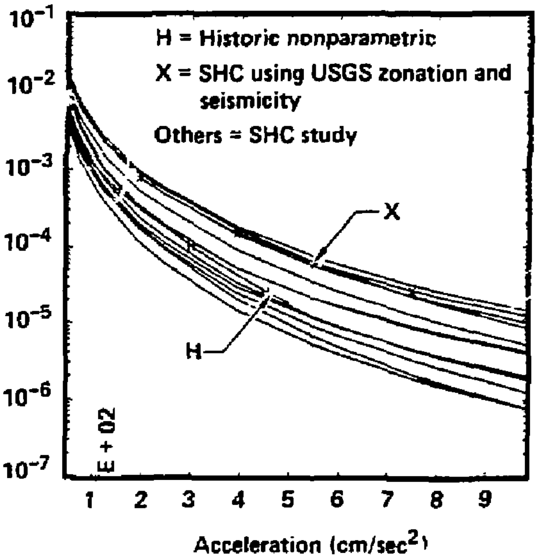

Fig. 5. Comparison of results for a site in the Southeast U.S.

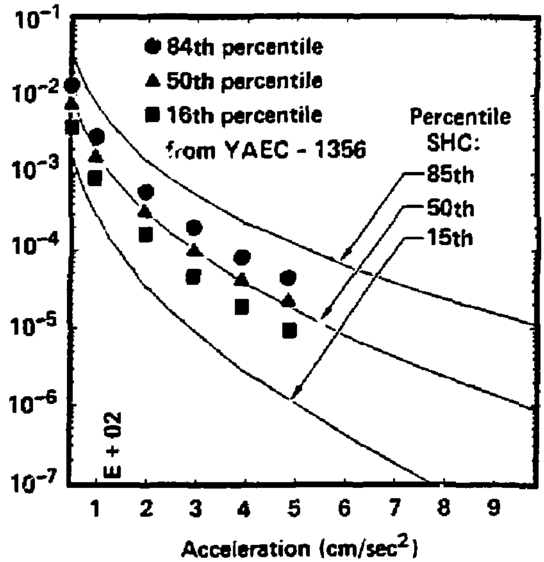

Fig. 6. Constant percentile (CPHC) hazard estimate at the Maine Yankee site (New England) for the YAEC and SHC studies.

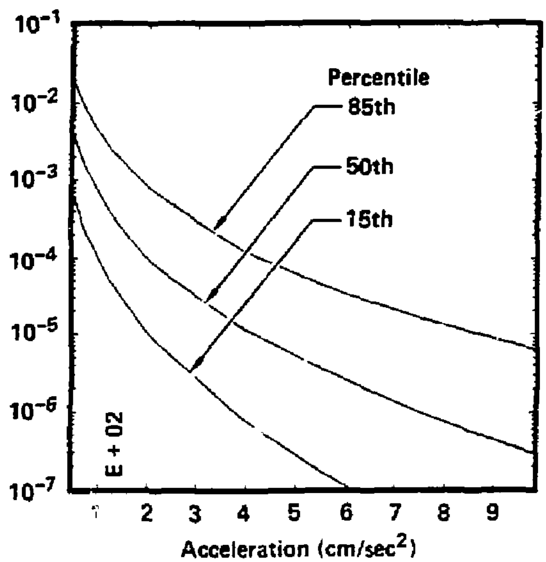

Fig. 7. Combined constant percentile hazard curves (CPHC) including the SHC site correction for the Braidwood site (North Central U.S.). This set of results was obtained by aggregating the hazard estimates of all the experts.

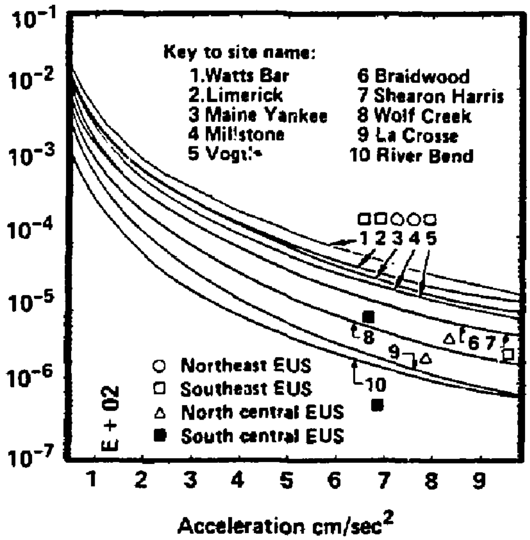

Fig. 8. Summary of the best estimate hazard curves (BEHC) for the 10 sites of the SHC study.

APPENDIX C.2

Probabilistic Assessment of the Seismic Hazard for Eastern United States Nuclear Power Plants
by J. B. Savy, D. L. Bernreuter and R. W. Mensing

Published in proceedings of the second Symposium on Current Issues Related to Nuclear Power Plant Structures, Equipment and Piping with Emphasis on Resolution of Seismic Issues in Low Seismicity Regions.

Held at Walt Disney World Hilton
Orlando, Florida
December 7–9, 1988

PROBABILISTIC ASSESSMENT OF THE SEISMIC HAZARD FOR EASTERN UNITED STATES NUCLEAR POWER PLANTS

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ABSTRACT

The purpose of the seismic hazard characterization of the Eastern United States project, for the Nuclear Regulatory Commission, was to develop a methodology and data bases to estimate the seismic hazard at all the plant sites east of the Rocky Mountains.

A summary of important conclusions reached in this multi year study is presented in this paper. The magnitude and role of the uncertainty in the hazard estimates is emphasized in regard of the intended final use of the results.

1. INTRODUCTION

The impetus for this study came from two unrelated needs of the Nuclear Regulatory Commission (NRC). One stimulus arose from the NRC funded "Seismic Safety Margins Research Programs" (SSMRP). The SSMRP's task of simplified methods needed to have available data and analysis software necessary to compute the seismic hazard at any site located east of the Rocky Mountains which we refer to as the Eastern United States (EUS) in a form suitable for use in probabilistic risk assessment (PRA). The second stimulus was the result of the NRC's discussions with the U.S. Geological Survey (USGS) regarding the USGS's proposed clarification of their past position with respect to the 1886 Charleston earthquake.

The results of this study were presented in Bernreuter et. al., (1), and the objectives were:

1. to develop a seismic hazard characterization methodology for the entire region of the United States east of the Rocky Mountains.

2. to apply the methodology to selected sites to assist the NRC staff in their assessment of the implications in the clarification of the USGS position on the Charleston earthquake, and the implications of the occurrence of the recent earthquakes such as that which occurred in New Brunswick, Canada, in 1982.

The methodology used in that 1985 study evolved from two earlier studies that the Lawrence Livermore National Laboratory (LLNL) performed for the NRC. One study, (2), was part of the NRC's Systematic Evaluation Program (SEP) and is simply referred hereafter to as the SEP study. The other study was part of the SSMRP.

At the time (1980-1985), an improved hazard analysis methodology and EUS seismicity and ground motion data set were required for several reasons:

- Although the entire EUS was considered at the time of the SEP study, attention was focused on the areas around the SEP sites--mainly in the Central United States (CUS) and New England. The zonation of other areas was not performed with the same level of detail.

- The peer review process, both by our Peer Review Panel and other reviewers, identified some areas of possible improvements in the SEP methodology.

- Since the SEP zonations were provided by our EUS Seismicity Panel in early 1979, a number of important studies had been completed and several significant EUS earthquakes had occurred which could impact the Panel members' understanding of the seismotectonics of the EUS.

- Our understanding of the EUS ground motion had improved since the time the SEP study was performed.

By the time our methodology was firmed up, the expert opinions collected and the calculations performed (i.e. by 1985), the Electric Power Research Institute (EPRI) had embarked on a parallel study.

We performed a comparative study, (3) to help in understanding the reasons for differences in results between the LLNL and the EPRI studies. The three main differences were found to be: (1) the minimum magnitude value of the earthquakes contributing to the hazard in the EUS, (2) the ground motion attenuation models, and (3) the fact that LLNL accounted for local site characteristics and EPRI did not. Several years passed between the 1985 study and the application of the methodology to all the sites in the EUS. In recognition of the fact that during that time a considerable amount of research in seismotectonics and in the field of strong ground motion prediction, in particular with the development of the so called random vibration or stochastic approach, NRC decided to follow our recommendations and have a final round of feedback with all our experts prior to finalizing the input to the analysis.

In addition, we critically reviewed our methodology which lead to minor improvements and we also provided an extensive account of documentation on the ways the experts interpreted our questionnaires and how they developed their answers. Some of the improvements were necessitated by the recognition of the fact that the results of our study will be used, together with results from other studies such as the EPRI study or the USGS study, to evaluate the relative hazard between the different plant sites in the EUS.

2. METHODOLOGY

The methodology used in this study is developed around three basic elements:

1. The estimation of the seismic hazard, (the hazard model) is analytically defined by the now classical Cornell model (1, 3, 4, 5, 6)

The various elements, seismicity and ground motion attenuation are expressed separately and integrated to provide an estimate of the probability of exceedance of the peak ground acceleration (PGA) and of the 5% damping spectral velocity at five frequencies.

2. It is recognized that every element of the hazard modeling is subject to uncertainties. The random (or physical) uncertainties in the prediction of the ground motion are analytically accounted for in the hazard model. Other uncertainties, random and model uncertainties, are propagated in the analysis by means of a Monte Carlo simulation technique.

The uncertainty in the seismicity distribution is accounted for by generating a large set of zonation maps and associated seismicity parameters (a- and b- values, upper magnitude cutoffs) and the uncertainty in the ground motion modeling is accounted for by using a set of 11 alternative models for the attenuation of the peak ground acceleration (PGA) and for the attenuation of the spectral velocity at the five frequencies.

The local soil site conditions at each site was acknowledged and each time a site correction factor was used, it was described by a probability distribution function to model the uncertainty found in site amplification data.

In the Monte Carlo technique, each hazard estimate (simulation) is done with a fixed value of the parameters. (A single zonation map, ground model, a single pair of a and b-values for each zone of the zonation map, a single value for the ground motion uncertainty-sigma, and a single value for the site correction factor). The process is repeated many times (2750 times in our analysis for PGA and 1650 for spectra), and in each simulation a new value of the uncertain parameters is drawn from their respective probability distribution.

The result of this experiment is a large set of artificial estimates of the seismic hazard from which the 50th (median), 15th and 85th percentile hazard curves are calculated to represent the central tendency (median) and total uncertainty (random and modeling) in the seismic hazard.

3. This study was intended to represent the opinion of the scientific community with respect to seismic hazard estimation. To this effect, two panels of experts were formed. The seismicity panel, composed of 11 experts (S-experts) in the field of seismicity of the E.U.S., and the ground motion panel, composed of five experts (G-experts), represent a cross section of the various schools of thoughts and opinions currently present in the scientific community. The opinion of each of these experts was elicited via questionnaires to develop the input necessary to the hazard model.

The questionnaires were such that they enabled the experts to express their opinion as to which models, or parameter values were the most likely to represent the true state of nature. In addition, whenever necessary, the experts had to describe their opinion on the uncertainty about the parameter value they selected in a qualitative and quantitative fashion.

Several feed back meetings were organized to ensure the experts opinions were interpreted correctly and to give the experts an opportunity to critically review their answers to the questionnaires and eventually to modify them.

These three elements, seismic hazard model, use of expert opinion and propagation of the uncertainty form the basis of our methodology. Other methods available today, may vary in several respects. For example, many seismic hazard analyses do not recognize the variability in the estimates due to the source of the input (i.e. they may use only one expert to define the seismicity or the ground motion model). Some do not account for the uncertainty in the many uncertain parameters in such an analysis (e.g. a and b-values, upper magnitude cutoff, etc).

The method developed by the Electric Power Research Institute (EPRI) (7) has many common elements to ours. The basic hazard model is the same, the input is obtained through the elicitation of expert's opinion and all types of possible uncertainties are recognized including the variability in the expert opinions. The overall uncertainty is propagated by the means of the enumeration method where all the possible combinations of parameters are considered, in contrast to using a Monte Carlo method which selects alternatives at random from known probability distributions.

3. GROUND MOTION MODELING

The seismic hazard model requires an estimate of the probability of exceedance of a given level of ground motion (i.e., PGA or PSRV), for an earthquake with known magnitude and location. We divided the problem into two independent ones.

1. For a know earthquake (i.e. magnitude and distance from the earthquake source to the site considered), and assuming generic soil type at the site (i.e., rock, or deep soil), we estimate the ground motion at that site. This is usually referred to as the ground motion attenuation modeling.

2. If the subsoil conditions at the actual site are different from the generic conditions, we apply a correction to the estimate of the ground motion. This part is usually referred to as the site soil correction.

For smaller studies, (i.e. when studying only one site), the above two items need not be separated. Actually, with the necessary resources of time and effort, a site specific type of modeling is almost always preferable to a generic type of approach. In our experience, the improvements reside more in the amount of uncertainty than in the actual values of the estimates. For example, the median hazard estimates of the site generic case may be only a few percent away from the specific case, but the 15th and 85th percentile curves may show much wider uncertainties. In this section, we review the attenuation part of the ground motion modeling, the next section is concerned with the site correction aspect.

Consistent with the philosophy of our methodology, the ground motion model input was developed by elicitation of the G-experts opinion, with two rounds of feed back. The intent was not to obtain what some would be tempted to call "The Model", but rather to sample the experts to ensure that all the models that the experts deemed rational and possible be considered. Each expert was free to select as many models as he wished and assign whatever weight he wanted to each one of them. The total weight of the models for a given expert was unity, and the weight of each expert was the normalized self weight given by the expert himself (the self weights were roughly 1/5 for each of the five G-experts).

The final set of attenuation models selected by the experts includes a range of available models including the empirical, intensity based models (Veneziano (8), Trifunac model (9), the empirical model of Nuttli (1), and the theoretical models of the Atkinson type (10) also called random vibration models (RV models). The difference between the various types of models is shown in Figs. 1 and 2 for the attenuation of the PGA for two events, of magnitude 5 and 7. Fig. 1 shows the best estimate models for each of the 5 G-experts for a rock site (i.e. the model which they believed were the most appropriate to represent the median PGA for a given magnitude and distance). Fig. 2 shows the additional models selected by the experts to express their uncertainty in the models.

Examination of these two figures immediately draws several conclusions.

1. The dispersion between the models is large, approximately a factor of 10, in the range of distances of 50km to 200km.
2. The dispersion is much less within 50km.
3. The RV models are much lower than the other models. As much as a factor of 10 for distances greater than 100km, at both magnitudes 5 and 7.
4. Model number 3 in Fig. 1 (Trifunac's model), is higher than the rest of the models by a factor of approximately two, up to 200km for magnitude 7. However, Fig. 3 shows that the difference is much smaller for the deep soil case.

This selection of models is somewhat of a departure from our previous analyses, where the RV models were not used. In this analysis, the RV models account for approximately 50%, Nuttli's model 20%, Trifunac model 20% and Veneziano's model 10%.

In spite of these drastic changes in the ground motion models from our previous study on 10 test sites in the EUS (6), and some changes in the seismicity modeling, the estimates of the seismic hazard in terms of exceedance of PGA, did not drastically change, as can be seen in Fig. 4 and 5.

The ground motion attenuation models of the response spectral velocity, in addition of being of the three types, empirical, semi-empirical and theoretical, could be either based on original spectral shapes (the RV models, and Trifunac's model), or Newmark-Hall type models constructed with PGA and velocity models of the types described for PGA: Fig. 6 shows the best estimate spectral models for the five G-experts for the rock case. Model 1 of Fig.6, is a "pure" RV model, and model 3 is a Newmark-Hall model (11) constructed with RV models of PGA and velocity. Model 2 is the Trifunac model, and models 4 and 5 are Newmark-Hall models based on semi-empirical relationships of PGA and velocity attenuation models.

