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SEISMIC HAZARD CHARACTERIZATION OF THE EASTERN UNITED STATES

Volume 1: METHODOLOGY AND RESULTS FOR TEN SITES

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ABSTRACT

The EUS Seismic Hazard Characterization Project (SHC) is the outgrowth of an earlier study performed as part of the U.S. Nuclear Regulatory Commission's (NRC) Systematic Evaluation Program (SEP). The objectives of the SHC are: 1) to develop a seismic hazard characterization methodology for the region east of the Rocky Mountains; and 2) the application of the methodology to ten sites to assist the NRC staff in their assessment of the implications in the clarification of the U.S. Geological Survey (USGS) position on the Charleston earthquake.

As in the SEP, the fundamental characteristic of the methodology used in SHC consists in using opinions for all the input data. The most important improvement over the methodology used in the SEP leads to an estimate of the distribution of the hazard rather than just point estimates. An important aspect of eliciting expert opinion consists in holding feedback meetings in order to fine tune the methodology and the input data. Estimates of the hazard peak ground acceleration and spectral velocity at ten representative sites are discussed including a sensitivity analysis and a comparison with the SEP results at four sites. The methodology and the data were analyzed by a panel of experts in a formal peer review process to identify the weak points in the analysis and recommend improvements.

The results were also compared with results obtained by using other methodologies such as the "Historical" method and other zonation and seismicity data provided by USGS.

The method developed in this project leads to stable results in good agreement with other methods.

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A large portion of the software programming was performed by Larry Golen of the Lawrence Livermore National Laboratory Computations group and many secretarial persons spent long hours on this report. In this regard, a special thank you goes to Sherry Christensen and Sue Aubuchon.

LIST OF ABBREVIATIONS

A	Symbol* for seismicity expert Number 10
ALEAS	Computer code to compute the BE Hazard and the CP Hazard for each seismicity expert.
AMHC	Arithmetic Mean Hazard Curve
B	Symbol* for seismicity expert Number 11
BE	Best Estimate
BEHC	Best Estimate Hazard Curve
BEM	Best Estimate Map
BEUHS	Best Estimate Uniform Hazard Spectrum
BR	Braidwood
C	Symbol* for seismicity expert Number 12
COMAP	Computer code to generate the set of all alternative maps and the discrete probability density of maps.
COMB	Computer code to combine BE Hazard and CP Hazard over all seismicity experts.
CP	Constant Percentile
CPHC	Constant Percentile Hazard Curve
CPUHS	Constant Percentile Uniform Hazard Spectrum
CUS	Central United States
CZ	Complementary Zone
D	Symbol* for seismicity expert Number 13
EUS	Eastern United States
GMEj	j-th member of the Ground Motion Panel
GMHC	Geometric Mean Hazard Curve
GMP	Ground Motion Panel
HC	Hazard Curve
LB	Lower Bound
LC	La Crosse
LI	Limerick
MI	Millstone
MY	Maine Yankee
PGA	Peak Ground Acceleration
PGV	Peak Ground Velocity
PRD	Computer code to compute the probability distribution of epicentral distances to the site.
PSV	Pseudo Relative Velocity
Q1	Questionnaire 1- Zonation
Q2	Questionnaire 2 - Seismicity
Q3	Questionnaire 3 - Regional Self Weights
Q4	Questionnaire 4 - Ground Motion Models
Q5	Questionnaire 5 - Feedback on Zonation and Seismicity
Q6	Questionnaire 6 - Feedback on Ground Motion Models

* These symbols are used as identifiers in the figures of Section 5

RB	River Bend
RP	Return Period
SEP	Systematic Evaluation Program
SH	Shearon Harris
SHC	Seismic Hazard Characterization
SZP	Seismicity/Zonation Panel
UB	Upper Bound
UHS	Uniform Hazard Spectrum
VO	Vogtle
WB	Watts Bar
WC	Wolf Creek
ZSE_i	i-th member of the zonation-seismicity panel

* These symbols are used as identifiers in the figures of Section 5

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SECTION 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 in 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 USGS clarification was finally issued on November 18, 1982, in a letter to the NRC, which states that:

> "Because the geologic and tectonic features of the Charleston region are similar to those in other regions of the eastern seaboard, we conclude that although there is no recent or historical evidence that other regions have experienced strong earthquakes, the historical record is not, of itself, sufficient ground for ruling out the occurrence in these other regions of strong seismic ground motions similar to those experienced near Charleston in 1886. Although the probability of strong ground motion due to an earthquake in any given year at a particular location in the eastern seaboard may be very low, deterministic and probabilistic evaluations of the seismic hazard should be made for individual sites in the eastern seaboard to establish the seismic engineering parameters for critical facilities."

Anticipation of this letter led the Office of Nuclear Reactor Regulation to jointly fund this project with the Office of Nuclear Regulatory Research. The objectives of this program are:

1. to develop a seismic hazard characterization methodology for the entire region of the United States east of the Rocky Mountains (Referred to as EUS in this report).

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 eastern U.S. earthquakes in New Brunswick and New Hampshire.

The methodology used in this study evolved from two earlier studies LLNL performed for the NRC. One study, Bernreuter and Minichino (1983), 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.

To fulfill NRC's current needs, 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 methodology.

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

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

In this study, as in the SEP study, extensive use is made of expert judgment to obtain the seismicity data required to perform a seismic hazard analysis at any site in the EUS. We have incorporated a number of important improvements suggested by the SEP Peer Review Panel and other reviewers (Bernreuter, 1981b). The most important improvements are:

- The Seismicity Panel was expanded to ensure that there were experts from all regions of the EUS on the panel.

- Uncertainty in zonation is accounted for by considering up to 30 different combinations of maps per expert (see Section 2.4)

- Each expert provided all of the seismicity parameters needed for the hazard analysis.

- The members of the EUS Ground Motion Modeling Panel provided a ranking of the various EUS ground motion models. They also selected methods to correct for the effect of the depth and type of soil at each site on the expected ground motion.

- Our hazard analysis software was extensively rewritten so that the experts could be given considerable flexibility in the format for expressing their opinions about seismicity and a complete uncertainty analysis could be performed for each pair of seismicity and ground motion experts.

As in the SEP study, the analysis was performed for each seismicity expert independently and the opinions of the experts were only combined at the final step using the regional self weights supplied by the panel members.

This report is just one element of NRC's overall approach to address the Charleston issue raised by the USGS. In this study we attempt to provide a representative sample of expert judgment about the seismotectonic parameters that influence the estimates of the seismic hazard, in the form of strong shaking induced by future earthquakes, at particular sites. We formed appropriate panels of experts and initiated an extensive elicitation process asking them to use all of the known data, theory and their personal insights to respond to our questionnaires. Using this data we performed a complete seismic hazard analysis for ten sites. These results and extensive discussion of the methodology, Bernreuter et al. (1984), were then fed back to the panel members. This provided the panel members with an opportunity to review the implications of their input judgments and to refine any aspects which they felt were unrealistic.

The results presented in this report are based on the updated responses by our panel members from both the Seismicity and Ground Motion Panels. In this sense they are final results. However, as judgment plays a very significant role in developing the input data, it is possible, considering the significant uncertainties included in the analysis, that in the future various experts will modify their views thus leading to results which may differ from those presented here.

It should be noted that we have also updated our methodology from that discussed in Bernreuter et al. (1984). In particular, the revised method allows the experts to select the truncated exponential distribution and to include correlation between their estimates of the parameters of the distribution for the magnitudes of earthquakes for each zone. Further, the revisions include improved simulation methods, allowance for truncation of the maximum ground motion, and corrections to account for the effect that soil conditions, at a site, have on the expected ground motion.

We have attempted to keep this report self contained at the expense of repeating some of the discussion, data and results given in Bernreuter et al. (1984). In addition, we have split this report into two volumes. Volume 1 contains the discussion of methodology, results and necessary input data. Volume 2 contains all of the questionnaires and reports provided to our panels.

SECTION 2: METHODOLOGY

2.1 Overview

The methodology used in this study differs from other studies in several ways. One of the major differences is the formal approach we use to elicit expert opinion and incorporate it into the analaysis. This element is similar to the SEP methodology and discussed in Section 2.2. Another major difference is in the attention given the difference between random and modeling uncertainty, as well as inclusion of uncertainty in zonation maps and ground motion models. A third difference is in the way the computer programs have been structured to efficiently perform the uncertainty analysis which includes a distribution of maps from each seismicity expert, distributions for including the uncertainty in each of the seismicity parameters and a distribution of ground motion models for each of the ground motion experts.

To understand how the hazard analysis programs have been structured, it may be helpful to first examine a simplified description of the analysis process. A key step in the evaluation of the seismic hazard at a site is the determination of the annual probability that the Peak Ground Acceleration (PGA) exceeds some level a at the site, i.e., P(A > a), for a given set of zones (one possible map), a set of seismicity parameters for each zone, and a given ground motion model. We can compute P(A > a) for source zone S, for each expert, given that an earthquake has occurred in source zone S, using

$$P_S(A > a) = \int_m \int_r P(A > a \mid m, r)\, f_{M_S}(m)\, f_{R_S}(r)\ dm\, dr\ , \tag{2.1}$$

where $P(A > a \mid m, r)$ is the probability that the acceleration A at the site is greater than a, given that an earthquake of magnitude m has occurred in zone s at a distance r from the site; $P(A > a \mid m, r)$ is a function of the ground motion model. Also, $f_{Ms}(m)$ is the probability density function for the distribution of the magnitudes (or epicentral intensities) of earthquakes in source zone S. Evaluation of this distribution is based on the magnitude-recurrence model and related parameters provided by the panel members. Each expert estimates a separate distribution for each zone for each expert. Finally, $f_{Rs}(r)$ is the density function for the distribution of distances from the site in source zone S and is a function only of the source zone's shape and distance from the site. This distribution is derived from the geometry of the source zones provided by each expert. The integral Eq. 2.1 is evaluated over the range $M_o \leq m \leq M_{SU}$, where M_o is the lowest magnitude considered in the calculation (here 3.75) and M_{SU} is the upper magnitude cut-off in zone S, and the entire range of distances (r) of the site to the source.

Evaluation of Eq. 2.1 for each source zone gives the probability that the PGA at the site will exceed amplitude a, given an earthquake in source zone S. We assume that the earthquake location is uniformly distributed throughout the zone and the occurrence over time is a Possion process. Thus, the expected number of exceedences, i.e. A > a, is the product of the probability, in Eq. 2.1, for each source zone multiplied by the mean activity rate λ_o for the source zone. The total expected number of exceedences is calculated as the sum of expected numbers of exceedences from each source zone. Then the probability, per year, that the PGA due to at least one earthquake, i.e. the probability that the maximum PGA, per year, will exceed amplitude a, is, based on the Poisson assumption:

$$P(A > a) = 1 - \prod_{S} \exp\left[-\lambda_{so} P_s (A > a) \right] \qquad (2.2)$$

To describe the uncertainty in estimating the hazard these equations must be evaluated many times for different ground motion models or different choices of seismicity parameters. Typically, the distribution $f_{Rs}(r)$ would be recomputed for each change in parameters. This is costly, particularly, as in our case, where a Monte Carlo simulation analysis is used. To avoid this we compute the distribution $f_{Rs}(r)$ separately and formulate all possible maps, i.e., sets of $f_{Rs}(r)$ for the zones involved in each map. As discussed in Sections 2.3 and 2.4, this data is part of the input into the actual hazard computation. The hazard analysis and the combination of the seismicity experts is discussed in 2.5. Section 2.2 is a discussion of the process of eliciting the experts' opinions.

2.2 Elicitation of Expert Opinion

A variety of ways in which expert opinion may be elicited were reviewed by Mensing (1981). Our approach, inspired by Mensing, combines several different methods. It is characterized by the following key features: (see Table 2.3)

- o Two panels of experts were formed. (see Tables 2.1 andl 2.2)
- o Detailed questionnaires, requiring several days of effort by the panelist to complete, were distributed.
- o Panel members were generally paid.
- o Follow-up discussions and a feedback meeting were held for each panel.
- o The responses of each panel member were used in a separate hazard analysis and combined at the last step with other experts.
- o The elicitation process and hazard analysis methodology were subject to peer review. (see Section 7)
- o An additional informal feedback loop was performed in finalize the input data.

Our elicitation procedure was based on the experience gained during the SEP study and incorporates suggestions made by both the SEP Peer Review Panel and the SSMRP Panel on Subjective Inputs as well as other reviewers' comments. Two panels were assembled. Fourteen well known geoscientists knowledgeable about the seismicity and tectonics of the Eastern and Central U.S. formed the first panel called the EUS Seismicity Panel (see Table 2.1). Drs. Stevens and Wentworth subsequently resigned from the panel after providing us with their zonation maps. Dr. Basham resigned after providing his seismicity parameters, limited to Canada thus making his data incomplete for use in our analysis. However he participated in the zonation seismicity feedback meeting, providing many useful inputs and generating discussions on the seismicity of Canada and the North East of the United States with the other panel members. The remaining eleven experts provided input to develop the overall earthquake occurrence model. The second panel, referred to as the Ground Motion Modeling Panel, included five members. (see Table 2.2)

As can be seen in the flow chart of Table 2-3, a large amount of interaction, formal and informal, took place between LLNL and the expert panel members. However, at no time during the elicitation were the experts forced or even encouraged to reach a concensus. This study was designed as an expert opinion sampler. It is conceptually different from other current studies, such as the one sponsored by the Electric Power Research Institute, whose goals are to reach a concensus of opinion at some levels in the analysis.

Our goal in eliciting subjective judgment in the manner outlined in Table 2-3 was twofold. First, we believe it would give an accurate representation of the experts' views about parameters that affect seismic hazard. Second, it enables us to retain the diversity of opinion which may exist in the scientific community. Six Questionnaires were designed and sent to the experts in order to collect all the necessary data for the analysis. They are the following:

Questionnaire 1 - Zonation Questionnaire (Q1)
Questionnaire 2 - Seismicity Questionnaire (Q2)
Questionnaire 3 - Questionnaire on Regional Self Weights (Q3)
Questionnaire 4 - Ground Motion Models Questionnaire (Q4)
Questionnaire 5 - Feedback Questionnaire on Zonation/Seismicity (Q5)
Questionnaire 6 - Feedback Questionnaire on Ground Motion Models(Q6)

Questionnaires Q1, Q2, Q3, and Q5 pertain to the panel of experts on zonation and seismicity described in Table 2-1. Q4 and Q6 pertain to the Ground Motion Model Panel described in Table 2-2. A copy of these questionnaires is given in Volume 2 of this report, in the exact form as they were sent to the experts. Q1 through Q5 also appear in the interim report NUREG/CR 3756. Q5 is based on the discussions about the methodology which took place at the feedback meeting with the seismicity panel.

In the following sections, we briefly describe the intent and highlights of Q1 and Q2. In each case we desired not only an expert's opinion regarding the "most probable value" of a parameter but also, whenever possible, a measure of his uncertainty in determining the value of the parameter. Uncertainty distributions were developed through a multistep procedure. For example, for

TABLE 2-1

EUS ZONATION AND SEISMICITY PANEL MEMBERS

Dr. Peter W. Basham[2]

Professor Gilbert A. Bollinger[1]

Mr. Richard J. Holt[1]

Professor Arch C. Johnston

Dr. Alan L. Kafka

Professor James E. Lawson

Professor L. Tim Long[5]

Professor Otto W. Nuttli[1]&[4]

Dr. Paul W. Pomeroy[1]

Dr. J. Carl Stepp

Dr. Anne E. Stevens[3]

Professor Ronald L. Street[1]

Professor M. Nafi Toksöz[1]&[4]

Dr. Carl M. Wentworth[3]

Notes:

(1) Also participated in the SEP Panels

(2) Only provided zones and seismicity parameters for Canada

(3) Only provided zonation--no seismicity parameters

(4) Also member of the Ground Motion Panel (Table 2-2)

(5) Also member of the Peer Review Panel (Table 7-1)

TABLE 2-2

EUS GROUND MOTION MODEL PANEL MEMBERS

David M. Boore[1]

Kenneth Campbell

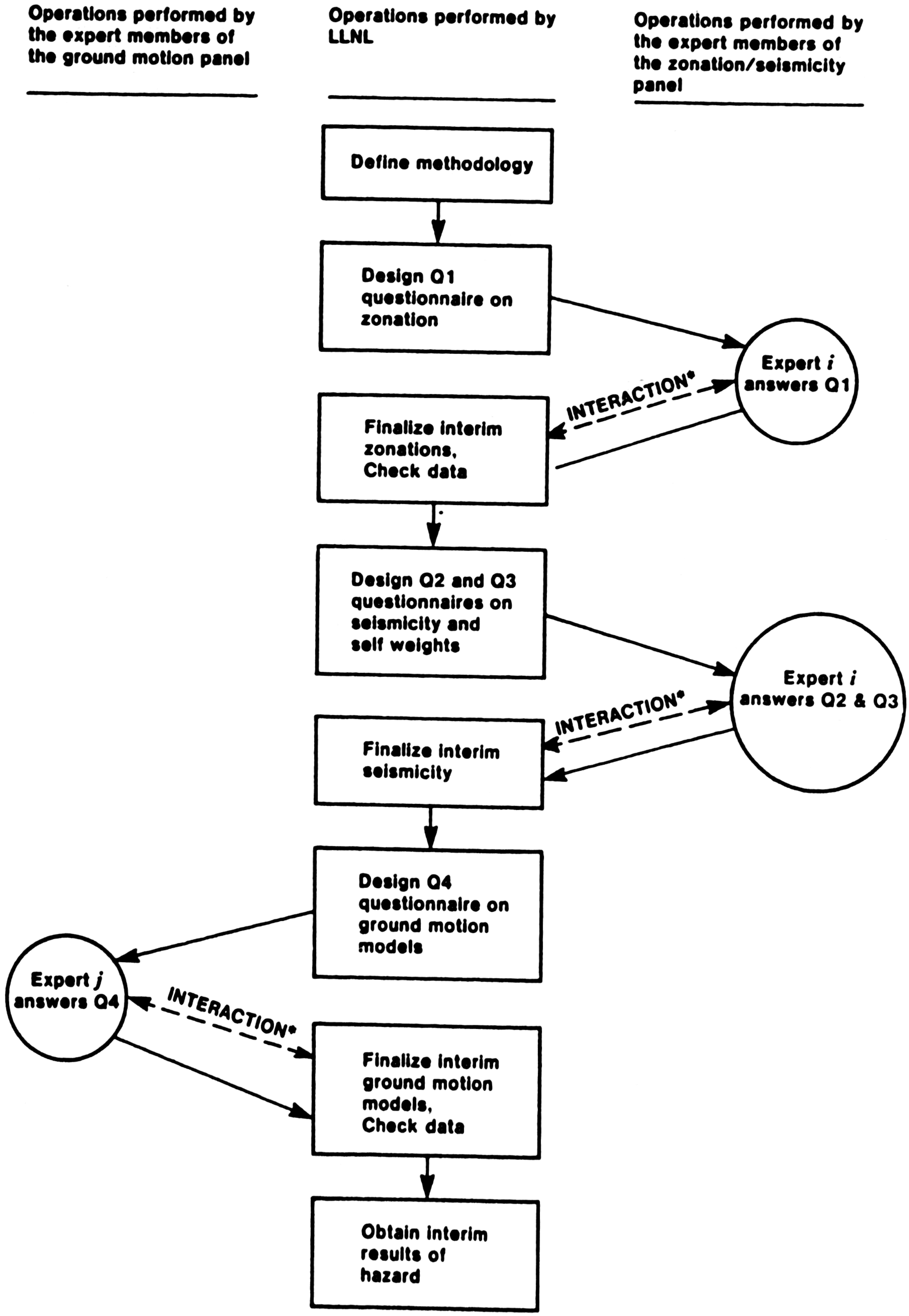
Professor Otto W. Nuttli[1]&[2]

Professor Nafi Toksöz[2]

Professor Mihailo Trifunac[1]

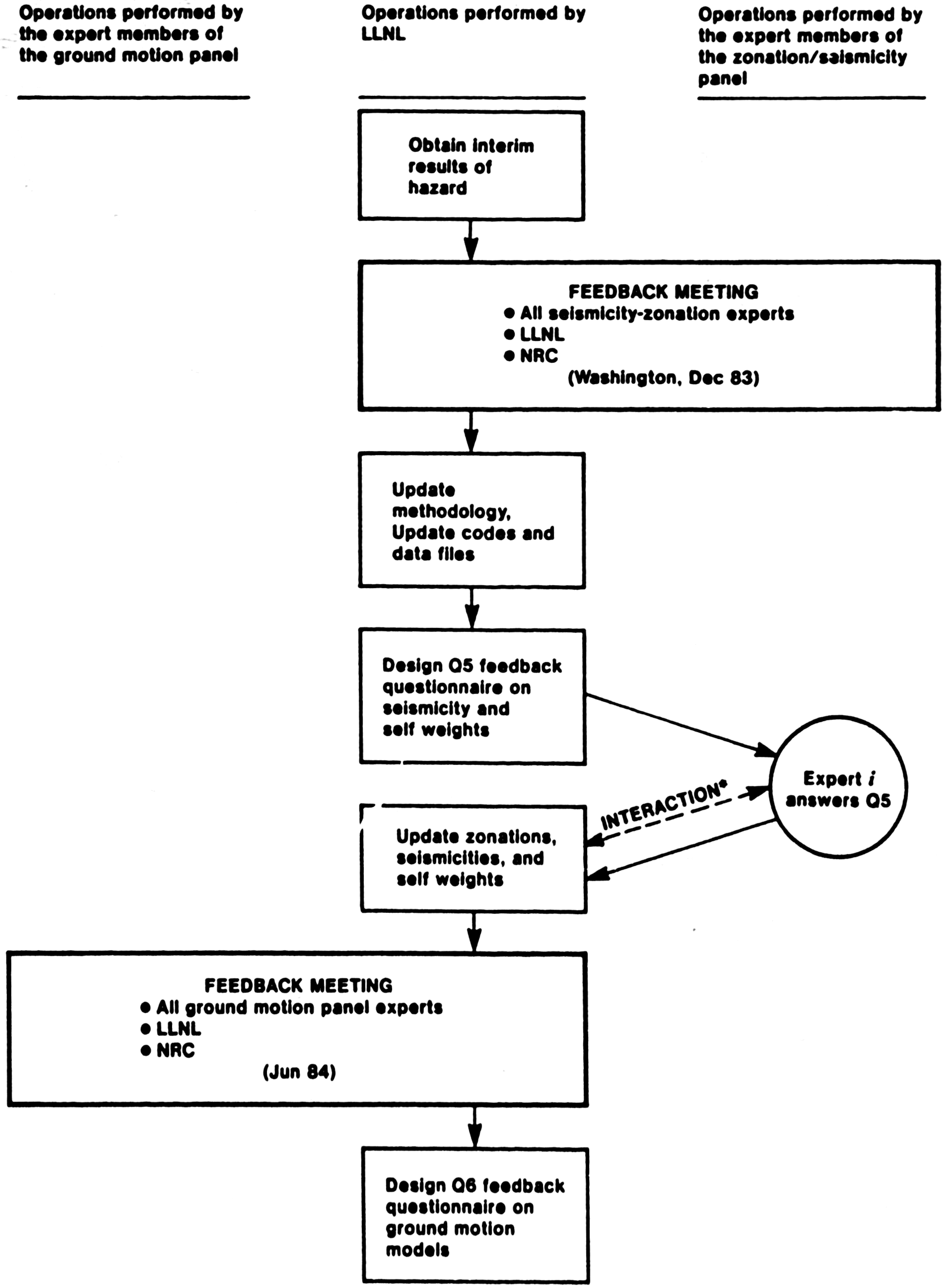
Notes: (1) Participated as a member of the SEP EUS Ground Motion Panel.

(2) Also member of the Seismicity Panel (See Table 2-1)



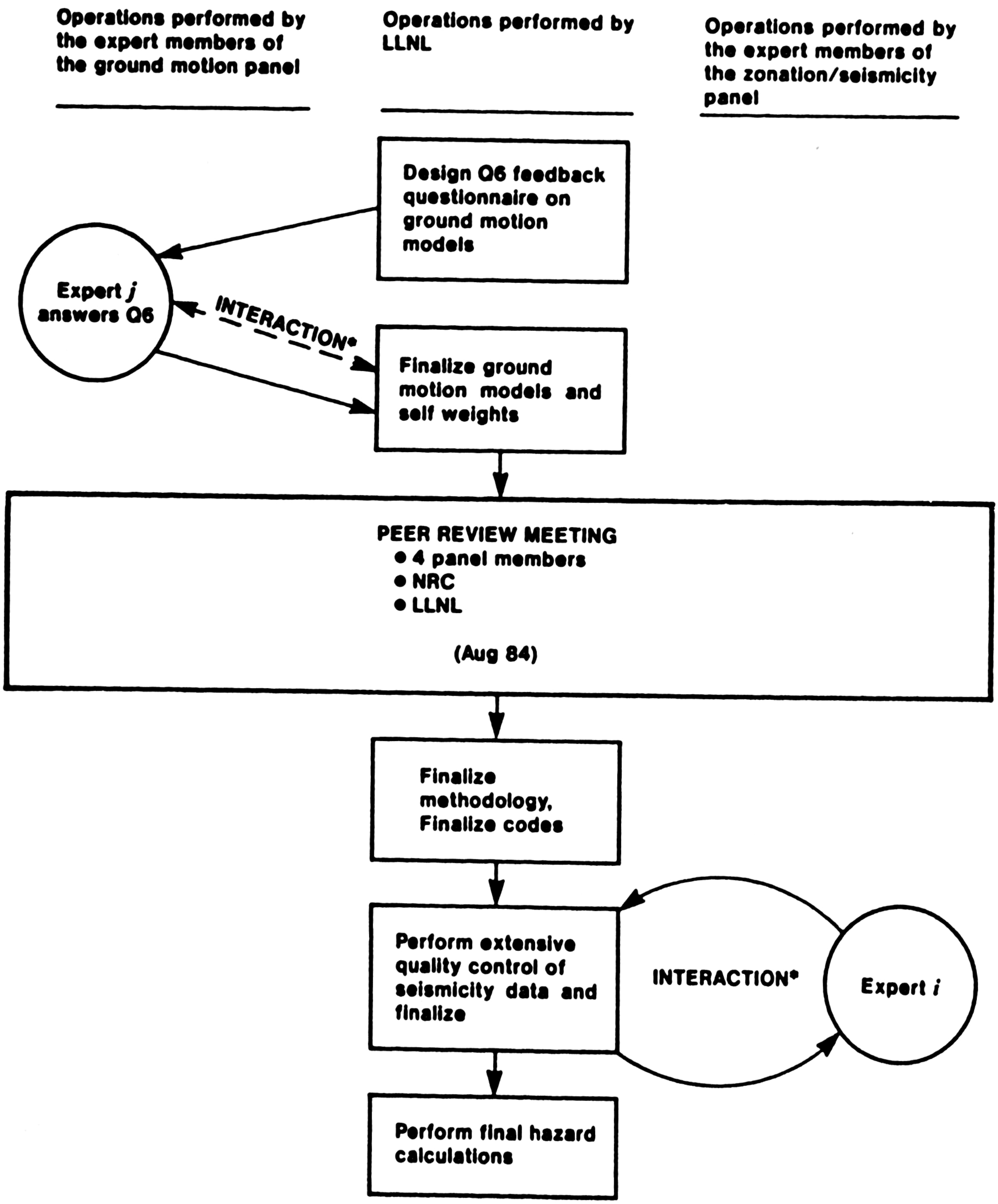
* Mostly by phone or mail, but also meetings in person for a few cases.

TABLE 2-3 SCHEMATIC REPRESENTATION OF THE FLOW OF OPERATIONS IN THE ELICITATION OF THE EXPERTS' OPINIONS.



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

TABLE 2-3 (continued)



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

TABLE 2-3 (continued)

the EUS seismicity panel, the first step was a questionnaire sent to each expert to obtain a graphic zonation of the EUS. Major inconsistencies and other problems arising from the responses were then resolved through personal communications. In questionaire Q2, the experts were asked to provide estimates of the seismicity parameters. They were given the choice of using their own catalogue of historical earthquakes or a catalogue provided by LLNL, if they so desired. In all cases the subjective task of removing aftershocks and accounting for the incompleteness of the catalogues was expressly left to the experts. After all questionnaires were returned by the experts, they were asked which catalogues they used, what kind of completeness corrections they applied, and how they decided to define events as aftershocks.
It appears that the LLNL catalogue was seldom used except for the regions where some experts had little experience, that is, generally in the regions for which their self weight was the lowest.

A formal feedback meeting was held to review and discuss the assumptions we made in the methodology as well as in our interpretation of the experts' responses. A questionnaire was then sent out to allow panel members to review and, if they choose, to modify their initial responses. Finally, one more set of interactions took place after the peer review meeting to finalize the input data by using the suggestions provided by the peer reviewers.

The experts of both the seismicity and ground motion panels were instructed to avoid cognitive biases insofar as possible. For the EUS seismicity panel, for example, four points were emphasized:

- Answers were to be based on experience, geologic and tectonic considerations, and all other available data.

- The level of confidence each expert placed in his answers would be explicitly considered. Therefore, since his input would undergo filtering and weighting when combined with the opinion of other experts, the expert was asked not to feel reluctant to express nonclassical viewpoints.

- The questionnaire was designed to contain redundancy, which was necessary for cross-checking and for establishing the consistency of the results. The experts were asked not to try to deliberately derive answers to later questions from earlier answers, since it would defeat the purpose of redundancy.

- The experts were urged to attempt answering all questions.

The application of this methodology to obtain the necessary input for the hazard analysis programs is discussed in Section 3.

Finally a peer review panel was assembled to help in identifying the possible weaknesses in the methodology or in the input data. The comments of the peer review experts were used to update the seismicity data by using a dual process of quality control and interaction with the seismicity experts.

2.3 Seismic Zonation, Complementary Zone and Probability of Distances

The difficulty of associating the location of most historical earthquakes which have occurred in the EUS with some known geotectonic formations has led to several basic simplifying assumptions in modeling the seismicity of the EUS common to most hazard analyses. First, it was assumed that, given a zone provided by a zonation expert, earthquakes could occur uniformly at random within this zone. Second, all earthquakes were assumed to be point sources, thus neglecting the fact that earthquakes are created by the rupture of tectonic faults of finite length. Thus, as discussed in Section 2.1, the geometric input necessary for the hazard calculations only needs to be the distribution, described by the density function $f_R(r)$ of the distance from the site to any point pertaining to the seismic source zone.

This distribution is the proportion of a given zone located within specific ranges of distances to the site. In the following, this distribution of distances will be referred to as the Probability of Distances and will be abbreviated by PRD. The program module which was specifically developed for the purpose of calculating the PRDs was appropriately named PRD.

The calculation of PRD for a zone, given a site, is straight forward, as is illustrated in Fig. 2.1. The proportion Π_{ij} of zone i bounded by distances R_{j-1} and R_j from the site is:

$$\Pi_{ij} = \frac{A_j}{(\text{total area of zone i})} \qquad (2.3)$$

where A_j is the portion of the points of zone i at a distance r such that

$$R_{j-1} < r \leq R_j.$$

In the process of developing the program PRD, several practical aspects led to decisions of some importance for the calculated hazard at the site. These are related to the following:

(a) The format of the input zonation maps.
(b) The discrete nature of the calculations and the necessity of keeping the computer time for the overall analysis within reasonable bounds.

With respect to (a), tThe seismic zones provided by the experts had highly irregular shapes and a wide spectrum of sizes (as can be seen in the experts' maps displayed in Appendix A. Furthermore, most experts provided some alternatives to their best estimate zonations and in some cases there was no overall zone to model the remaining part of the EUS not specifically zoned.

The former aspect precluded the use of an analytical solution for performing the calculation in Eq. 2.3 and led to a discrete solution where a zone was discretized into small quadrangles. The latter two points were resolved by creating an ad hoc zone indexing system, allowing an easy treatment of zones within zones, and an overall complementary zone (CZ), shown in Fig. 2.2, was created when not provided by the expert. This complementary zone was meant to include all parts of the EUS not specifically zoned by the expert. Strictly speaking, if an expert thought that he had included all potential seismic areas into specific zones, then the seismicity of the complementary zone should be zero. However, it was clear in our individual feedback discussions with the experts that a lack of specific zonation in some areas of the EUS might reflect more a lack of knowledge rather than the conviction that these areas were aseismic. Therefore, in some cases the complementary zone may have a non-zero seismicity. This is a very important point in light of the fact that some sites are located within the complementary zone for some seismicity expert's zonations. For these sites the hazard is primarily governed by the seismicity of the CZ.

(b) In order to get good resolution, the size of the quadrangles mentioned above must be as small as possible, especially when computing the PRD for the portions of zone close to the site or at the location of the site. On the other hand, it is necessary to keep the dimensions of these quadrangles as large as possible to avoid prohibitive computer time.

Thus it was assumed that there exists a distance, relative to the site, beyond which the effects of earthquake occurrences beyond that distance is negligible at the site. This distance we called the radius of the circle of influence. Furthermore, it was assumed that the resolution in the calculations of the PRD could be a function of the distance from the site. Therefore, the size of the quadrangle was made equal to a 1 km square up to a distance of 24 km from the site, 3 km square from 24 km to 900 km, and 20 km square from 900 km to 1250 km. The zones entirely beyond 1250 km were not considered. These values were based on careful examination of sensitivity analyses where the minimum quadrangle size was as low as .1 km for the close-in zones and as large as 100 km in the remote zones. The close-in switch distance of 24 km was chosen after varying it from 5 km to 50 km.