In toto, the contribution from RV models was approximately 53%, (including 44% of "pure" RV models and 9% of Newmark-Hall-RV models), 27% of Newmark-Hall-semi-empirical models, and 20% for the Lee and Trifunac model (12). In other words, the pure RV models accounted for 44%, Newmark-Hall models 36% and Lee and Trifunac, 20%. Fig. 6, shows the difference in behavior between the various spectral models. These median models are defined at five periods (0.04, 0.1, 0.2, 0.4, and 1.0 second). Examination of Fig. 6, leads to the following immediate conclusions:

1. The variability for 0.2, 0.4, and 1.0 sec. is much greater than for 0.04 and 0.1 sec., with the variability being the greatest at 1.0 sec.
This is due mostly to the vastly different behavior of the "pure" RV model (model #1 in Fig. 6) by comparison to the Newmark-Hall type model.

2. At low period (0.04 sec), the "pure" RV model is higher than the other models, especially for the higher magnitudes, and it is substantially lower at higher periods. Thus, when comparing previous results to the present study, the present estimates show a drastic change in the estimated spectral shape, with relatively much higher

levels at low period and much lower levels at higher periods. Fig. 7 shows this "flattening" effect for a typical site in the North Central region of the E.U.S.

4. SITE CORRECTION

The ground motion attenuation models selected by the G-experts where derived either for rock site conditions or deep soil. The Trifunac model was derived for rock, deep soil or some other category which the author calls intermediate. In each trial, the Monte-Carlo simulation process selects at random one of the ground motion models, at a rate proportional to the weights assigned by the experts. Thus, each time the ground motion model selected did not match the soil site conditions, a correction was applied. The opinions of the experts were elicited to define what type of corrections and how the corrections should be applied. In the end, two types were selected.

1. The simple correction approximates the soil sites conditions to only two generic categories, either rock or soil, or three categories in the case of the Trifunac's model.

2. The categorical correction differentiates all of the E.U.S. sites into eight different generic categories. Rock, deep soil, shallow till-like soil (three different depths) and shallow sand-like soil (three different depths).

The experts were also given the opportunity to apply no correction at all, if they did not believe that the data available showed any definite trend depending on the site soil type. This latter alternative was not selected by any of the experts. Four of the G-experts opted for the categorical (eight categories) correction method and one G-expert opted for the simple correction.

The simple correction consists in applying a fixed multiplication factor to the median attenuation curve. By contract, the correction applied in the categorical correction has some variability. This variability was described by a probability distribution function from which the correction factors were drawn in each of the Monte Carlo trials. In terms of interpretation, and usage, of the final seismic hazard results, there is a fundamental difference between the two methods of correction. One, the simple correction, deterministic, does not account for the uncertainty inherent in predicting the amplification at a shallow soil site, the other does (Probabilistic case). In the deterministic case, the hazard curve derived for a soil site would be exactly the hazard curve derived for a rock site at the same location multiplied (in the PGA axis direction) by the correction factor from rock to soil.

This is not true in the probabilistic case where several random variables with various symmetrical or unsymmetrical probability density functions. With the choices of probability density functions in our analysis, the probabilistic correction leads to a median hazard curve slightly (up to 10% in PGA) lower than if a deterministic case with correction factor equal to the median of the probabilistic distribution of the probabilistic correction factor were used. In addition, the uncertainty bounds on the total hazard are larger. The 85th percentile hazard curve can be up to two times higher (in PGA values) than the deterministic case.

The conclusion is that it is appropriate to perform the correction on the hazard curve if one believes that the correction factor is a fixed value, known without uncertainty. It is not appropriate to perform such a correction on the hazard curve if the correction factor is known with uncertainty.

Thus, in our analysis where one-fifth of the corrections were deterministic and four-fifth were probabilistic, it would not be appropriate to perform the site correction on the hazard curve.

One interesting consequence of having several types of correction factors is that it makes it regionally dependent, due to the complex interaction between zonation and seismicity-ground motion and site correction. The reader is referred to Bernreuter et.al., Vol. 6 (1)for more details on the mechanics of this regional dependency. Table 1 gives a summary of the site correction results for 12 sites in the E.U.S. In this table, the soil category is one of the eight categories discussed earlier in this section, columns 1, 2, and 3 are the ratios of PGA values, read on the median hazard curves, at fixed probability of exceedance values (10^{-3}, 10^{-4}, and 10^{-5}) between the soil and rock cases. Column (4) is an average of columns 1, 2, and 3. Column (6) is the deterministic correction factor for the Trifunac model and column (7) is the median of the probabilistic correction factor used in the categorical correction method. Column (5) is a weighted average of columns (6) and (7). If there were no regional effects, we would expect the actual correction factors (i.e. column 4), to be close to the weighted averages (i.e. column 5). The deviation from the value in column (5) is due to the complex interaction between ground motion models, seismicity zones and seismicity parameters. Depending on all those factors the impact will be that the correction advocated by G-expert 5 will have more or less weight, relative to the other 4 experts. For Oconee, the combination of the above mentioned interactions leads to an impact of G-expert five greater than the equal weight case. For the other sites, but Three Miles Island, the effect is reversed and the impact of G-experts 5 is diluted.
The case of Arkansas, Callaway and Duane Arnold requires additional scrutiny. For those three sites, Table 1 shows that the effective amplification factors (column (4)) obtained in our simulation are close to the case when G-expert 5's model is not used (compare columns 4 and 7). This phenomenon seems extreme and can be explained as follows, (remembering that we are comparing median hazard curves for rock and for soil):

- For the rock case, the contribution to the hazard comes from distant large earthquakes. Figure 1 shows that in that range, G-expert 5's ground motion model (number 3 on Fig. 1) is much higher than the rest of the models. Thus, the resultant median value is more representative of the other four ground motion models.

- For the shallow soil case, the large, distant earthquakes are also dominant, and G-experts 5's model falls within the cluster of other models, thus, the median will be representative of all the models, and in particular again close to the median without Expert 5.

The result is that the final ratio of PGA between shallow and rock cases for these three sites is close to the case when only the categorized correction is used (i.e., the correction recommended by all but G-expert 5).
This discussion indicates that in general the hazard curve computed for shallow soil is close (here, never more than 10% higher in the direction parallel to the ground motion (PGA) axis and more often within 1 or 2%) to what would be obtained by simply applying a median correction factor to the hazard curve for rock. However, the complexity of the process makes it very difficult to isolate the parameters which make this ratio deviate at some sites from the expected ratio and thus makes it, for the time being, impossible to predict.
Thus, when using the results of our analysis, it is incorrect, even approximately, to routinely correct a rock hazard curve to get an estimate of a soil hazard curve, when a combination of site corrections are used, in addition the site correction is in effect region dependent.

5. USE OF THE RESULTS OF THE SEISMIC HAZARD ANALYSIS

The results of a seismic hazard analysis can be used in a variety of ways either in a relative or absolute sense.

Hazard curves used in Probabilistic risk assessment (PRA) studies rely on the estimates as true estimates of the hazard (absolute sense). So does any investigation of a single site without comparing it to other sites. For this reason it is important to incorporate the entire specification of the hazard, including its uncertainty, rather than a point estimate or even a mean or median value. To this effect, most PRA now use a family of curves to represent the uncertainty in the seismic hazard estimates.

Comparison between plant sites, regions or groups of sites rely mostly on the relative level of hazard between the sites.

Fig. 8 shows the median hazard curves for 19 sites in the north eastern part of the EUS and Fig. 9 for 16 sites in the north central region. It is clear based on these median values that on the average, the seismic hazard in the north central region is lower than that of the north east.

Another use of the results is in comparing the spectral shapes of the uniform hazard spectra (UHS) at different sites.

The spectral level is sensitive to both the rate of occurrence and earthquake magnitude. The longer period part of the CPUHS is very strongly influenced by magnitude. Thus, sites which are influenced by very large earthquakes, e.g., around the New Madrid region, will have more longer period energy than sites in New England where the local activity from smaller earthquakes is important. There is some influence of attenuation on the short period end of the spectrum, but it is relatively small.

This is illustrated in Fig. 10 where we compare, for two rock sites, the spectral shapes between a site (Arkansas) where very large earthquakes dominate the hazard as contrasted to a site (Limerick) at which the seismic hazard is governed primarily by smaller nearby earthquakes. The main difference in spectral shape is at the longer periods. There is some difference at the short period end but it is relatively small.

Another important use of the hazard estimates consists in sorting the various sites according to criteria based on the probability of exceedance of some pre-chosen ground motion value. As an example, Fig. 11 shows an ordering of the 69 sites in the EUS according to the median value of the hazard at 0.2g. Fig. 11 shows that, depending on the type of criteria one would choose, several kind of groupings could be obtained. The first two sites in the ordering, could be considered as forming a group by themselves, then the next five sites could form a second group, etc.....

On the other hand, if the sites were ordered according to the arithmetic mean of the hazard (shown by the symbol "A" on Fig. 11), the order would be quite different. The same would be true of the 85th percentile (represented by the "*" symbol in Fig. 11). Furthermore, using the hazard at 0.6g instead of 0.2g would also lead to different results. Thus, it is quite obvious that ordering the sites on the basis of seismic hazard alone could be misleading at best and always tainted with some arbitrariness.

Risk based criteria could help in ordering the sites but could also be misleading if one is not careful in selecting the criteria for ordering. One alternative would be to order the sites on the basis of probability of core melt, or even on the total consequences of release, but clearly this would require enormous efforts to include all sites.

More simply however, generic plant fragility functions could be developed from the 20 or more existing PRA's, and the probability of core-melt could be estimated for all sites. More simple methods yet can be thought off which in some manner consider some aspect of risk.

In a follow up project, our charter was to develop grouping techniques and identification of outliers purely on the bases of the seismic hazard at the 69 plant sites. Without specifically involving risk, we considered the probability of exceedance of the SSE values and multiples of the SSE, 0.3g and 0.5g. In addition we defined a new hazard parameter equal to a linear combination of the hazard at the five periods available. This new measure of the hazard places the emphasis on different periods at will, emphasizing the periods which are more important for a given plant. For example the 0.4 sec. to 0.1 sec. period window is in general more important than the rest of the spectrum. In other cases one might want to emphasize the low period range, smaller than 0.02 sec.
This methodology was reported in Bernreuter (13).

6. CONCLUSION

The detailed conclusions reached in the course of this study are given in (1). The following is a summary of the most important ones:

(1) There is substantial uncertainty in the estimated hazard. The typical range in the value of the probability of exceedance between the 15th and 85th percentile curves for the PGA is on the order of 40 times, for low PGA; it is more than 100 at high PGA values. This translates into an approximate factor of 4 in ground motion for the 15th-85th range of values in the PGA given a fixed return period, and similarly an approximate factor of 4 in the ground motion for the range of values in the PSRV for a given return period.

The range between the 15th and the 85th percentile hazard curves represents the total uncertainty in estimating the seismic hazard at a site due to two sources of uncertainty:

- The uncertainty of each expert in the zonation, models and values of the parameters of the analyses
- The variation in the hazard estimates due to the diversity of opinions between experts.

The latter, or inter-expert variation is an important contributor to the total uncertainty in the estimated hazard. Specifically, the magnitude of uncertainty introduced by the diversity of opinions between experts is of the same order, on the average, as the uncertainty in the hazard due to the uncertainty of an individual expert in the value of the parameters. However, at times the uncertainty between experts can be very large.

(2) The 50th percentile CPHC appears to be a stable estimator of the seismic hazard at the site. That is, it is the least sensitive to changes in the parameters, when compared to other estimators considered in this study.

(3) The process of estimating the seismic hazard in the EUS is reasonably stable. Comparison with our previous results indicated that there has not been a major shift in results over the past few years, although there have been some significant perturbations in the form of recent occurrences of EUS earthquakes and the completion of several major studies of the seismotectonics of the EUS. In the feedback performed in this study, there were some changes introduced by members of both the Seismicity and GM Panels. However, the computed hazard

when aggregated over all experts did not significantly change. However, the introduction of the "new" random vibration models introduced a significant change in the spectral shape by raising the spectral values in the high frequency range and lowering it in the low frequency range.

(4) It is difficult to rank the uncertainties, because zonation and the parameters of the recurrence models are hard to separate. Nevertheless, our results indicate that the uncertainty in zonation, and ground motion models are more significant than the uncertainty associated with the seismicity parameters. The largest contribution to modeling uncertainty comes from the uncertainty of the ground motion. The correction for local site effects is a significant contribution to the overall uncertainty introduced by the ground motion models. However, as already noted, the uncertainty introduced by zonation and recurrence models is also significant and of the same order.

(5) We found that the correction for the site's soil category had an important effect on the estimated hazard.

(6) We found that with our methodology, in general the site soil correction is not a linear operation on the hazard curve. Thus it is, in general, incorrect to modify a hazard curve calculated for a rock site by multiplying by a constant number (i.e., mean or median correction factor) to obtain the hazard curve at the same site for a different soil condition. Performing this incorrect operation could lead to errors in the estimate of the PGA, for a fixed return period, by as much as 10 percent. However, we found that for some sites, multiplying the median hazard curve for rock by the median correction factor would have given approximately the same median hazard curve we obtained by performing the full analysis with our probabilistic correction factors. Unfortunately, at the present time, we have not been able to develop criteria to identify when performing such operation is acceptable.

(7) Although the soil site correction is not region dependent, we found that other complex interactions, with zonation seismicity and ground motion models, made the site correction actually region dependent in our methodology.

ACKNOWLEDGMENTS

This work was supported by the United States Nuclear Regulatory Commission under a memorandum of understanding with the Department of Energy. The NRC project manager was Gus Giese-Koch.

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TABLE 1

RATIOS OF PGA VALUES BETWEEN SHALLOW AND ROCK CONDITIONS FOR FIXED VALUES OF THE HAZARD

	Site	Soil Category	Ratio Shallow/Rock Prob. of Exceed. 10^{-3} (1)	10^{-4} (2)	10^{-5} (3)	Avg. (4)	All Equal Weight (5)	Only G5* (6)	W/O G5** (7)
1	Nine Mile Point	Sand-1	1.57	1.58	1.59	1.58	1.47	0.73	1.65
2	Susquehanna	Till-2	1.30	1.30	1.30	1.30	1.25	0.73	1.38
3	Three Mile Island	Sand-1	1.50	1.47	1.44	1.47	1.47	0.73	1.65
4	Browns Ferry	Sand-1	1.56	1.66	1.68	1.63	1.47	0.73	1.65
5	Catawba	Sand-1	1.59	1.58	1.55	1.57	1.47	0.73	1.65
6	Farley	Sand-1	N/A	1.56	1.49	1.53	1.47	0.73	1.65
7	North Anna	Sand-1	1.51	1.50	1.51	1.51	1.47	0.73	1.65
8	Oconee	Sand-1	1.37	1.44	1.47	1.43	1.47	0.73	1.65
9	Summer	Sand-1	1.47	1.62	1.61	1.57	1.47	0.73	1.65
10	Arkansas	Till-1	1.51	1.50	1.50	1.50	1.39	0.73	1.55
11	Callaway	Sand-1	1.65	1.70	1.72	1.69	1.47	0.73	1.65
12	Duane Arnold	Till-1	N/A	1.50	1.50	1.50	1.39	0.73	1.55

* Ratio of PGA shallow/rock given by G-expert 5 only

** Ratio of PGA shallow/rock given by G-experts 1, 2, 3 and 4 only

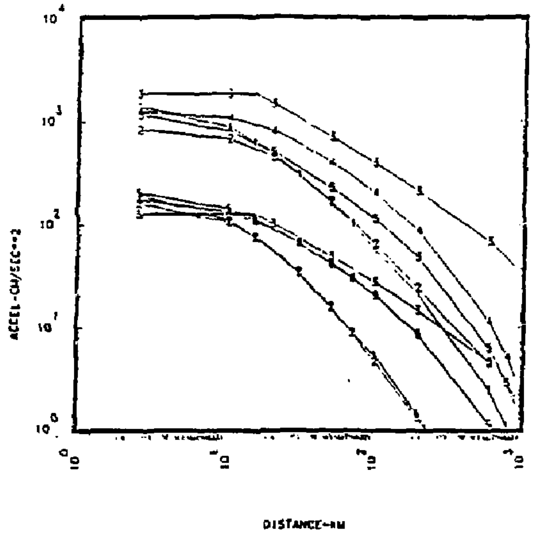

Figure 1 Best estimate PGA models plotted for magnitudes of 5 and 7. Rock base Case.

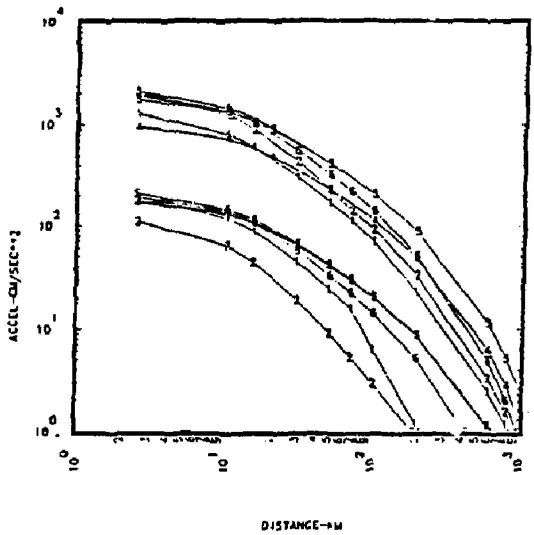

Figure 2 Remaining PGA models plotted for magnitudes of 5 and 7. Rock base case.

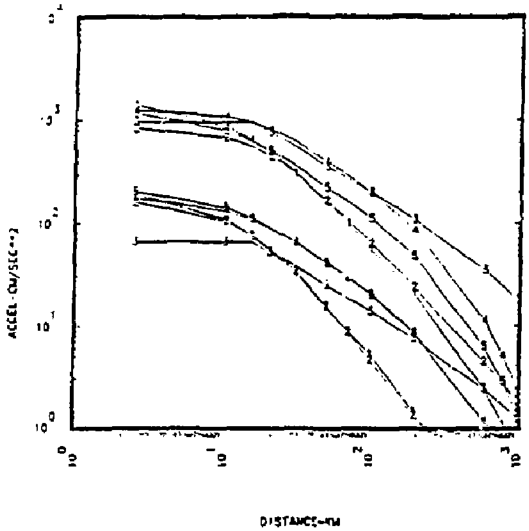

Figure 3 Best estimate PGA models corrected to generic deep soil for magnitudes of 5 and 7.

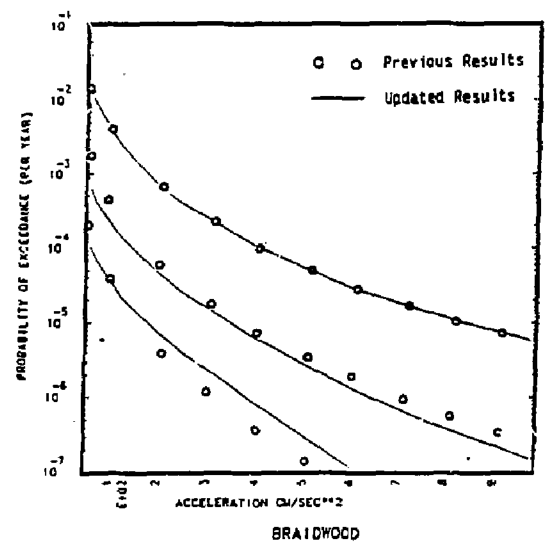

Figure 4 Comparison of the 15th, 50th and 85th percentile CPHC's aggregated over all S and G-Experts between the new input and the previous input from the S and G-Experts for the Braidwood site.

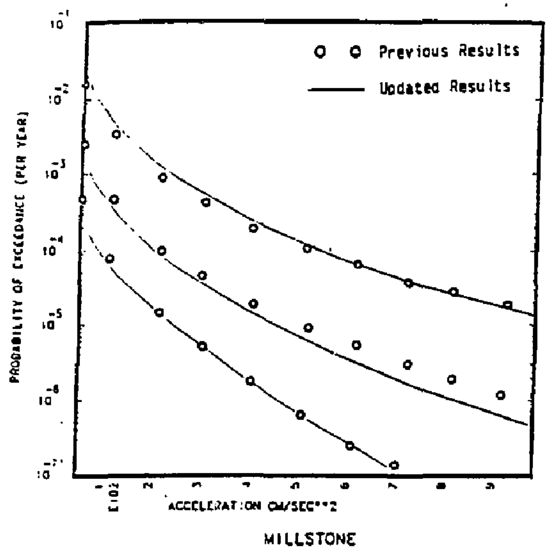

Figure 5 Comparison of the 15th, 50th and 85th percentile CPHCs aggregated over all S and G-Experts between the new input and the previous input from the S and G-Experts for the Millstone site.

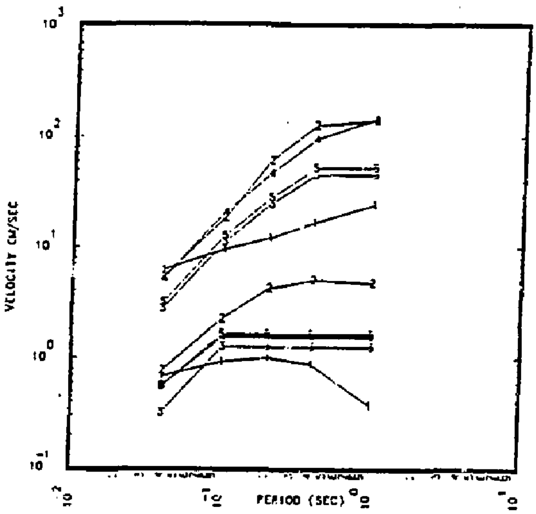

Figure 6 Best estimate 5 percent damped relative velocity spectra models listed in Table 3.6 plotted for magnitudes of 5 and 7 at a distance of 25 km. Rock base case.

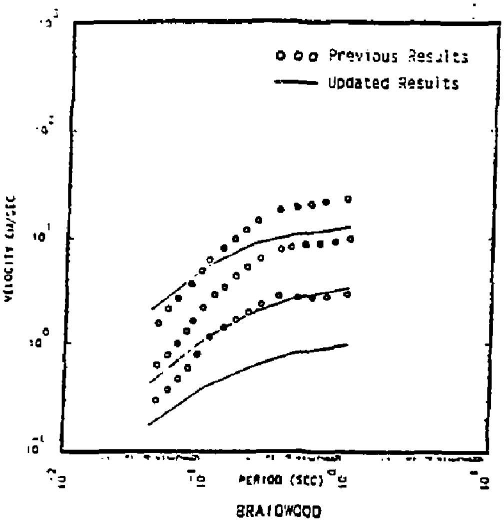

Figure 7 Comparison of the 1000 year return period 15th, 50th and 85th percentile CPUHS for 5 percent damping aggregated over all S and G-Experts between the new input and our previous input from the S and G-Experts for the Millstone site.

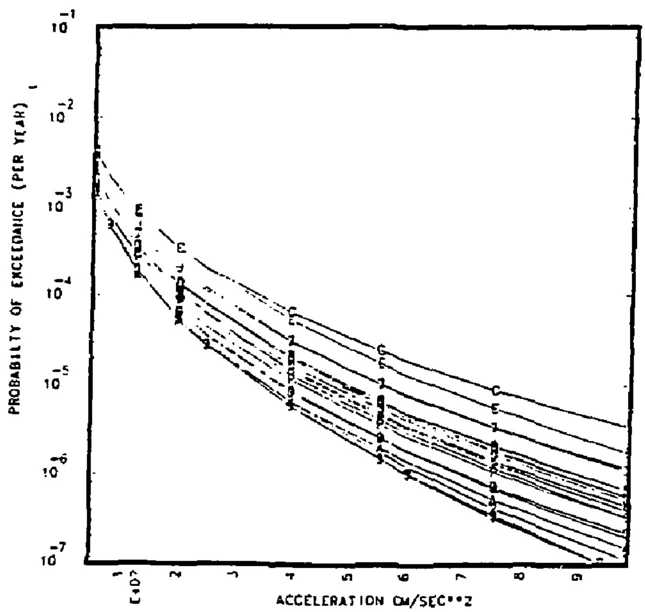

Figure 8 Comparison of the median CPHCs for the 19 sites in the North East.

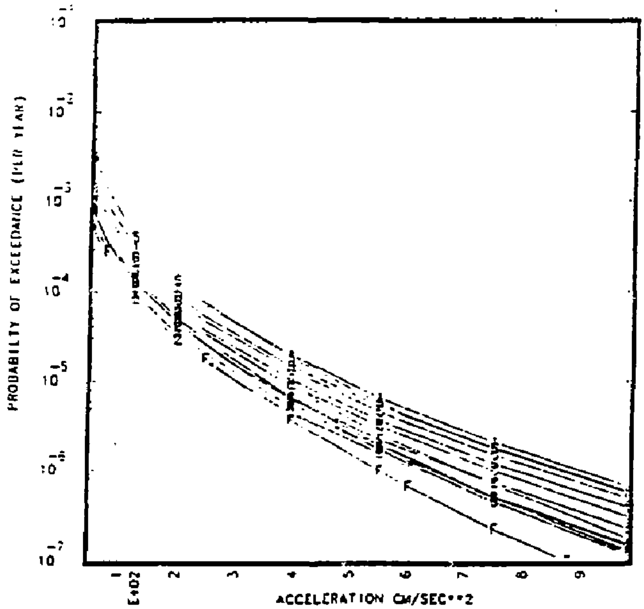

Figure 9 Comparison of the median CPHCs for the 16 sites in the North Central E.U.S.

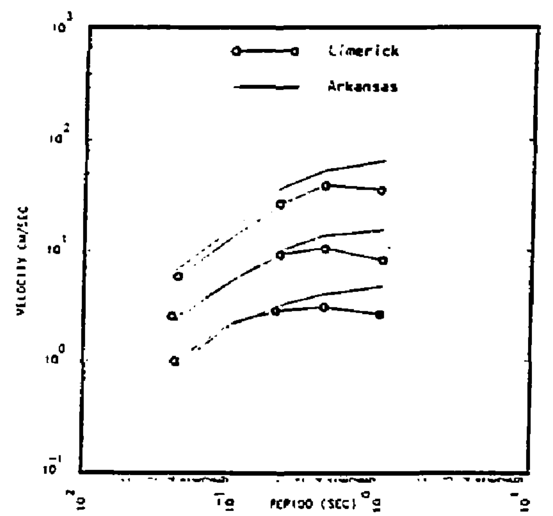

Figure 10 Comparison of the 10,000 year return period CPUHS between the Arkansas and Limerick sites (both rock sites).

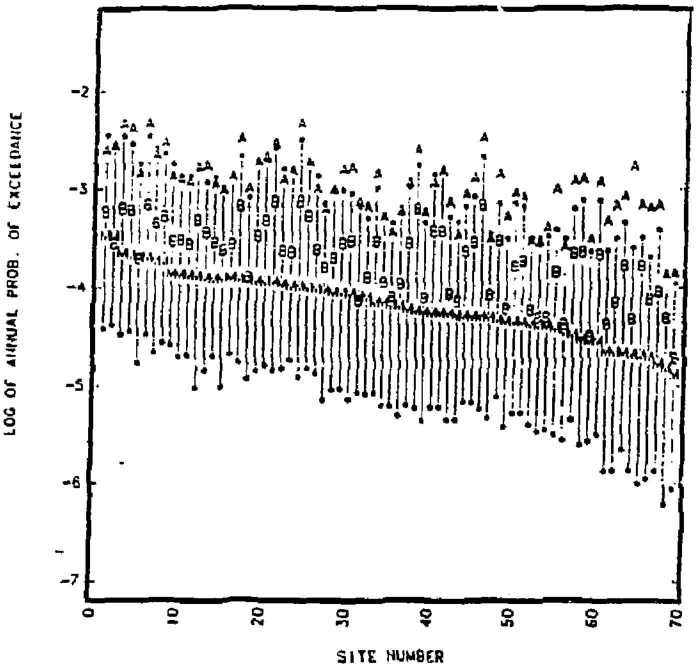

Figure 11 The 69 sites have been ordered by median probability of exceeding 0.2g. The symbols A, B, M and *, respectively represent the arithmetic mean, the best estimate, the median and the 85-15th percentile hazards. Note that if the site had been ordered according to other than the median hazard, a different order would have been obtained.

APPENDIX C.3

Uncertainties in Seismic Hazard Analysis Using Expert Opinion for the Eastern United States

by J. B. Savy, D. L. Bernreuter and R. W. Mensing

Presented at the international ANS/ENS Topical Meeting on
Probabilistic Safety Methods and Applications
Also UCRL 92190

February 24 – March 1, 1985
San Francisco, California

UNCERTAINTIES IN SEISMIC HAZARD ANALYSIS
USING EXPERT OPINION FOR THE EASTERN UNITED STATES *

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I. INTRODUCTION

In the late 1970's, the Lawrence Livermore National Laboratory (LLNL) developed a Seismic Hazard Methodology for the Nuclear Regulatory Commission (NRC) to be applied at a few sites in the Eastern United States (EUS), (Bernreuter and Minichino),[1] under the Seismic Evaluation Program (SEP). Bernreuter, [2] and [3] The fundamental characteristic of SEP was to supplement the lack of earthquake data for the EUS by a set of expert opinions. However successful this project was, it was limited by the geographical extend of the area considered and by some of its mathematical assumptions. This led to the "Seismic Hazard Characterization of the EUS" project (SHC), where we consider the entire EUS, east of the Rockies and we provide a rigorous methodology to quantify the uncertainty in the hazard. In SHC, we formally distinguish between modeling and random uncertainty and propagate them in the calculations.

In addition to the traditional characteristics of present day Seismic Hazard analysis (i.e. consideration of random uncertainty in seismicity and ground motions) the determining characteristics and goals which governed in the development of our methodology are as follows:

- The lacking data would be supplemented by subjective expert opinion.
- Two panels of individual experts would be formed for data collecting. One for zonation and seismicity (Panel S) and one for ground motion prediction (Panel G).
- Each member of the panels would be chosen for his/her competence and knowledge and would be treated anonymously in order to avoid suppressing non classical view points under peer pressure.

*This work was supported by the United States Nuclear Regulatory Commission under a Memorandum of Understanding with the United States Department of Energy.

- o The input of each panel member would be treated independently, the hazard calculated with his/her input, and the result would be combined at the end between experts.
- o The uncertainty in the shape and size of the seismic sources would be included in the anlaysis.
- o The uncertainty in the ground motion modeling would be included and one independent Peer Review Panel would be formed to evaluate our methodology, the quality of our data and to identify the weakness and recommend improvements.

The above requirements led to a two-tier effort. We developed, on one hand a method of elicitation of expert opinion and on the other hand, a mathematical model of the Hazard. A detailed description of the methodology is given in Bernreuter et.al, [4] and [5].