The output of the program module PRD consists of a set of arrays of PRD's, one array for each seismic zone, for each alternative zone, and for the complementary zone if necessary. The content of each array is the set of proportions of the zone within each of the distances from the site. For reason of cost, the number of these intervals was also kept to the minimum possible. The intervals start small and increase in a roughly exponential fashion. After considering several sets of intervals, the following intervals were retained for the final calculations (in km):

5,5,5,10,10,15,25,25,25,25,50,50,50,100,100,200,200,350

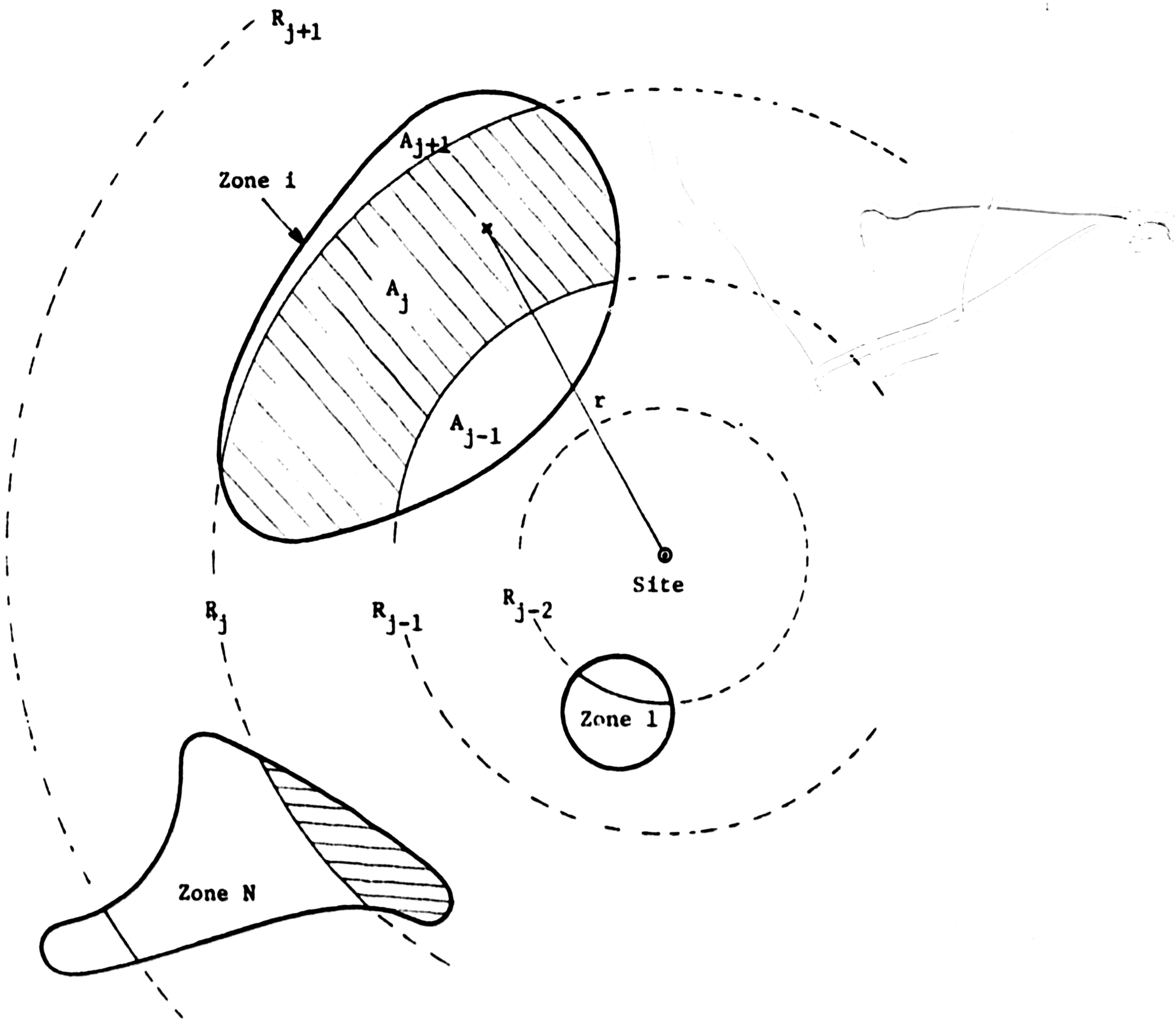


Figure 2.1 Distance Distribution for a Zone

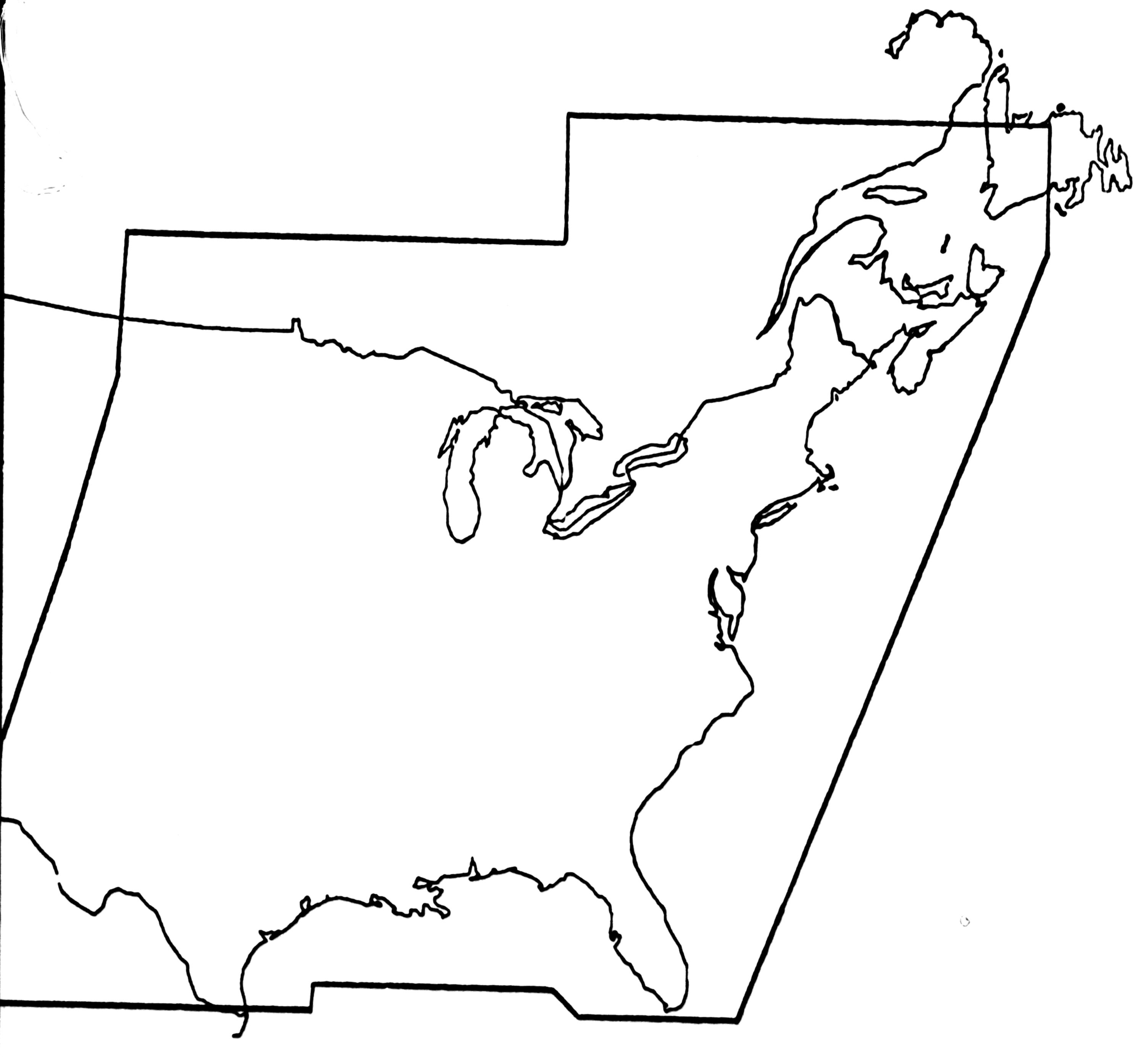


Figure 2.2 Extent of the Complementary Zone for the EUS

Thus the outer limits of the distances(values of the R_j of Fig. 2.1) are:

5,10,15,25,35,50,75,100,125,150,200,250,300,400,500,700,900,1250 km, and the actual distance array used in the hazard calculations is the array of mid-points:

2.5,7.5,12.5,20,30,42.5,62.5,87.5,112.5,137.5,175,225,275,350,450, 600,800 and 1075 km

2.4 Set of Alternative Maps

Each expert was given the opportunity to provide a best estimate map (BEM) and a set of alternatives to express his uncertainty in developing the zonation of the EUS. (For a more detailed discussion on the process of elicitation of responses from the experts and the data they provided, see Volume II Appendix A.)

The experts' uncertainty associated with zonation was expressed by:

a. Their level of confidence in the existence of each zone or cluster of zones identified in the BEM.

b. The replacement zone that the area in question becomes if it does not exist. This replacement zone, named the "host" zone, is not necessarily the CZ. The Host zone is defined here as being the contiguous zone which expands to fill the gap left when a zone (whose boundaries are all within the Host zone is removed (see Table 2.3).

c. Their level of confidence in the shape of each zone or cluster of zones identified in the BEM.

d. An alternative shape of the replacement zone to the zone in (c) above. This replacement zone is named the "alternate" zone.

For purposes of the analysis, all levels of confidence were normalized and treated as probability values (see Appendix C).

In order to integrate the experts' uncertainty into the hazard analysis, an uncertainty analysis, based on a simulation process was developed. Each simulation draws a realization of each of the uncertain variables, e.g. zonation, from a probability distribution (this process is described in detail in Appendix C). For the uncertainty analysis the zonations were treated as random and for the purpose of the simulations a set of all possible maps with associated probabilities were developed based on the set of alternative zonations by the experts. Thus, for each expert, a discrete probability distribution of zonation maps was created. This was accomplished by the program module named COMAP and is schematically described in Table 2-4 where an example of possible maps is given, starting with two zones in the BEM. The fundamental idea used in COMAP consists in starting with the best estimate

TABLE 2-4

Example of Generation of Possible Maps.

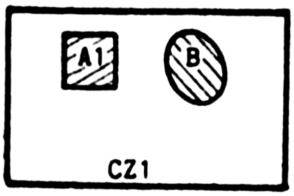
Assume an expert's zonation map includes two zones plus the complementary zone:

- o Zone A has a probability of existence equal to 1.0, and can take two different shapes A1 and A2 with probability .6 and .4 respectively.

- o Zone B has a probability of existence equal to .7, and therefore a probability of nonexistence equal to .3. Zone B has only one possible shape.

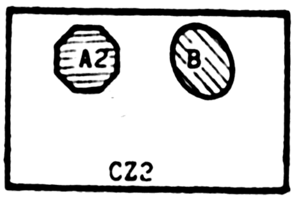
Four maps can be generated with respective weights w_1, w_2, w_3 and w_4.

MAP 1:



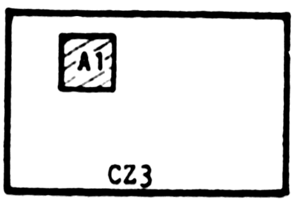
B.E.M ,{A1, B,CZ1} w_1= (.7) (.6) = .42

MAP 2:



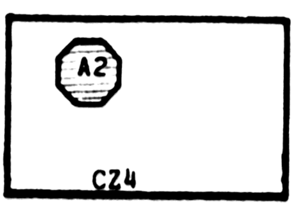
{A2, B,CZ2} ; w_2= (.7) (.4) = .28

MAP 3:



{A1, CZ3} ; w_3= (.3) (.6) = .18

MAP 4:



{A2, CZ4} ; w_4= (.3) (.4) = .12

The complementary zone CZ is different for each of the four cases. It plays the role of the Host zone for A1,A2 and B.

map, as a set of zones, and performing all of the following operations to generate all possible maps:

a. Remove each zone or combination of zones with non-zero probability of non-existence (probability of existence not equal to 1.0) from the BEM and replace them by their respective host zone. At the same time compute the probability associated with each arrangement of the zones which constitutes these maps.

b. Remove from the BEM each zone or combination of zones with non-zero probability of having an alternate shape (probability of the shape in the BEM not equal to 1.0) and replace them by their respective alternative shapes. At the same time, compute the probability associated with each of these possible cases.

c. Take each of the possible maps defined in (a) and perform the operation in (b) on the remaining zones initially in the BEM, using the convention that when a zone does not exist (i.e., was removed from the BEM), it could not be replaced by an alternate zone. Furthermore, when a cluster of zones is to be replaced by another cluster of zones, this could be performed only if all of the zones of the cluster of zones to be replaced actually existed. All the time is the probability associated with each of these possible cases is computed.

In practice, the process discribed above led to a very large number of maps for most experts. However, the probability associated with a given map decreases very fast, as it becomes more and more different from the B.E.M. The Monte Carlo simulation technique used to calculate the uncertainty distribution of the hazard is described in Appendix C.

To be consistent, a map should be selected at random from all possible maps for each simulation. However it was not feasible to implement such a scheme due to the exhorbitant computer core size and computer time that would have been involved. Instead, an approximate (truncated) distribution of the maps was obtained, using the module COMAP, in which the maps with very low probability have been discarded. The assumptions made to finally end up with a manageable number of possible maps, the effects of which were tested to determine their validity, were:

a. The maps (arrangement of zones as described in (a), (b), (c) above) with probability less than 1% of the BEM probability were discarded.

b. The total number of maps was set to a maximum of 30 per seismicity expert.

Since the geometry of some of the host zones changed as a result of the combinations (eliminating a zone or replacing a zone by its alternate), it was necessary to update their PRD (see Sec. 2.3). This operation was performed on the final set of 30 or less selected maps. This information and the weights (probabilities) associated with each of these maps was then used as the basic geometric input to the program module ALEAS which computes the hazard at the site. ALEAS treats this set of 30 (or less) maps and their associated probabilities as a discrete probability distribution from which it draws in the simulation process.

2.5 Calculation of the Hazard and its Uncertainty Distribution

2.5.1 General Considerations

Many of the methods of evaluation of the seismic hazard at a site acknowledge the variable nature of earthquake occurrences and of the ground motion attenuation data. In particular, the SEP study, which preceeded the present one, focused on including such random variation, which we call the "random uncertainty", into the final hazard. There is, however, another type of uncertainty which is more likely to introduce systematic bias into the results. This we call modeling uncertainty. For example, modeling uncertainty is associated with the choice of a zonation map and the choice of a particular ground motion attenuation equation. In the present study considerable effort went into developing a methodology which also include modeling uncertainty into the results. The complexity of the problem made it difficult to express modeling uncertainty by a straightforward analytical method and a simulation technique was adopted instead. The details of this technique are described in Appendix C. This section is only meant to give the reader a general understanding of the method. The overall steps, practical assumptions, and some of the important technical points adopted in the program module ALEAS, which calculates the hazard, are described briefly here.

2.5.2 Random and Modeling Uncertainty

Consider a simple hypothetical ground motion attenuation model of the following form,

$$\text{Log PGA} = bM - c \text{ Log } R + E \qquad (2.4)$$

In this equation b and c are constants, M is the magnitude of an earthquake, R is the distance from the source of the earthquake to the site, and E is a random variable with zero mean and standard deviation σ

With this model, for a given magnitude M and distance R, the PGA can be predicted, but only in terms of a conditional probability statement of the form:

$$P\,[\text{PGA} \geq a \mid M, R] \qquad (2.5)$$

Given M and R, this probability depends on the distribution of the random variable E which describes the random variation in PGA for different events, all with the same magnitude and at the same distance from the site.

In this example, the constants b, c and σ are fixed and characterize the model of attenuation. The distribution of the random variable E is a model of the random variation in PGA.

Similarly, given that an earthquake has occurred, the magnitude M of the earthquake is variable. The random variation in M is represented by the magnitude recurrence relationship, for example, the Gutenberg-Richter (1956) equation. Theoretically, the knowledge of the ground motion model, the distribution of M with the knowledge of the zonation and seismicity is sufficient to calculate the hazard at a site. Thus, the hazard depends on the models of attenuation and recurrence chosen for the analysis. However, Eq.2.4 is not the only ground motion attenuation model which can be used. That is there may be uncertainty in the ground motion model and/or in the magnitude (or intensity) distribution. Thus, in the present study these uncertainties are identified as modeling uncertainties. Modeling uncertainties are recognized in the following items:

- o Many possible choices of ground motion attenuation models. This includes choices of b, c and σ in the example of Eq. 2.4.

- o Many possible different conceptual zonations for a given zonation expert.

- o Given a seismic zone specified by an expert, many possible models of earthquake recurrence. This is expressed by a range of values in the parameters of the recurrence equation. In addition, each seismicity expert was given the choice between two differents models of recurrence. The first model called here the "LLNL" model assumes that the linear Gutenberg-Richter relationship applies between two values of magnitude (the domain of validity). Outside of this domain, the recurrence law is extrapolated on the basis of additional assumptions, as described in Section 3.3. The second possible choice is the "Truncated Exponential" model (also see Section 3.3).

- o Given a seismic zone specified by an expert, the value of the upper limit of magnitude or intensity exist. This is expressed by a range of values in M_U or I_U.

2.5.3 The Method of Simulation

Simulation is used to develop bounds, which describe modeling uncertainty, for the hazard at a site. In this method, the hazard at the site is calculated many times, as many as necessary to describe the uncertainty in the hazard, due to the modeling uncertainties described above in the inputs. In each of the calculations a set of the models is chosen and used to calculate the hazard, which for a ground motion parameter A is in the form:

$$P[\ A > a]$$

Then for each new simulation, a set of new models is chosen. Let us assume that N_s simulations are performed for each seismicity expert. For each new simulation a zonation map is drawn from the distribution of maps described in Section 2.4, i.e., if $W_{m1}, W_{m2}, \ldots, W_{mj}, \ldots, W_{mM}$ are the probabilities associated with maps 1, 2, ..., j, ..., M, the expected proportion of the times that the j^{th} map is used is equal to $N_s W_{sj}$. For each simulation, a ground motion model is selected in the same manner as the maps. The distribution of ground motion models is derived from the input of the Ground Motion Panel experts. Uncertainty in all of the remaining model parameters are defined by continuous analytical functions and for each simulation they are drawn from their respective probability distribution in the usual fashion used in Monte Carlo simulations. These parameters include the earthquake upper magnitude for each zone, the coefficients of the model of earthquake occurrence and the standard deviation of the random variation associated with the ground motion parameter. The probability distributions are determined from the responses of the seismicity and the ground motion experts, (see Section 3 and Appendix C). Basically, the distribution for each parameter is based on the best estimate, a lower bound and an upper bound provided by the experts.

In the analysis performed in the first phase of this study and described in Bernreuter et al (1984), the random variables "a" and "b" were assumed to be lognormally distributed. This assumption was discussed with the experts at the feedback meetings and further analysis showed that, due to the very high skewness in some cases, it was not applicable. Instead, we selected a triangular distribution for these parameters (a,b). In the extensive sensitivity analysis performed in this study, described in Section 4 of this report, we compared the effects of these two distributions. The most important conclusion was the fact that the use of the triangular distribution leads to a greater sample variation than the lognormal probability distribution. As a result adequate stability of the percentile curves can only be achieved by using more simulations when using the triangular distribution.

In the case of the lognormal distribution, the coefficients were previously computed by equating the best estimate to the mode of the distribution and by equating the lower and upper bounds (given by the experts), to the 2.5 and 97.5 percentiles of the distribution as shown on Fig. 2.3. When a triangular distribution is used to model the variations in "a's" and "b's", and M_U, the expert's best estimate is equated to the mode and the expert's bounds are similarly considered to be the 2.5 and 97.5 percentiles, as shown in Fig. 2.3 where the lognormal and triangular distributions are compared.

2.5.4 Weighted Hazard

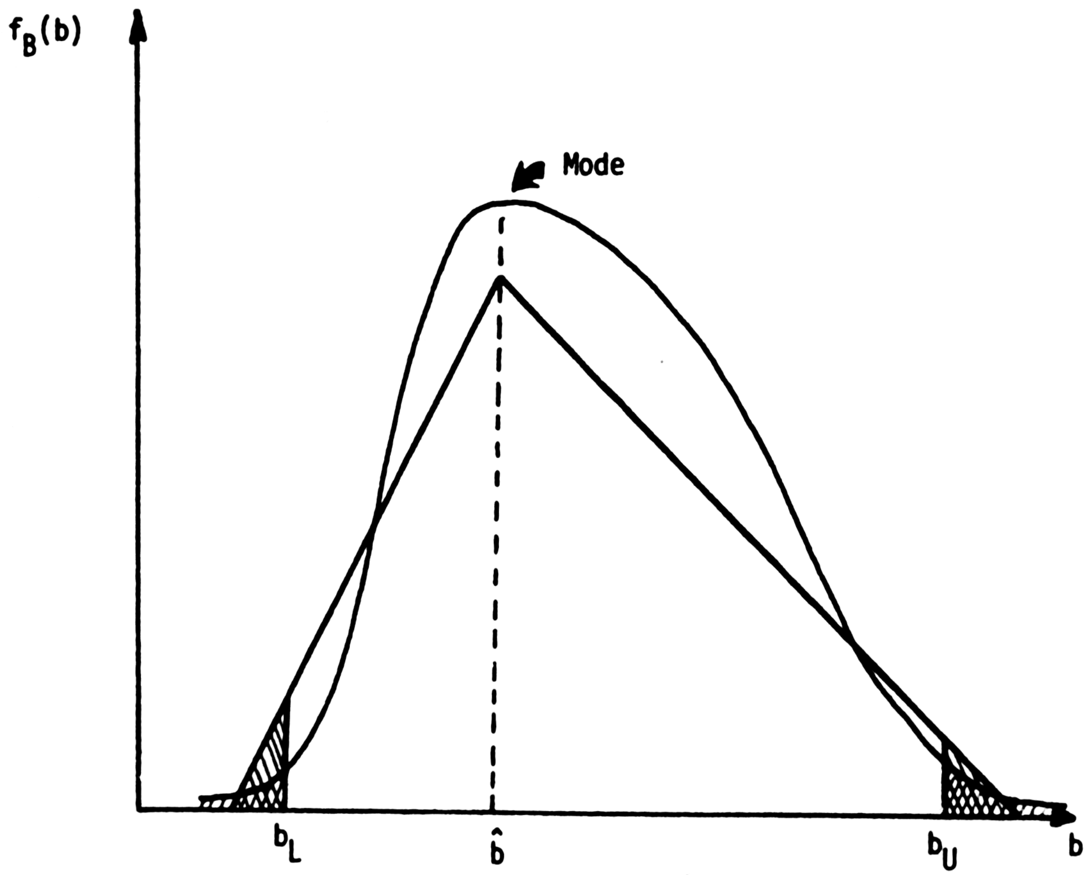
The seismic hazard analysis at a site depends on the zonation and seismicity parameters provided by the seismicity experts and the distribution of ground motion models and GMP variation provided by the ground motion experts. Since there were several experts on each of the panels, a hazard calculation, either a best estimate calculation, or a Monte Carlo simulation, as described in Appendix C can be made for each pair of experts, (i.e. a seismicity expert and a ground motion expert). To describe the seismic hazard at a site, it is reasonable to combine the estimates over all pairs of experts, either to get an overall "best estimate" seismic hazard curve or to describe the uncertainty, including the variation between experts, in estimating the hazard at a site. When combining hazard estimates over experts it is necessary to consider how the combination is to be achieved. The method used in this study is a weighted combination where the weights are based on self-weights provided by the experts. Only the general concept of the method used is presented here, the details appear in Appendix C, Volume 1.

Before discussing the concept of combining over experts, it is appropriate to distinguish the self-weights used in that combination and the "weights" that the ground motion experts associated with the ground motion models (and the "weights" associated with the zonation maps). In the latter case, the weights or level of confidence quantify the experts' degree of belief in the appropriateness of the ground motion models (or zonation map) in describing the attenuation of motion between source and site (or in describing regions of uniform seismicity). These weights are used to define a discrete probability distribution for the ground motion models (or class of zonation maps) which form the basis for selecting models and maps in the Monte Carlo simulation.

With regard to the self-weights, these were developed to reflect how each expert perceives his level of expertise, relative to the overall scientific community, about the seismicity and ground motion modeling, respectively. The relative expertise of the ground motion experts is assumed to be with regard to the applicability of the ground motion attenuation models presented in the ground motion questionnaire and do not depend on the region of the EUS. In the case of the seismicity experts, four regions were identified, as shown in Fig. 2.4. These four regions are: Northeast (NE), Southeast (SE), North Central (NC) and South Central (SC). The determination of these regions was also based on the locations of the large scale dominant tectonic models and considerations of attenuation characteristics as described in a study by Singh and Herrmann, 1983. Each seismicity expert was asked to provide his self weights for each of the four regions. These regional self weights are used to compute a single seismicity expert's weight in a way which emphasizes an expert whose self weight is high in the region contributing the most to the hazard at the site. The method then involves one of combining the results over seismicity experts and ground motion experts when the weight associated with each one of them is known. Two cases have to be considered.

Case (a) "Best Estimate" Hazard

The term "best estimate" (BE) is actually a misnomer. In the present context, it refers to the hazard computed with all the parameters of the analysis set equal to the value defined as the best estimate by the experts. In that case the calculation is performed with the best estimate zonation maps, the best estimate upper magnitude cutoffs, best estimate parameters in the definition of the earthquake occurrence and finally the best estimate models including the measure of random variation σ, of ground motion attenuation. The hazard at a given time period, t years, is given by the probability that the maximum PGA in t years, A_t, exceeds the value a. This is expressed by $P(A_t \geq a)$ and is a combination of the results over all the experts. It is simply obtained by a weighted average, as shown in Eq. 2.6, where w_{Au} is the weight for the



$$P\,[b_L < B \leq b_U] = .95$$

Figure 2.3 Estimation of the parameter of the probability distribution of B.

The best estimate $\hat{b}$, provided by the expert is equated to the mode. b_L is taken as the 2.5th percentile and b_U as the 97.5th percentile of the distribution, where b_L and b_U are the lower and upper bounds provided by the expert.

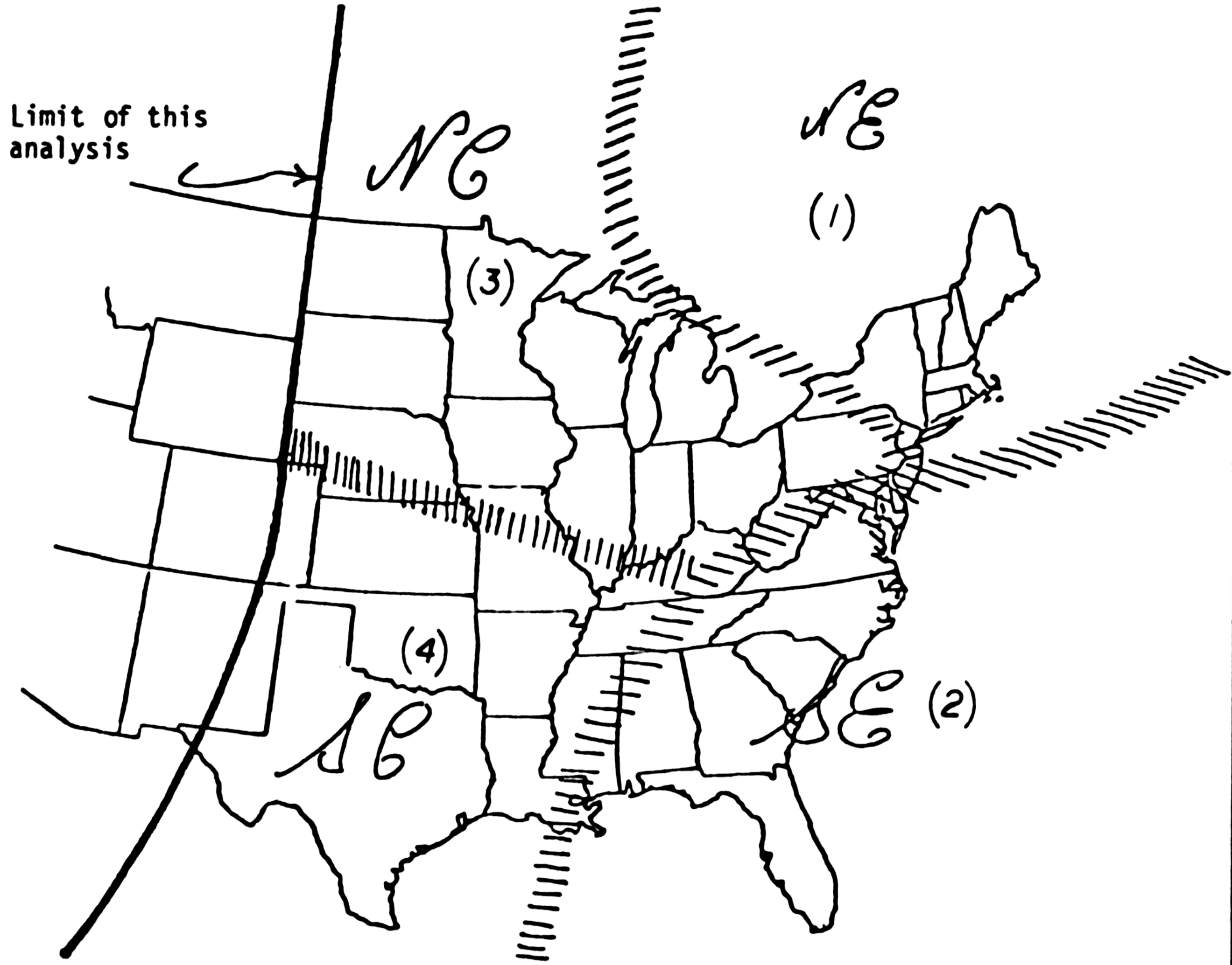


Figure 2.4 Identification of four regions of the Eastern U.S. based on a compilation of the seismic zonation expert maps developed in this study and a map of Q_0- contours from Singh & Herrmann (1983).

u^{th} ground motion attenuation expert and w_s is the weight for the s^{th} seismicity expert.

$$\hat{P}_s(A_t > a) = \sum_{u=1}^{U} w_{Au} \; \hat{P}_{su}(A_t > a) \Big/ \sum_{u=1}^{U} w_{Au}$$

(2.6)

$$\hat{P}(A_t > a) = \sum_{s=1}^{S} w_s \; \hat{P}_s(A_t > a) \Big/ \sum_{s=1}^{S} w_s$$

In this equation S is the total number of seismicity experts, U is the total number of ground motion attenuation experts and $P_{su}(A_t \geq a)$ is the "best estimate" hazard for a choice of seismicity S and ground motion expert u. $P_s(A_t > a)$ is the estimated hazard for expert s combined over all ground motion experts, and $P(A_t > a)$ is the estimated hazard combined over all seismicity and ground motion experts.

Case (b) Uncertainty Distribution of the Hazard; Derivation of Percentiles

For each pair of experts (s,u), the sth seismicity expert and the uth ground motion experts, the simulation based on the uncertainties in the models, e.g. zonation maps and ground motion models, and the seismicity parameters, e.g. a,b, M_U, produces a set or distribution of values for the hazard $P(A_t > a)$ for a fixed a. This uncertainty distribution is denoted

$$P_{s,u} \{p_a \leq p\}$$

where $p_a = P(A_t > a)$ denotes the hazard, now treated as a random variable because of the uncertainty. The uncertainty distribution for the hazard, combined over all pairs of experts, is taken as the weighted average of the individual distributions $P_{s,u} \{p_a \leq p\}$ using the weights (w_{Au}, w_s). This is expressed in Eq. 2.7,

$$P\{p_a \le p\} = \sum_{s=1}^{S} \sum_{u=1}^{U} w_s w_{Au} P_{s,u}\{p_a \le p\} \Big/ \sum_{s=1}^{S} \sum_{u=1}^{U} w_S w_{Au} \qquad (2.7)$$

Uncertainty bounds for the hazard, which reflect the uncertainties associated with estimating the hazard at a site, are based on evaluating the percentiles of the uncertainty distribution. The different percentile levels for $P(A_t \ge a)$, for each a, are assessed from the distribution of the hazard in Eq. 2.7. This applies, in particular, to the single variable PGA and PGV. In the case of the determination of the Uniform Hazard Response Spectra, the same operation is repeated for each frequency.

To produce corresponding 15th and 85th curves,which reflect the uncertainties in estimating in the hazard curve at a site, the points $p_{.15}(a_i)$, $i=1,\ldots I$, are combined to form the 15th percentile curve and, correspondingly, the points $p_{.85}$ (a_i) are combined to form the 85th percentile curve.

One must be careful in interpreting the bounds as hazard curves which correspond to a specific set of input parameters. The bounds are analogous to the bounds which are used to define Uniform Hazard Spectra (UHS). The UHS is the locus of points each corresponding to the same probability of exceedance and does not represent a distinct spectrum since the inherent physical correlation between the values at different frequencies has been lost in the calculations. However, it can be interpreted as an envelope of all possible spectra. Similarly the 85th and 15th percentile hazard curves do not represent the hazard curve corresponding to a specific set of input parameters. Rather they are the locus of hazard values, such that the "Probability" in the hazard exceeding that value is greater than .85 (or .15) for each a. It can be interpreted as an envelope of all possible hazard curves. It is not correct to interpret the 85th percentile curve as a hazard curve which will not be exceeded by 85 percent of the hazard curves produced by the uncertain parameters. It is true, however, that for a fixed value a the value $P_{.85}(A > a)$, taken from the 85th percentile curve at a, is an estimate of the value of $P(A > a)$ which has "degree of belief" or "confidence" 0.85 that it will not be exceeded, where the "confidence" is a weighted average of the level of confidence of the individual experts.

SECTION 3: DEVELOPMENT OF INPUT DATA

3.1 Background

The data used to develop the input parameters required for the hazard analysis were derived from six questionnaires and extensive formal and informal feedback with individual panel members as described in Section 2. Four questionnaires were sent to the EUS Seismicity Panel and two questionnaires to the EUS Ground Motion Panel. As these questionnaires, supporting documents, and responses are rather long and involved, we only discuss the most significant features of the questionnaires and only give examples of the responses in this section. The texts of the questionnaires are given in Volume 2. For easy reference Appendix A (Volume 1) contains the maps and seismicity data used in the analysis and Appendix B (Volume 1) gives the equations and plots of the ground motion models used in the analysis.

3.2 Zonation

A basic element of a seismic characterization is the definition of the areas where future earthquakes might occur. The first questionnaire (Q1) elicited this information from the EUS Seismicity Panel.

The first section of Q1 outlined the source zone approach to seismic characterization. This was outlined primarily for those panel members that did not participate in the SEP (Bernreuter and Minichino, 1983). The second part of the questionnaire was concerned with source zone configuration.