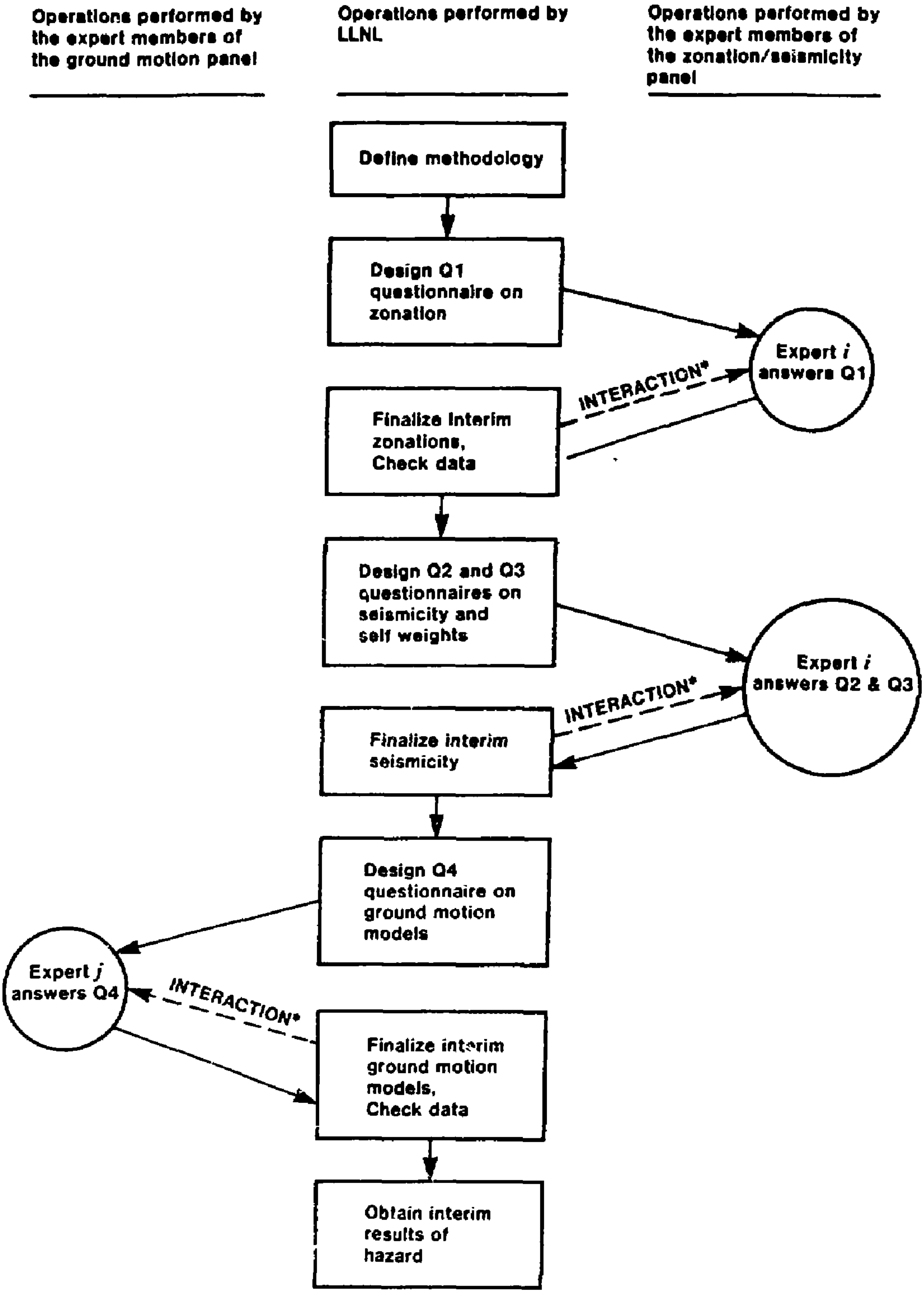
2. METHODOLOGY

2.1 Elicitation of Expert Opinion

A variety of ways in which expert opinion may be elicited were reviewed by Mensing [6]. Our approach, inspired by Mensing combines several different methods including setting up independent panels of experts and using questionnaires. The expert panels were made as large as possible and included the most recognized experts in their fields. Eleven experts participated in the Panel S and five experts in the Panel G.

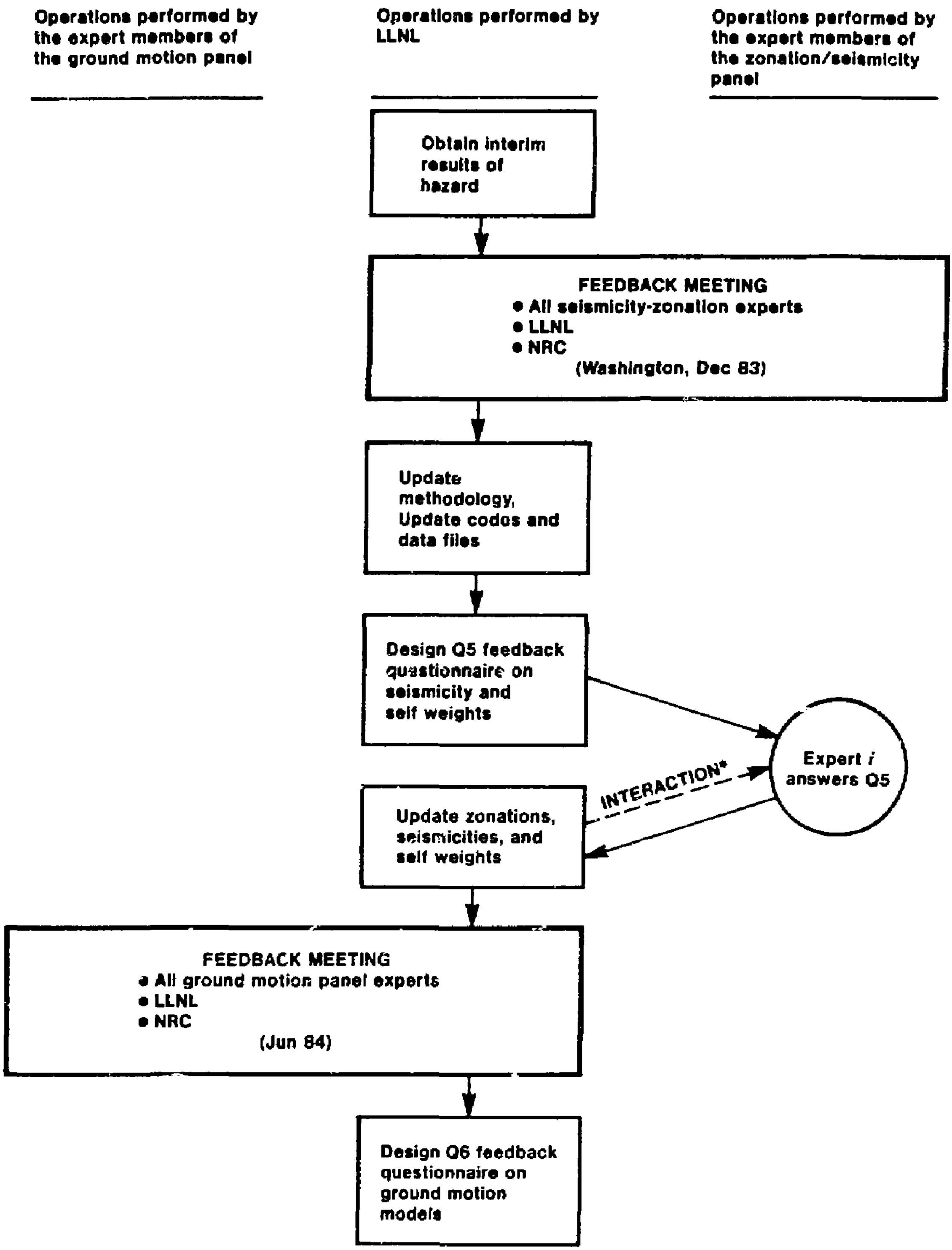
2.1.1 Elicitation of Expert Opinion on Zonation and Seismicity

The overall methodology outlined in Fig. 2.1 was first defined and two questionnaires were sent to the S-experts to elicit their opinion on zonation, and on seismicity. In the first questionnaire, on zonation (Q1), they were provided with a set of maps of the EUS and were asked to draw a set of seismic zones which would constitute their Best Estimate zonation Map (BEM). A seismic zone was defined as an area of uniform seismicity characteristics (i.e., where the earthquake recurrence and upper magnitude cutoff can be viewed as uniform). Their responses to a set of qualitative and quantitative questions were used to assess their uncertainty around their BEM. These questions concerned their level of confidence in the existence of each one of the zones in their BEM, the shape of these zones, and a set of alternative zones.



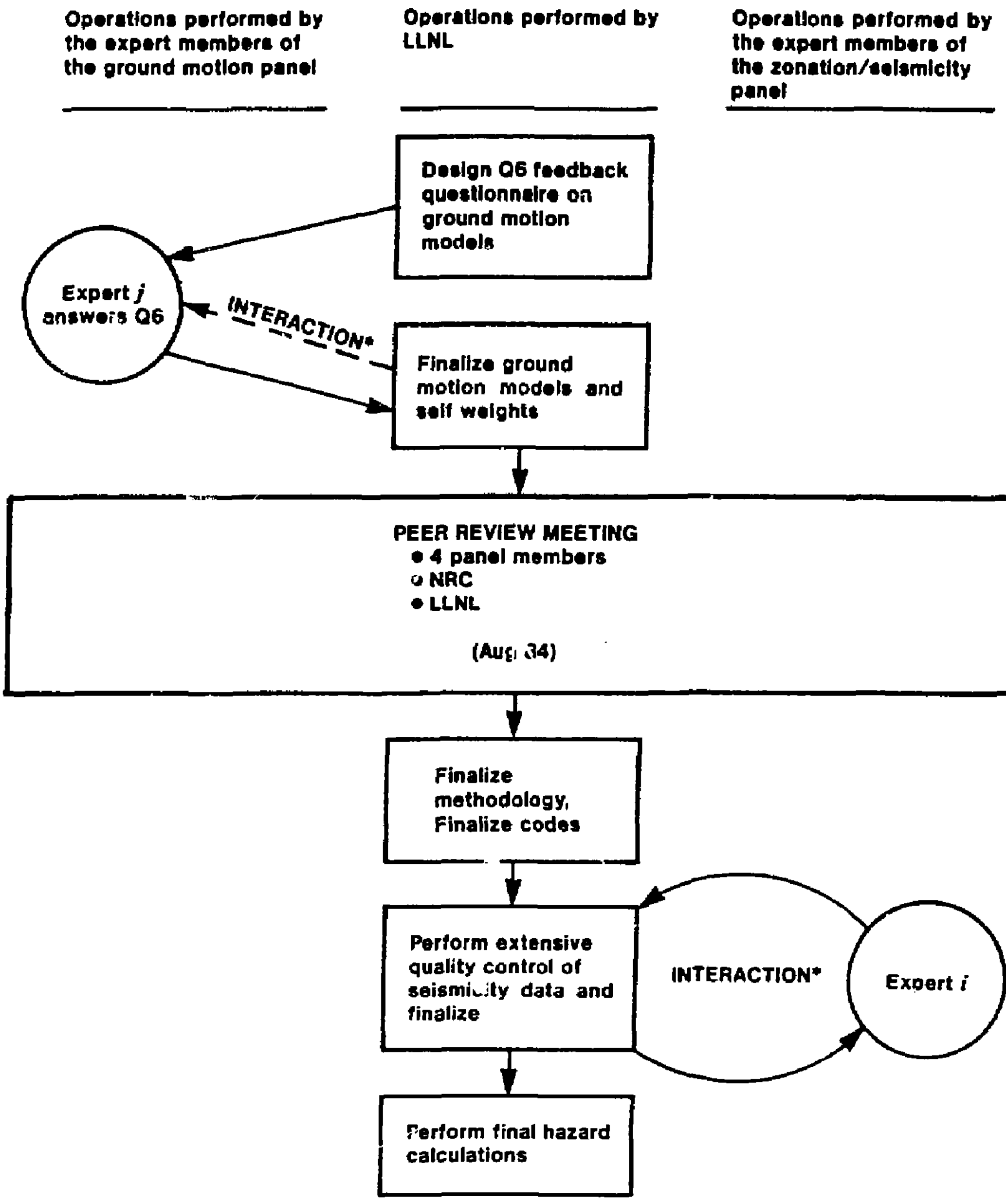
* Mostly by phone or mail, but also meetings in person for a few cases.

Figure 2.1 Flow Chart of the Analysis



* Mostly by phone or mail, but also meetings in person for a few cases.

Figure 2.1 (continued)



* Mostly by phone or mail, but also meetings in person for a few cases.

Figure 2.1 (Continued)

In the second questionnaire, on seismicity (Q2), the experts were asked to provide a mathematical model for the recurrence of earthquakes in each of the zones they identified in Q1 without limitation to the log-linear relationship. For this purpose, they used the catalogues of data they found most relevant in their analyses. Most of them used their own data, but some also used a "default" catalogue provided by LLNL, in particular for the regions where they had the least expertise.

Then a comprehensive feedback meeting took place to give the experts an opportunity to understand the fine details of the analyses, to clear up any misunderstandings and to confront their ideas with different, possible conficting ones. A questionnaire (Q5) aimed at solving the problems raised at the feedback meeting gave the experts a chance to update their input to the analysis. In addition, an extensive quality check of these input was performed as recommended by the Peer Review Panel. Fig. 2.2, 2.3, 2.4 and 2.5 are typical subjective zonation inputs given by two S-experts.

The above described process of experts elicitation took approximately two (2) years, during the second year of which a large part of the S-panel was also involved in other ongoing projects, such as the Energy Power Research Institute's (EPRI) project, (King and Stepp [7] and [8], whose purpose is similar to the SHC. Very minor changes occurred in the experts' opinions between the beginning of the elicitation process and their final responses. In addition, the experts who had also participated in the SEP showed a great deal of stability.

2.1.2 Elicitation of Experts' Opinion on Ground Motion

A catalogue of available ground motion models was assembled and was provided to the experts of the G-Panel, together with a detailed description and comparison of the models.

After one iteration in the elicitation feedback process (see fig. 2.1), the G-experts were asked to select a set of models appropriate for use in each of the four regions of the EUS (i.e., New England, Southeast, North Central and South Central), and to assign a level of confidence on each model. The PGA models selected by two of the experts are displayed in Fig. 2.6 to 2.10. In addition, the experts were asked to evaluate three different methods of accounting for local site characterics, by assigning a level of confidence to each method. The three methods considered here, excluded the complete site specific state-of-the-art type of analysis and was more directed toward a generic type of simple analyses since it will eventually be applied to a large number of sites.

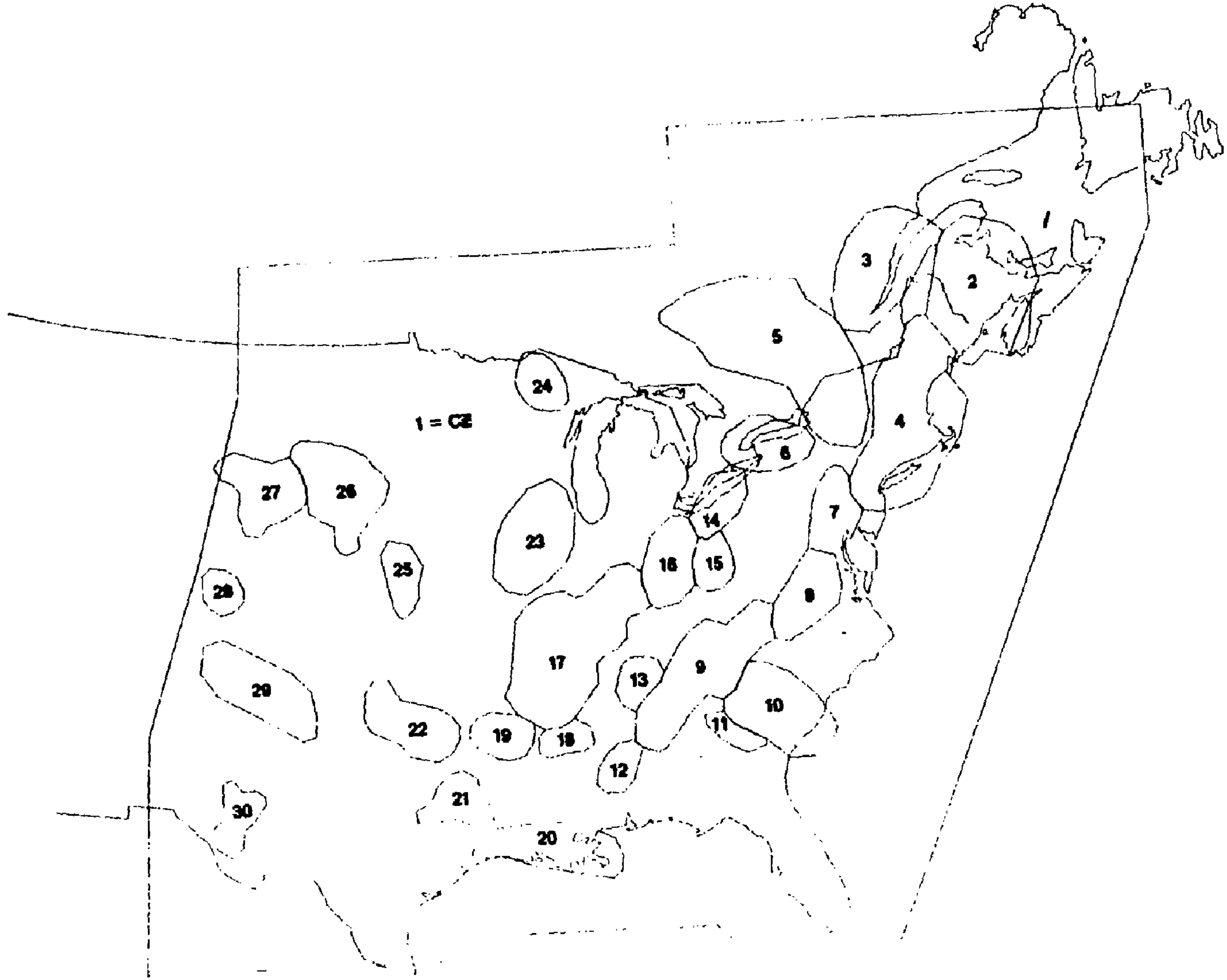


Figure 2.2 Seismic zonation base map for Expert 6.

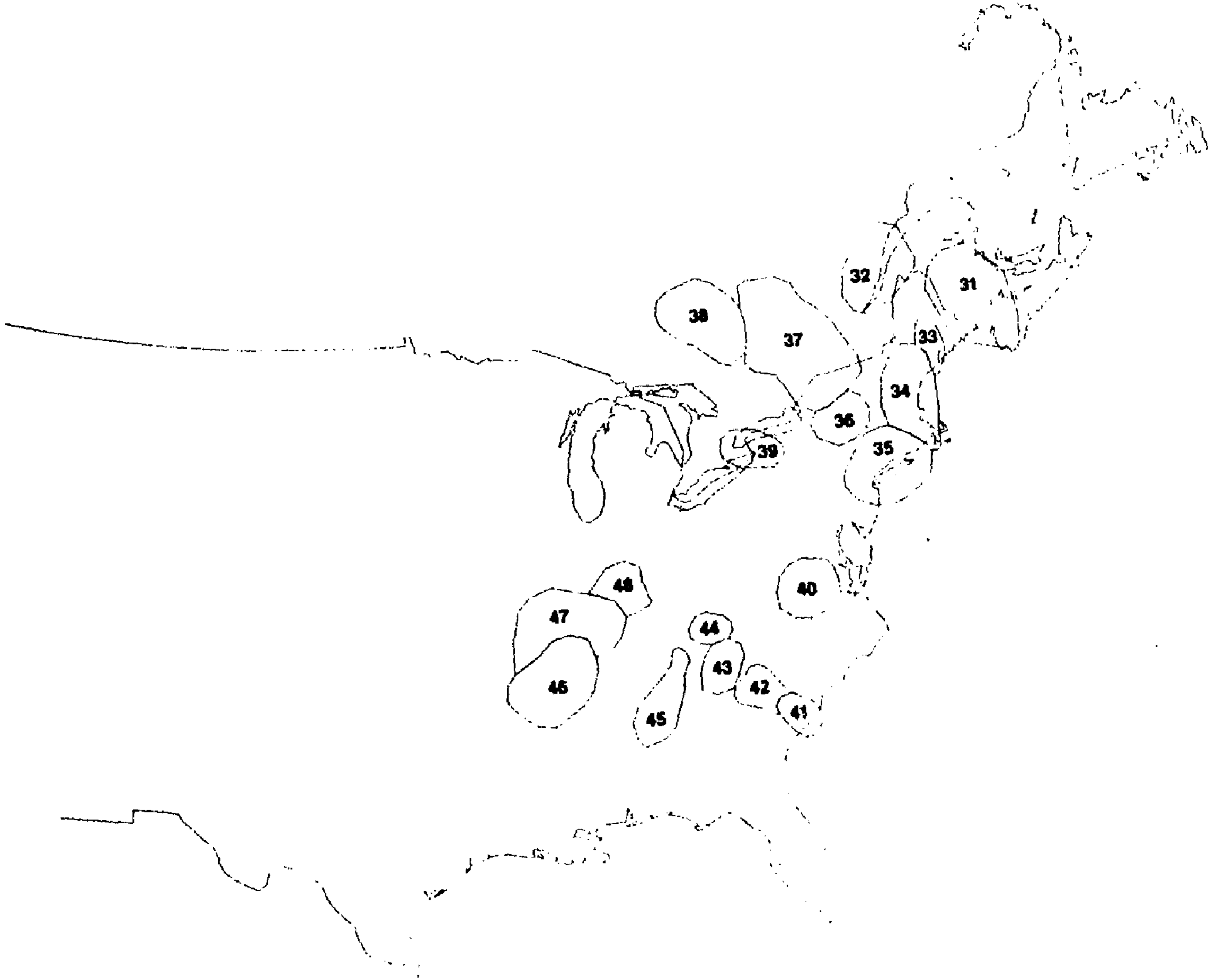


Figure 2.3 Map of alternative seismic zonations to Expert 6's base map.

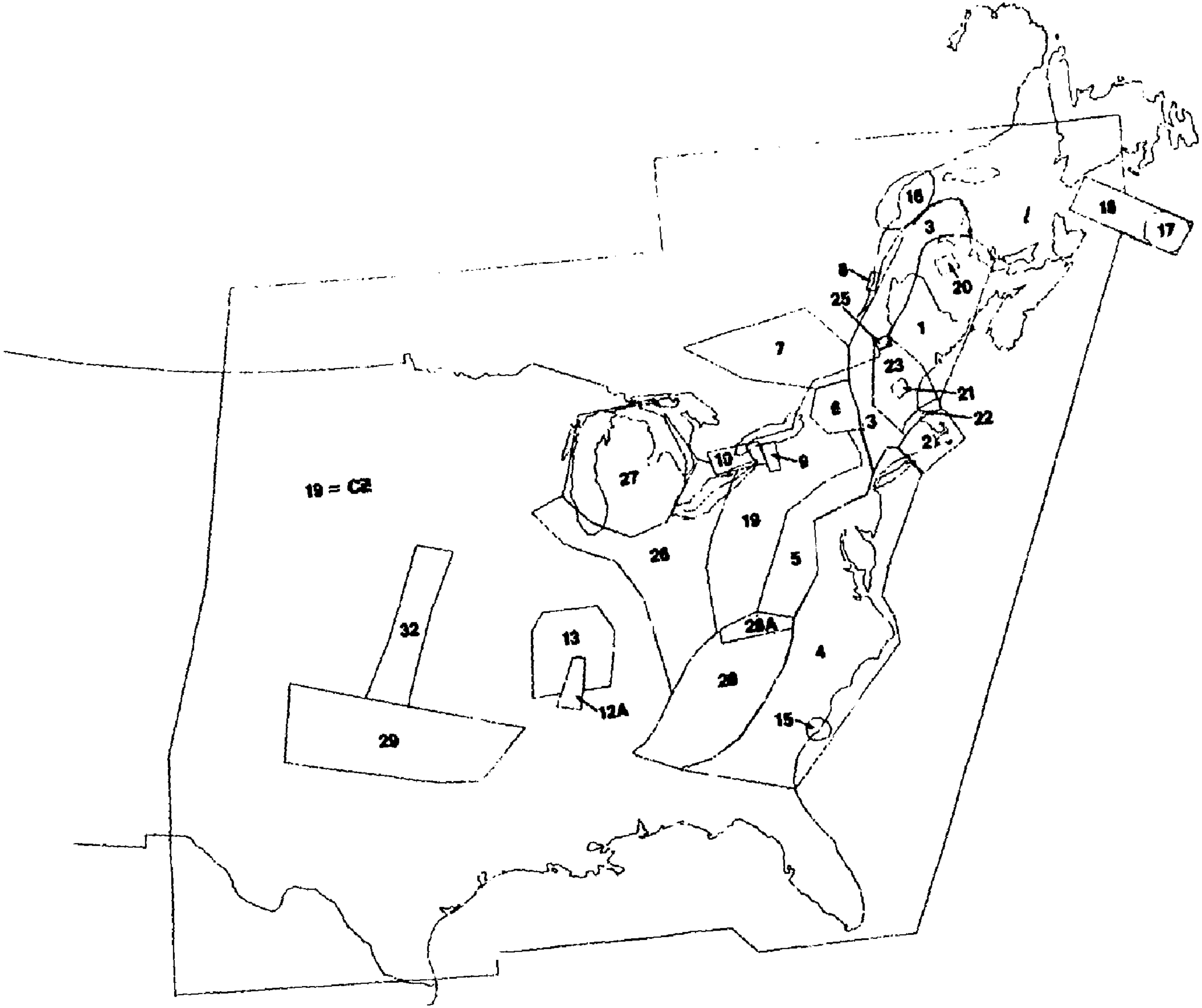


Figure 2.4 Seismic zonation base map for Expert 10.

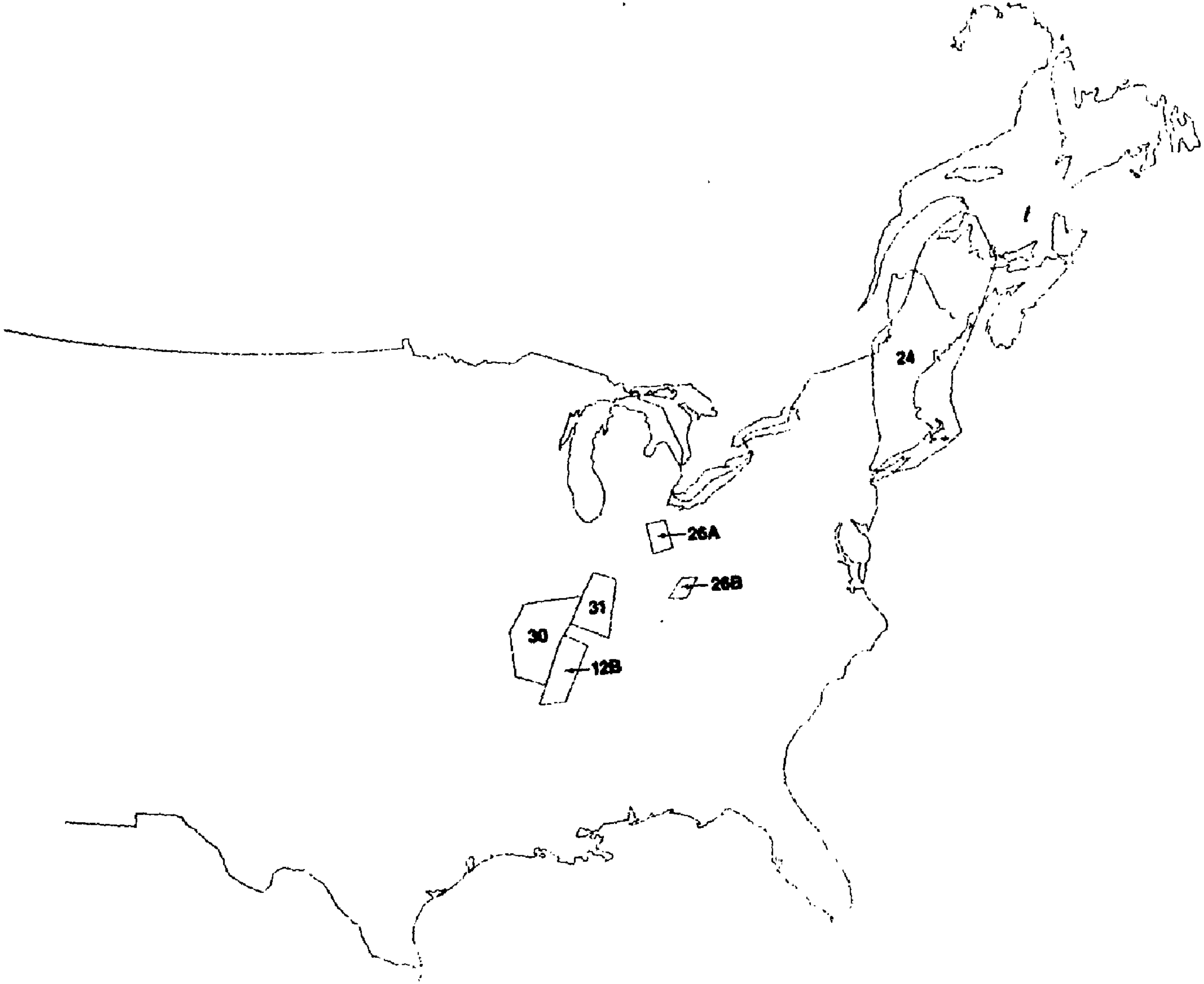


Figure 2.5 Map of alternative seismic zonations to Expert 10's base map.