A source zone was defined as a region which has homogeneous seismic characteristics in terms of rate of activity, magnitude distribution and upper magnitude cutoff. It was also noted that the intent of the questionnaire was to obtain the geographic boundaries of the major seismic zones and local tectonic features, e.g., faults, which should be considered in a seismic hazard analysis. The region of interest was defined to be the Eastern United States and Southeastern Canada extending west to the Rocky Mountain front or roughly 104°W. We provided the panel members with black and white copies of the appropriate section of P. King's (1969) Tectonic Map of North America (King 1969a, and 1969b). Among several possible maps, King's map was selected since it was considered least likely to introduce biases in the choices of tectonic models.

The experts were asked to express their uncertainty in formulating the seismic zonation of the EUS. They were asked to express uncertainty in terms of:

- the existence/non-existence of an individual zone or cluster of zones, i.e., should/should not an individual zone or cluster of zones be treated as a source separate from the area surrounding it.

- the boundary shape of an individual zone or boundaries of a cluster of adjacent zones.

To assist the panel members in understanding our questions regarding their expression of uncertainty, we provided an example response illustrating the information we were seeking.

The panel members, using the maps we supplied, were asked to draw their base map of potential source zone configurations for the EUS. This map is referred to as the Best Estimate Map(BEM) in this study. They were then asked to indicate, in a table, those regions which they were not certain should be identified as a zone. For these zones the experts were asked to provide their level of confidence about the existence of the zones and indicate what zone the zone(s) become part of it they do not exist. Finally, the experts were asked to isolate the zones for which they wanted to provide alternate shapes. They could provide as many alternative boundaries as they felt necessary by listing, in a table, the alternatives and giving their confidence (relative to the other alternative shapes for that zone or cluster of zones) in each alternative boundary shape. These results, updated during feedback, are given in Appendix A. There were only minor changes to a few maps as a result of our feedback interaction with the experts.

The maps returned by the experts were digitized for use in the computer program PRD discussed in Section 2.3 which computes $f_{R_S}(r)$, using Eq. (2.3). Then the computer program COMAP, discussed in Section 2.4, generates all possible maps for each expert. As discussed in Section 2.4, the input of some experts provided a very large number of possible maps. As as result,we limited the number of maps generated to a maximum of 30 per seismicity expert per site.

3.3 Seismicity Data

The seismicity data needed for the seismic hazard analysis program, discussed in Section 2.5, was obtained from the members of the EUS Seismicity Panel in response to the second questionnaire (Q2), the feedback questionnaire (Q5) and through informal discussions and meetings with various panel members. In Q2 the experts were asked to supply, for each of the zones they had identified in response to Q1, best estimates for:

- o the largest earthquake in a zone (upper magnitude cut off)
- o the expected frequency or rate of earthquakes
- o the magnitude (or intensity) recurrence relation

In addition, they were asked to express their uncertainty in estimating these parameters by providing an interval of values for each parameter to which they would associate a high degree of confidence that it contained the true value.

We indicated that unless otherwise specified by the panel members, we would treat the bounds of the interval as the 2.5th and 97.5th percentiles except for the interval for the largest earthquake in each zone. We treated that parameter interval as the 100 percent bounds, i.e.,no value of the upper magnitude cutoff would exceed the upper bound.

The experts were invited to use their own catalogue of earthquakes to derive the seismicity parameters for their zones. In addition we provided them with a catalogue developed by LLNL. The details of this catalogue are given in Volume 2. In our informal feedback with the panel members most experts indicated that they made extensive use of a number of catalogues. In order to assist the panel members in answering the questions in Q2, we supplied them with a list of the earthquakes, from the LLNL catalogue, which occurred in each of their zones sorted both by size and by date. We also supplied them plots of the cumulative number of events in each of their zones using the LLNL catalogue. In addition, we offered to supply the same data using their data base (provided it was on computer tape). However no panel members took advantage of this offer. We emphasized that we had not applied any correction for incompleteness nor removed the aftershocks and that they (the panel members) should correct the plots we provided them for incompleteness and aftershocks as they saw fit.

After an introductory section defining the purpose of the Questionnaire (Q2) and the terms used in it, a section was included describing how the responses to the questions would be used in the analysis. For example, the concept of upper magnitude cutoff, M_U, which we defined as the upper limit for the distribution of earthquake magnitude within a zone given the current tectonic and seismic conditions, was discussed extensively. We also reminded the panel that some magnitude scales (most notably the m_b scale) appear to saturate. Thus, the upper limit magnitude would be limited by this saturation value. To avoid the problems of changing magnitude scales we suggested that they might want to extrapolate beyond the saturation value. For most zones this was not a problem; however, there were a few zones for which this was a problem. These problems were resolved by individual discussions with the panel members as required.

A third questionnaire (Q3) was sent to the members of the Seismicity Panel in order to obtain their self weights for the four regions identified (Northeast, Southeast, North Central, South Central).

Feedback

As indicated in Section 2, an important element of the elicitation process, was the feedback step. The main purposes of the feedback step were to:

1) Give the Panel Members a better understanding of our methodology, the assumptions contained in our methodology, and the assumptions we made in interpreting their responses.

2) Give the panel members a better understanding of the sensitivities of the computed hazard to different parameters and assumptions.

3) Have a discussion of regional tectonics among the experts to ensure that all panel members were aware of any new significant developments for each region of the EUS.

4) Allow the panel members to reassess their input relative to the input of the other panel members and the resultant computed seismic hazard at selected sites.

It was noted that the panel members were not asked to defend any of their inputs. As far as possible, each expert's input remained anonymous. However, the feedback provided a forum for regional experts to exchange information and thoughts so that e.g., the New England experts were presented the views of South Central U.S. experts and vice-versa.

At the feedback meeting and in the follow-up questionnaire we put special emphasis on carefully reviewing.

- o How we developed the maps to be used in the analysis from the data provided by each panel members.
- o The definition and importance of the upper magnitude cutoff.
- o Both the desirable and undesirable features of the earthquake recurrence model used in the analysis at the time of the feedback meeting (referred to as the LLNL model) as contrasted to the truncated exponential model.
- o Our concerns about the large ranges of values given for the a and b parameters of the earthquake recurrence model.
- o The possible need for correlation between the a and b parameters during simulation and how such correlation could be introduced.
- o The need to correct the historical catalogue for incompleteness and removal of aftershocks.
- o The importance of the experts' estimates of the seismicity in the Complementary Zone (CZ).
- o The definition of self weights and confidence bounds to reach a common understanding of their meaning.

After the meeting a feedback questionnaire (Q5) was sent to the panel. In this questionnaire the topics covered at the feedback meeting were reviewed and the panel members were requested to update their responses. In this questionnaire the experts were asked to choose between the LLNL recurrence model and the truncated exponential model. This was suggested at the feedback meeting. The experts were also asked to indicate any correlation that might exist in their estimate of the coefficent a,b. They were asked to choose between no, partial or full negative correlation between the a and b parameters of the earthquake recurrence model. Table 3.3.1 gives the choices made by the various experts. The significance of the various choices is discussed in Section 4. The responses were evenly divided between the LLNL model and the truncated exponential model and between no and partial correlation.

Because there was such a wide variation in both the normalized seismicity and size of the upper magnitude cutoff assigned to the large CZ, we asked each panel member to reconsider his maps and pay careful attention to the CZ. We provided each panel member with a detailed description of his CZ and compared normalized rates and upper magnitude cutoffs between all experts. We suggested that they might want to breakup this large zone into smaller regional CZ's.

Only Expert (13) subdivided his CZ. The others left them intact. In fact there was little change in the maps or seismicity parameters as a result of feedback. The panel members indicated that they had considered the points we raised in the process of defining the various zones.

As suggested by the Peer Review Panel, we also compared each expert's earthquake occurrence model for each zone to the historical data for that zone. This comparison was made over several time periods to reduce the problems introduced by incompleteness. From these comparisons we identified a number of zones which suggested possible errors in the seismicity estimates made by various experts. This information was forwarded to the appropriate panel members and we asked them to reconsider their estimates of seismicity. In some cases the experts agreed that their initial estimate were not adequate. In other cases the experts liked their original estimates, indicating that they had either used different catalogues, methods of correcting for incompletness and/or relations to convert between intensity and magnitude.

Finally, the panel members also updated their self weights.

In summary the feedback on seismicity resulted in only relatively minor changes to the input provided in response to the first three questionnaires to the seismicity panel and used to perform the analysis in Bernreuter et al. (1984). The most significant changes were changes in the estimates of a and b- values for specific zones by some experts and corrections to errors introduced by improper interpretation of some information provided by some panel members for a few zones.

The final updated maps and seismicity parameters are given in Appendix A.

3.4 Ground Motion Models

An important part of the hazard analyses in this project was the consideration of multiple ground motion models. Uncertainty between the models was based on the Ground Motion Panel Members assigning weights to each of the available models potentially applicable to the EUS. In this section highlights of the questionnaires on ground motion modeling are described and the inputs from the experts are presented. Appendix C in Volume 2 provides a complete review of the available ground motion models. Appendix E in Volume 2 (Questionnaire 6) contains a detailed discussion of how we modeled local site effects, another issue considered by the Ground Motion Panel.

TABLE 3.3.1

Summary of Updated Choices of
Recurrence Models and Correlations Between a & b

Expert #	Recurrence Models	a & b Correlation
1	L	P
2	L	N
3	T	P
4	T	F
5	L	P
6	T	P
7	T	P
10	L	P
11	L	N
12	T	N
13	L	N

L = LLNL Model

T = Trancated Exponential Model

N = No Correlation

P = Partial Correlation

F = Fully Correlated

Seven individuals were to participate in the evaluatin of the ground motion models, however, two of them subsequently declined to be members of the "Ground Motion Panel." Table 3.4.1 is a list of the five experts which constitutes the Ground Motion Panel.

The initial a meeting with the Ground Motion Panel was held in January of 1983. At this meeting the panel indicated that they would like to have an overview report giving the various ground motion models and their basis. This report became part of questionnaire 4 which was sent to the Ground Motion Panel. This report/questionnaire is given in Volume 2 as Appendix C (Questionnaire Q4).

In the first part of Q4 an explanation of how ground motion models are used in the analysis was included. It stated that the study is only concerned with the horizontal components of ground motion and that the measure of distance is the epicentral distance. There was some concern about what distance should be used in the analysis. This point was emphasized at the initial meeting and was the object of comments from Dr. Trifunac and responses to the comments by Dr. Campbell.

Our choice of the epicentral distance was based on the fact that the EUS, in general, does not exhibit any active fault traces thus making it impossible to use the shortest distance or any metric based on fault length and direction. The experts were made aware of this fact in Q4 and were requested to consider it in their answers to the questionnaire. In addition to the initial explanation a catalogue of models is presented where the different models are classified according to the way they were developed. There appears to be three general ways by which models are derived, at least when the ground motion parameter is either Peak Ground Acceleration or Peak Ground Velocity. Ground motion models are either based on:

1. (I) Using site intensity as an intermediate variable and relating site intensity to the ground motion parameter by using one of the following five approaches:

   - No weighting
   - Distance weighting
   - Magnitude weighting
   - Magnitude and distance weighting
   - Semi-empirical

2. (D) Using the ground motion measurements directly.

3. (T) Using theoretical considerations for modeling the ground motion.

Table 3.4.1 List of Experts of the "Ground Motion Panel"

David M. Boore	(USGS)
Kenneth W. Campbell[1]	(USGS)
Professor Otto W. Nuttli[2]	(St. Louis Univ.)
Professor Nafi Toksoz[2]	(MIT)
Professor Mihailo D. Trifunac	(USC)

(1) At the start of this project Dr. Campbell was with TERA, Corp., and for a short while he was also at LLNL before joining the USGS.

(2) Also a member of the Zonation Panel

Treating the five approaches for developing intensity based models separately, the overall number of classes for modeling the PGA and the PGV is seven. Very few models are available when the ground motion parameter is a spectral value (i.e. the pseudo spectral velocity, Sv, or the absolute acceleration, S_A). Thus a set of spectral shapes was chosen, which combined with a choice of PGA, PGV or PGA and PGV models, provided a larger set of spectral models to be considered from.

The spectral models available were the two models developed in the SEP. These models are basically intensity based, one being derived with magnitude weighting and the other with distance weighting. A third model which is also intensity based but with no weighting is the model developed by Trifunac and Anderson (1977). The three shapes of spectra (which, combined with a PGA, a PGV or both models, provide the additional spectral models) are the following:

REG. Guide 1.60	:	Combined with a PGA model
NBS, 1978 - ATC	:	Combined with a PGA model
Newmark-Hall	:	Combined with a PGA and a PGV model

In order to assist the experts in their evaluation of each of the models, a major portion of the questionnaire described all of the available models to be considered, compared them to one another and to the little amount of strong ground motion data available in the EUS.

The questionnaire itself was organized as follows:

For each of the ground motion parameters (PGA, PGV or Spectra), the expert was asked to respond to the following questions, for each of the four regions of the EUS (Northeast, Southeast, North Central and South Central) and considering two possible measures of earthquake size (m_b and MMI).

1. Among all the ground motion models available which one is the most appropriate model i.e., the best estimate model?

2. For each class of models (7 classes for PGA and PGV, 3 classes of spectral shapes and 2 SEP models for spectra), which is the most appropriate model?

3. Indicate is the confidence level that you associate with each class. This confidence level should be a number between 0 and 1 such that the sum over all classes is 1.

4. What other models should be considered?

5. Assuming that the random uncertainty has a lognormal distribution, what is your best estimate of the standard deviation on the logarithm (σ), i.e. the coefficient of variation (cov) of the ground motion parameter? What is an interval which you believe, with a high degree of confidence, represents the possible range of σ?

Finally in order to combine the results for several experts by the method presented in Section 2.5, the experts were asked to indicate their level of expertise with regard to assessing the worth of ground motion models.

It should be noted that at the time the interim results were computed, Bernreuter et al. (1984), only four of the five Ground Motion Experts had provided their input.

A feedback meeting was held with the Ground Motion Panel in June, 1984. The objectives of this meeting were the same as the feedback meeting with the Seismicity Panel. The Ground Motion Panel feedback meeting we introduced several important improvements in the elicitation regarding ground motion modeling:

- o The panel members were asked to weigh several different approaches to incorporate a correction for local site effects into the analysis.
- o The panel members were allowed to choose between four methods of truncating the variation in the ground motion at a site.
- o We removed the restriction of having to select only one ground motion model from each of the seven classes defined in Q4. Instead, the experts could select a set of models among <u>all</u> available models.

The discussion accompanying Q6 in Appendix E of Volume 2 gives a detailed overview of the topics discussed at the meeting and the information presented to the panel members.

The feedback loop with the Ground Motion Panel resulted in significant changes. First, a new model was introduced (Atkinson, 1984) which was selected as the best estimate model by Expert 3. Several other experts selected it as one of their models. Expert 4 selected a different model for his best estimate spectral model. Expert 1 modified his selection of ground motion models to better account for the fact that epicentral distance is being used in the analysis. Expert 5 modified the ground motion model he selected as his best estimate. Previously the PGA model had been based on what we called the unmodified Gupta-Nuttli attenuation of intensity relation. (See the report accompanying Q4 in Appendix C of Volume 2 regarding the modified Gupta-Nuttli relation). This resulted in a lowering of the PGA at any magnitude and distance by a factor of 1.65. In addition we expanded our software so that we could properly model the distribution attached to Expert 5's choice of spectral models. Previously we had modeled it as a lognormal distribution.

Adjustment for site soil conditions was another improvement introduced at the feedback phase. Site correction factors were introduced into the analysis in the following way. First, the ground motion models are all assumed applicable for the same base case - generic deep soil. Secondly, each expert then provided weights (Table 3.4.2) for the following three approaches to adjusting the ground motion parameter from the base case to account for other soil conditions:

1) None - no correction applied.

2) Simple - Sites are considered either soil or rock and a simple correction is applied to correct the base case model for rock sites. These simple correction factors are shown in Figure 3.4.1. The correction factor for PGA is plotted at 0.01 seconds. Two different sets of correction factors were chosen. Experts 1-4 used a set of correction factors developed by Joyner and Boore (1982). These correction factors are denoted by the symbol S in Figure 3.4.1. Expert 5 chose to use the correction factors developed by Trifunac and Anderson (1977) and are denoted by the symbol 5 in Figure 3.4.1. For reference the median correction factors for rock - denoted by the symbol C - is also plotted in Figure 3.4.1.

3) Categorical - Sites are put into one of 8 categories listed in Table 3.4.3. A set of correction factors were developed, as described in Q6 in Appendix E of Volume 2, using the SHAKE computer program. These median correction factors are shown in Figures 3.4.1 to 3.4.3. In the simulation process the correction factor used for each period is selected assuming that the error is lognormally distributed about the median. The value of the standard deviation of the natural log of the correction factor is 0.5. The correction for PGA is shown at 0.01 sec in Figures 3.4.1 to 3.4.3.

It can be seen from Table 3.4.2 that in the simulation for PGA about 14% of the time no correction is used, 40% of the time the simple correction is applied and 46% of the time the variable categorical correction is used. Generally the experts would have preferred the use of a site specific approach. However, budget and schedule limitations precluded the development of site specific amplification factors at each site.

Tables 3.4.4a-g list the PGA models selected by the panel members, the weights they associated to each model and the overall relative weight of each model for each of the four regions shown in Figure 2.4. The panel members were allowed to change their models as a function of a given seismicity expert's choice of either magnitude or intensity for his earthquake recurrence model for a particular zone. Thus there is a table for magnitude and a table for intensity for each region except for region 2 where the PGA models were the same. The models are listed by a number in Tables 3.4.2a-g. These numbers refer to the model numbers given in Table B1 in Appendix B which gives the name and coefficients of each of the models. Table 3.4.5 gives the relative weight of the most important models. It should be noted that the models grouped together in Table 3.4.5 have the same base but have differences in the regional attenuation coefficent or in the distance metric. Some of these differences are illustrated in Figure 3.4.4 for Campbell's (1982) model for region 1 and in Figure 3.4.5 for Nuttli's (1983) model for region 1 and in Figure 3.4.6 for Atkinson's (1984) model for region 1.

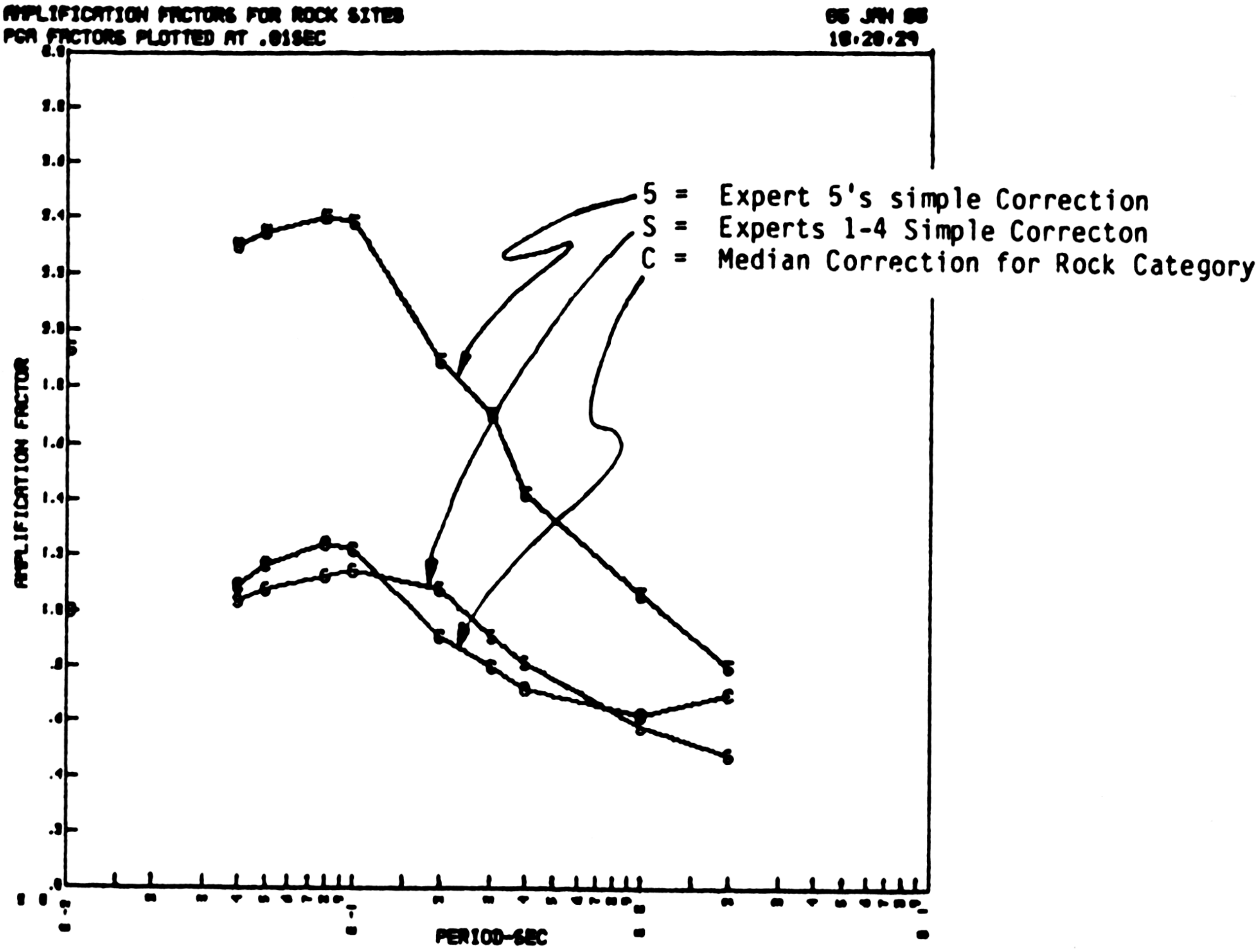

AMPLIFICATION FACTORS FOR ROCK SITES
PGA FACTORS PLOTTED AT .01SEC
5 = Expert 5's simple Correction
S = Experts 1-4 Simple Correcton
C = Median Correction for Rock Category
AMPLIFICATION FACTOR
PERIOD-SEC

Figure 3.4.1

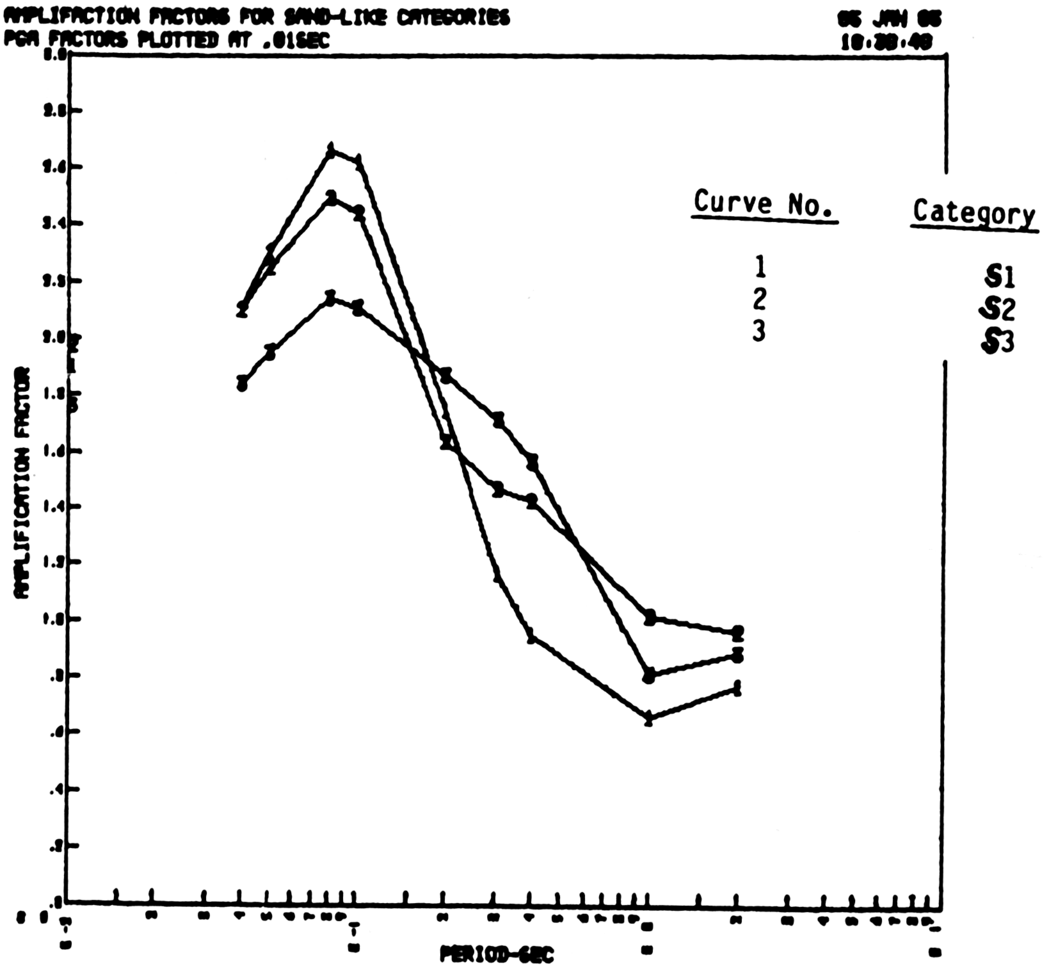

AMPLIFACTION FACTORS FOR SAND-LIKE CATEGORIES
PGA FACTORS PLOTTED AT .01SEC
AMPLIFICATION FACTOR
PERIOD-SEC
Curve No.
Category
1 S1
2 S2
3 S3

Figure 3.4.2

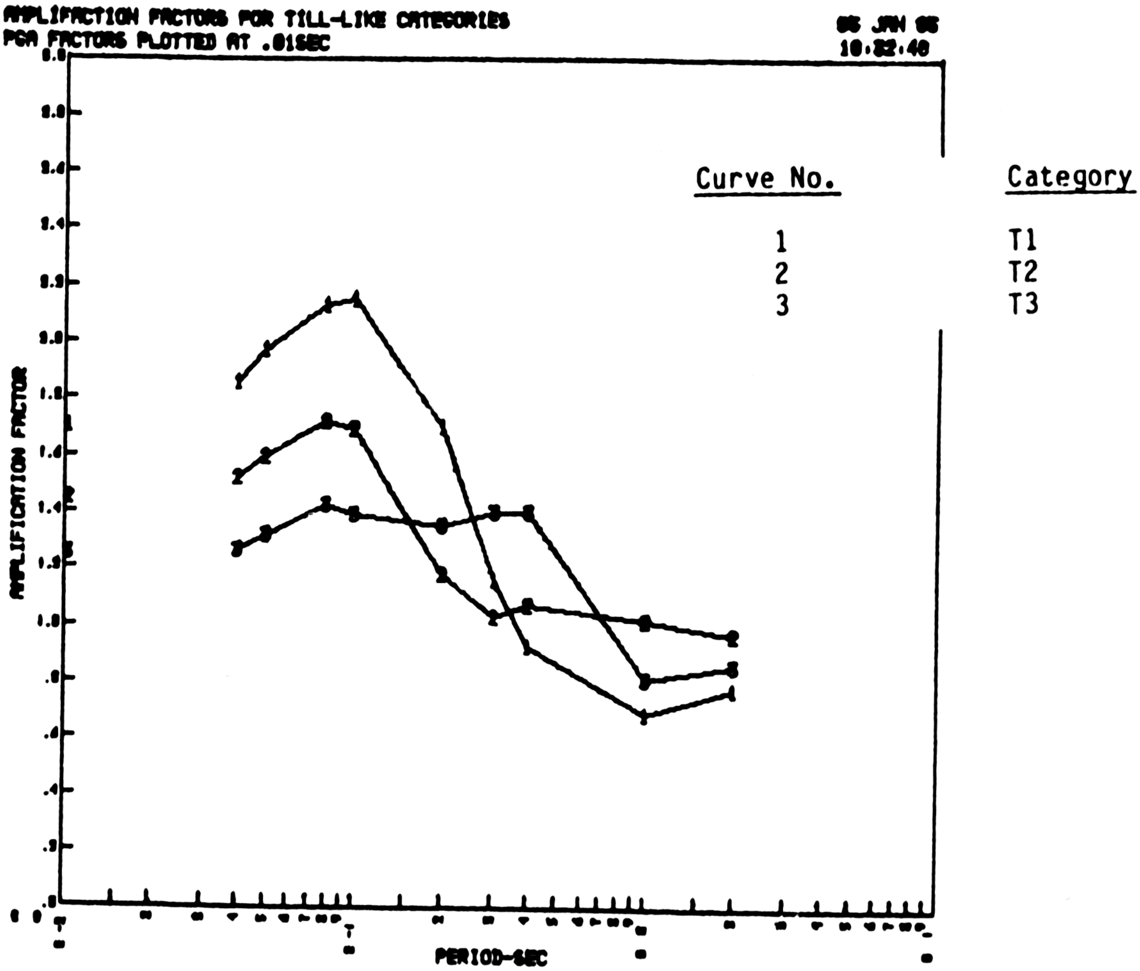

AMPLIFACTION FACTORS FOR TILL-LIKE CATEGORIES
PGA FACTORS PLOTTED AT .01SEC
AMPLIFICATION FACTOR
PERIOD-SEC
Curve No.
Category
1
T1
2
T2
3
T3

Figure 3.4.3

Table 3.4.2

Weights Provided by EUS Ground Motion Panel Members for the Three Approaches Used to Correct for Local Site Effects.

	EXPERT 1		2		3		4		5		Total[1] Weight	
Approach	PGA	Sv	PGA	Sv	PGA	Sv	PGA	Sv	PGA	Sv	PGA	Sv
None	0	0	.4	.1	0	0	.25	.1	0	0	.14	.04
Simple	.2	.2	.3	.3	.2	.2	.50	.6	.8	.8	.4	.43
Categorical	.8	.8	.3	.6	.8	.8	.25	.3	.2	.2	.46	.53

(1) Includes self weight of each expert.

Table 3.4.3

Definition of the Eight Site Categories

(1) Generic Rock

(2)-(4) Sand Like

Cat		Depth
(2)	S1	25 to 80 ft.
(3)	S2	80 to 180 ft.
(4)	S3	180 to 300 ft.

(5)-(7) Till Like

Cat		Depth
(5)	T1	25 to 80 ft.
(6)	T2	80 to 180 ft.
(7)	T3	180 to 300 ft.

(8) Deep Soil - Generic Base Case

Table 3.4.4a
Region 1

Weights Given by the Ground Motion Panel Experts for the Various PGA Models for the Case when the Seismicity Expert's Earthquake Recurrence Model is in <u>Magnitude</u>.

Model	Expert 1	Expert 2[a]	Expert 3	Expert 4	Expert 5	Relative Weight of Model
1	.35					.07
4			.20	.3		.11
5	.45					.09
8			.1	.5		.15
9	.20					.04
12				.1		.03
13		.316	.7			.18
14					1.0	.18
17		.211				.04
21				.1		.03
25		.105				.02
26		.105				.02
27		.105				.02
29		.053				.01
31		.105				.02

[a] Expert 2 dropped a lowly weighted model. These weights resulted from the renormalization of the remaining models.

Table 3.4.4b

Region 1

Weights Given by the Ground Motion Panel Experts for the Various PGA Models for the Case when the Seismicity Expert's Earthquake Recurrence Model is in Intensity.

Model	EXPERT 1	2	3	4	5	Relative Weight of Model
1	.35					.07
4			.20	.30		.11
5	.45					.09
8		.05	.10	.50		.16
9	.20					.04
12				.10		.03
13			.70			.13
14					1.0	.18
17		.40				.07
21				.10		.03
25		.10				.02
26		.10				.02
27		.20				.04
29		.05				.01
31		.10				.02

Table 3.4.4c
Region 2

Weights Given by the Ground Motion Panel Experts for the Various PGA Models for the Case when the Seismicity Expert's Earthquake Recurrence Model is in both Magnitude and Intensity.

Model	EXPERT 1	2	3	4	5	Relative Weight of Model
1	.35					.07
4			.20	.30		.11
5	.45					.09
8		.05	.10	.50		.16
9	.20					.04
12				.10		.03
13			.70			.13
14					1.0	.18
18		.10				.02
19		.10				.02
20		.20				.04
21				.10		.03
28		.40				.07
29		.05				.01
32		.10				.02

Table 3.4.4d
Region 3

Weights Given by the Ground Motion Panel Experts for the various PGA Models for the Case when the Seismicity Expert's Earthquake Recurrence Model is in Magnitude.

Model	EXPERT 1	2	3	4	5	Relative Weight of Model
2	.35					.07
4			.20	.30		.11
6	.45					.09
8			.10	.50		.15
10	.20					.04
12				.10		.03
13		.316	.70			.18
14					1.0	.18
21				.10		.03
22		.105				.02
23		.105				.02
24		.105				.02
29		.053				.01
30		.211				.04
33		.105				.02

Table 3.4.4e
Region 3

Weights Given by the Ground Motion Panel Experts for the Various PGA Models for the Case when the Seismicity Expert's Earthquake Recurrence Model is in Intensity.

Model	EXPERT 1	2	3	4	5	Relative Weight of Model
2	.35					.07
4			.20	.30		.11
6	.45					.09
8		.05	.10	.50		.16
10	.20					.04
12				.10		.03
13			.70			.13
14					1.0	.18
21				.10		.03
22		.10				.02
23		.10				.02
24		.20				.04
29		.05				.01
30		.40				.07
33		.10				.02

Table 3.4.4f
Region 4

Weights Given by the Ground Motion Panel Experts for the Various PGA Models for the Case when the Seismicity Expert's Earthquake Recurrence Model is in Magnitude.

Model	EXPERT 1	2	3	4	5	Relative Weight of Model
3	.35					.07
4			.20	.30		.11
7	.45					.09
8			.10	.50		.15
11	.20					.04
12				.10		.03
13		.211	.70			.16
14		.105			1.0	.18
16		.105				.02
21		.211		.10		.06
28		.211(BE)				.04
29		.053				.01
34		.105				.02

Table 3.4.4g
Region 4

Weights Given by the Ground Motion Panel Experts for the Various PGA Models for the Case when the Seismicity Expert's Earthquake Recurrence Model is in Intensity.

Model	EXPERT 1	2	3	4	5	Relative Weight of Model
3	.35					.07
4			.20	.30		.11
7	.45					.09
8		.05	.10	.50		.16
11	.20					.04
12				.10		.03
13			.70			.13
14		.10			1.0	.20
16		.10				.02
21		.20				.04
28		.40				.07
29		.05				.01
34		.10				.02

Table 3.4.5
Most Heavily Weighted Models

Model Name	Eq. Number in Q4 Appendix C Volume 2	Eq. Numbers in Appendix B Table B1 Volume 1	Region 1		2		3		4	
			M	I	M	I	M	I	M	I
Campbell (1982)	D13	1-4	.18	.18	.18	.18	.18	.18	.18	.18
Nuttli (1984)	D21	5-8	.24	.25	.25	.25	.24	.25	.24	.25
Atkinson (1984)	D22	9-13	.25	.20	.20	.20	.25	.20	.23	.20
Trifunac	A3-G16	14	.18	.18	.18	.18	.18	.18	.18	.20

Figures 3.4.7a-d compare the updated base case best estimate PGA models selected by the experts for each of the four regions. Only Expert 2 chose a different best estimate model for the cases when the seismicity expert's earthquake recurrence models were in intensity. These models are denoted by an I in the figure's legend. It is seen from Figures 3.4.7 a-d and that there is a significant difference in the models chosen by the different ground motion experts.

In Appendix B all of the ground motion models are plotted for each of the five experts.

At the feedback meeting we also reviewed how we were using the self weights provided by the panel members in our analysis. We asked them to reevaluate their self weights and Table 3.4.6 gives their final values.

For the interim analysis as reported in Bernreuter et al. (1984) the hazard analysis was based on modeling the variation in the ground motion parameter, given magnitude (and/or intensity) and distance, with a lognormal distribution, i.e. as having an unbounded range. At the feedback meeting some of the panel members indicated that a more appropriate model would be one which restricted the ground motion parameter (GMP) to a finite range. To accommodate this view we included a model for the GMP based on a truncated lognormal distribution. Four interpretations of saturation were allowed, (Note: the discussion is given in terms of acceleration although a similar discussion holds for velocity and spectra):

- o Type 1: No truncation.
- o Type 2: There is an absolute maximum acceleration, independent of magnitude and distance, which will not be exceeded.
- o Type 3: The maximum acceleration is a function of magnitude and distance; this is modeled by assuming the maximum acceleration is a fixed number of standard deviations from the mean in the lognormal distribution of the GMP's.
- o Type 4: For any magnitude and distance the maximum acceleration is the minimum of an absolute maximum and a fixed number of standard deviations from the mean; this is an envelope of Type 2 and 3 saturation.

The 3 types of limits,drawn as a function of distance R for a fixed magnitude m, are depicted in Figure 3.4.8.

- o Type 2, an absolute maximum acceleration, a_1, results in the horizontal curve C_1.
- o Type 3, the maximum acceleration is a fixed number, n, of standard deviations from the mean, thus the limit curve is C_2 which "parallels" the mean curve, a(m, R).
- o Type 4, the envelope of Type 2 and 3, results in the curve C_3.

COMPARISON OF TWO VERSIONS OF CAMPBELL'S 82 MODEL

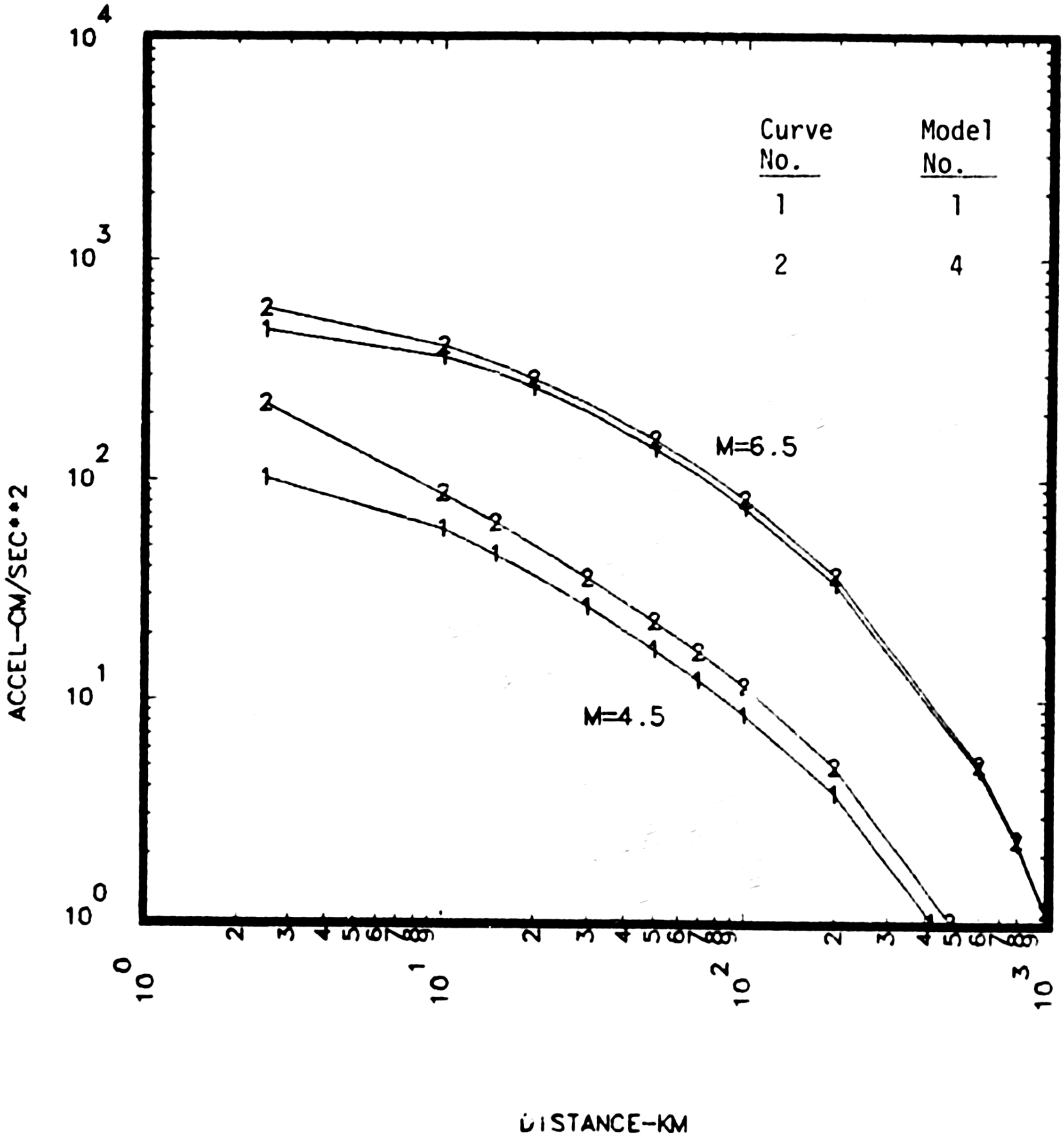


Figure 3.4.4

COMPARISON OF TWO VERSIONS OF NUTTLI'S(84) MODEL

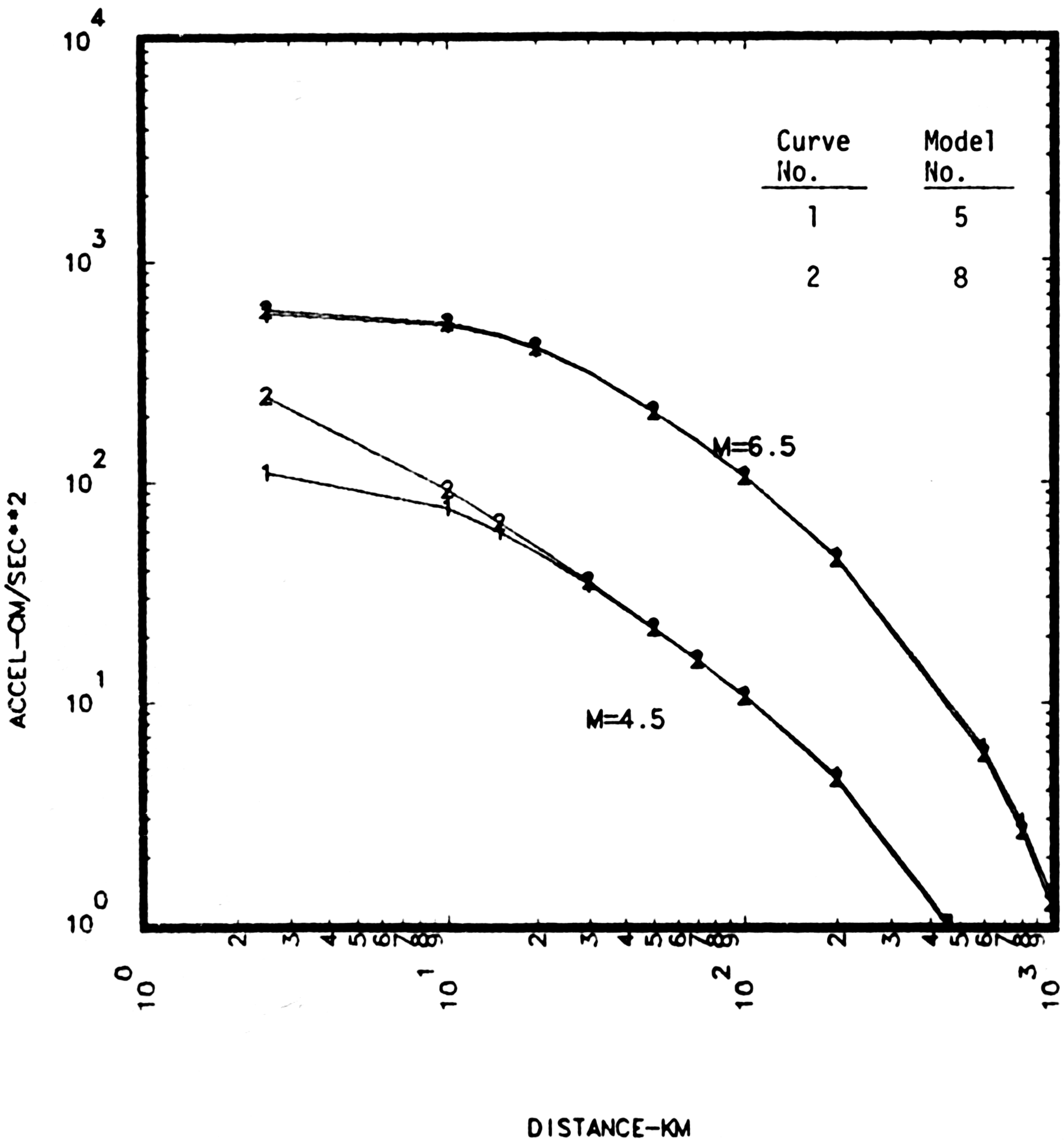


Figure 3.4.5

COMPARISON OF THREE VERSIONS OF ATKINSON'S MODEL

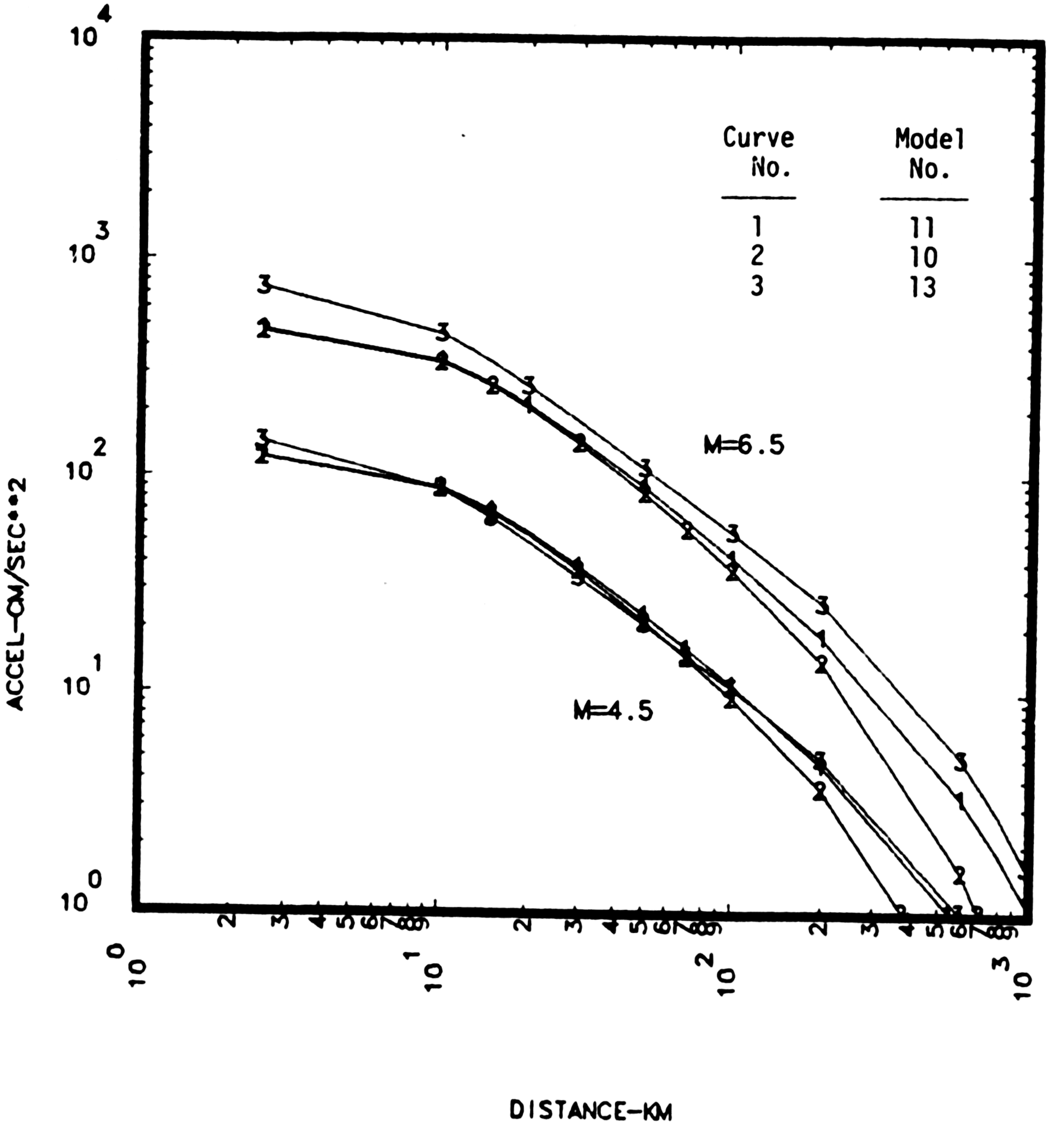
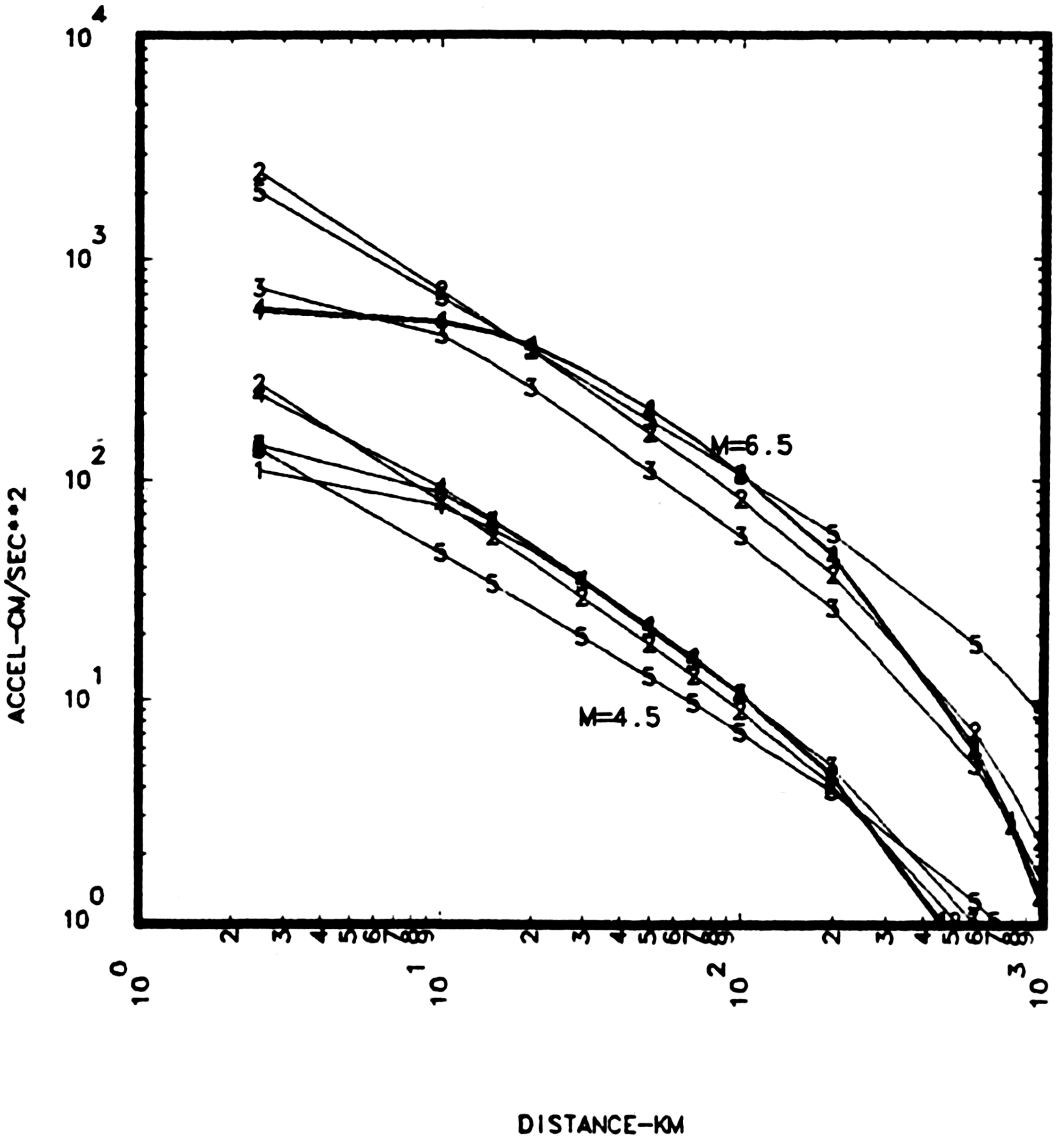


Figure 3.4.6

BEST ESTIMATE PGA MODELS FOR REGION 1



ꞅigure 3.4.7.a

Curve No.	Model No.	X No.
1	5	1
2	17 (Intensity	2
3	13 Model)	2,3
4	8	4
5	14	5

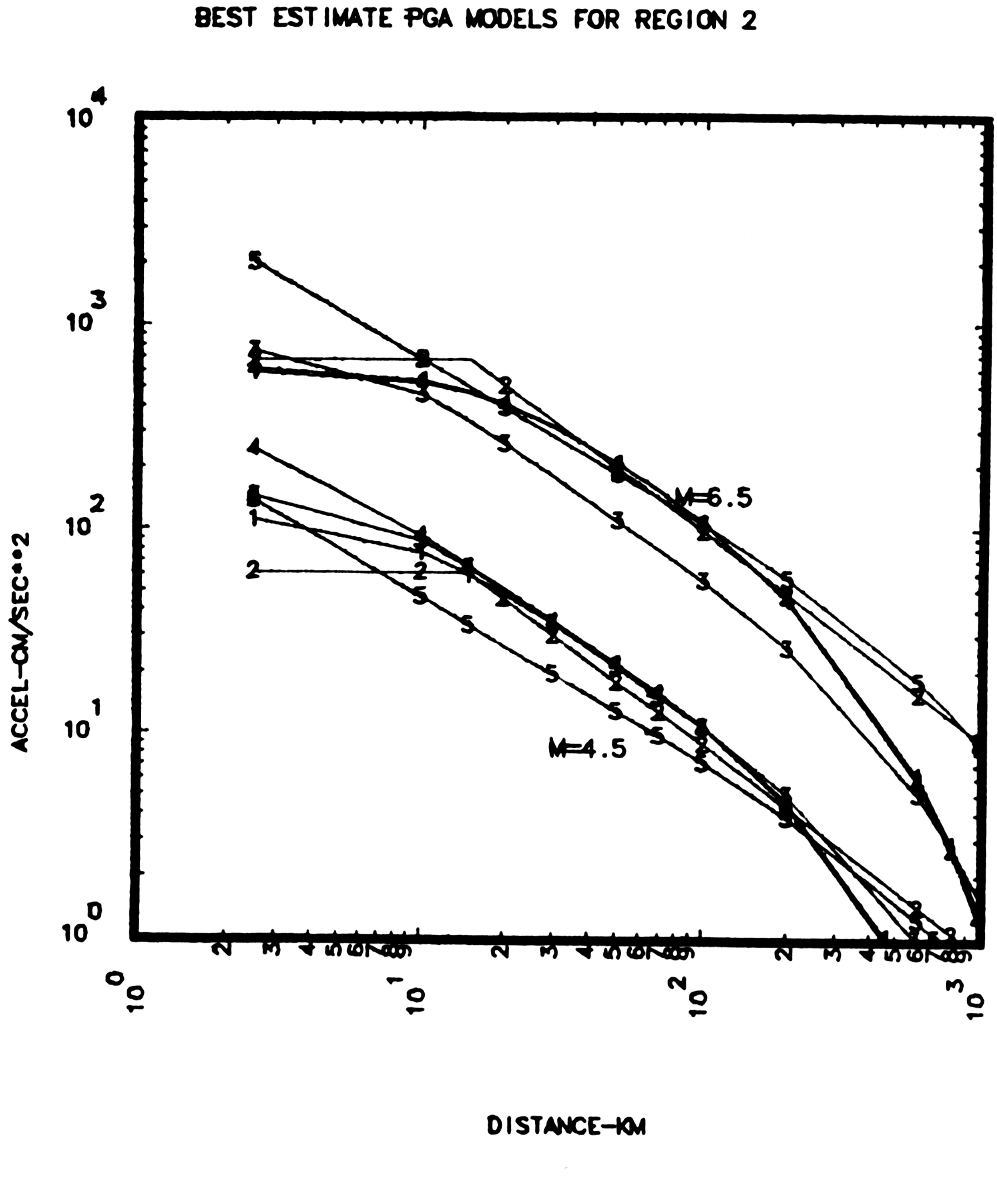


Figure 3.4.7b

Curve No.	Model No.	X No.
1	5	1
2	28	2
3	13	3
4	8	4
5	14	5

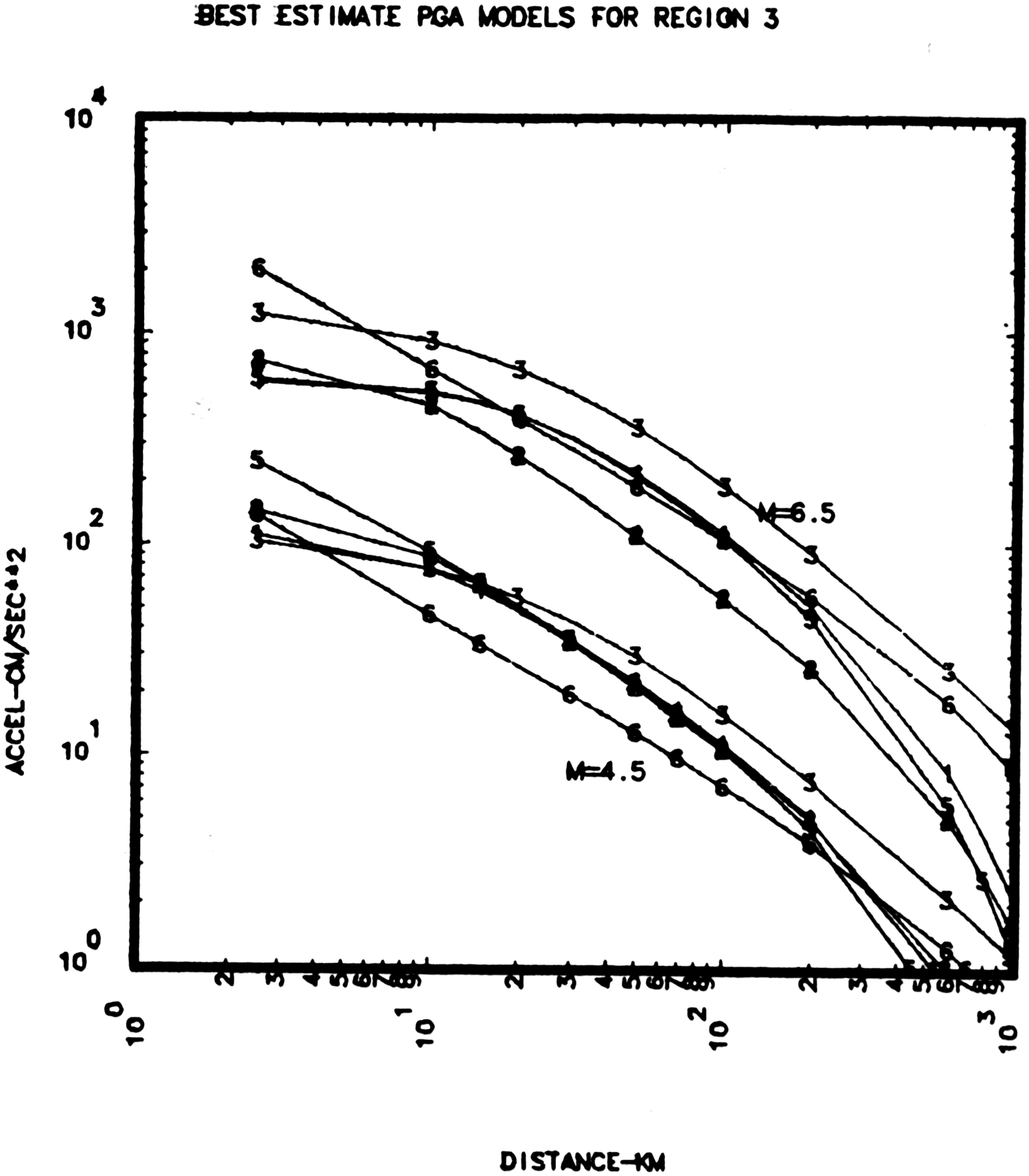


Figure 3.4.7c

Curve No	Model No.		X No.
1	6		1
2	13	(Intensity)	2
3	30		2
4	13		3
5	8		4
6	14		5

BEST ESTIMATE PGA MODELS FOR REGION 4

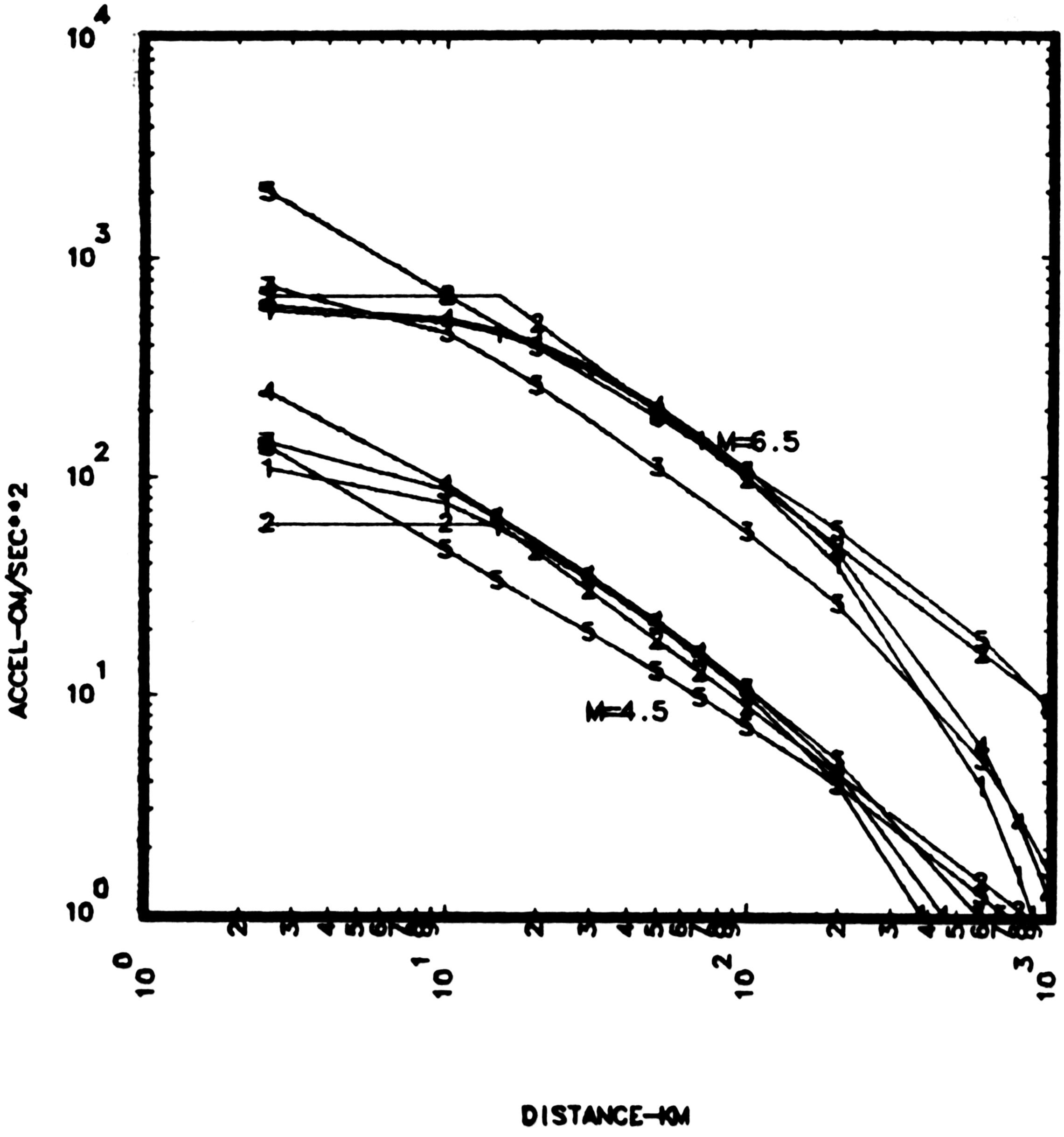


Figure 3.4.7d

Curve No.	Model No.	X No.
1	7	1
2	28	2
3	13	3
4	8	4
5	14	5

Table 3.4.6

Final Self Weights Provided by Experts

Expert No.	Self Weight
1	0.8
2	0.7
3	0.7
4	1.0
5	0.7

The choices, no truncation or type of truncation, made by the experts are given in Table 3.4.7.

Table 3.4.8 summarizes the estimates of random variation, expressed in terms of the standard deviation of a lognormal distribution, provided by the experts except for expert 5 who provided a different type of model for the spectra (Trifunac and Anderson 1977)

Tables 3.4.9 a-d list, by region, the spectral models and weights provided by the panel members and the overall weight of each model. The model numbers given in Tables 3.4.9 a-d cross reference the model numbers given in Table B1 of Appendix B which gives the names and coefficients of the models. The spectral models are defined at nine periods. Each period is assumed to be independent of the others. The equations are for the base case - deep generic soil. The best estimate models for region 1 are plotted in Figure 3.4.9a for a distance of 15km and in Figure 3.4.9b for a distance of 100km for magnitudes of 4.5 and 6.5. Only Experts 1 and 2 changed their models for the different regions. The differences between regions for Expert 1 are small, however, this is not the case for Expert 2 as shown in Figure 3.4.10a and b. All the models chosen by each expert are plotted in Appendix B.

It is seen from Figures 3.4.9 and 10 that there is a significant difference between the models selected as best estimate models by the various panel members. It is also seen that the difference is most significant at longer periods.

3.5 Selection of the Ten Test Sites

The ten sites used for analysis were selected by the staff of NRC's Geosciences Branch using the following criteria:
The ten sites should

1. Provide regional coverage of all areas that are being examined in the hazard program. This should include regions such as the northeast and upper midwest which have been studied in the past and regions such as the sougheast and gulf coast where little hazard information is currently available. Sites should also be chosen to provide initial (if possible) assessment of the potential impact of the USGS Charleston earthquake clarification letter.

2. Provide cross representation of plant vintage. The range of plant ages will allow an initial assessment of whether older plants may be more impacted by the hazard analysis than newer plants.