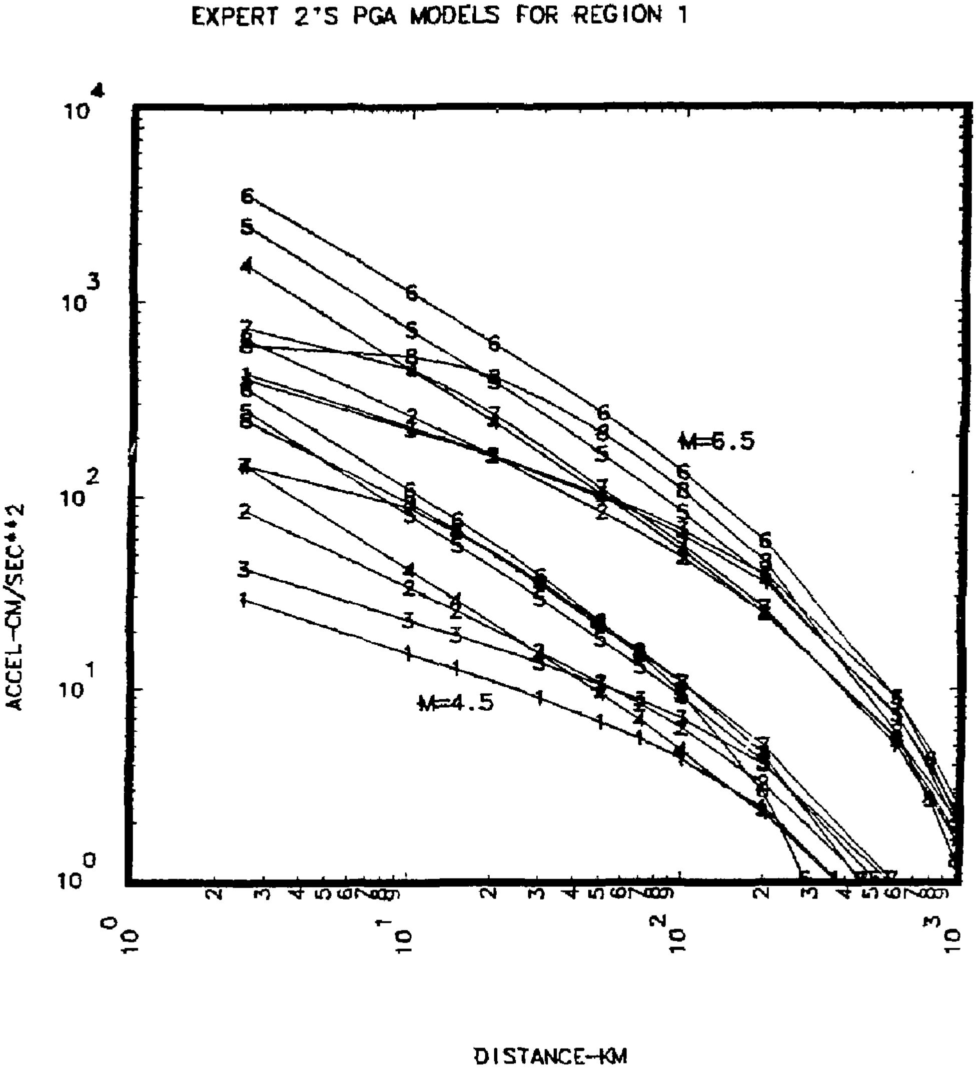

EXPERT 2'S PGA MODELS FOR REGION 1
ACCEL-CM/SEC**2
DISTANCE-KM
M=6.5
M=4.5

Figure 2.6

EXPERT 2'S PGA MODELS FOR REGION 2

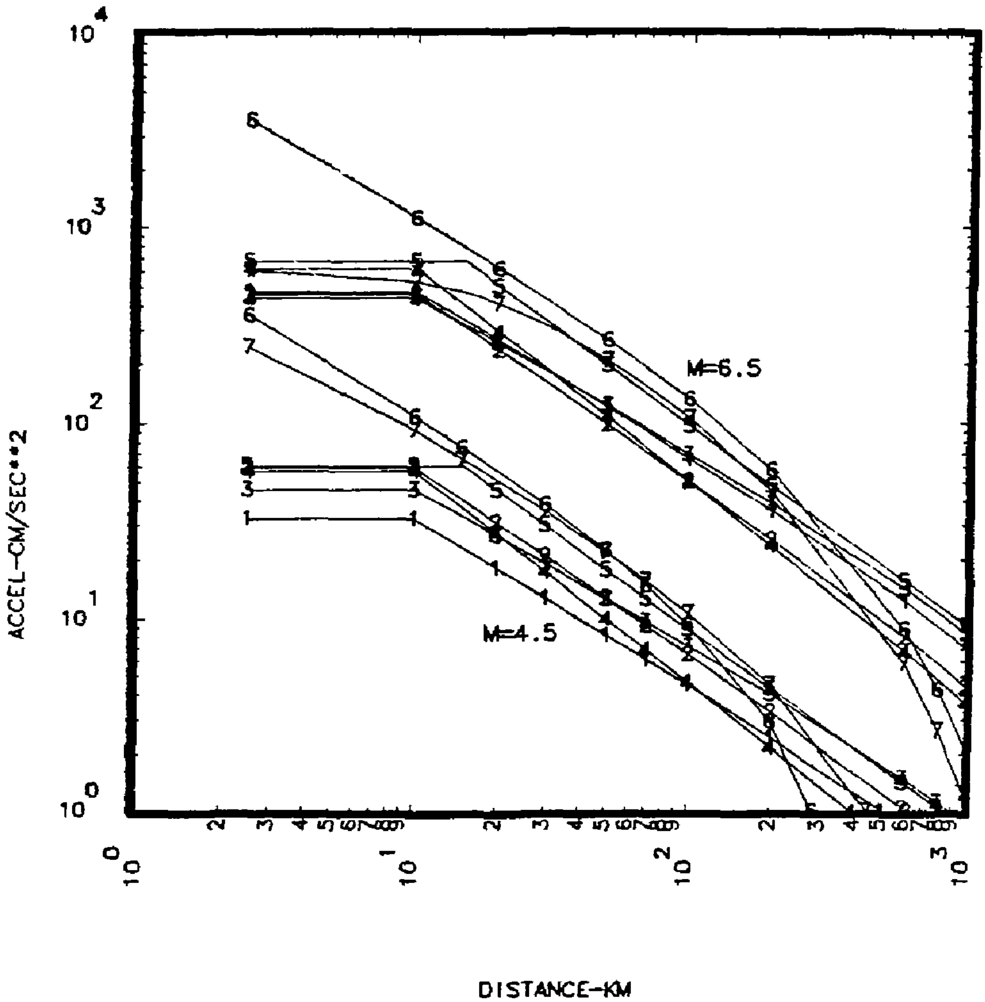


Figure 2.7

EXPERT 2'S PGA MODELS FOR REGION 3

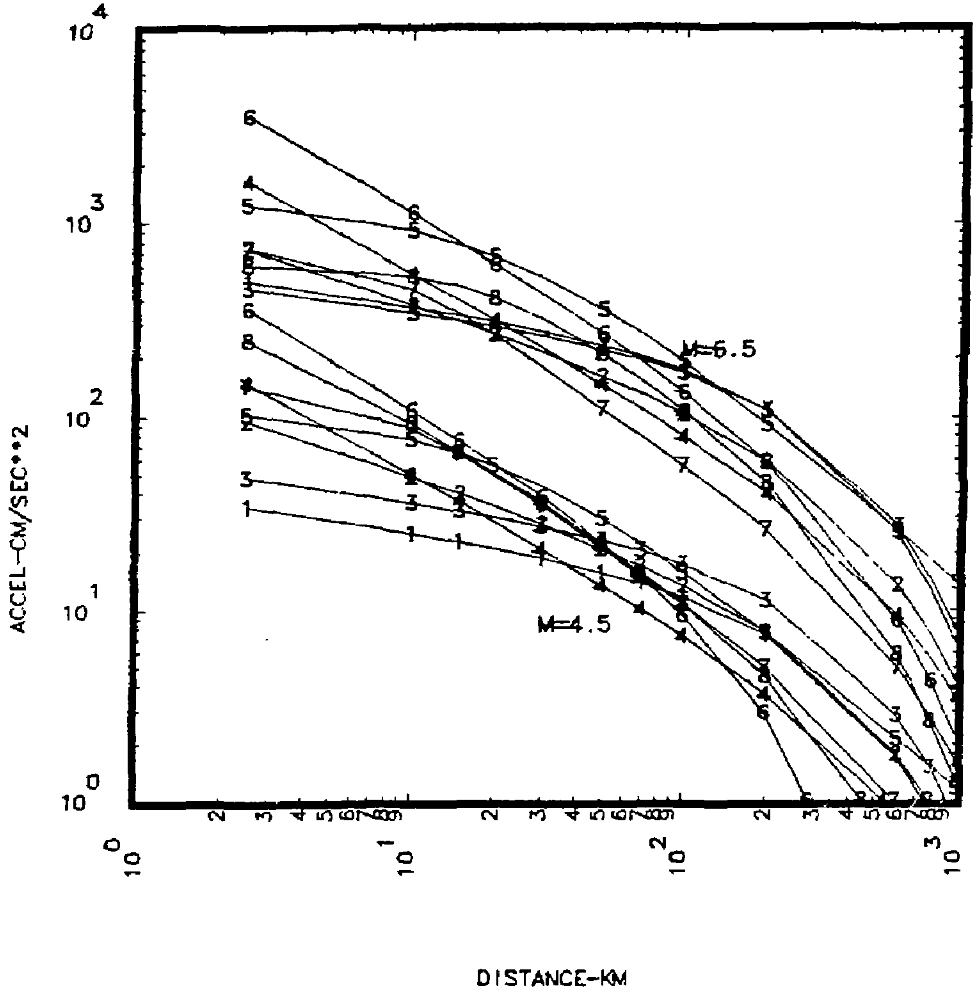


Figure 2.8

EXPERT 2'S PGA MODELS FOR REGION 4

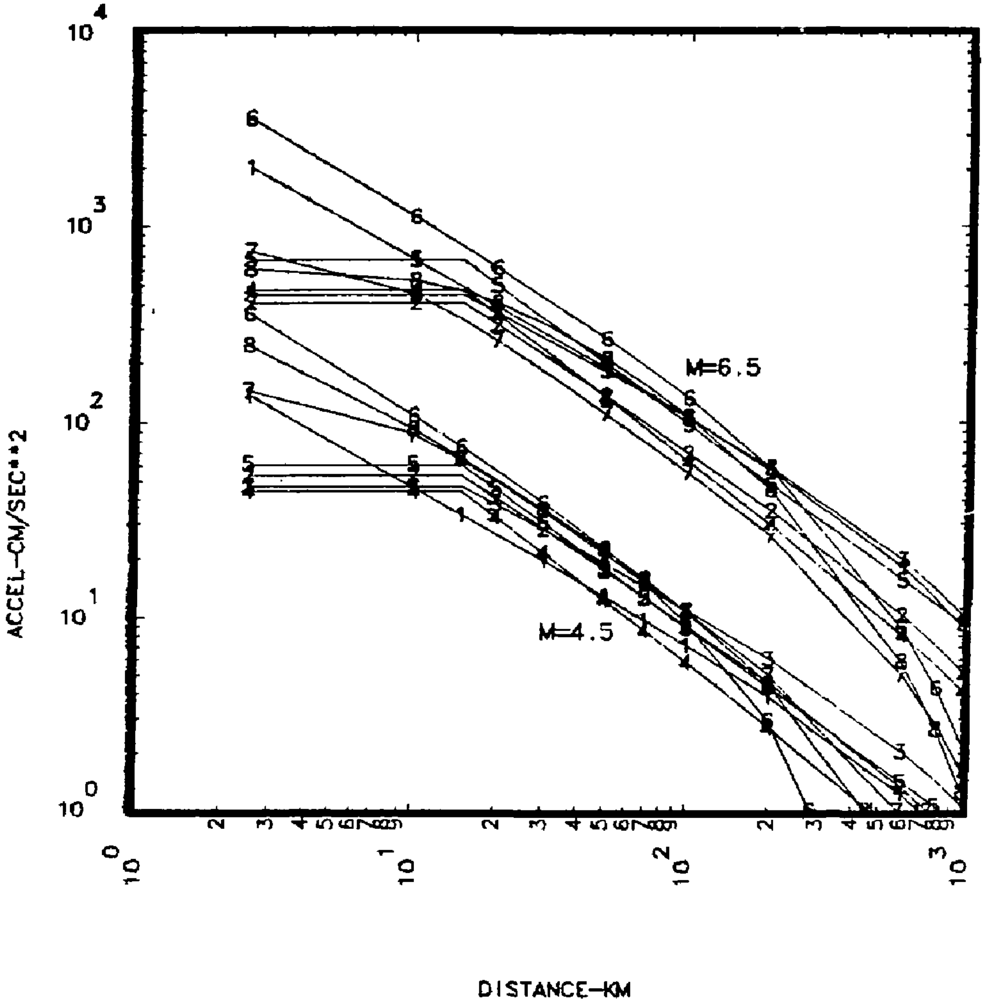


Figure 2.9

EXPERT 4'S PGA MODELS FOR ALL REGIONS

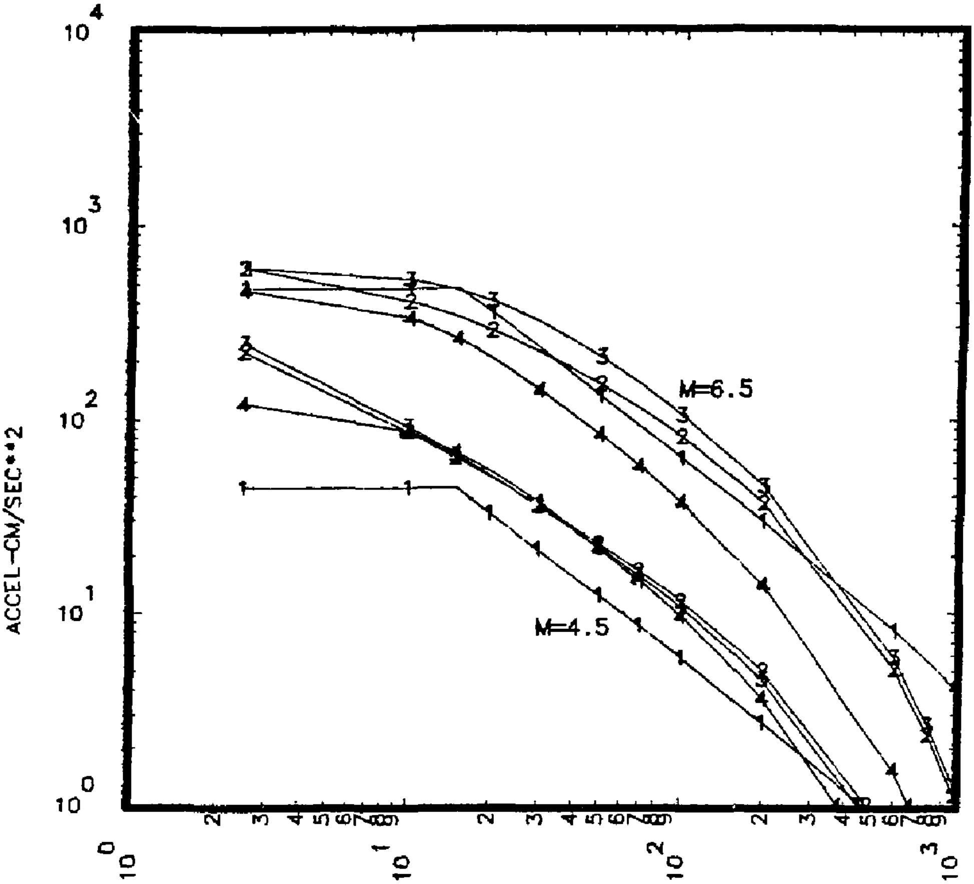


Figure 2.10

2.1.3 Weighting of the Experts Opinion

There are many possible ways of combining expert opinion. In this study we limited ourselves to using the self weights provided by the experts, where the self weighting was done relative to the scientific community at large. These weights were then used to compute a weighted distribution of the hazard, as described below.

2.2 Calculation of the Hazard

2.2.1 The Simulation Approach

Considerable effort went into developing a methodology, which accounts for systematic as well as random uncertainty. We adopted a Monte Carlo simulation technique where the continuous values of the random variables were drawn from simple continuous probability density function such as lognormal or triangular. The ground motion models selected in each simulation were drawn from the catalogues of models to which the G-experts had assigned weights. (normalized weights were used as probability densities and the maps were drawn from this "distribution of maps"). Hence, for a couple of S-G experts, prior to combining over all G-experts (i.e. for a single S-expert) and over all S and G experts, a typical simulation is as follows:

- o Draw a map from the distribution of maps for this S-expert
- o For each one of the N seismic sources in the sample map, draw a set of seismicity parameters from their respective distribution. i.e.:
  - a value for the a parameter of the recurrence law
  - a value for the b parameter of the recurrence law (b is allowed to have three levels of correlation with a as is specifed by the S-expert in response to the questionnaire)
  - the upper value of the magnitude (or intensity) cutoff
- o Draw a ground motion model from the distribution of models
- o Draw a value for the random uncertainty parameter which is associated with the selected ground motion, for the appropriate EUS region (NE,SE,NC or SC)
- o Draw a site correction method

The hazard is calculated for each of the N seismic sources and combined over sources.

2.2.2 The Hazard Model

The hazard is expressed in terms of the probability of exceedence of the ground motion parameter A i.e. the peak ground acceleration,(PGA) or the pseudo relative velocity (PSV). For a single source i, it is expressed in the usual fashion (Cornell, [9])by the equation:

$$P_i \; (A>a) = \int_m \int_r P_i \quad (A > a \mid m, r) \;\; f_{R_i}(r) \quad f_{M_i}(m) \;\; dm \; dr \tag{1}$$

In this equation, $P_i(A \; a \; m,r)$ is the probability that A at the site is greater than a, given that an earthquake of magnitude m has occurred at distance r from the site in zone i. It is a function of the ground motion model and therfore depends on the region hosting the site. $f_{M_i}(m)$ is the conditionnal frequency of magnitude and depends on the choice of model of earthquake recurrence and its parameters for zone i. The recurrence models selected by the experts were:

- *the truncated exponential model for the all range of possible magnitude* (or intensity) values. (Weickert, [10])
- a piece-wise exponential model with two pieces in the range of magnitude (or intensity) values, or,
- a third model developed by LLNL. In this model, the middle part is purely exponential in a range of magnitude (or intensity) specified by the S-expert and the endtail is determined arbitrarily with the restriction that it satisfies conditions of continuity and that the probability of and event of magnitude (or intensity) equal to the cutoff be zero. Under careful analysis, this model implies that there is a magnitude range, near the upper magnitude cutoff where earthquakes are more frequent than at lower magnitudes. This is a concept similar to the concept of characteristic earthquake and the experts who selected it were made aware of this characteristic.

f_{R_i} (r) is the density function for the distribution of *distances from the site to a random* source in the source zone i. It is a function of the shape of source zone i, and its distance from the site. This definition of the distance was chosen over others (i.e., distance to the closest point on the surface trace or shortest distance to the fault surface, Joyner and Boore [11], Campbell [12]because, to date it has been difficult to identify the fault surfaces responsible for the seismicity of the EUS. Thus, in any given *seismic zone the events are assumed to occur any place at random in the zone. This* assumption was emphasized to the G-experts who were asked to factor its consequences in their selection of the ground motion models and their associated weights.

Evaluation of eq. (1) for source i gives the total probability that the ground motion A of amplitude a will be exceeded, given an earthquake in source i.

The occurrence of earthquakes is assumed to follow a Poisson process. Thus the expected number of exceedences is equal of the sum of the probability for each source multiplied by the mean activity rate for each source, and the hazard from all source zones is:

$$P(A > a) = 1 - \exp\left[-(\text{total number of exceedences of amplitude } a)\right] \qquad (2)$$

2.2.3 Aggregation of Expert Opinions

In order to retain the diversity of opinion that might have existed between the experts, the hazard was evaluated for every pair of S and G experts and combined over all pairs. The method for combining the individual results is based on a weighted average of the individual hazard curves or uncertainty distributions. The weights for the G-experts are the normalized values of the self weights. The weights for the S-experts are themselves a weighted average of the four regional self weights provided by the experts.

$$w_s = \sum_k w_{sk} \; P \; (A = A_k) \qquad (3)$$

In eq. (3), w_s, is the weight for the S-expert, w_{sk} is the self weight of the expert in the k-th region (k=NE,SE,NC,SC) and $P(A = A_k)$ is the probability that the maximum A at the *site results from an earthquake originating in the k-th region. One appealing feature of this weighting scheme is that it will weight highly an expert whose self weight is high in the region contributing the most to the hazard.*

2.2.4 Results Presented in Report

The results of the hazard analysis presented in the final report are given in terms of the PGA and in terms of Uniform Hazard Velocity Response spectra. For both parameters a "Best Estimate" and the 15th, 50th and 85th percentiles hazard curves are presented. Where the "Best Estimate" is in actuality the hazard obtained by setting the values of all the random variables equal to the best estimate given by the experts. The results were presented for ten sites approximately uniformly distributed in the EUS, in a report to NRC (in press). A previous report Bernreuter et.al, [5], presented the methodology and the results obtained after the first iteration of experts' elicitation (i.e., before feedback, see Fig. 2.1)

3. SENSITIVITY ANALYSIS

3.1 Introduction

A detailed sensitivity analysis was performed to evaluate the relative importance of the uncertainty in each of the following variables:

- the zonation maps
- the seismicity parameters (a's and b's)
- the upper magnitude cutoffs
- the earthquake recurrence model (LLNL model vs. truncated exponential)
- the ground motion models

3.2 Uncertainty in the Zonation Maps

The sensitivity to the zonation maps is strongly site and expert dependent. For instance a site located in a region of complex zonation configuration such as NE shows more uncertainty from the maps than a site located in a stable region. This parameter was examined by setting all the random parameters equal to their best estimate except for the maps, and using one ground motion model to eliminate the ground motion modeling uncertainty. A typical set of constant percentile hazard curves (CPHC) for an hypothetical site in the North Central part of the EUS is shown in Fig. 3.1. In this case, the average difference between the 15th and the 85th percentile of the probability of exceedence is in the order of 5 to 10 times. Fig. 3.1 is obtained by combination over all the experts. The uncertainty was larger for some S-experts and much lower for others.

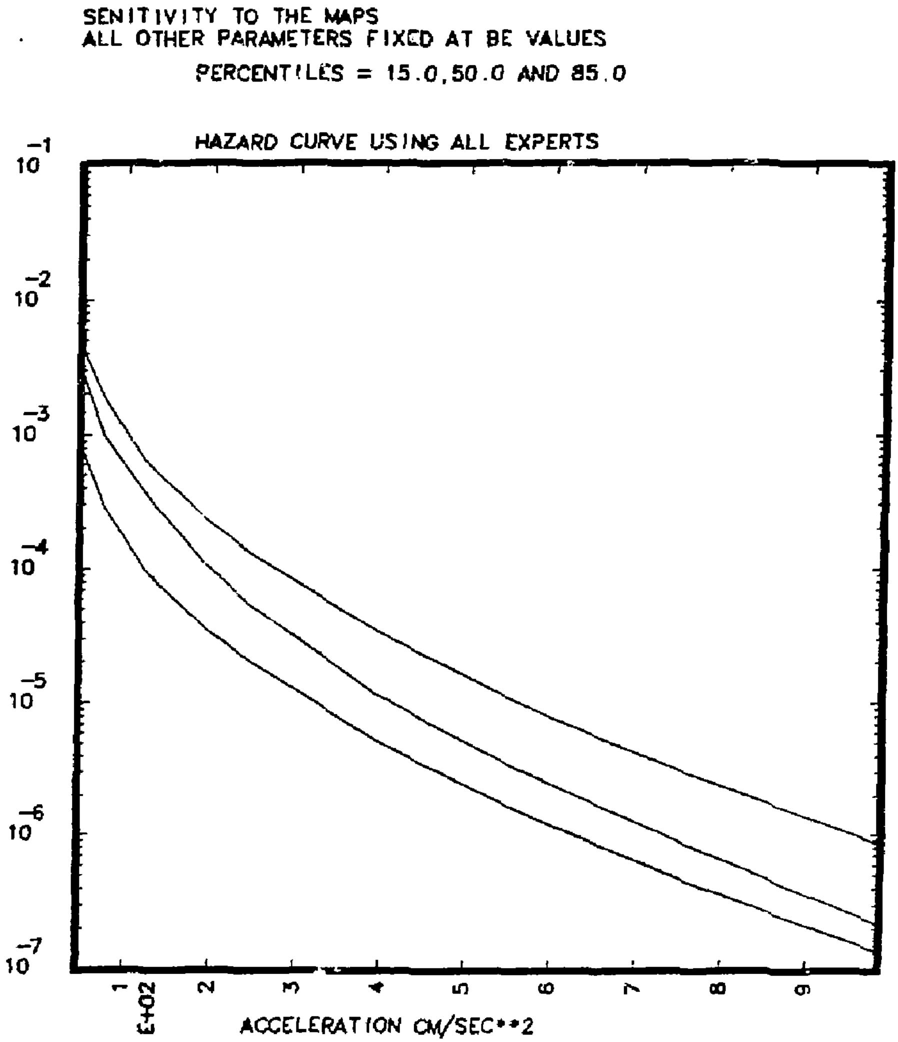

SENITIVITY TO THE MAPS
ALL OTHER PARAMETERS FIXED AT BE VALUES
PERCENTILES = 15.0,50.0 AND 85.0
HAZARD CURVE USING ALL EXPERTS
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
1
2
3
4
5
6
7
8
9
E+02
ACCELERATION CM/SEC**2

Figure 3.1

3.3 Uncertainty in the Seismicity Parameters

In Fig. 3.2, all the parameters, except the a value of the recurrence models are kept equal to their Best Estimate. One ground motion model only is used and the calculation is made for the same hypothetical site of Fig. 3.1. The modeling uncertainty of the earthquake recurrence is included in the result of Fig. 3.2 since the actual model (Truncated exponential or LLNL model) selected by the experts were used.

In Fig. 3.3 only the b parameters are allowed to vary, and in Fig. 3.4 only the upper magnitude cutoffs are simulated. It is seen that the uncertainty is larger for the case were only the parameter b is simulated than for the other two cases. However, the order of magnitude difference between the 15th and the 85th percentile curves is approximately a factor of 10. On the average however, it is noted that the range of variation between between S-experts is smaller with respect to their uncertainty in the seismicity than in their uncertainty in the zonations. i.e., some S-experts have no uncertainty in their zonation and some have a large uncertainty, but they all have some, medium to large uncertainties in their seismicity parameters.

3.4 Uncertainty in the Ground Motion Models

The ground motion experts selected a total of 36 ground motion models of attenuation of the PGA, for the four different regions (NE,SE,NC,SC) and the two scales (Magnitude and Intensity). They selected 23 models of response spectra (for 9 frequencies), three different methods of truncating the ground motion prediction and two types of mathematical models for the random uncertainty. In addition, the experts were allowed to select any method of site correction among three. We present here only the uncertainty in the PGA models and their random uncertainty.

The results shown in Fig. 3.5 were obtained with a single ground motion model and the random uncertainty was included. The standard deviation (SIGMA in Fig. 3.5) is defined by its best estimate of .5 with 5th and 95th percentile of .35 and .65. These are typical values. Fig. 3.5 shows that the order of magnitude of the uncertainty introduced by this parameter is lower than for other parameters in this analysis. By contrast, Fig. 3.6 displays a comparison between the case where all the random parameters are allowed to vary and the case where only the ground motion uncertainty is included (random and modeling). It shows that for this particular hypothetical site the largest part of the uncertainty come from the uncertainty in the ground motion prediction.