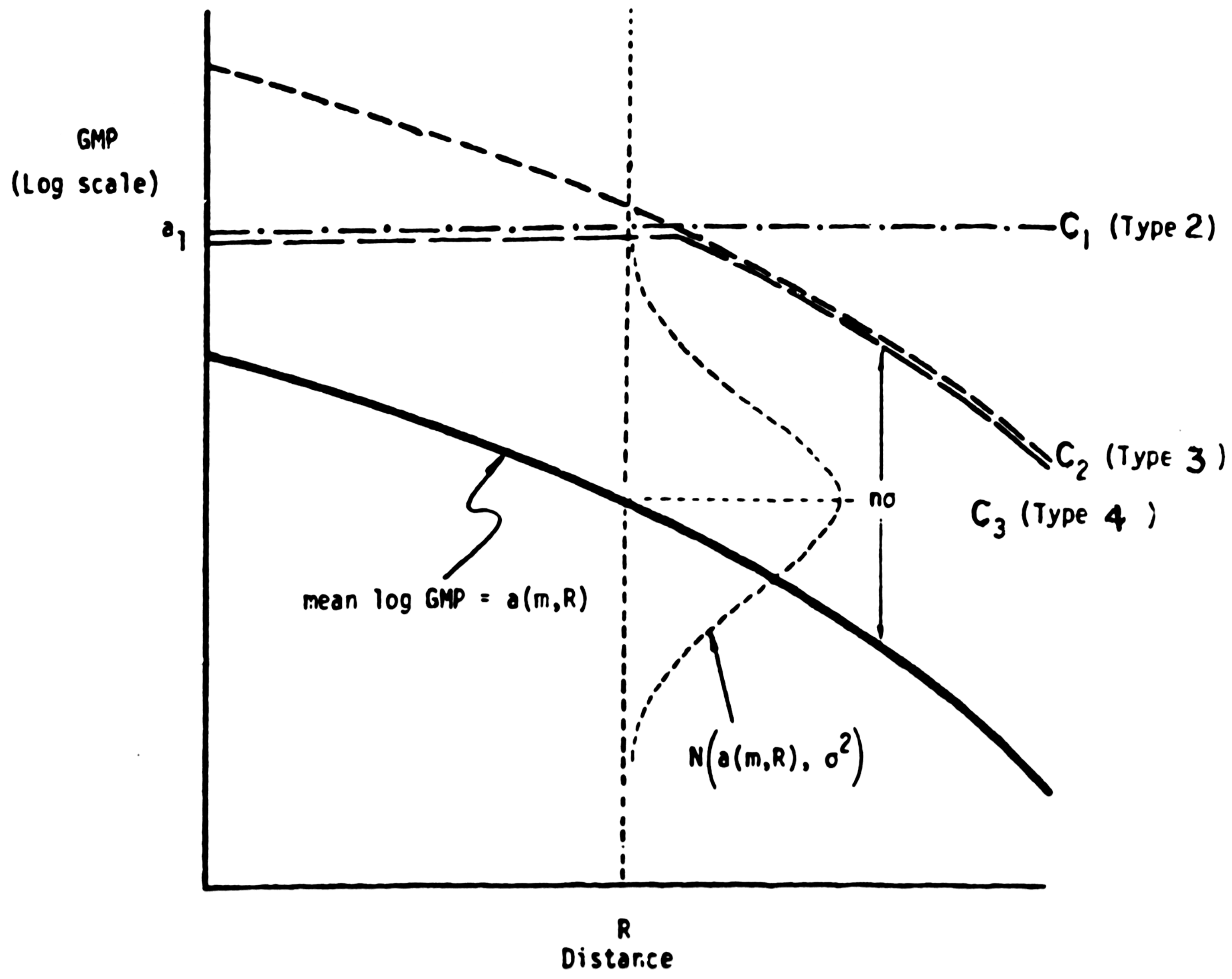


Figure 3.4.8 Saturation
Description of the three types of models considered for the physical saturation of the ground motion. The random variation of the logarithm of the GMP is modeled by a normal distribution with mean a (m,R) and standard deviation σ

3. Provide for comparison with hazard estimates undertaken as part of SEP phase II. This will allow a direct assessment of the hazard program improvements, particularly regarding the treatment of uncertainty.

4. Provide a cross representation of site conditions at test sites. This will allow an initial assessment of the impact of site conditions on the final hazard results.

The ten sites selected were:

1. River Bend - deep soil site; location - Gulf Coastal Plain; important issues include a region which has little or no hazard estimates.

2. Wolf Creek - rock site; partial (4 experts) hazard estimates have been completed from SEP phase II; location-west central United States; important issues include Central Stable Region and Nemaha Uplift.

3. Braidwood - treated as a rock site; hazard estimates, including SEP Phase II, have been made for nearby sites at Dresden and the Zion PRA; both rock and shallow soil conditions; location-central United States; important issues include northern extent of New Madrid and seismic zones in Illinois.

4. La Crosse - operating plant; hazard estimate made for SEP Phase II; sand-like soil site in category S2; location-north central United States; important issues include Central Stable Region and area of low seismicity, partial hazard estimates have been completed by consultant to licensee.

5. Watts Bar - hazard estimates made by TVA in 1978; both rock and shallow soil conditions; location-Appalachian region; important issues include possible eastern Tennessee seismic zone; treated as a rock site.

6. Vogtle - no hazard estimates have been made; deep soil site; location-Southeast United States; important issues include a region which has little or no hazard estimates and the site is within close proximity to Charleston, South Carolina.

7. Shearon Harris - no hazard estimates have been made; both rock and shallow soil conditions; location-North Carolina; important issues include southeast location although somewhat removed from Charleston; treated as a rock site.

8. Limerick - no hazard estimates have been made; rock site; location-southeastern Pennsylvania; important issues include effect of Charleston on eastern seaboard plants located away from Charleston.

9. Millstone - hazard estimates made for SEP phase II; both rock and shallow soil site; location-coastal Connecticut; treated as a rock site.

10. Maine Yankee - rock site; location-Maine; important issue is that this is the closest nuclear power plant to the 1982 New Brunswick earthquake.

The locations of these sites are shown in Figure 3.5.1.

Table 3.4.7

Method of Truncation of the Ground Motion Variation

Expert	Type of Truncation: PGA	Max[1] PGA	N	Type Truncation: Spectra	Max[2] S_v	N
1	4	1750.	3	4	200	3.
2	2	2000.	-	2	600.	-
3	2	2500	-	4	1000.	2.
4	4	1500.	2.5	3	-	2.5
5	1	-	-	1	-	-

(1) PGA in cm/sec/sec

(2) S_v in cm/sec

Table 3.4.8

Random Variation

Expert No.	PGA Best Estimate	PGA Bounds Lower	PGA Bounds Upper	SPECTRA Best Estimate	SPECTRA Bounds Lower	SPECTRA Bounds Upper
1	0.50	0.35	0.65	0.50	0.35	0.65
2	0.60	0.40	0.80	0.50	0.30	0.70
3	0.60	0.42	0.72	0.65	0.53	0.77
4	0.55	0.34	0.69	0.60	0.40	0.80
5	0.70	0.70	0.70	Not Applicable		

Note: Expert 5's S_v model was not modeled with a lognormal error term.

Table 3.4.9a
Region 1

Weights Given by the Ground Motion Panel Experts for the various Spectral Models

Model/Expert No.	1	2	3	4	5	Relative Weight of Model
58		.1		.4		.12
67		.1		.35		.11
76				.08		.02
85				.07		.02
94		.1			1.0	.20
184			.1	.1		.04
247			.8			.14
256			.1			.02
193	.7					.14
220	.3					.05
148		.2				.04
121		.4				.07
175		.1				.02

Note: The spectral models are defined by nine frequencies and are identified in the Table by the first equation. For example, in Table B1 of Appendix B, Volume 1 the spectral model SEP1 is made up of model numbers 58-66.

Table 3.4.9b

Region 2

Weights Given by the Ground Motion Panel Experts for the Various Spectral Models.

Model/Expert No.	1	2	3	4	5	Relative Weight of Model
58		.1		.4		.12
67		.1		.35		.11
76				.08		.02
85				.07		.02
94		.1			1.0	.20
184			.1	.1		.04
247			.8			.14
256			.1			.02
193	.7					.14
220	.3					.05
139		.4				.07
112		.2				.04
166		.1				.02

Note: The spectral models are defined by nine frequencies and are identified in the Table by the first equation. For example, in Table B1 of Appendix B, Volume 1 the spectral model SEP1 is made up of model numbers 58-66.

Table 3.4.9c

Region 3

Weights Given by the Ground Motion Panel Experts for the Various Spectral Models.

Model/Expert No.	1	2	3	4	5	Relative Weight of Model
58		.1		.4		.12
67		.1		.35		.11
76				.08		.02
85				.07		.02
94		.1			1.0	.20
184			.1	.1		.04
247			.8			.14
256			.1			.02
202	.7					.14
229	.3					.05
130		.2				.04
103		.4				.07
157		.1				.02

Note: The spectral models are defined by nine frequencies and are identified in this Table by the first equation. For example, in Table B1 of Appendix B, Volume 1 the spectral model SEP1 is made up of model numbers 58-66.

<u>Table 3.4.9d</u>

<u>Region 4</u>

Weights Given by the Ground Motion Panel Experts for the Various Spectral Models.

Model/Expert No.	1	2	4	4	5	Relative Weight of Model
58		.1		.4		.12
67		.1		.35		.11
76				.08		.02
85				.07		.02
94		.1			1.0	.20
184			.1	.1		.04
247			.8			.14
256			.1			.02
211	.7					.14
238	.3					.05
139		.4				.07
112		.2				.04
166		.1				.02

Note: The spectral models are defined by nine frequencies and are identified in the Table by the first equation. For example, in Table B1 of Appendix B, Volume 1 the spectral model SEP1 is made up of model numbers 58-66.

BEST ESTIMATE SPECTRAL MODELS FOR REGION 1

R=15.KM

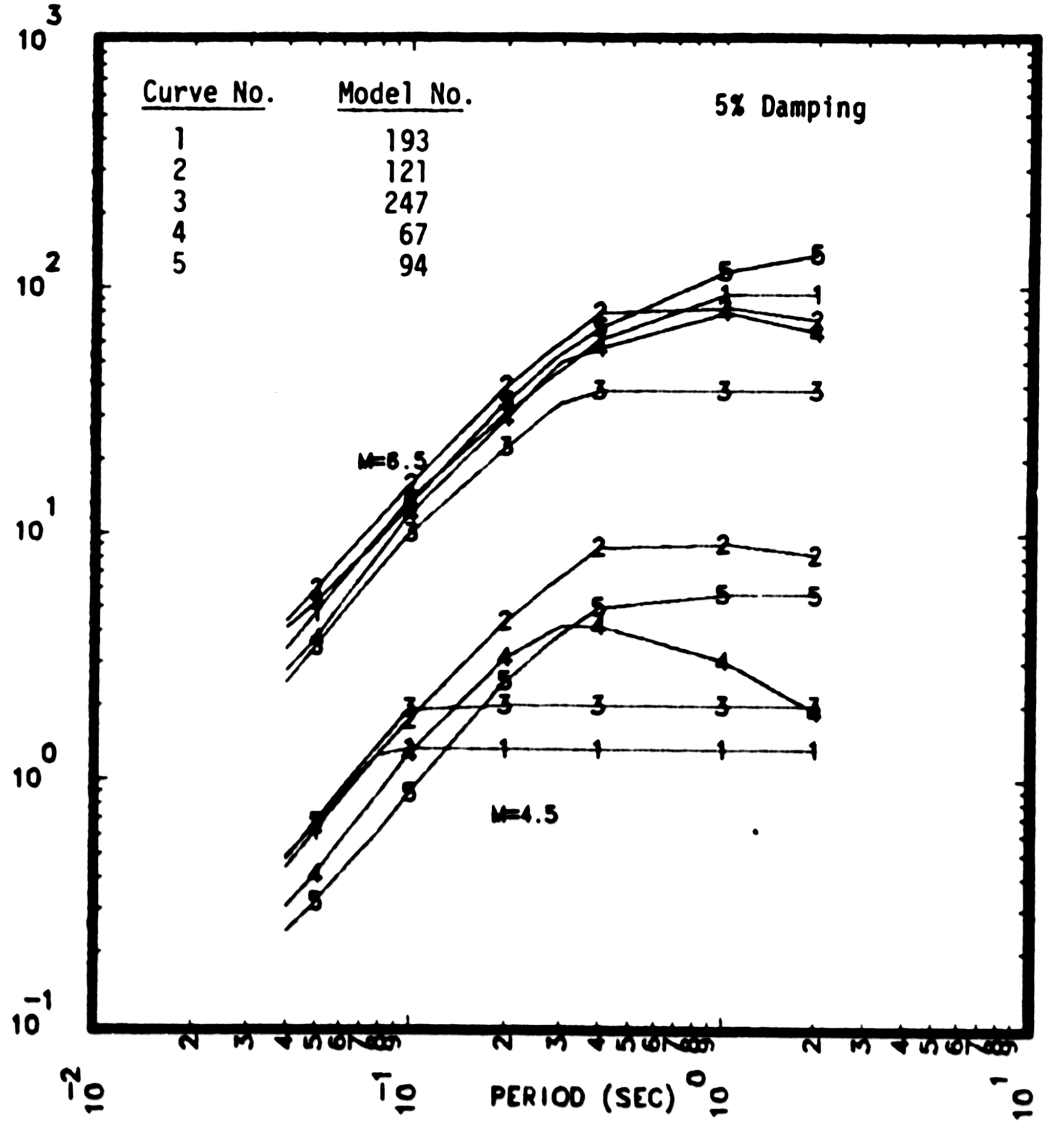


Figure 3.4.9a

BEST ESTIMATE SPECTRAL MODELS FOR REGION 1

R=100. KM

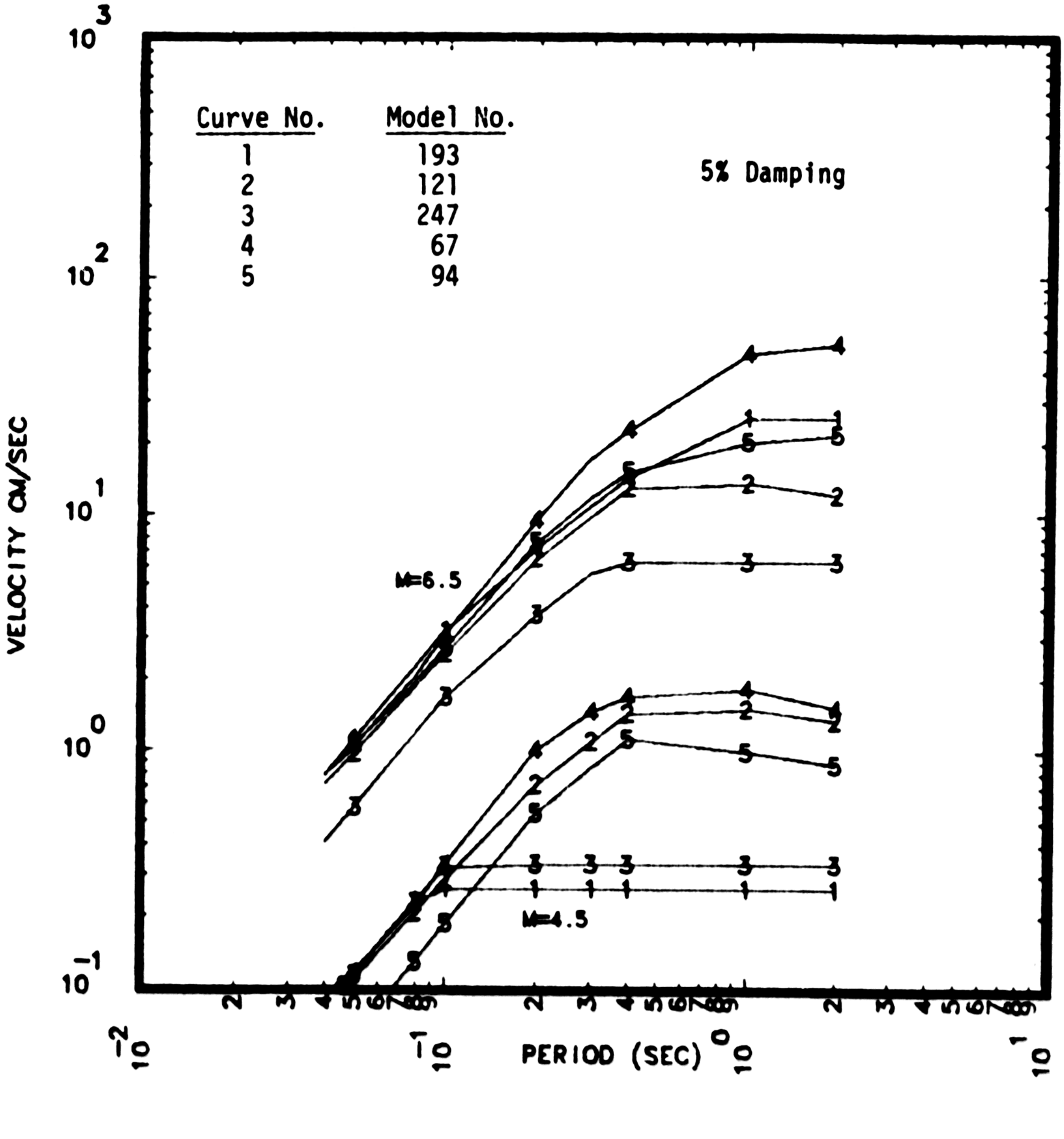


Figure 3.4.9b

GM EXPERT 2 BE SPECTRAL MODELS FOR THE 4 REGIONS

R=15. KM

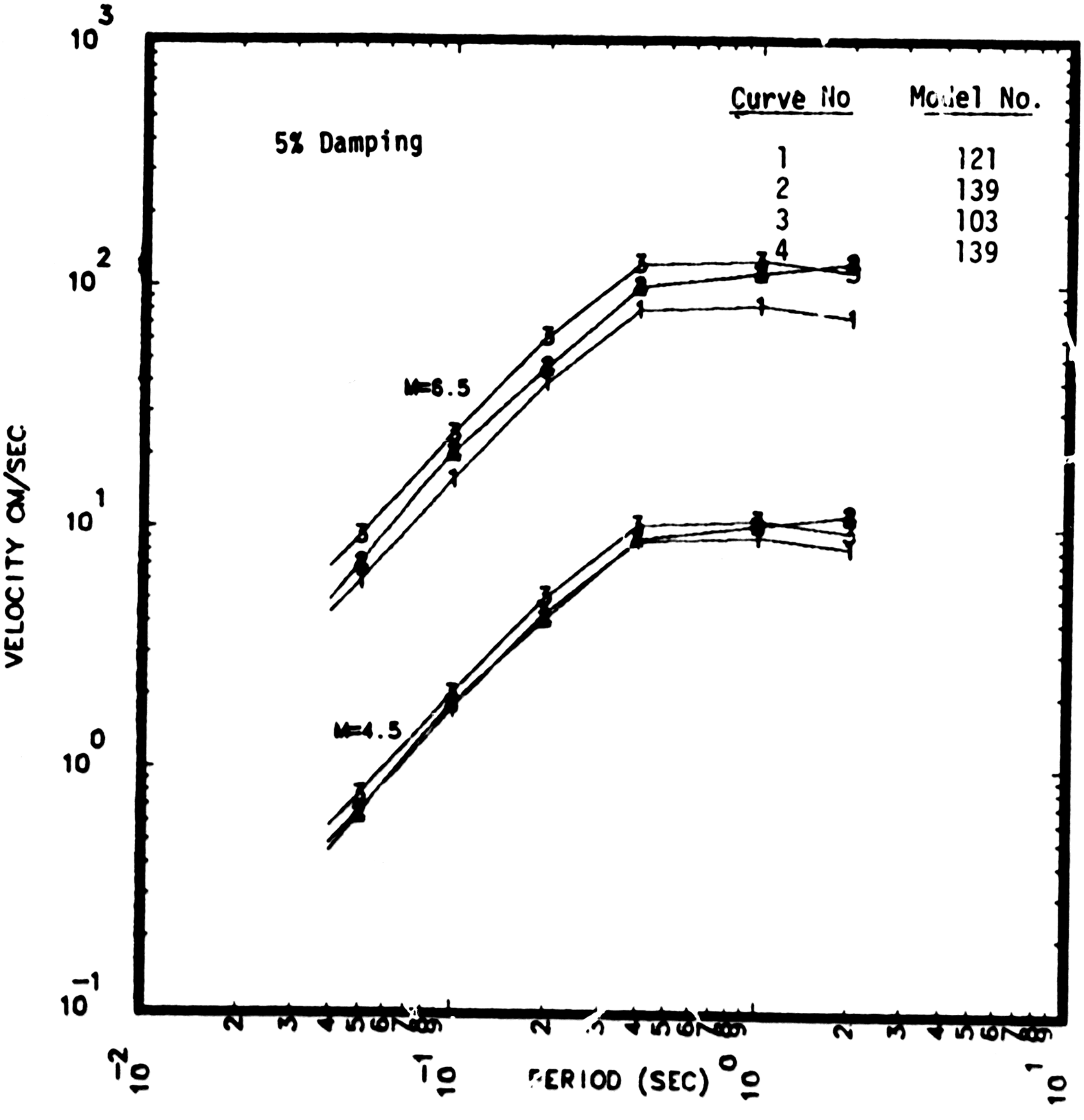
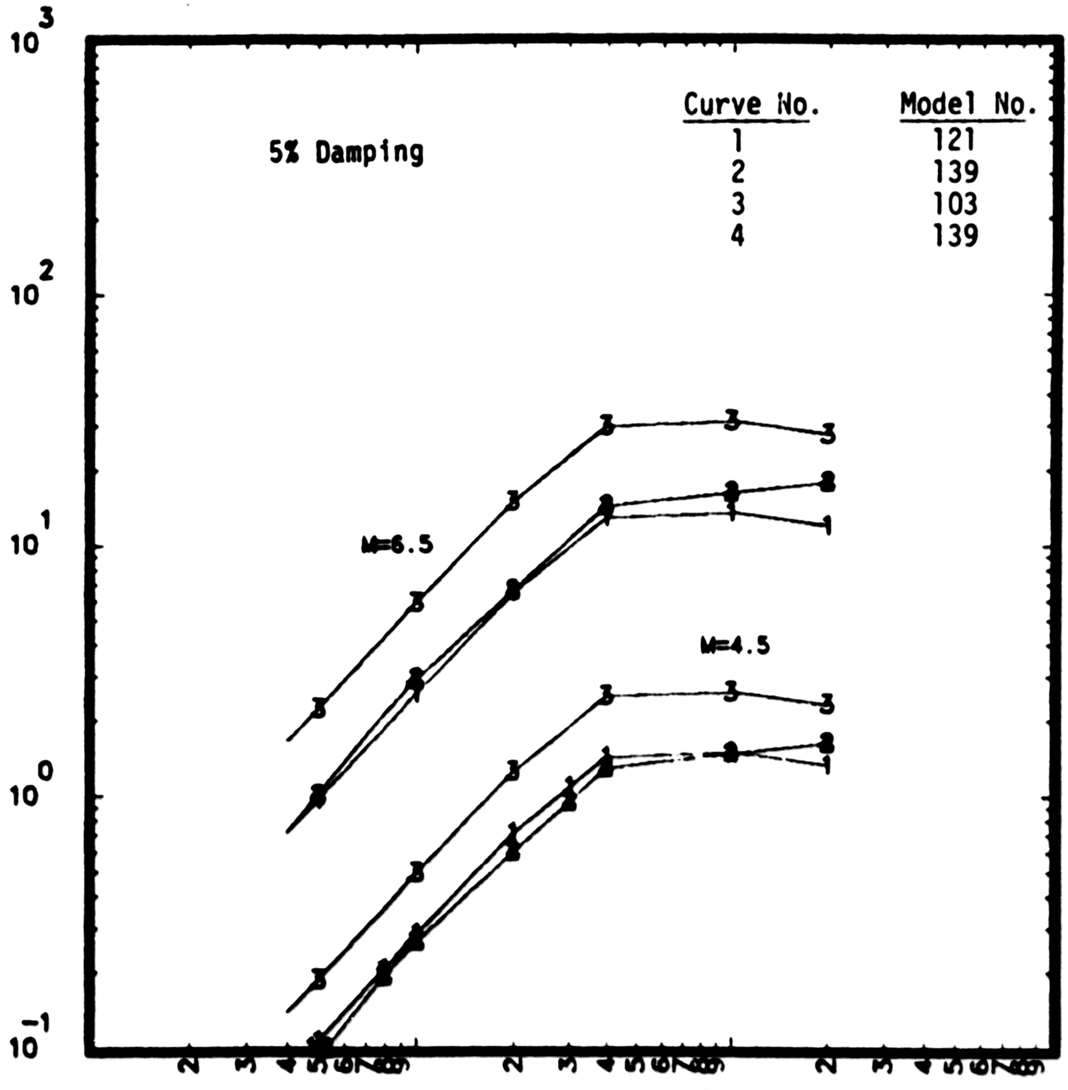


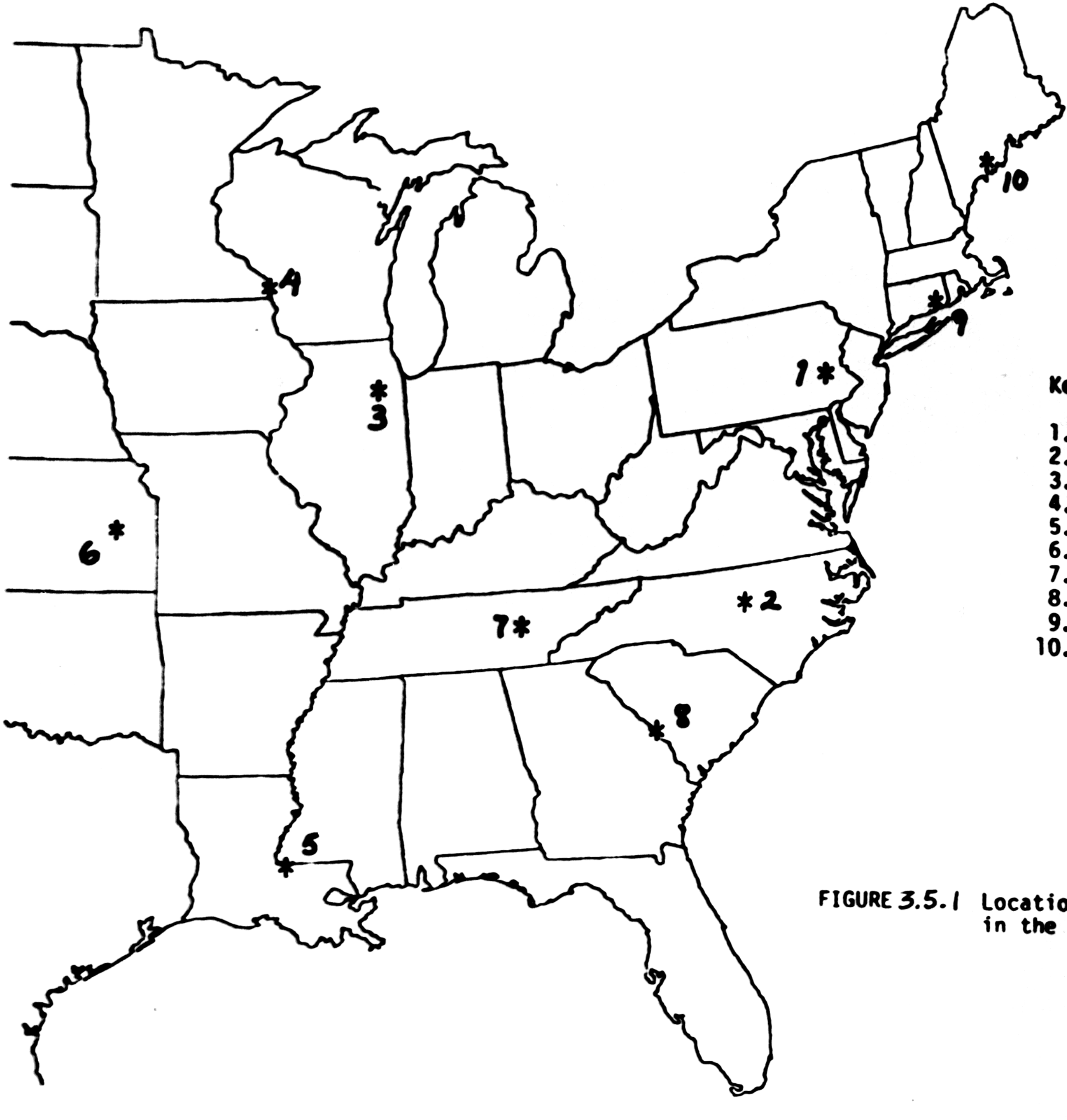
Figure 3.4.10a

EXPERT 2 BE SPECTRAL MODELS FOR THE 4 REGIONS

R=100. KM



F··ure 3.4.10b



Key to Site Index Numbers

1. Limerick
2. Shearon Harris
3. Braidwood
4. La Crosse
5. River Bend
6. Wolf Creek
7. Watts Bar
8. Vogtle
9. Millstone
10. Maine Yankee

FIGURE 3.5.1 Location of the Sample Sites in the EUS

SECTION 4: SENSITIVITY ANALYSIS

4.1 Introduction

In this section we examine the sensitivity of the calculated hazard to changes in various input parameters as an aid to understanding the results of the analyses for the ten sites presented in Section 5. We are interested in not only how changes in the best estimate (BE) values of parameters affect the hazard curve but also how the uncertainty about the BE values influence one's assessment of the seismic hazard at a site. In particular, we examine the influence of the following variables on the computed hazard:

1. The uncertainty individual experts have about their zonations.

2. Changes in both the BE values of the "a" and "b" parameters of the magnitude recurrence relation and how the uncertainty in these parameters is modeled.

3. Change in the BE values and reduction of uncertainty in the estimate of the upper magnitude cutoff M_U.

4. The earthquake recurrence model used.

5. The model uncertainty in the ground motion models.

6. Site correction.

There are a number of different estimators of the seismic hazard at a site that could be used. In this report we typically use best estimate hazard curves (BEHC) and constant percentile hazard curves (CPHC). As discussed in Appendix C, what is termed BEHC for a particular pair of seismicity and ground motion experts is the hazard curve based on selecting the seismicity expert's BE map and BE values for all of the seismicity parameters coupled with the BE ground motion model for the ground motion expert. (See Section 2.5.4 and Appendix C for more details). Thus a BEHC is developed for each ground motion expert and seismicity expert for each site. The BEHC is not necessarily the "best estimator", but is simply one possible estimator of the seismic hazard at a site. The first level of aggregation consists in combining BEHC over ground motion experts for a given seismicity expert using the self-weights provided by the Ground Motion Panel members. The resultant curves for each seismicity expert for each site are provided in Sections 4 and 5. The second level of aggregration consists in combining the overall resultant BEHC for each pair of ground motion and seismicity experts for a site using the self weights provided by both the ground motion and seismicity experts to obtain the combined BEHC for each site. It is important to keep in mind that this combination is arithmetical (i.e. the aggregation is performed on the values of probabilites rather than their logarithm) so that outliers are important. We also present the constant percentage hazard curves CPHC which result from our simulation procedure for individual experts as well as combined over all seismicity experts and ground motion experts.

The BEHC appears to constitute a natural choice for the case when each expert's uncertainty in his parameter is not included. However, there are several different ways to present the results of the uncertainty analysis, e.g., percentiles, full frequency distribution, means, median and moments. After careful consideration of these possible candidates, we chose to use the 15th, 50th and 85th CPHC. We also investigated the relationship between the geometrical mean hazard curve (GMHC), which is obtained by averaging the logarithms of the probabilities and the arithmetic mean hazard curve (AMHC) to both the BEHC and the CPHC. Both the GMHC and the CPHC tend to de-emphasize outliers.

It is important to note the difference inherent between the different estimators. For instance, because the frequency distributions of the hazard is generally skewed, the GMHC, AMHC, BEHC and the median CPHC are generally different. In most cases, there is a significant difference between the AMHC and the GMHC indicating the presence of outliers. There is also generally reasonable agreement between the GMHC and the median CPHC.

In Sections 4 and 5 we also present best estimate uniform hazard spectra (BEUHS) and constant percentile uniform hazard spectra (CPUHS). By definition the uniform hazard spectrum is a spectrum in which each spectral amplitude has the same probability of being exceeded. In the development of the spectrum each frequency is considered independently and correlation between the spectral amplitudes is not taken into account. Predictions are made for one frequency at a time. All potential earthquakes, small and large, contributing to the hazard at the site are considered, using appropriate seismicity, attenuation and zonation models. The cumulative contribution to the loading at the given frequency is computed as a cumulative distribution function of the loading.

The pseudo-spectral velocity vs. period is then plotted and the loading corresponding to the return period of interest is used as the appropriate spectral amplitude at the given period. The procedure is repeated for other periods within the period range of interest and the spectrum is built point by point.

Since each frequency is treated independently, the shape of a specific spectrum shape corresponding to a particular earthquake is lost in the process. Thus, the uniform hazard spectrum is not representative of any single event. For example, if the structure is subjected to a nearby small earthquake, the ground motion will be most likely rich in short period energy; the low long period content of its spectrum will tend to be small. Conversely, if the event is distant, its spectrum will most probably have little energy in the short period range, and relatively more long period energy.

The results are very site and expert dependent (Bernreuter (1981a). Hence, there are certainly many exceptions to any conclusions reached and they should only be used as a guide for interpreting the results. Keeping this in mind, we selected four sites to explore the influence of the parameters mentioned above to help us reach "general" conclusions. In selecting these four sites, we attempted to span the range of factors that influence the results. Thus one site, River Bend, is located in a region of low seismicity and generally simple zonation. One site (Millstone) is located in an area of complex zonation and two sites (Braidwood in the midwest and Shearon Harris in the southeast) are located in regions of moderate zonation complexity. Only representative results are shown rather than giving the results for each site. This was generally for the Braidwood site.

To explore the relative contribution introduced by the Seismicity Panel and our modeling of the random uncertainty we performed a number of sensitivity studies using only one ground motion model (Model #8 of Table B-1 Nuttli, 1983). For these cases 100 simulations were performed. Unless otherwise noted no site correction was used and no truncation was applied to the PGA distribution.

Figures 4.1.1 a,b, and c show the results for the base sensitivity case. This is the case where all parameters are varied (except the ground motion model). Figure 4.1.1a shows the BEHC for each of the seismicity experts, Figure 4.1.1b shows the combined CPHC, Figure 4.1.1.c shows a comparison of the BEHC, the GMHC and the CPHC. It is seen from Figure 4.1.1c that as noted earlier there is reasonable agreement between the GMHC and the 50th percentile CPHC and that the BEHC lies between the GMHC and the AMHC.

It should be noted that all the hazard curves plotted in this report are plots of PGA vs. annual probability of exceedance. The correspondence between expert numbers and plot symbols is given in Table 4.1.1.

4.2 Maps

Each expert was asked to express his/her uncertainty about both the existence of individual zones and the shape their boundary. As can be seen from Table A1, many zones shown on the maps have probabilities of existence less than 1.0. For the uncertainty expressed by any expert about either the existence of zones or their shape to have any influence on the computed seismic hazard the site must be either within the zone or near zones that might not exist or whose boundary shape could change significantly. Thus for sites like River Bend or La Crosse, which are located away from zones that might not exist, the uncertainty about the existence/non-existence of a given zone for a given expert does not affect the answer. Millstone and Braidwood are located in regions with a number of nearby zones. The uncertainty a given expert has about the existence/non-existence of a given zone can have considerable impact on the computed hazard at these two sites.

To examine this latter point, we fixed all the parameters at their BE values except for the maps and performed 100 simulations for each seismicity

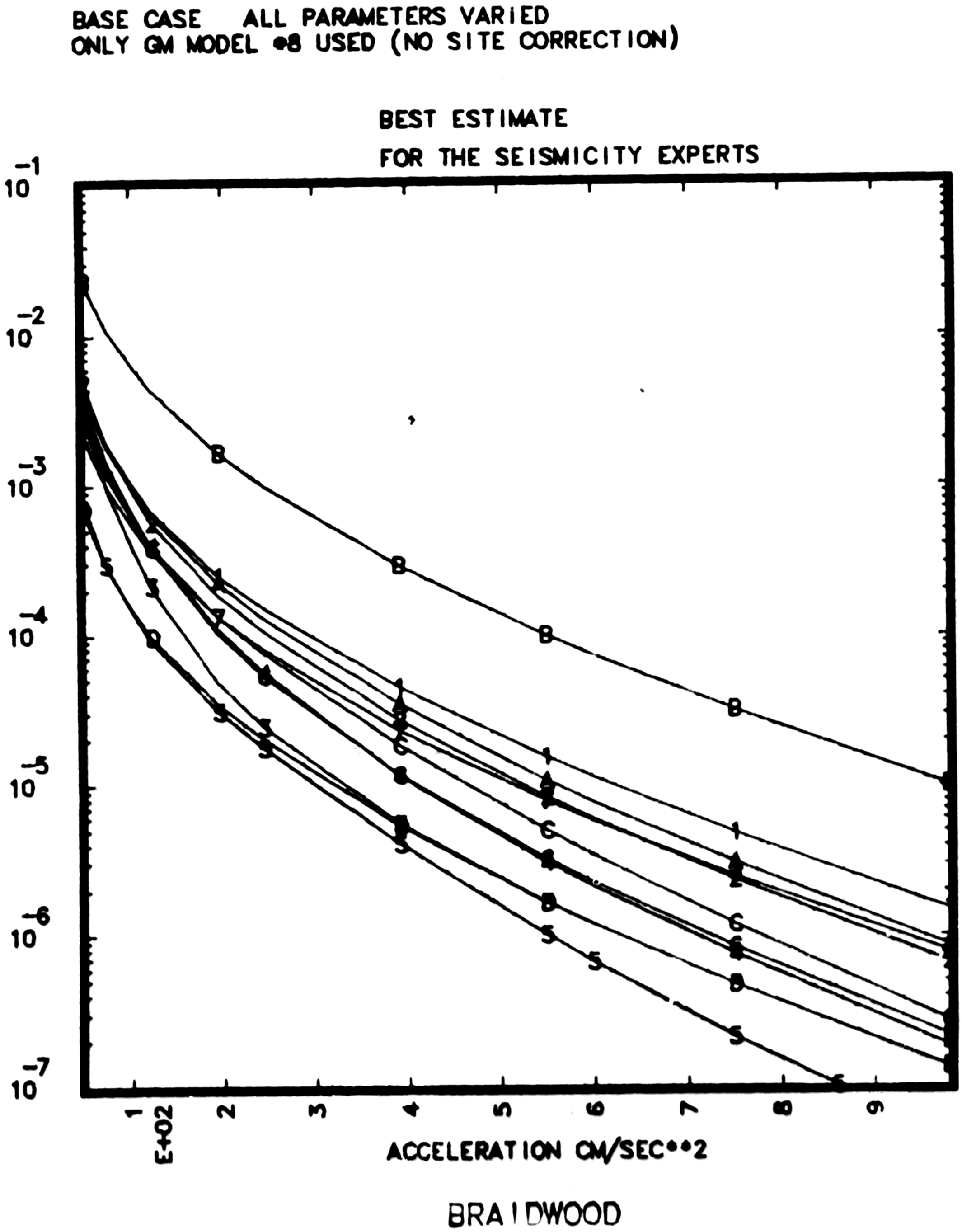
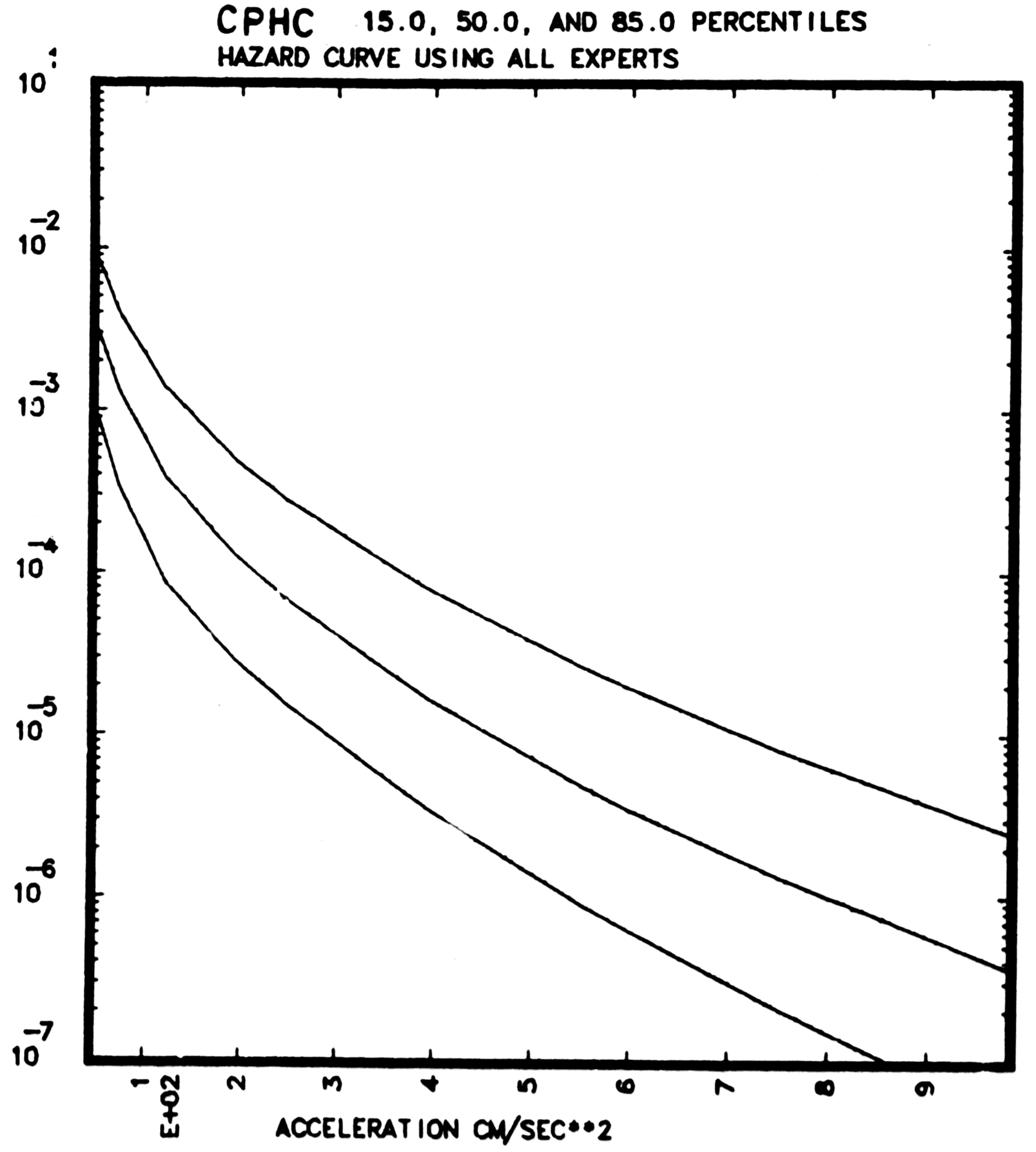

BASE CASE ALL PARAMETERS VARIED
ONLY GM MODEL #8 USED (NO SITE CORRECTION)
BEST ESTIMATE
FOR THE SEISMICITY EXPERTS
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
1 E+02 2 3 4 5 6 7 8 9
ACCELERATION CM/SEC**2
BRAIDWOOD

Figure 4.1.1a

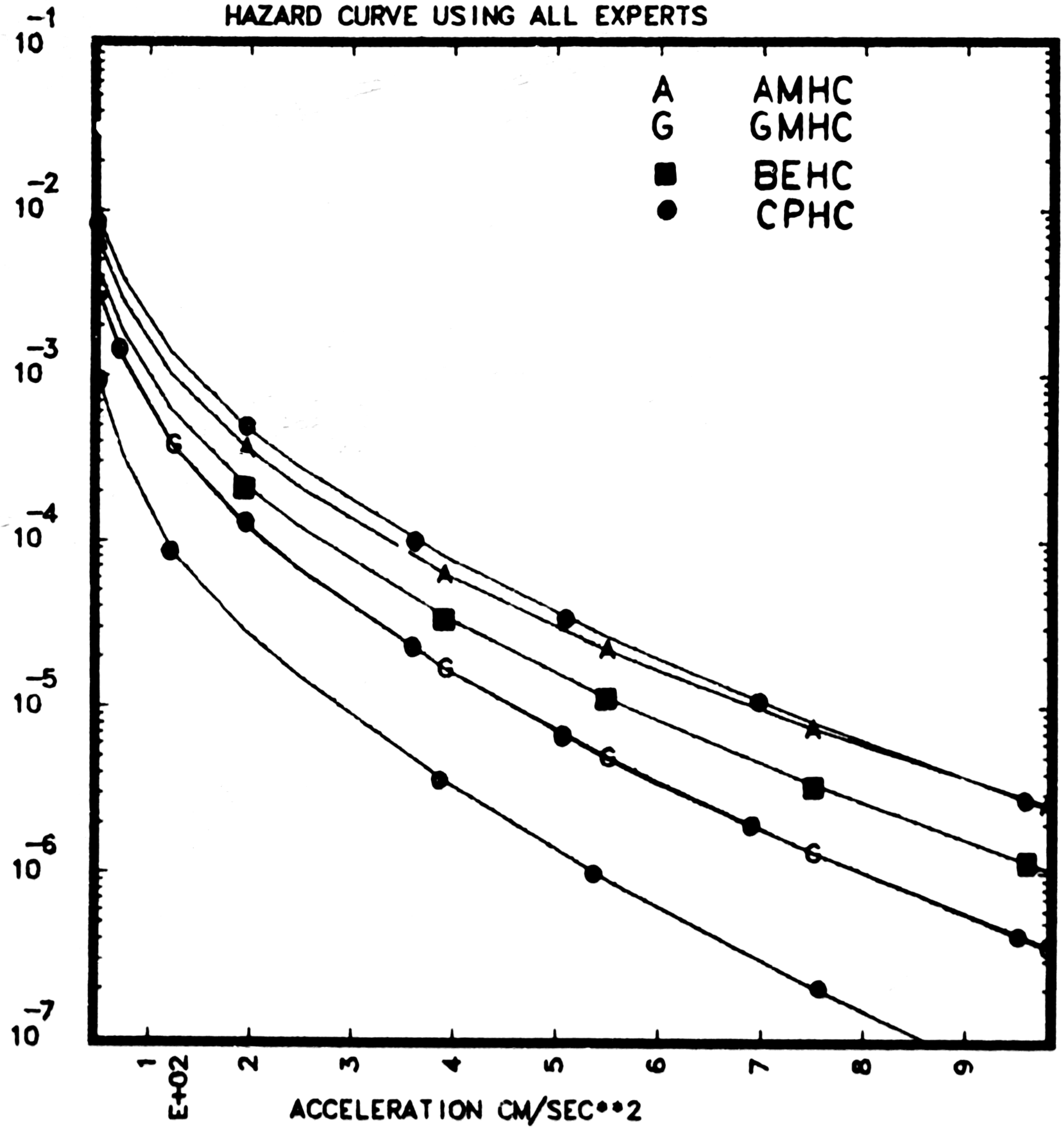
BASE CASE   ALL PARAMETERS VARIED
ONLY GM MODEL #8 USED (NO SITE CORRECTION)



BRAIDWOOD

Figure 4.1.1b

CPHC COMPARED TO THE BEHC, THE GMHC & THE AMHC



BRAIDWOOD

Figure 4.1.1c

TABLE 4.1.1

PLOT SYMBOLS USED ON BEHC and BEUHS

PLOT SYMBOL	SEISMICITY EXPERT NUMBER
1	1
2	2
3	3
4	4
5	5
6	6
7	7
A	10
B	11
C	12
D	13

expert. Thus for each expert 100 hazard curves were computed where the map was the only element that was changing in each simulation. If all the zones around the site had probability 1.0 of existence and there was no alternative boundary shapes to influence the results, then the simulation would yield 100 identical hazard curves. If the expert was uncertain about the existence of zones, then the 100 simulations would yield several sets of hazard curves. As would be expected, map uncertainty was much more important for some experts than for others and it varies considerably with the site. The importance of each expert's uncertainty about his zonation is given in Table 4.2.1. Figures 4.2.1, 4.2.2 and 4.2.3 are typical examples illustrating the significance of the uncertainty introduced by a given expert's uncertainty about his zonation. In Figures 4.2.1 and 4.2.2 all of the hazard curves fall on either the 15th percentile curve or the 50 percentile curve. It is the typical case when the expert's uncertainty about his zonation is important. This is due to the fact that two curves are superimposed as a result of the flat distribution of the maps. It means that of the 100 simulations, more than 50 of them gave the same or almost the same results, either at the low end or at the high end. Thus the 15th and 50th (or the 50th and 85th) percentiles are equal. For those cases where the expert's uncertainty about his zonation is not significant then all hazard curves are identical. In a few cases uncertainty is complex enough so that all three CPHC are generated as illustrated in Figure 4.2.3.

It is interesting to examine the factors contributing to the uncertainty in the CPHCs plotted on Figures 4.2.1 - 4.2.3. For Expert 1, at the Millstone site (Figure 4.2.1), the loading comes primarily from zone 22. Zone 22 has a probability of existence of 1.0 but its shape (and seismicity parameters) are equally likely to be replaced by zones 38 and 39. For Expert 13 the load is coming primarily from zone 10 which has a probability of existence of 0.6. This means that 40 percent of the time zone 10 is replaced with the CZ. In addition there is some uncertainty about the shape of zone 10 so that part of the time zone 13 replaces zone 10.

Figure 4.2.2 shows an extreme case of the uncertainty introduced by Expert 4's uncertainty in zonation for Braidwood. Zone 6 is the major contributor to the hazard but has a probability of existence of only 0.75. Thus 25 percent of the time zone 6 is replaced by zone 13 which has a much lower seismicity rate.

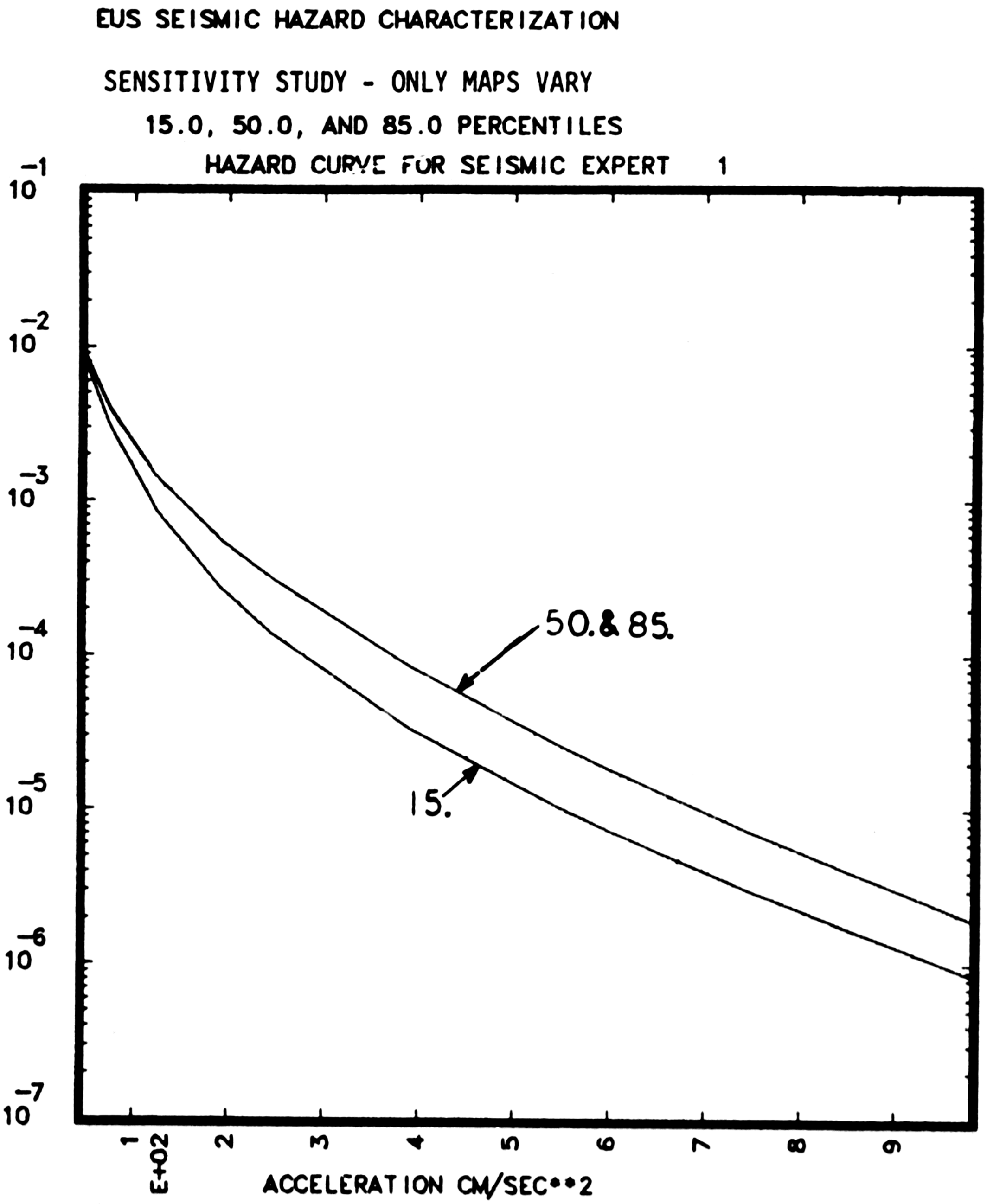
Note that the uncertainty we have been discussing is the uncertainty each expert has about his own maps. There is also a systematic uncertainty about the maps between experts- as can easily be seen by comparing the zonation maps for the different experts given in Appendix A. It is not a simple task to quantify this uncertainty because the selection of the other parameters of the model are not just a function of the zonation. If a set methodology was used to determine the a, b, and M_U values for a zone from a fixed catalogue, then the differences between hazard curves for different experts would be entirely due to zonation differences. However, this was not the case for this study. Each expert developed the a, b and M_U values independently using several different catalogues and approaches. A careful review of each experts' input

TABLE 4.2.1

Importance of Each Experts' Uncertainty About His Zonation on the Calculated Seismic Hazard at Four Sites Holding All Other Parameters Constant.

EXPERT NUMBER	SITE BR	MI	RB	SH
1	N	Y	N	N
2	Y	Y	N	Y
3	Y	Y	N	N
4	Y	N	N	N
5	N	N	N	Y
6	N	N	Y	Y
7	N	N	N	N
10	Y	Y	N	Y
11	N	Y	N	N
12	N	Y	N	N
13	N	Y	N	Y

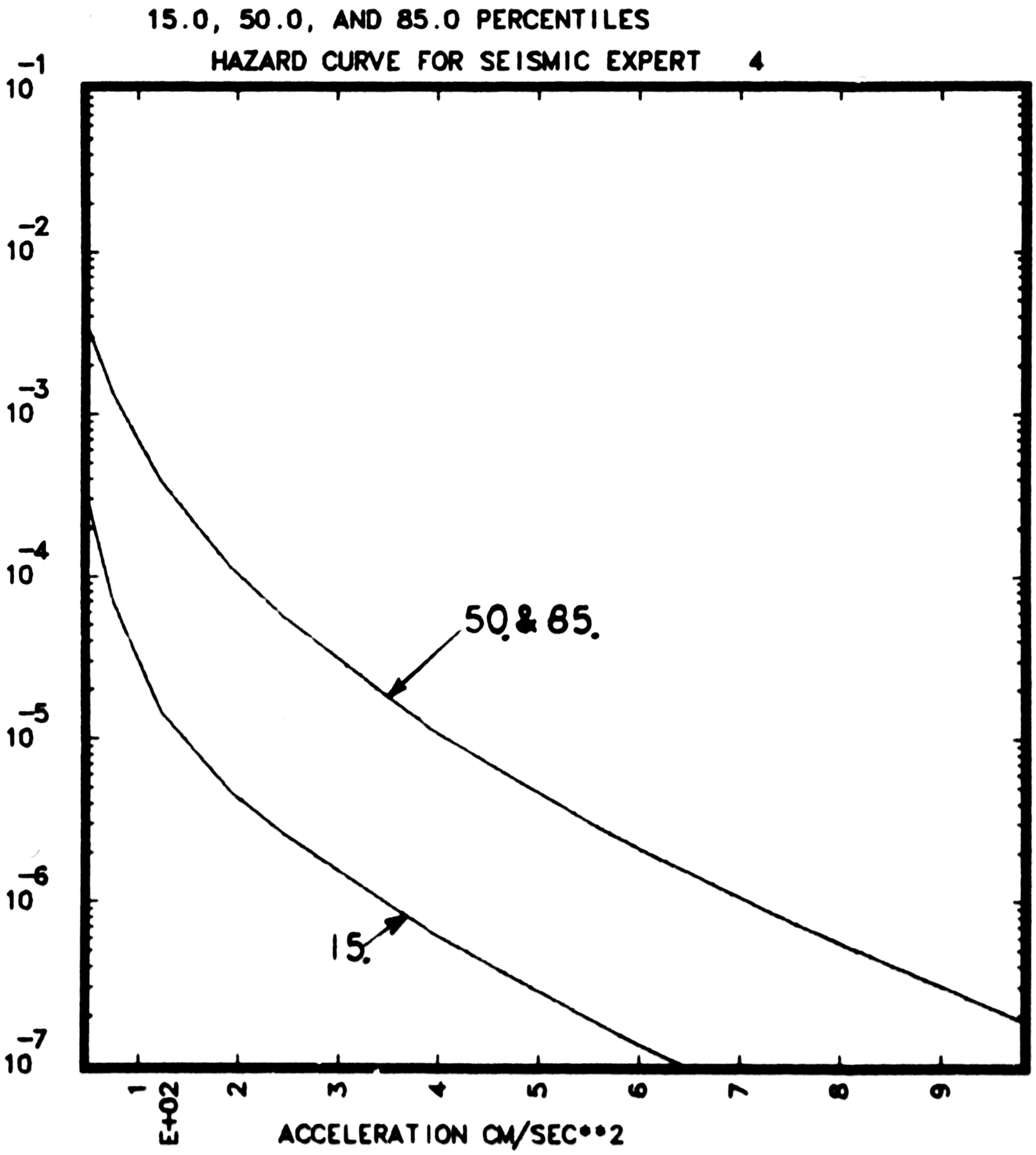
N = No influence
Y = Yes some influence
BR = Braidwood
MI = Millstone
RB = Riverbend
SH = Shearon Harris



MILLSTONE

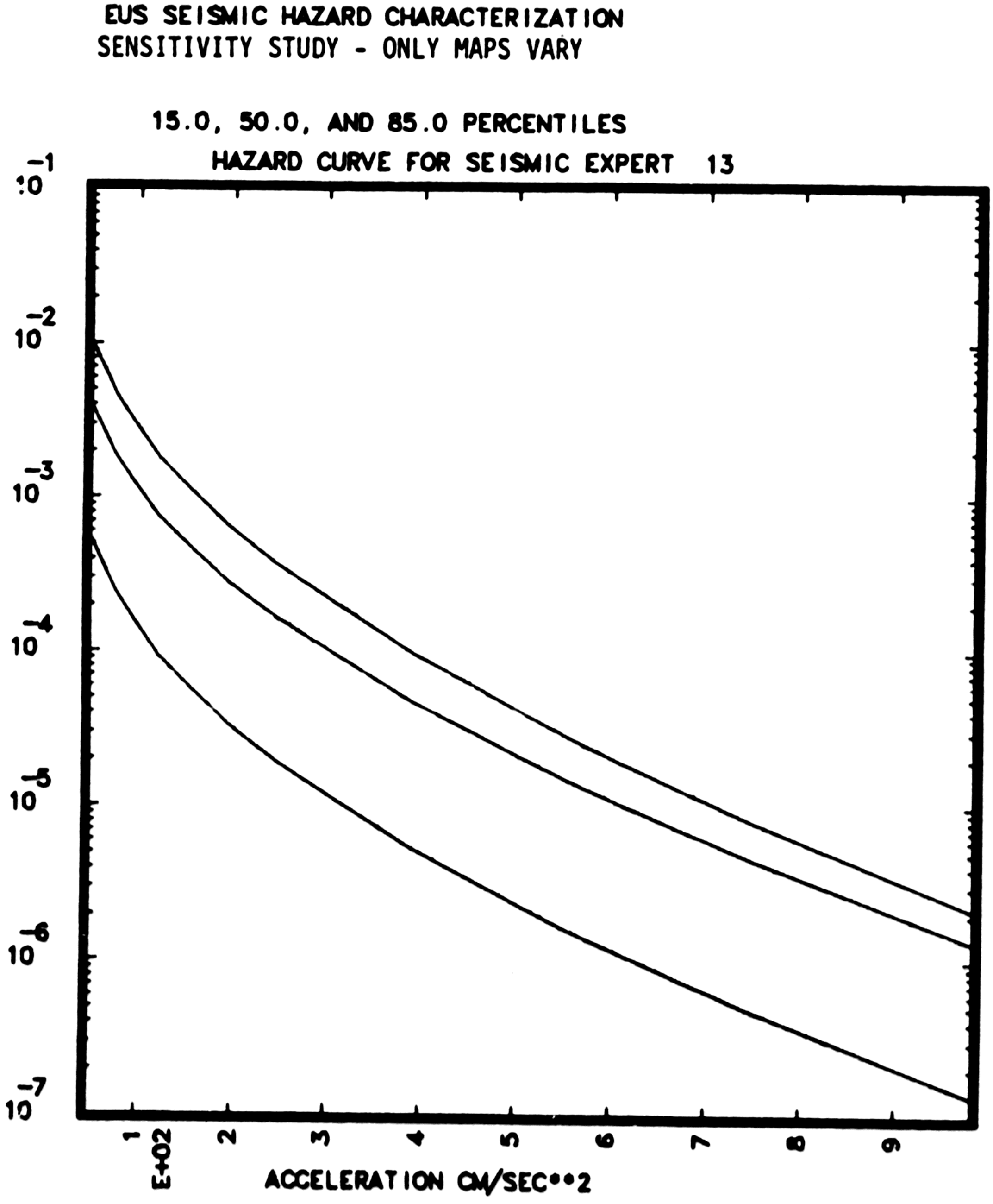
Figure 4.2.1

EUS SEISMIC HAZARD CHARACTERIZATION
SENSITIVITY STUDY - ONLY MAPS VARY



BRAIDWOOD

Figure 4.2.2



MILLSTONE

Figure 4.2.3

indicated that indeed different judgments had been made on how to correct for incompleteness, catalogues used and how to estimate the upper magnitude cutoff. The differences between experts' BEHC shown on Figure 4.1.1a is due in part to zonation differences and in part to the manner in which they have developed the earthquake recurrence models.

Figure 4.2.4 shows the CPHC for the case where only the maps are varied. It is observed that the uncertainty is much smaller than for the base case shown in Fig. 4.1.1b.

4.3 Seismicity Parameters

In this section we examine the influence of changes in both the BE values of the a and b parameters of the magnitude recurrence/relationship and the upper magnitude cutoff M_U, as well as, the uncertainty associated with these estimates. The influence of changes in the BE value of the a parameter is easily inferred from Eq. 2.2 as the a parameter is directly related to be mean rate of occurrence of earthquakes larger than M_o. Generally, only one zone is the major contributor to the hazard at a site. If this is the case, then Eq. 2.2 can be written (for small expected number of events) as

$$P\,[A > a] = \lambda P \qquad (4.3.1)$$

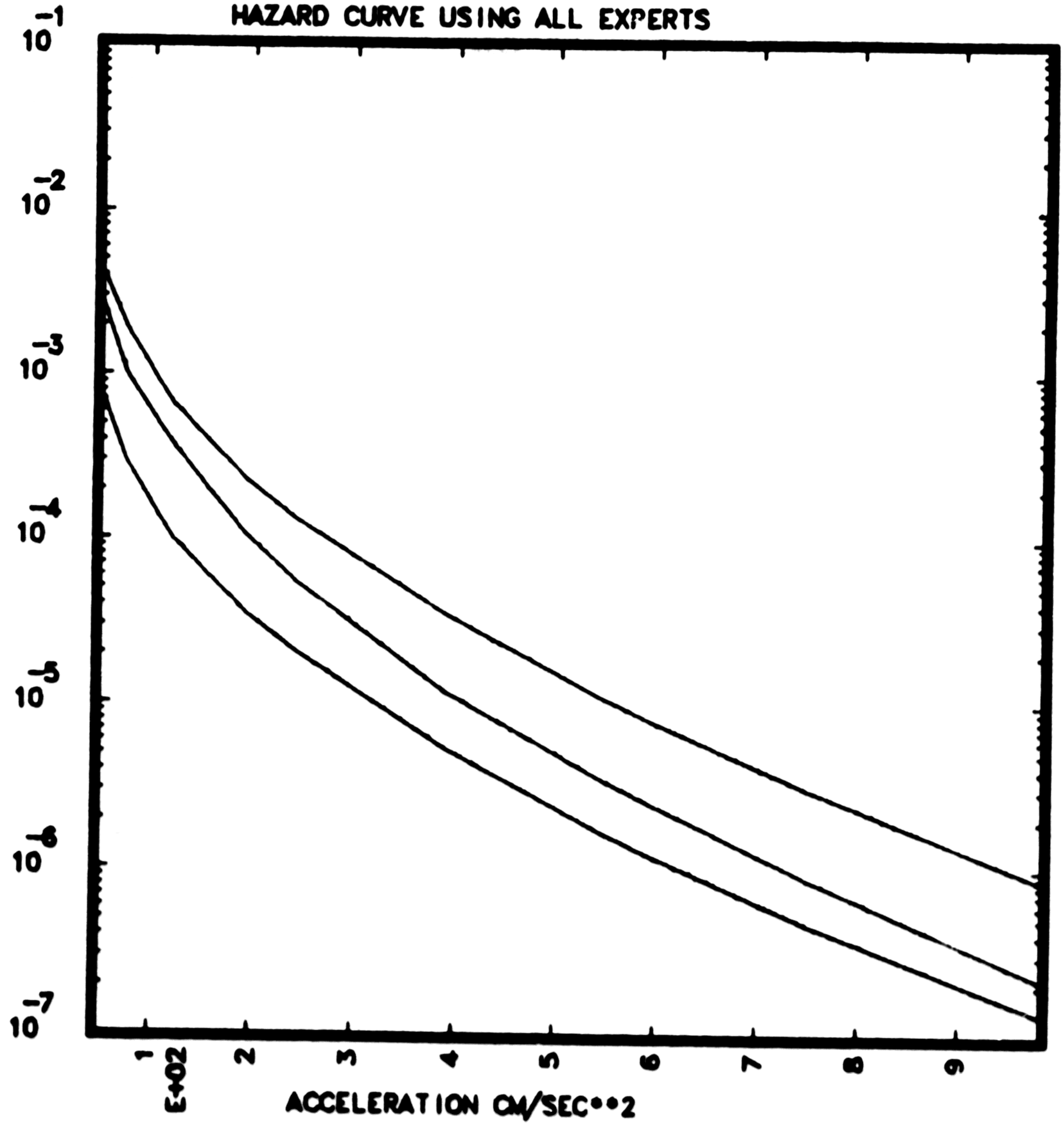
where λ = rate of occurrence of earthquake larger than M_o and,

P = value of Eq.2.1 for the zone

Thus it is seen that changing the rate of activity scales the hazard curve up (higher rate) or down (lower rate) linearly with changes in the rate. This is illustrated in Fig. 4.3.1. For all three cases shown in Fig. 4.3.1 M_U=6.25 and b = -0.9. for the curve labeled H, a = 6.0; B, a = 5.0; and L, a = 4.0. If more than one zone contributes significantly to the hazard then the effect can be more complex than illustrated in Fig. 4.3.1. It is not possible to develop a simple relation such as Fig. 4.3.1 to illustrate how changes in the b parameter affect the hazard curve as it was for determining how changes in the a parameter affect the hazard curve because the b parameter enter Eq. 2.1 in a more complex manner.

The b-value enters the calculations through the term $f_{S_M}(m)$ in Eq. 2.1; all other functions involved in the integrand of equation 2.1 remain the same. For the same number of events larger than M_o, different b-values simply change the number of events in any discrete magnitude interval. If the absolute value of b is smaller, then relatively there are more large events. This is illustrated in Fig. 4.3.2 where we computed the hazard curves resulting from using b-values of -0.9 for the curve labeled "B", -0.7 for the curve labeled H and-1.1 for the curve labeled L. For all three cases a = 5 and M_U = 6.25. It is seen that the computed hazard is a sensitive function of the b-value.