SENSITIVITY OF THE HAZARD TO THE A PARAMETER
ALL OTHER PARAMETERS FIXED AT BEST ESTIMATE VALU

PERCENTILES = 15.0,50.0 AND 85.0

HAZARD CURVE USING ALL EXPERTS

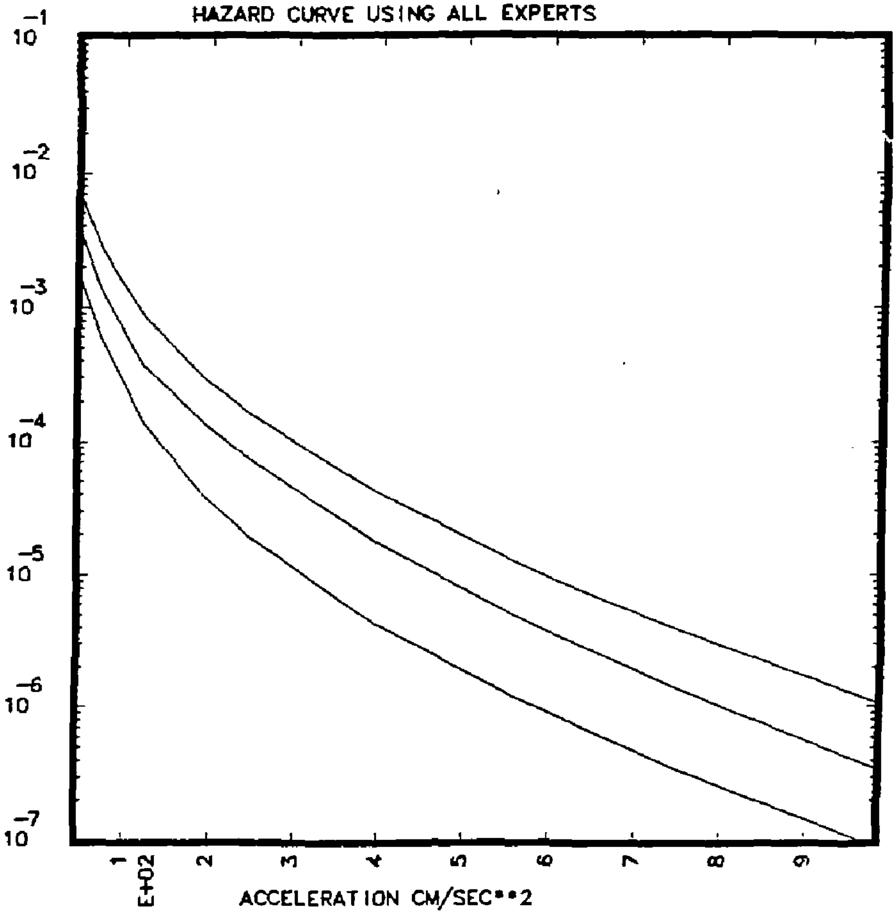


Figure 3.2

SENSITIVITY OF THE HAZARD TO THE B PARAMETER
ALL OTHER PARAMETERS FIXED AT BEST ESTIMATE VALUES

PERCENTILES = 15.0,50.0 AND 85.0

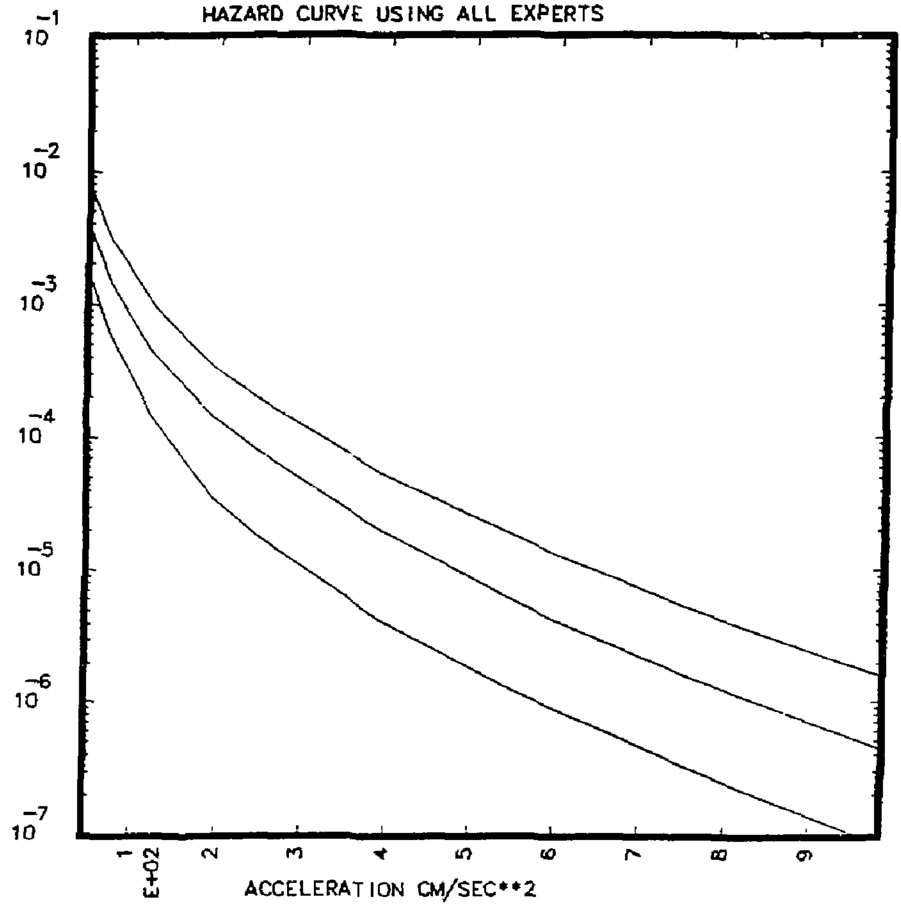
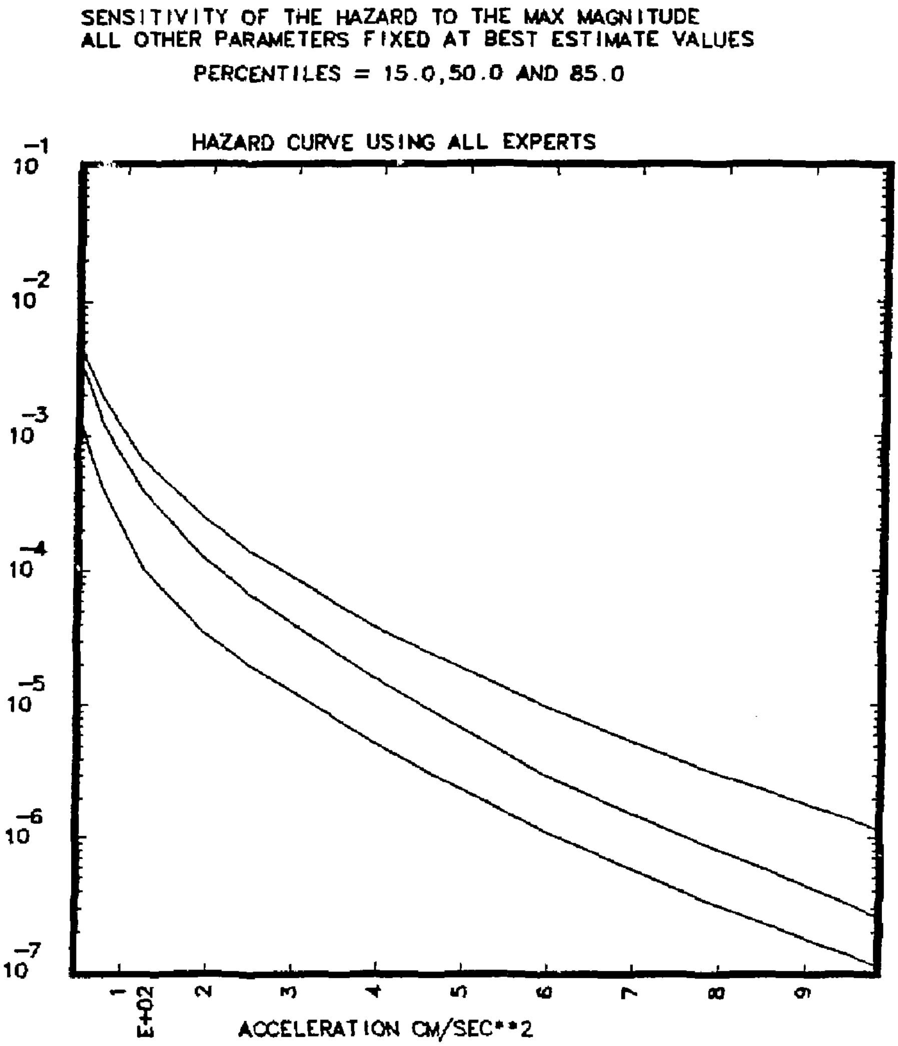


Figure 3.3



SENSITIVITY OF THE HAZARD TO THE MAX MAGNITUDE
ALL OTHER PARAMETERS FIXED AT BEST ESTIMATE VALUES
PERCENTILES = 15.0,50.0 AND 85.0
HAZARD CURVE USING ALL EXPERTS
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
1
E+02
2
3
4
5
6
7
8
9
ACCELERATION CM/SEC**2

Figure 3.4

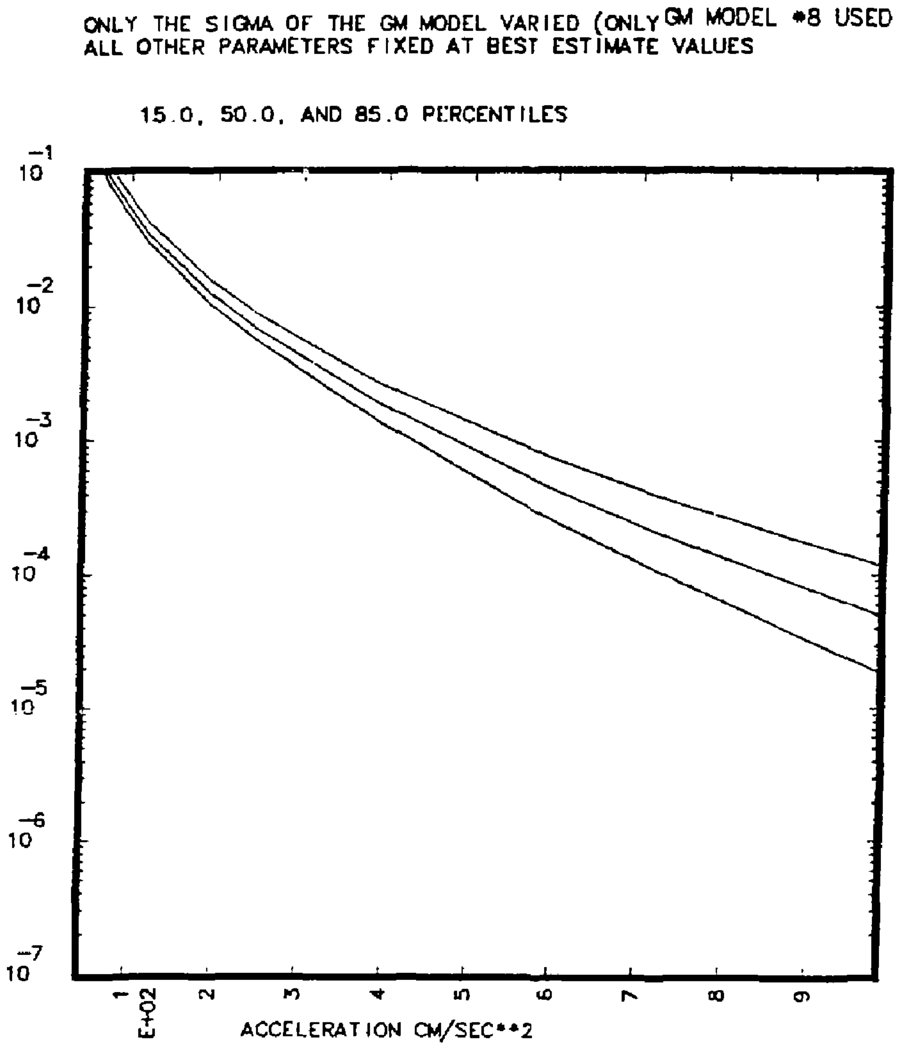

ONLY THE SIGMA OF THE GM MODEL VARIED (ONLY GM MODEL #8 USED
ALL OTHER PARAMETERS FIXED AT BEST ESTIMATE VALUES
15.0, 50.0, AND 85.0 PERCENTILES
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
1
E+02
2
3
4
5
6
7
8
9
ACCELERATION CM/SEC**2

Figure 3.5

THE UNCERTAINTY INTRODUCED BY THE GM MODELS

COMPARISON OF THE FULL SIMULATION CASE TO THE CASE WITH ALL PARAMETERS HELD AT BE VALUES EXCEPT ALL GM MODELS USED—15.,50.&85. PERCENTILES

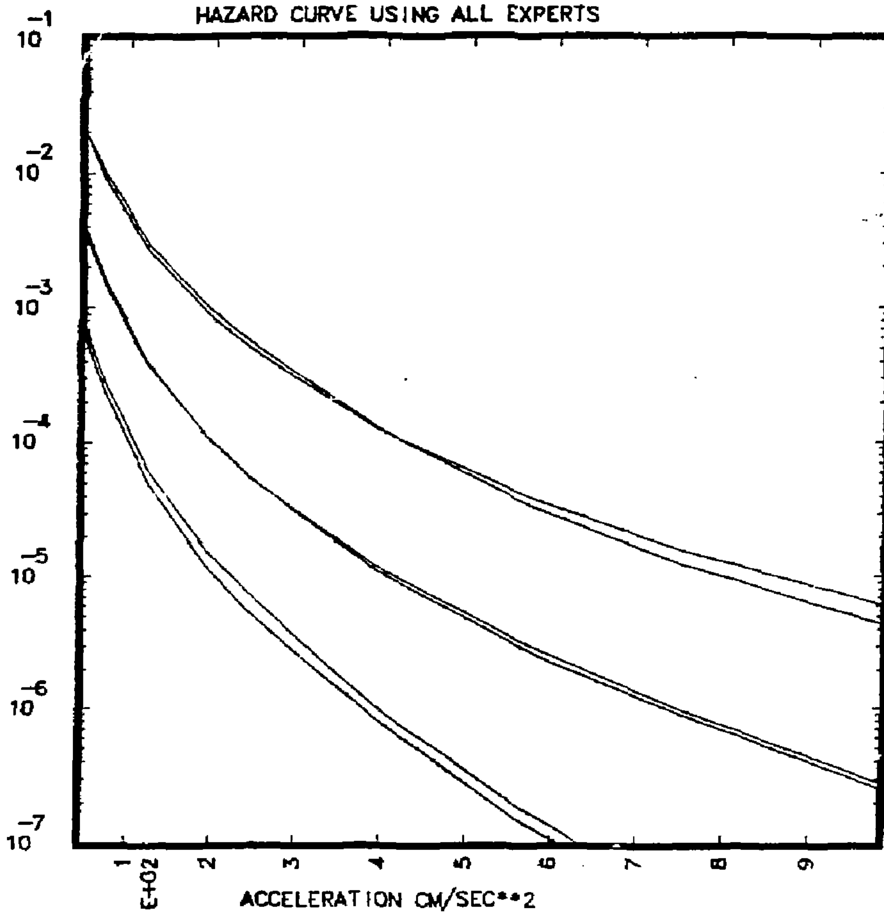


Figure 3.6

3.5 Other Parameters

Other important parameters were investigated in the SHC project, such as the different methods of site correction, the methods of truncation of the ground motion predictions, the methods of correlating the a and b parameters, the type of distribution function to use for the random parameters (lognormal or triangular) and the number of simulations to be used to reach a stable estimate of the uncertainty. In addition, an ongoing study is aimed at doing further sensitivity analysis on some of the remaining parameters. These include the study of the magnitude-intensity correlation, the different ways of assessing the seismicity parameters and an analysis of the weighting scheme.

4. CONCLUSION

We have presented a comprehensive methodology to calculate the Seismic Hazard in the EUS , which uses subjective input from experts and completely quantifies the uncertainty of the results, including random and modeling uncertainty. In general, it appeared that the uncertainty in the ground motion prediction was the largest, with some variation between regions (i.e. site locations) and seismicity experts. The zonations generated somewhat less uncertainty, however more erratic, and the other parameters had approximately the same amount of influence although more uniformly distributed between experts and regions. In general, there was one to two orders of magnitude difference between the 15th and the 85th percentile curves on the probability of the exceedence. These results are consistent with other results of current analyses. It shows that the uncertainty in the seismic hazard prediction is a manageable parameter. A typical final result is shown on Fig. 3.7 for a hypothetical case of a site in the North Central EUS. The complete data base and software packages will be available through NRC.

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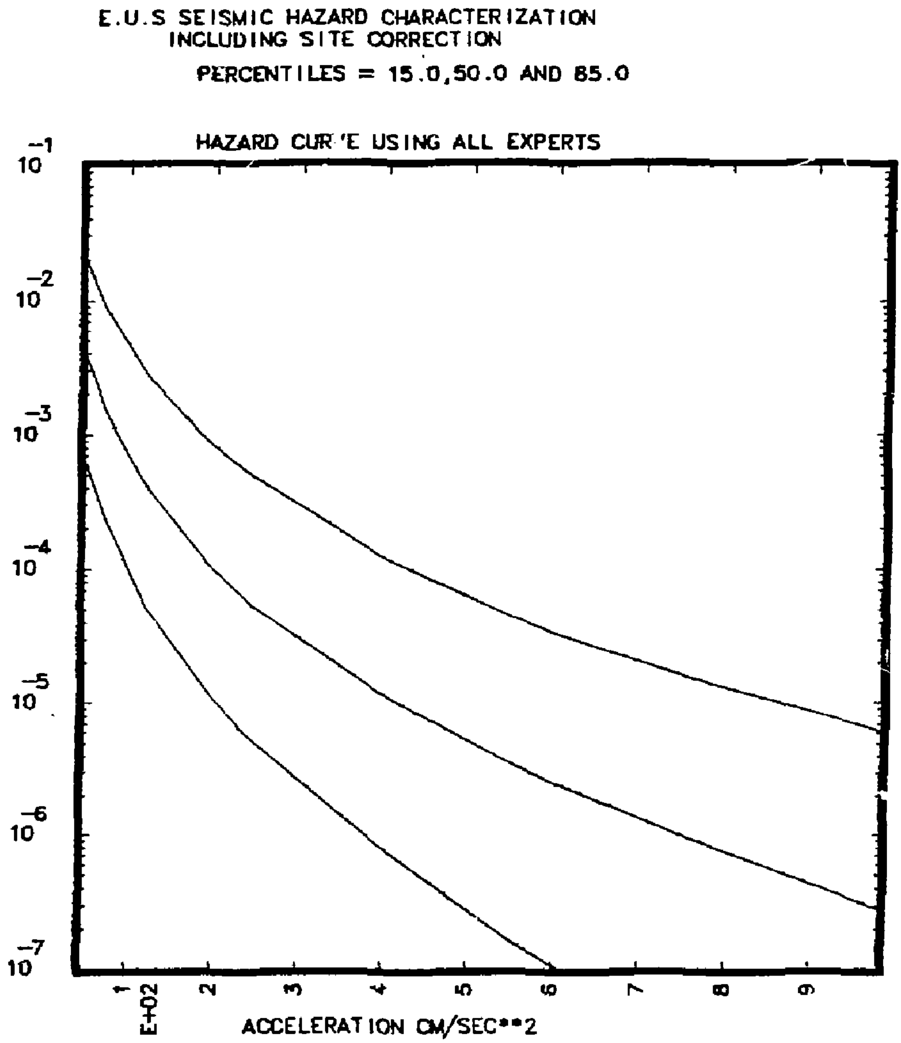
E.U.S SEISMIC HAZARD CHARACTERIZATION
INCLUDING SITE CORRECTION
PERCENTILES = 15.0,50.0 AND 85.0
HAZARD CUR'E USING ALL EXPERTS
10-1
10-2
10-3
10-4
10-5
10-6
10-7
1
2
3
4
5
6
7
8
9
E+02
ACCELERATION CM/SEC**2

Figure 3.7

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APPENDIX D

List of the experts who provided the seismicity and ground-motion input.

1. S-Experts: Seismicity-tectonics

Pr. G. Bollinger	VPI
R. Holt	Weston Geophysical, Boston
Pr. A. Jonston	Univ. of Tennessee
Pr. A. Kafka	Boston College, OBS
Pr. J. Lawson	Univ. of Oklahoma
Pr. T. Long	Georgia-Technology
Pr. O. Nuttli (deceased)	St. Louis University
Dr. P. Pomeroy	Rondout Associates, New York
Dr. C. Stepp	Electric Power Research Institute, Menlo Park, CA
Pr. R. Street	Univ. of Tennessee
Pr. N Toksöz	M.I.T.

2. G-Experts: Ground-motion

Pr. J. G. Anderson	Univ. of Nevada, Reno
Dr. D. Boore	U.S.G.S., Menlo Park, CA.
Dr. K. Campbell	U.S.G.S., Denver
Dr. J. Dwyer	Law Engineering, Atlanta
Pr. M. Trifunac	U.S.C.