SENITIVITY TO THE MAPS
ALL OTHER PARAMETERS FIXED AT BE VALUES
PERCENTILES = 15.0,50.0 AND 85.0



BRAIDWOOD

Figure 4.2.4

EFFECT OF VARIATION OF THE 'A' VALUE ON THE HAZARD

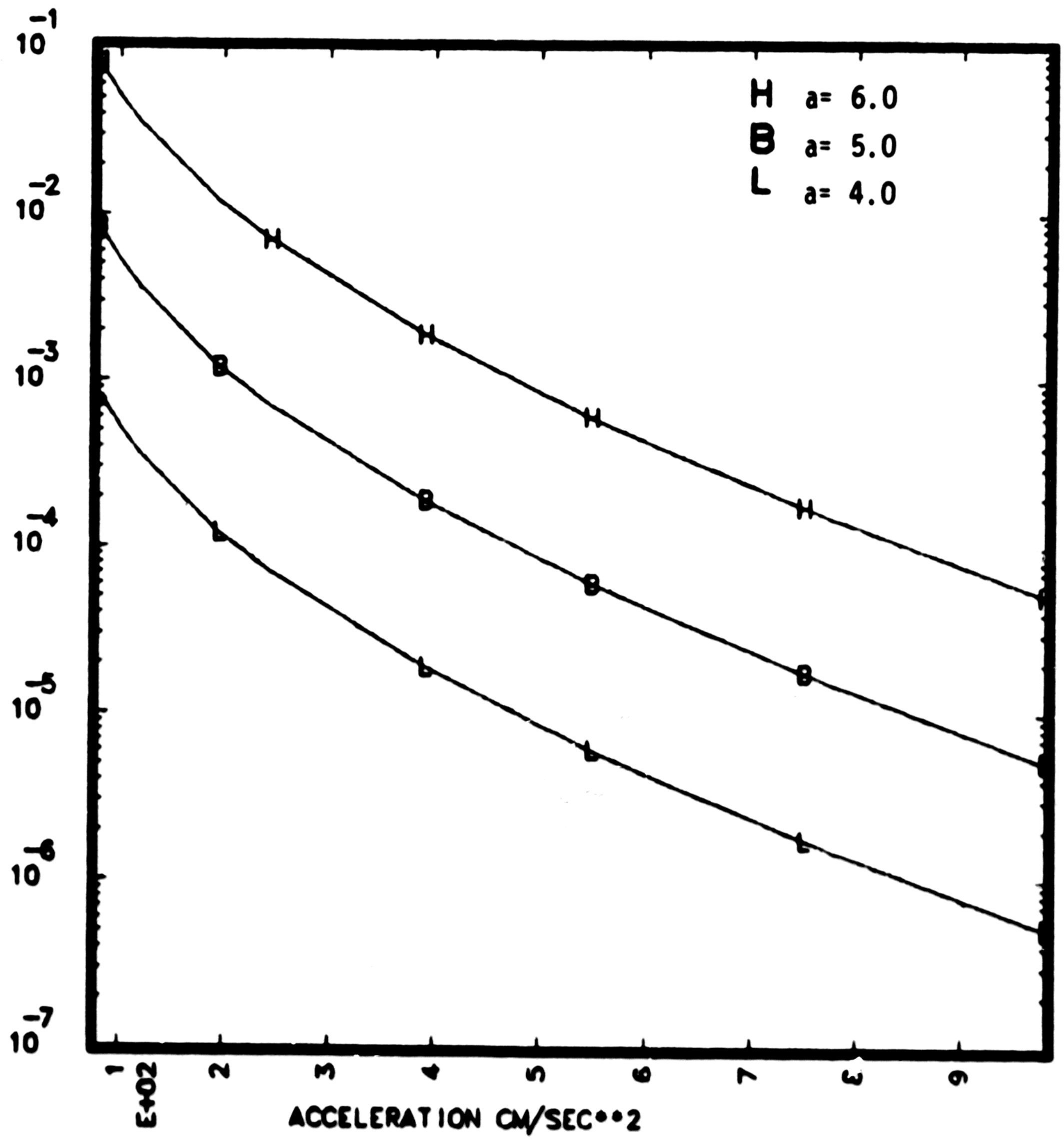


Figure 4.3.1

EFFECT OF VARIATION OF THE 'B' VALUE ON THE HAZARD

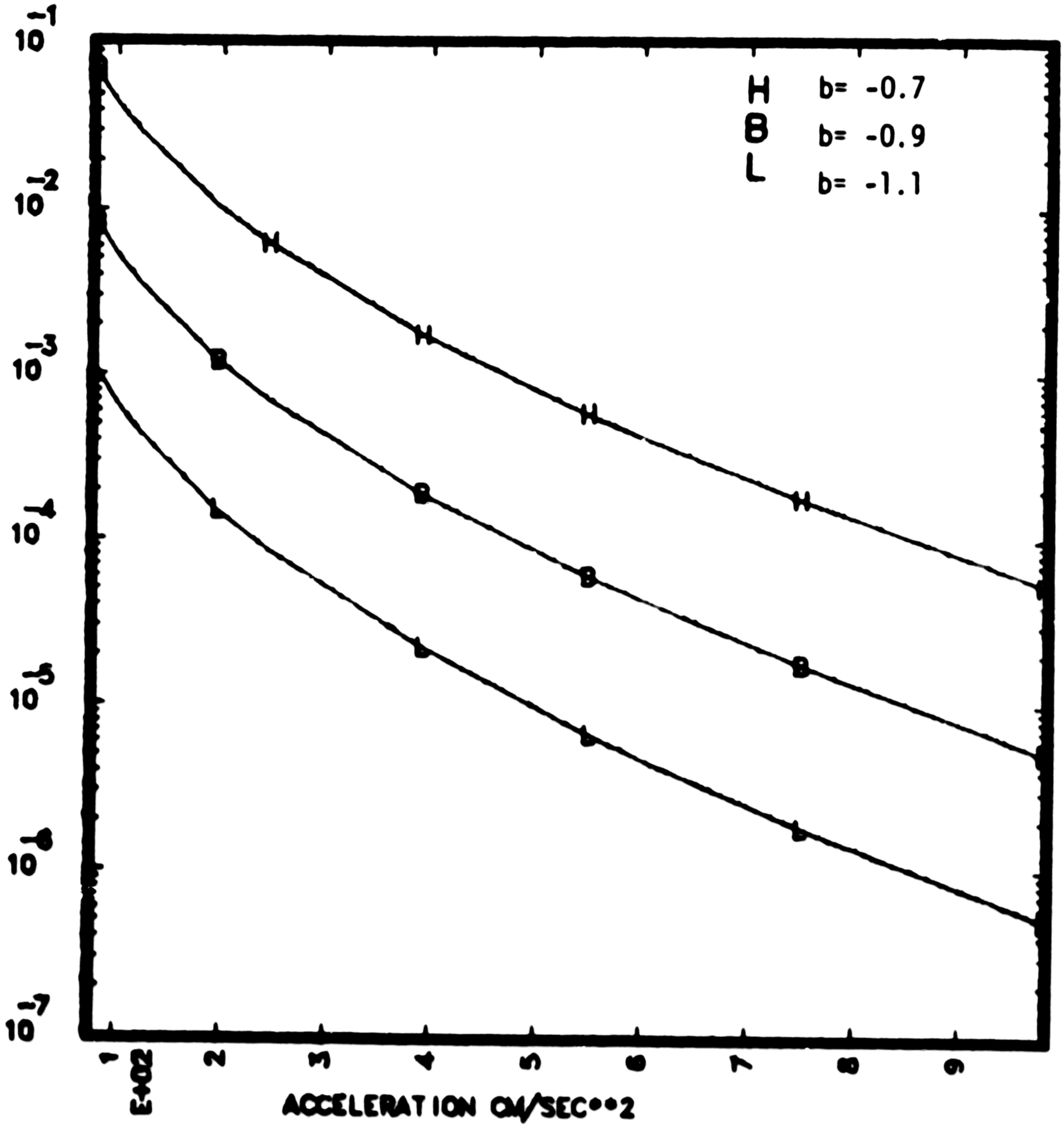


Figure 4.3.2

The influence of the value assigned to M_U, the upper magnitude cutoff, is illustrated in Fig. 4.3.3. The curve labeled B was computed using M_U= 6.25, b= -0.9 and a= 5. The curves labeled H and L were computed using the same a and b-values, however M_U = 7.25 for the curve labeled H and 5.25 for the curve labeled L. It is seen that the effect of a change in M_U is more significant at low probabilites than at higher probabilities of exceedance. This would be even more evident if a truncated ground motion model was used. (See section 4.4)

It should also be noted that the truncated exponential form of the earthquake recurrence model was used to develop the hazard curves plotted on Figs. 4.3.1-4.3.3. Figure 4.3.4 illustrates the impact of the difference between the LLNL model and the truncated exponential model. As described in both questionnaires 2 and 5, the LLNL model was based on the philosophy that linear model a + bm would not be changed over the domain of validity (M_{LB},M_{UB}). Thus, the only adjustments in the recurrence model were made for $m > M_{UB}$ when M_U, the upper magnitude cutoff, was greater than M_{UB}. If that occurred, then the model for N_m for $M_{UB} < m < M_U$ was (See Appendix C):

$$N_m = \alpha \, e^{\beta m} (M_U - m)^2 \qquad (4.3.2)$$

which satisfies the condition that $N_{M_U} = 0$. This type of truncation of the cumulative distribution leads to a jump in the density function i.e., the expected number of earthquakes in some magnitude interval (m, m + Δ) may be larger than in some higher interval (m',m' + Δ) where m' is larger than m. The truncated exponential model avoids this problem at the cost of some departure from the linear model a + bm. The significance of the difference between the LLNL model and the truncated exponential model depends upon the difference between M_{UB}, the upper bound for the linear range of the model, and the upper magnitude cutoff M_U. The difference between the two models is illustrated in Fig. 4.3.4. The curve labeled B on Fig. 4.3.4 is for the truncated exponential model with a= 6, b=-0.9 and M_U=6.25. The curves labeled H and L are for two LLNL models with the same a and b-values. However curve H has M_{UB}= 6.25 and curve L is for M_{UB}= 5.25. It is seen from Fig. 4.3.4 that the significance of the difference between the LLNL model and the truncated exponential model depends upon the value of M_{UB} and M_U given by the various experts for the zone contributing most to the hazard at the site. Generally the LLNL model leads to slightly higher hazard estimates than the truncated exponential model but, as can be seen from Fig. 4.3.4, there are cases when the LLNL leads to a lower hazard estimate than the truncated exponential model.

EFFECT OF THE VARIATION OF UPPER MAG. CUTTOFF

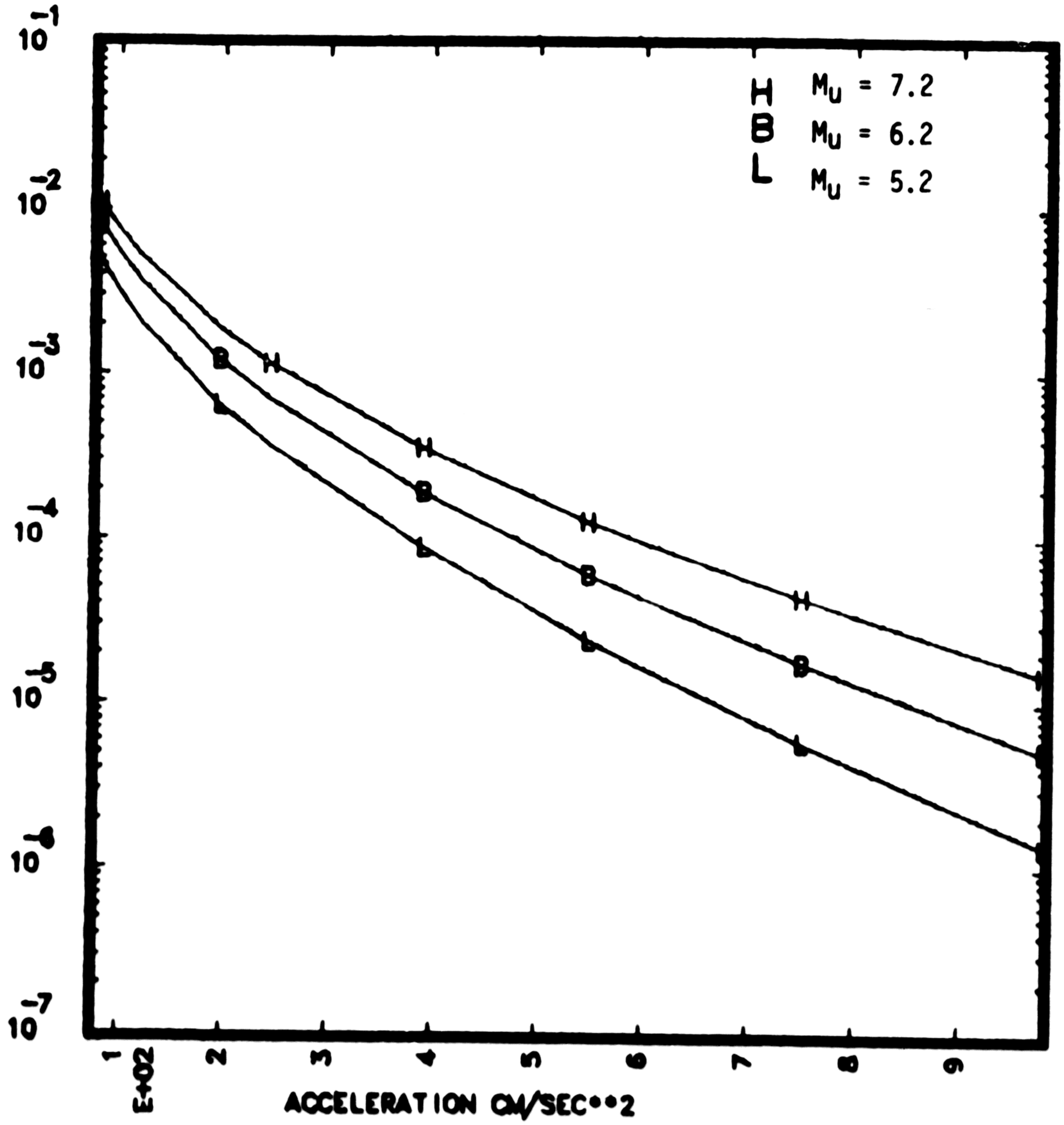


Figure 4.3.3

COMPARISON OF THE TRUNCATED EXPONENTIAL MODEL

TO THE LLNL MODELS FOR TWO LINEAR RANGES OF THE LLNL MODEL

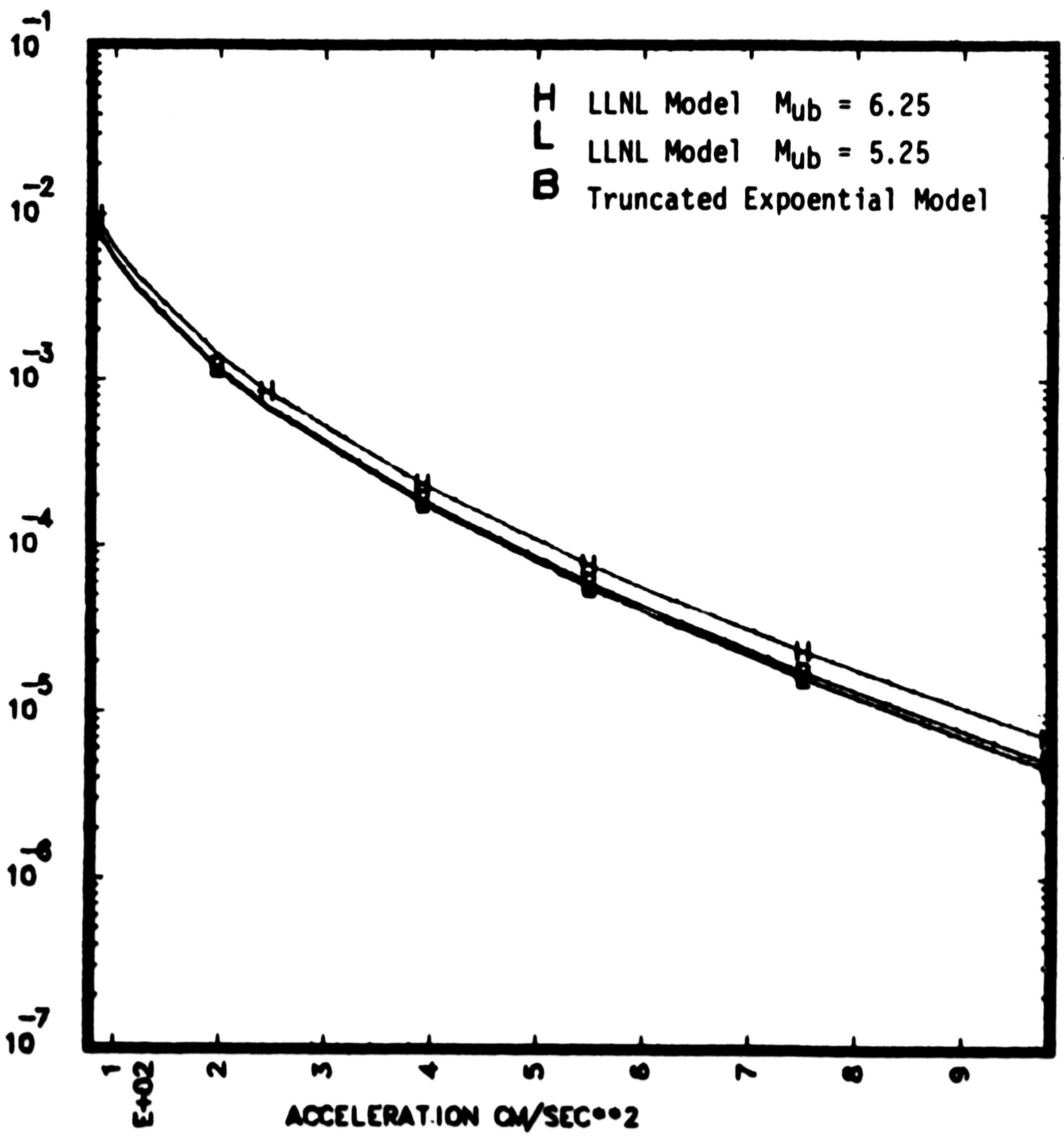


Figure 4.3.4

In addition both the ground motion model and the b-value influence the size of the difference between the seismic hazard computed using the LLNL model as compared to the truncated exponential model. The influence of the b- value is illustrated on Figs. 4.3.5a and 4.3.5b. Figure 4.3.5a shows the BEHCs obtained using the LLNL model compared to the truncated exponential model for three b-values. The BEHCs are the combined hazard curves obtained using ground motion models 5,8 and 13 of Table B-1. Figure 4.3.5b shows each hazard curve for b values of -0.7 and -1.1. In both figures the lower curve is for the truncated exponential model. It is seen from Fig. 4.3.5a that the size of the difference between the LLNL model and the truncated exponential model is a sensitive function of the b-value. This results from the fact that there are more large events when b=-0.7 as compared to the case when b= -1.1 and because the difference between the LLNL model and the truncated exponential model are most significant at the large magnitudes. It should be noted that Figs. 4.3.5a and b are based on the case where $M_{UB}=M_U$.

The influence of the ground motion model is illustrated in Fig. 4.3.5b. It is evident from Fig.4.3.5b that the influence of the b-value on the difference in computed hazard curves between the LLNL model and the truncated exponential model is much more significant than the ground motion model used. Figure 4.3.6 further illustrates this point. This case is a typical result obtained using the actual zonation and parameters supplied by one of the seismicity panel members.

Examination of the seismicity tables given in Appendix A indicates that the uncertainties expressed by the experts about their BE values of the a, b and M_U parameters for any particular zone are "large". Considering the important effect that changes in the value of these parameters have on the hazard estimates, we investigated their impact on the results. We made three sets of runs. For all three sets the ground motion model #8 was used. In the first set only the a-values varied. All other parameters were held fixed at their BE values. In the second set of runs only the b-values varied and in the third set only the upper magnitude cutoff M_U varied. The resulting CPHC for these three cases are shown on Figs. 4.3.7a, b, and c. It is seen that the uncertainty is larger when the b-value is varied than for the other two cases. The uncertainty each expert has relative to his upper magnitude cutoff in a given zone introduces relatively smaller uncertainties in the CPHC than from each expert's uncertainty in either his a- or b- values.

Figures 4.3.7a, 4.3.7b and 4.1.1b are superimposed in Fig. 4.3.8a and show that the 15-85th percentile bounds are wider for the base case than for the other two cases. However, the differences between the median CPHCs are small. The curves of Figs. 4.2.4, 4.3.7c and 4.1.1b are super imposed in Fig. 4.3.8b, showing that uncertainty associated with the maps (zonation models) is about of the same order of magnitude as the uncertainty associated with the upper magnitude cutoffs. The diversity of opinion of the experts may be quantified by estimating the 15th, 50th and 85th percentile curves from the BEHC of Fig. 4.1.1.a. Since there are 11 experts, the 15th percentile is the 2nd curve from the bottom the 85th percentile is the 2nd from the top and the 50th percentile is the 6th curve. i.e., for the particular example shown in

COMPARISON BETWEEN THE TRUNCATED EXPONENTIAL
MODEL & THE LLNL MODEL FOR 3 GM MODELS

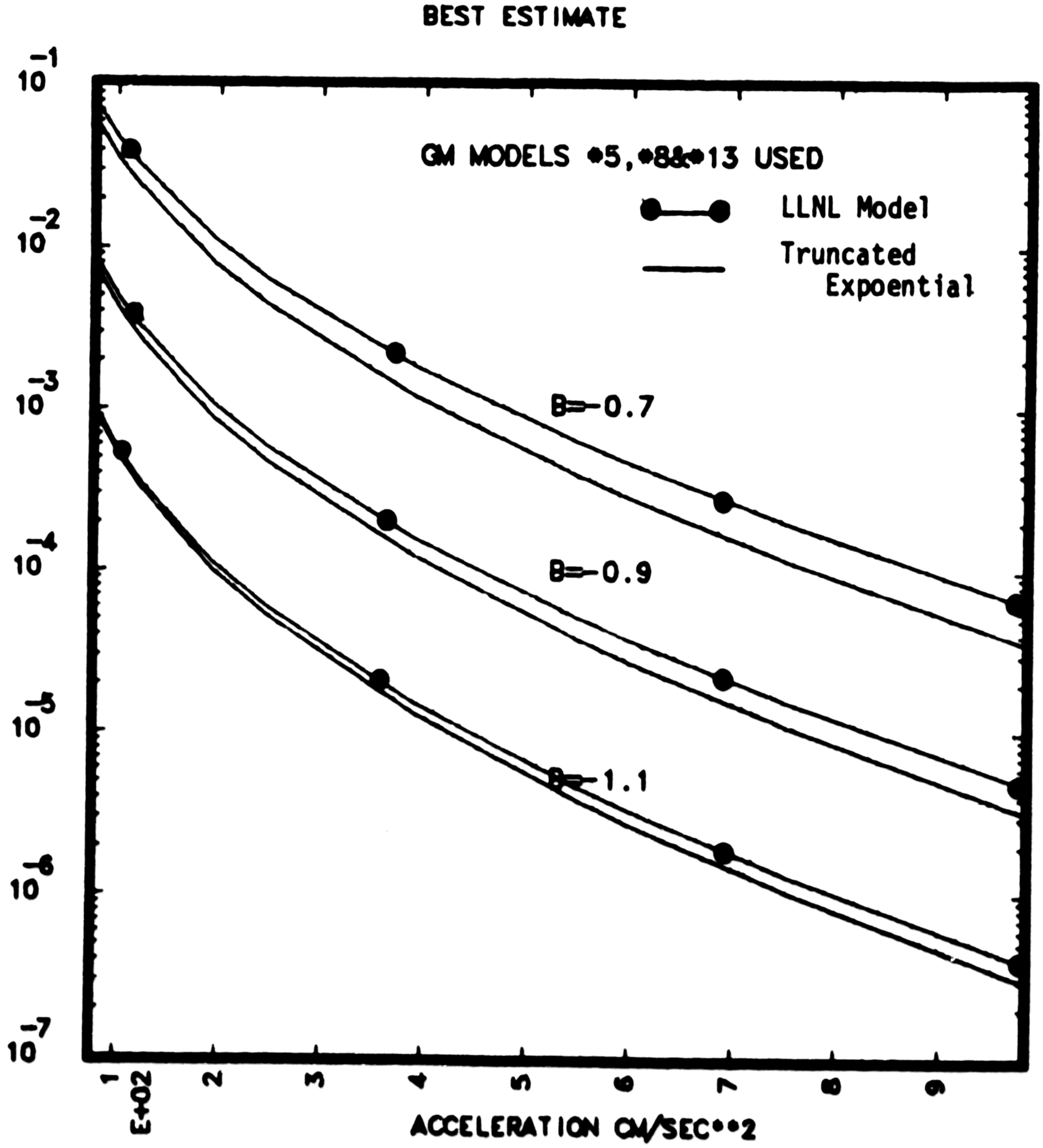


Figure 4.3.5a

COMPARISON BETWEEN THE TRUNCATED EXPONENTIAL
MODEL & THE LLNL MODEL FOR 3 GM MODELS

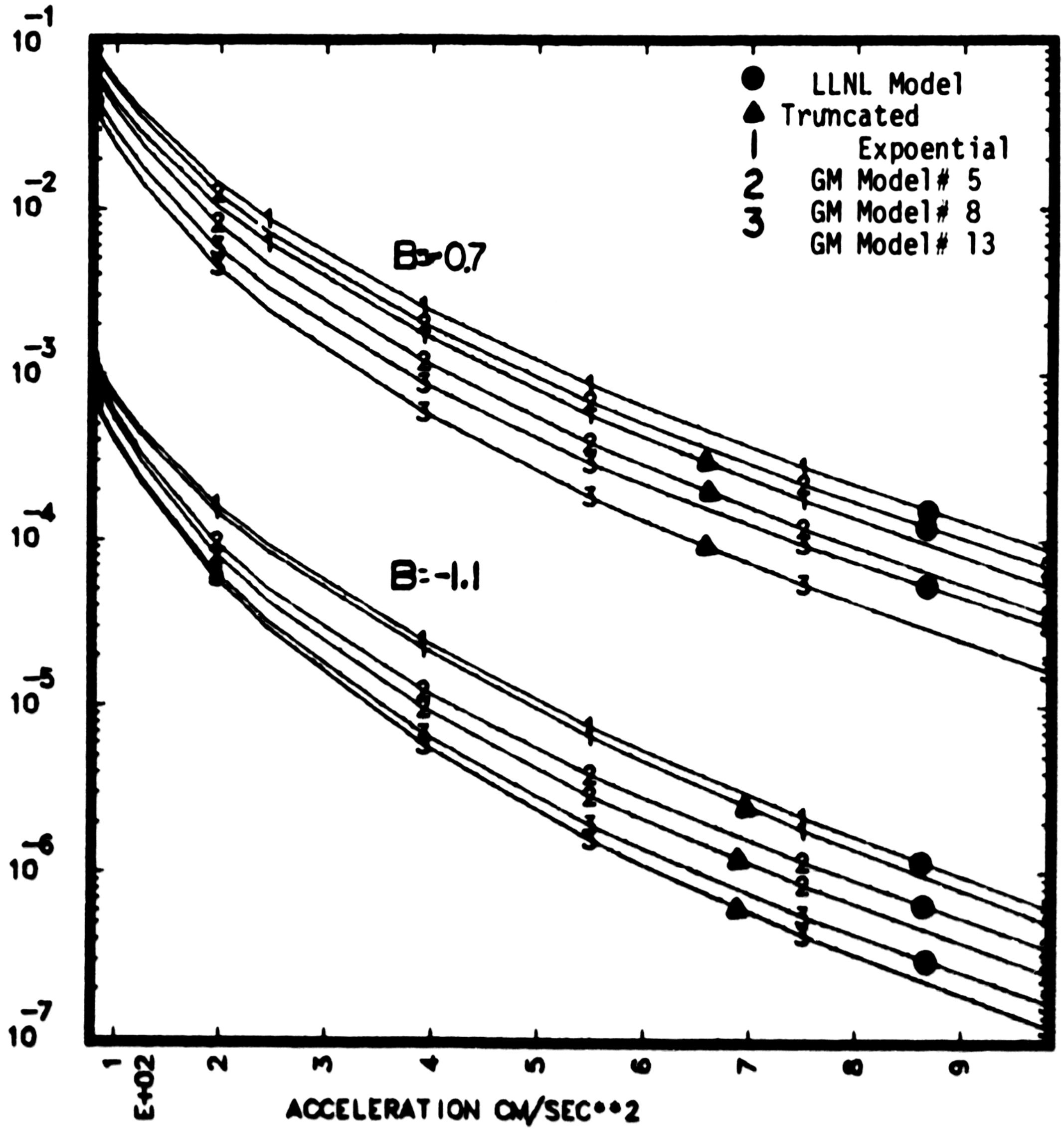
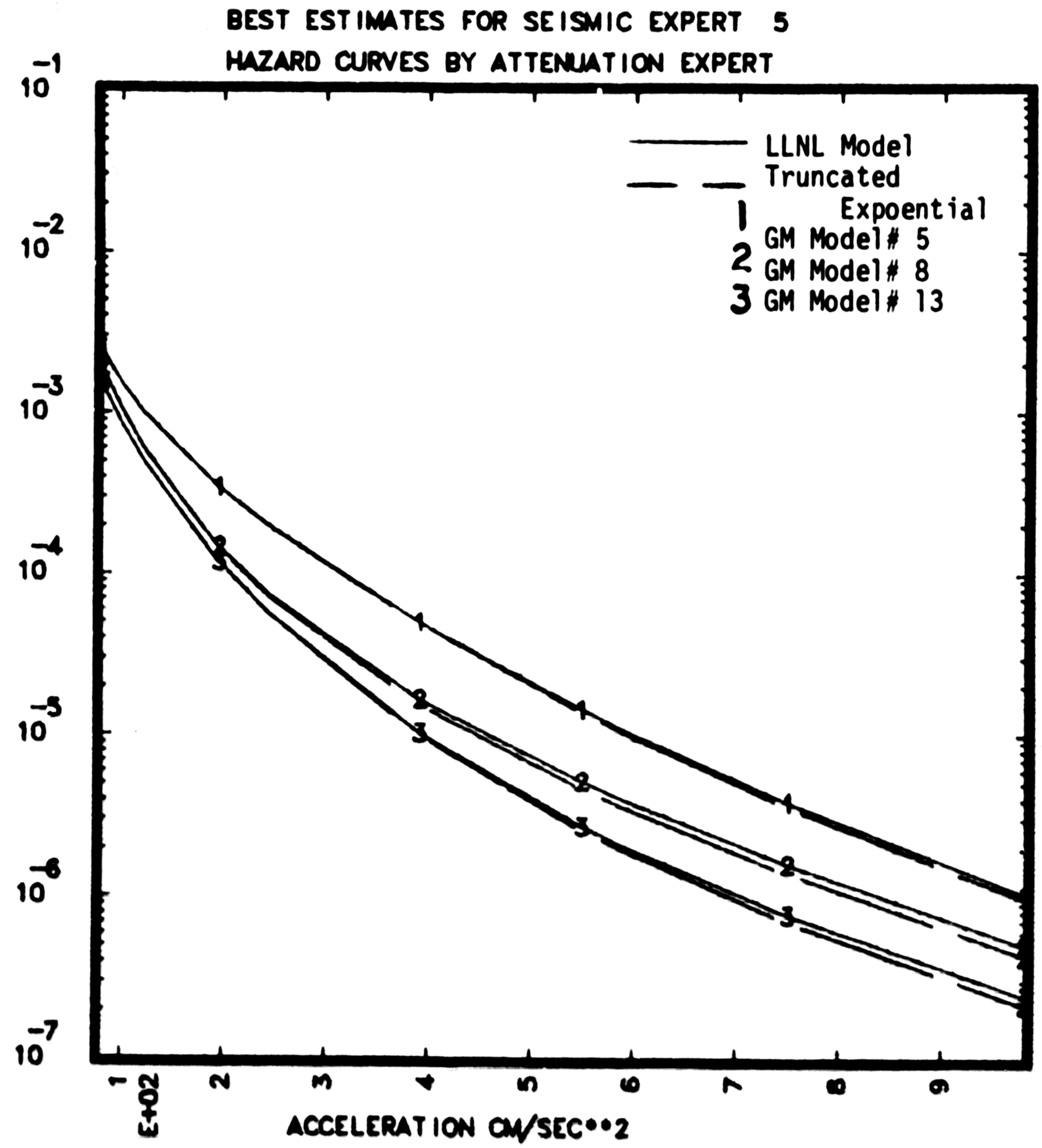


Figure 4.3.5b

COMPARISON BETWEEN THE TRUNCATED EXPONENTIAL MODEL & THE LLNL MODEL FOR 3 GM MODELS



MILLSTONE

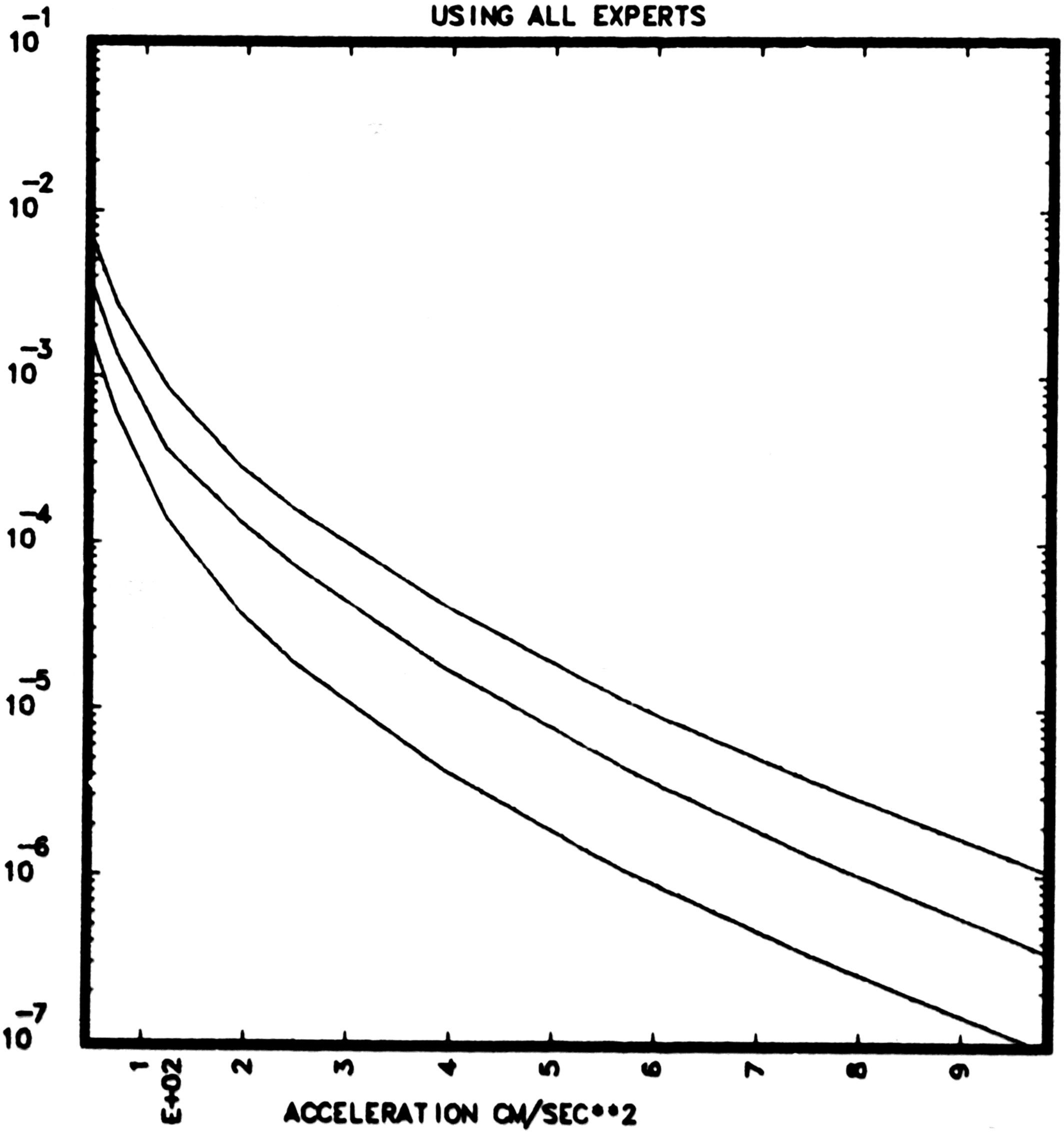
Figure 4.3.6

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

PERCENTILES = 15.0,50.0 AND 85.0

C PHC

USING ALL EXPERTS



BRAIDWOOD

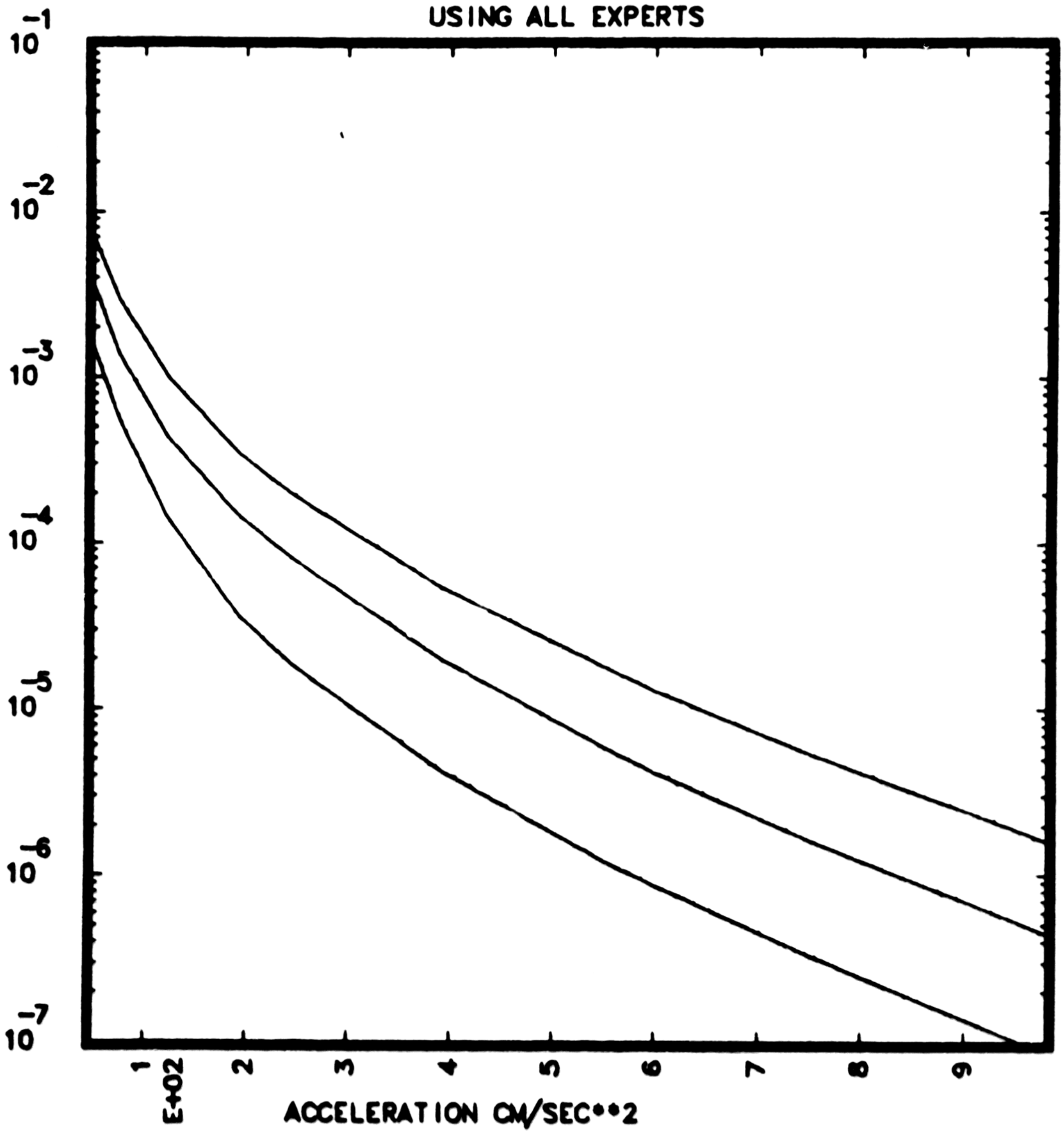
Figure 4.3.7a

SENSITIVIT'; OF THE HAZARD TO THE B PARAMETER
ALL OTHER PARAMETERS FIXED AT BEST ESTIMATE VALUES

PERCENTILES = 15.0,50.0 AND 85.0

CPHC

USING ALL EXPERTS



BRAIDWOOD

Figure 4.3.7b

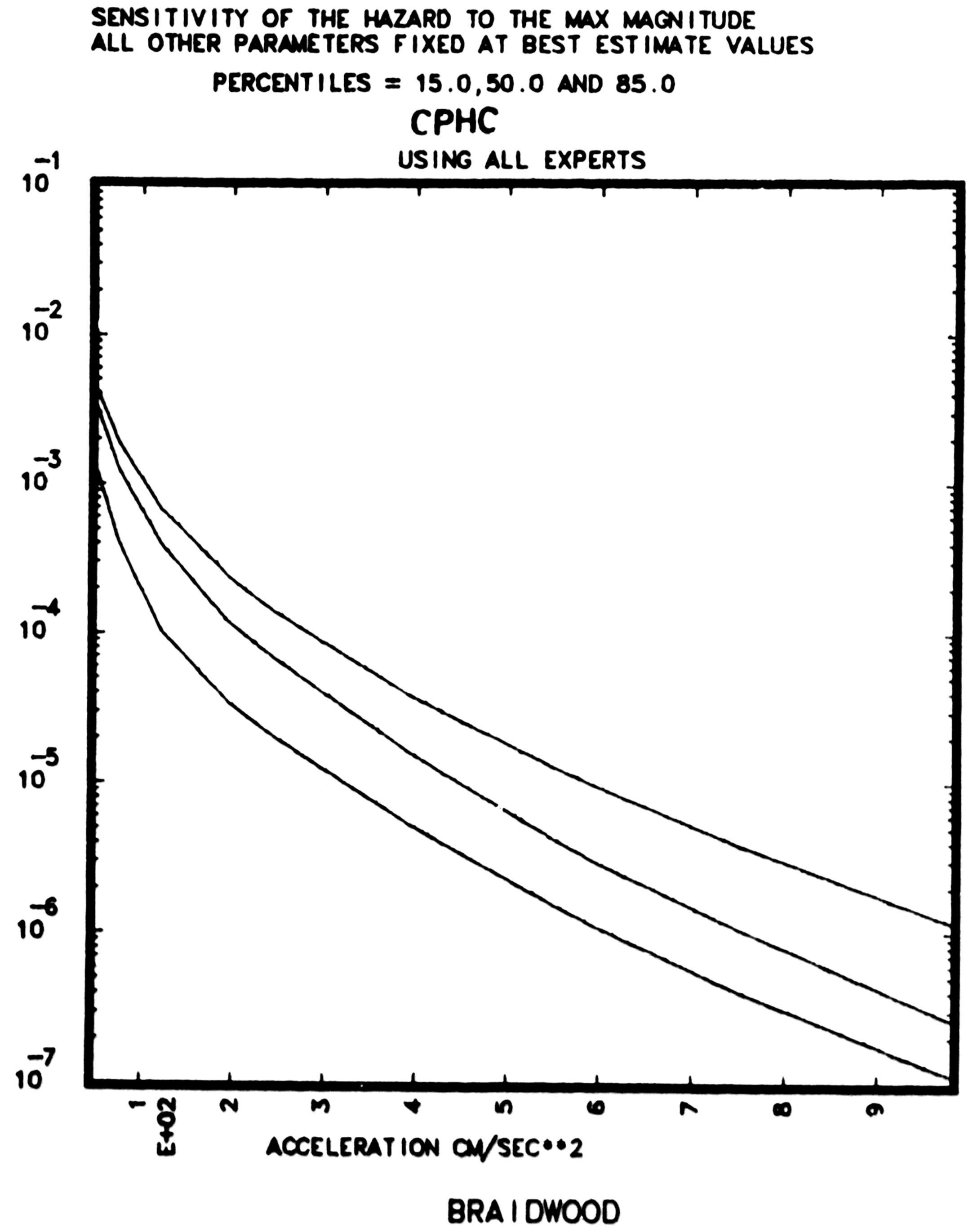
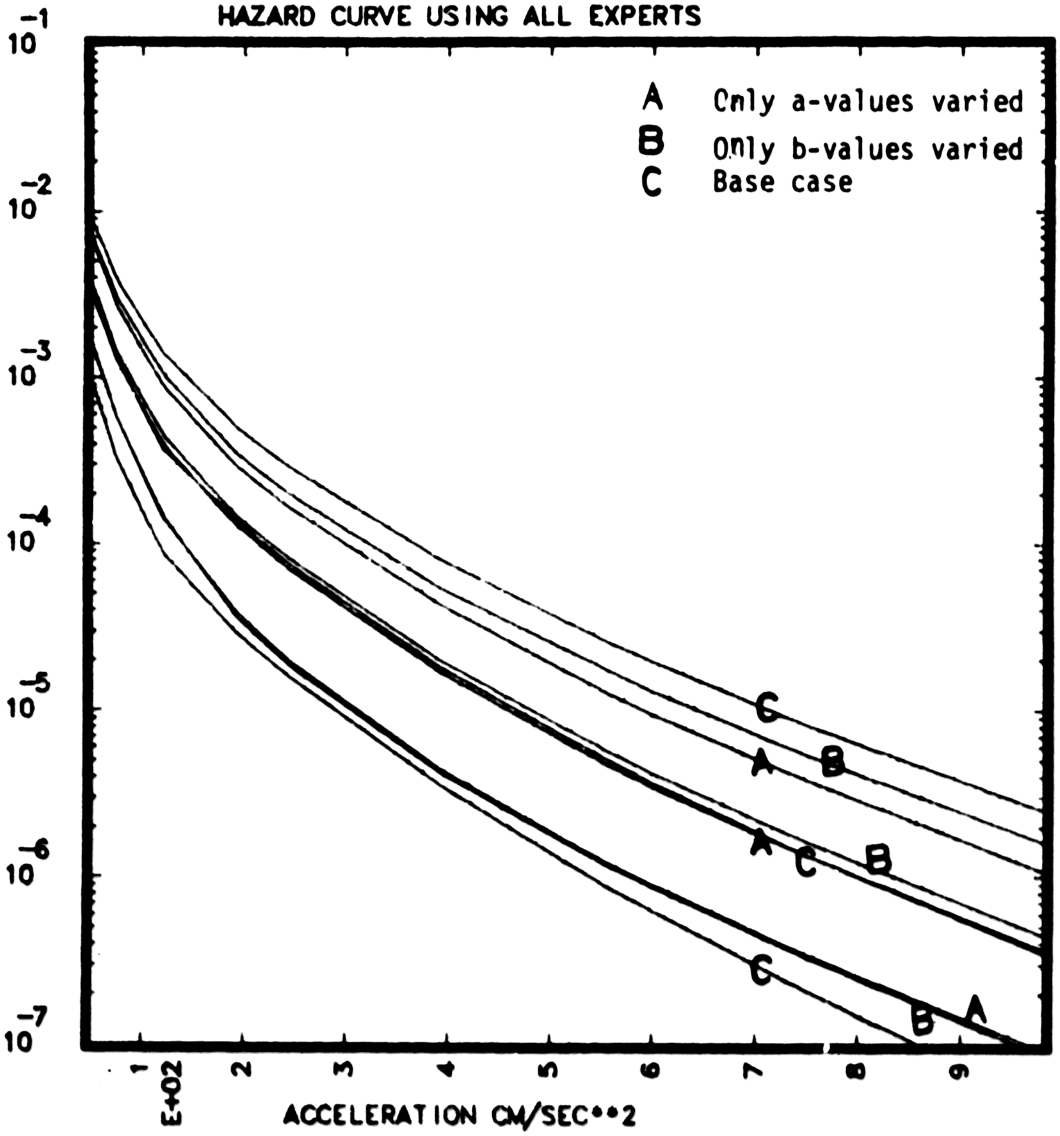

SENSITIVITY OF THE HAZARD TO THE MAX MAGNITUDE
ALL OTHER PARAMETERS FIXED AT BEST ESTIMATE VALUES
PERCENTILES = 15.0,50.0 AND 85.0
CPHC
USING ALL EXPERTS
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
1
E+02
2
3
4
5
6
7
8
9
ACCELERATION CM/SEC**2
BRAIDWOOD

Figure 4.3.7c

COMPARISON BETWEEN CPHC FOR THE BASE CASE TO THE CASE WITH ONLY A SIM & THE CASE WITH ONLY B SIMULATED

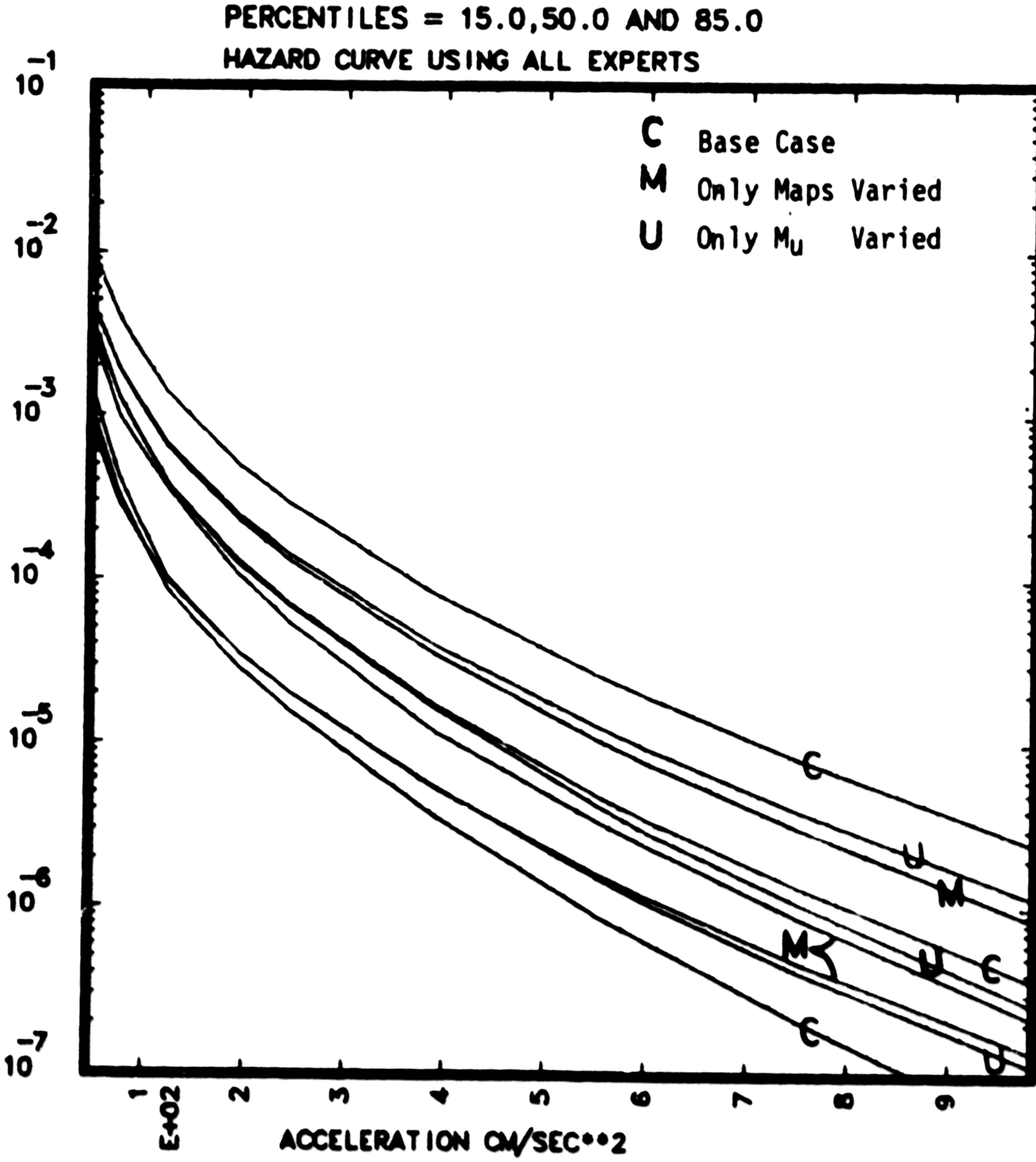
PERCENTILES = 15.0,50.0 AND 85.0



BRAIDWOOD

Figure 4.3.8a

COMPARISON BETWEEN CPHC FOR THE BASE CASE TO THE CASE
WITH ONLY MAPS SIMULATED & THE CASE WITH ONLY MU SIMULATED



BRAIDWOOD

Figure 4.3.8b

Fig. 4.1.1.a, these curves are the curve of expert 13, 1 and 12 respectively. A comparison of these 15-85th curves ranges with these other curves shown in this section for a single seismicity expert, shows that the diversity of opinion introduces an uncertainty in the same range of magnitude as the uncertainty for a single expert. The purpose of Fig. 4.3.8b was not to show the diversity of opinion between experts. It is relevant, however, to use it as such when we realize that the uncertainty for a single seismicity expert provided by the uncertainty in the magnitude cutoffs is almost negligible in the particular case shown. The CPHC, shown in Fig. 4.3.8b, for the case when only M_U varied, therefore can be interpreted as an approximation of the CPHC obtained by keeping all variable parameters equal to their best estimate and combining overall the seismicty experts. That is, the CPHC of Fig. 4.3.8b for the case when only M_U varies gives an estimate of the order of magnitude of the variation between experts.

4.4 Ground Motion Models

There are three main sources of uncertainty in our ground motion estimates. The first is the random uncertainty that exists because not all earthquakes of the same magnitude and located at the same distance from a given site give rise to the same PGA level and spectrum of motion at that site. The variations introduced by travel path, radiation pattern, type of faulting, etc. are considered together into the random uncertainty. These uncertainties are assumed to be the same independently of the model of the expected value of the ground motion for a given M (magnitude) and R (distance). In this study each Ground Motion Expert provided a BE value and confidence bounds for this uncertainty.

The second source is the way in which the expected value for a given M and R is modeled. As discussed in Questionnaire 4 in Vol. 2 there are a number of different ways in which the expected value of the ground motion can be estimated. In addition to the fact that different models are possible, different experts may have different opinions as to which are the "best" models. In this study these uncertainties have been included by having each Ground Motion Panel member select and provide weights for the seven "best" models. A third source of uncertainty is introduced by the effect of the local geology and topography on the ground motion at the site. The estimates for the random uncertainty are generally based on ground motion data recorded for a wide range of site conditions. The contribution to the uncertainty due to the variety of sites, (by contrast with the uncertainty for a given site) should be removed, but in practice it is very difficult to sort out the various contributing factors. This question is examined in the discussion accompanying questionnaire 6 in Vol. 2. In this analysis, the effect of local site conditions is modeled separately (see Questionnaire 6 in Volume 2). Consequently, the Ground Motion Panel Experts were asked to account for this fact in estimating the random uncertainty and in assigning weights to their ground motion mdoels.

Figure 4.4.1 shows the uncertainty introduced by a typical ground motion experts in his estimate of the BE value for the random uncertainty to be used with the ground motion models. For this comparison the BE of the random

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

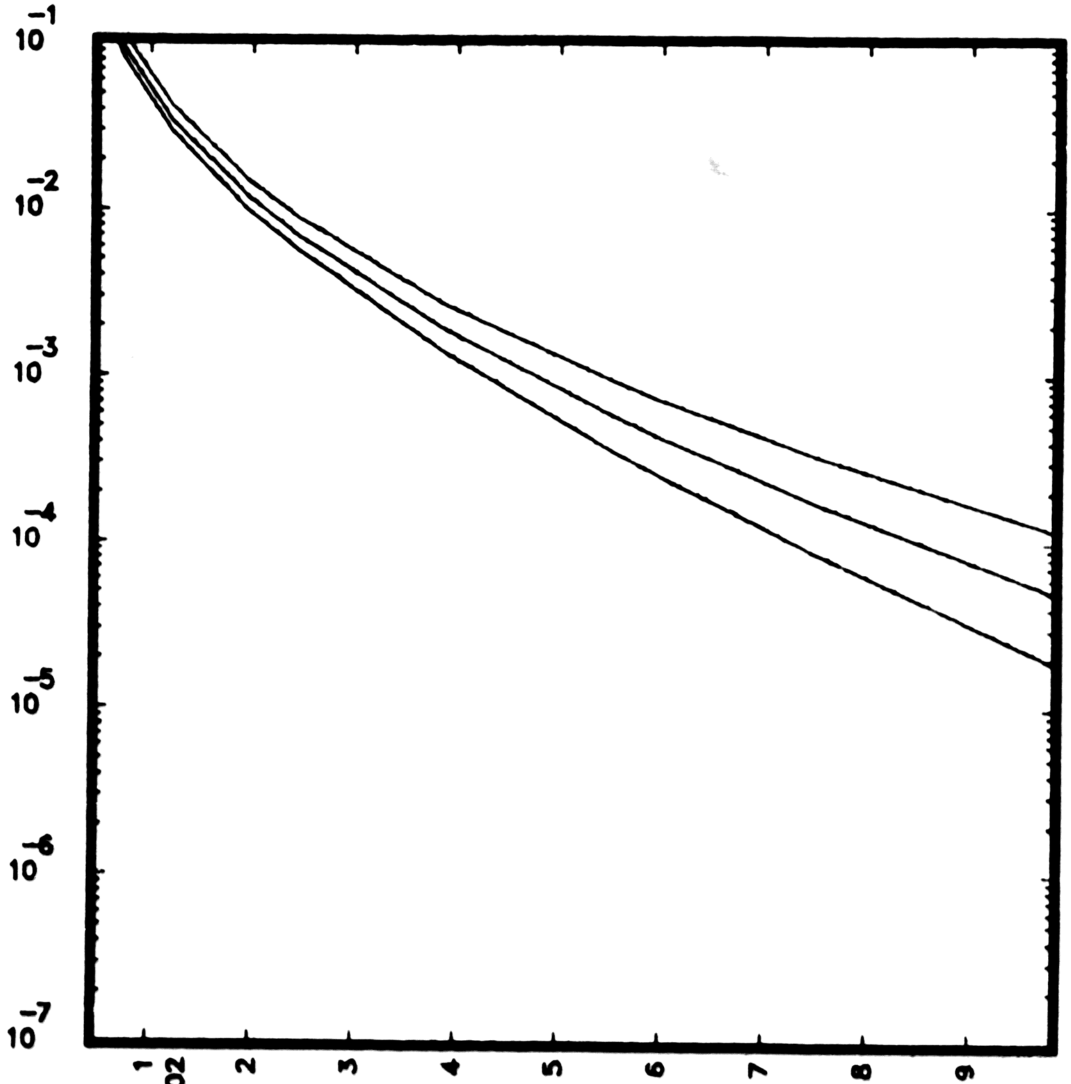


Figure 4.4.1

uncertainty is =.5 with 95th percentile bounds of 0.35 and 0.65. Ground motion model #8 was used and all other parameters were kept fixed at their BE values. It is seen from this figure that the uncertainty in the estimate for the random uncertainty used for the ground motion models becomes increasingly important at higher PGA values.

As discussed in Section 3, in addition to the uncertainty on the for the ground motion models the experts were allowed to select one of four ways of truncating the maximum ground motion that is expected from an earthquake of magnitude M at distance R (See Table 3.4.7.). Figure 4.4.2a shows the effect of truncating the ground motion distribution to 2 by comparing the truncated case with the untruncated case. It is seen that truncation of the distribution can have a significant effect on the hazard curves, particularly at the longer return periods (low annual probability of exceedance). Figure 4.4.2b shows the effect of type 2 (see Section 3) truncation where the ground motion (PGA) is not allowed to be greater than 1500 cm/sec. It is seen that this type of truncation only has a small effect on the hazard curve. It should be noted that if the truncation value was lower than 1100 cm./sec.^{2}, then the effect of truncation would be much larger. The values of absolute truncation provided by our panel members were large, the smallest being 1500 cm./sec.^{2}. Thus this type of truncation only contributed slightly to the uncertainty in our results.

Site correction contributes significantly to the uncertainty in the hazard estimates. The ground motion experts assigned a weight to each of the three proposed approaches of site correction. The categorical approach was the most heavily weighted. The use of the three different approaches introduces modeling uncertainty. In addition a random uncertainty is included in the categorical correction approach (See section 3 and Questionnaire 6 of Volume 2). Figure 4.4.3 shows the effect of this random uncertainty on the hazard at a site by comparing the case where the random uncertainty of the categorical correction approach is zero to the case where (random uncertainty) is 0.5. Typical uncertainty values were used for the other parameters for the two simulations. It is seen that the random uncertainty of the categorical site correction factor has a significant impact on the 15th and 85th CPHC; however, the median CPHC remains the same.

The uncertainty introduced because different experts selected different ground motion models is significant as illustrated on Figs. 4.4.4a and b. Figs. 4.4.4a and b show the BEHC for each of the Ground Motion Panel members. Figure 4.4.4a is for Seismicity Expert 1's BE models and Fig. 4.4.4b is for Expert 5's BE models. It is observed that there is considerable difference in the spread between the BEHC between the two figures indicating that the resultant hazard curves are a function of both the particular ground motion model used and the seismicity parameters. One factor that contributes to this difference is the fact that Ground Motion Expert 2 selected model #13 for earthquake recurrence models in magnitude and model #30 when the recurrence model is in intensity. Seismicity Expert 1's earthquake recurrence models are in magnitude and Seismicity Expert 5's are in intensity. It should also be noted that the BEHC for Ground Motion Expert 5 is much higher than for the

ONLY THE SIGMA OF THE GM MODEL VARIED (ONLY •8)
ALL OTHER PARAMETERS FIXED AT BEST ESTIMATE VALUES

COMPARISON OF 2-SIGMA TRUNCATED CASE TO UNTRUNCATED CASE

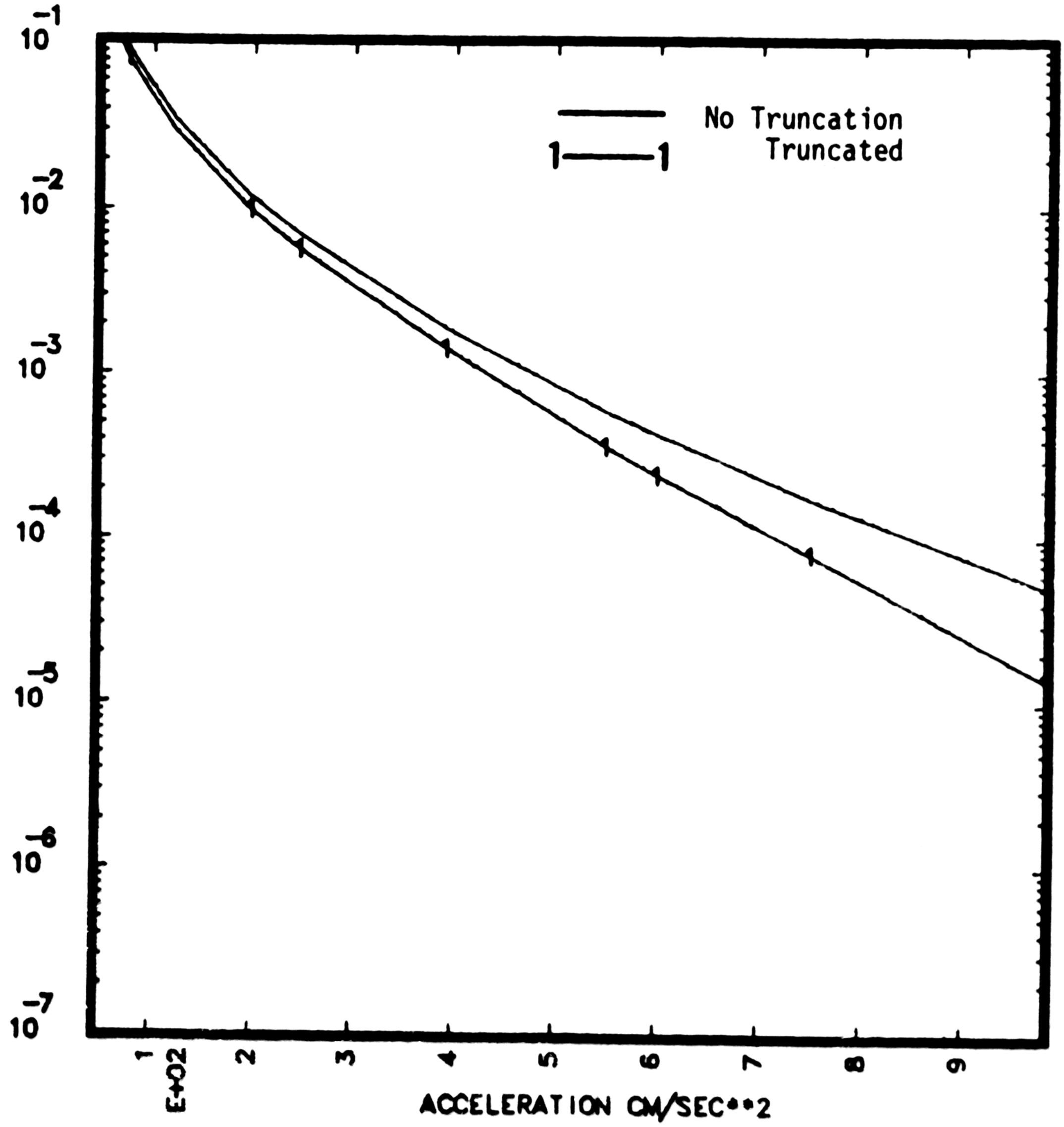


Figure 4.4.2a

COMPARISON OF UNTRUNCATED CASE TO CASE WITH THE MAXIMUM PGA TRUNCATED AT 1500. CM/SEC**2

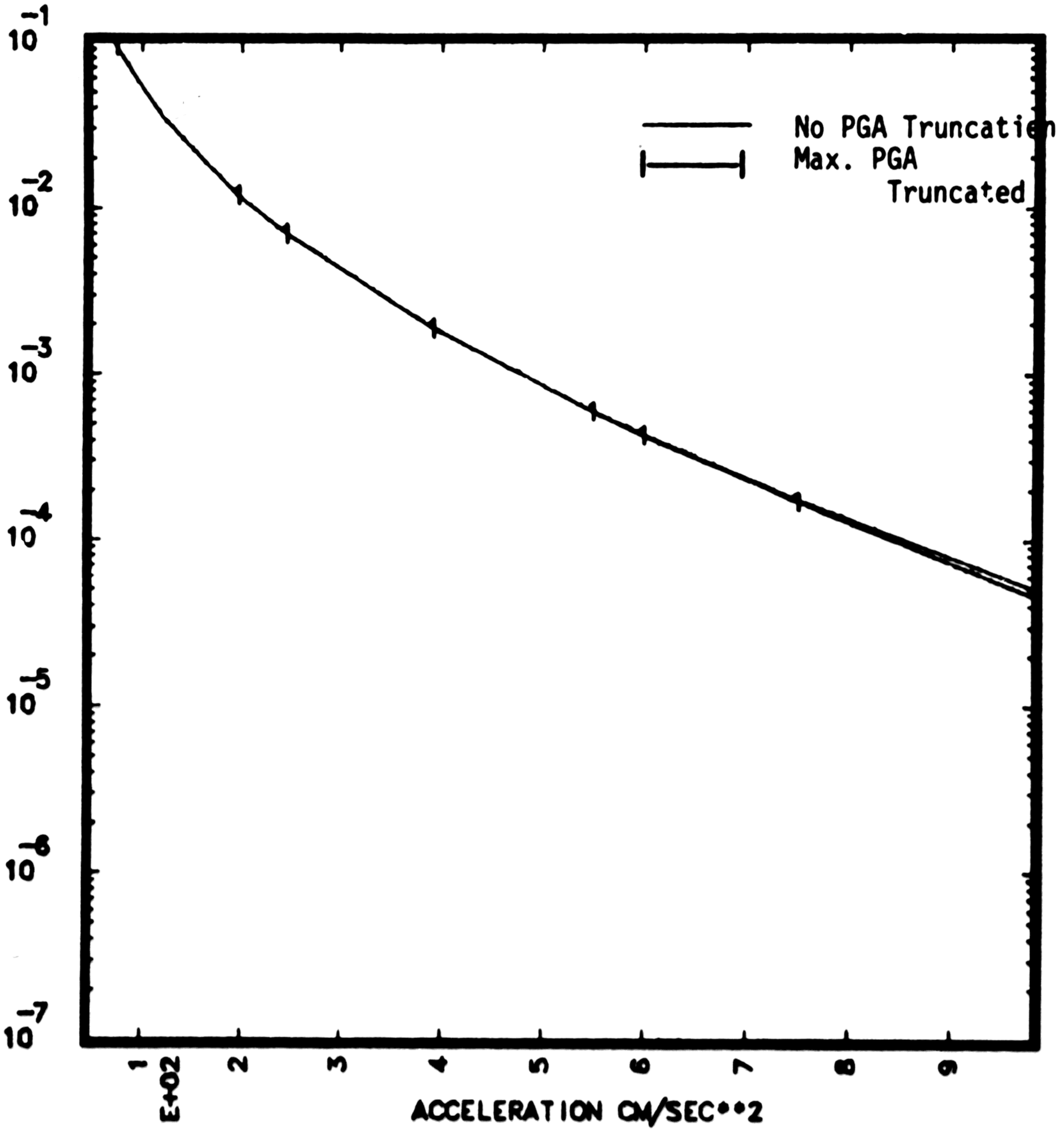


Figure 4.4.2b