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SEISMIC HAZARD ANALYSIS: A METHODOLOGY FOR THE EASTERN UNITED STATES

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1.0 INTRODUCTION

In order to assess the adequacy of a facility's design to earthquake loadings, two factors must be considered: an estimate of earthquake hazards at the facility site and an estimate of the facility's strength to resist those hazards. The integral of these two factors is often termed the earthquake risk, with the consequence measured in economic or public safety terms. This report describes various approaches used to estimate the first factor, earthquake hazard, for sites in the eastern United States. While both factors, the hazard and strength, are probabilistic in nature, for convenience, the estimate of facility's strength is usually conservatively approximated as deterministic. However, the ground motion induced by the earthquake and especially its occurrence at a specific site has not yet been estimated by truly deterministic techniques due to uncertainty in the specific earthquake process, particularly in the east. Even if truly deterministic techniques were available, a probabilistic approach to estimating the earthquake hazard has a unique benefit to a decision-maker because probabilistic estimates allow a quantitative comparison of design or safety margins associated with different approaches. That is generally not possible with a deterministic estimate.

In estimating seismic hazard at sites in the Eastern United States (EUS), two fundamental problems face the analyst: one, the paucity of applicable measured data with which to make a meaningful prediction of seismic hazard at a low probability of exceedence, and, two, the substantial uncertainty as to the first principles associated with earthquake processes. However, regardless of such limitations, estimates of seismic hazard at a specific site often are required.

Certain common traits appear in all methodologies used to predict seismic hazard because of these two fundamental problems. Since all methods utilize the same basic data to a large degree, there is a strong tendency for overlap of both results and methodology. This is true in the methodologies explored in this study. A second trait involves the need to consider subjective input to reach a useful estimate of seismic hazard at a low probability of exceedence. All the methods considered in this report also require substantial subjective input from selected experts.

The major contribution from this study is a probabilistic model, the Uniform Hazard Model, which uses subjective input with which many estimates of seismic hazard can be compared. Unlike the other approaches to determining seismic input, the subjective input and assumptions used in this model are clearly available for peer review. Also, expert opinion from more than a few individuals can be accomodated in the model developed.

The report is organized in seven sections: Introduction, Methodology Development, Subjective Input, Uniform Hazard Methodology (UHM), Application of UHM, Sensitivity for Sample Site and Uniform Hazard Spectrum.

Section 2, Methodology Development, briefly describes the methodologies examined and compares four selected methods to other approaches that have been developed. Since substantial effort was spent in developing the UHM, the remainder of the report discusses that effort. Section 3 describes the approach used to obtain subjective input. Section 4 describes the theory and mathematics employed. Section 5 describes the application of UHM to a specific site and Section 6 describes the sensitivity of certain assumptions to that site. The last section, Uniform Hazard Spectrum, highlights features of the results of the Uniform Hazard methodology that should be considered in design applications.

As in most studies, the past effort and ideas of others have been used to great benefit. Of particular note in this study were the contributions of D. L. Bernreuter and L. Reiter.

2.0 METHODOLOGY DEVELOPMENT

Development of analytical methods to predict seismic hazard for sites in the United States has evolved significantly in the last several years. The fundamental problem faced by all methods has been and will be prediction of "extreme" seismic hazards for sites with little or no measured earthquake data coupled with substantial uncertainty as to first principles associated with earthquake processes. As a result of these problems, no single methodology approach has been completely successful; for example, deterministic models, even when geologic and tectonic conditions are reasonably well defined, must rely on subjective judgment in the selection of certain parameters for simulation of earthquakes and probabilistic models. Even when sample size is sufficient for classical statistical techniques to yield usable predictions, statistics cannot resolve uncertainty in the knowledge of basic earth processes.

Regardless of such limitations, estimates of seismic hazard often are required. Therefore new methodologies must be developed which, while unable to yield absolute answers, can combine available knowledge, objective and subjective, in an analytical framework that allows for critical review and useful comparative evaluation. In describing the approach used here, it is instructive to evaluate the basic approaches available to the analyst and their application in seismic hazard assessment.

2.1 DETERMINISTIC APPROACH

Only recently have pure deterministic approaches been used in analysis of seismic hazard. Here we use the word <u>deterministic</u> in the same sense as it applies to seismic structural analysis. For example, in structural analysis, one uses first principles and models of the structures, which can be very elaborate and reasonably include all of the important parameters to compute the building loads. The major difficulty with completing the structural analysis is modeling failure of the structure. Because little is known about modeling failure, conservative assumptions are often used.

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In the western United States (WUS), engineering seismology has advanced to the stage that similar, deterministic, first principle models are being applied to the earthquake process. However, even in the West where the specific, seismically active, structures can be identified, sufficient unknowns exist that certain subjective data are required for the models to predict reasonable resultant ground motion. Strict application of this approach to the East is not possible since the source of seismicity is not well known.

As a point of comparison, the NRC approach outlined in Appendix A of 10 CFR 100 is often incorrectly termed deterministic. However, that approach is not strictly deterministic, in that it is not based on first principles. No true modeling is done and the design acceleration is arrived at by using judgment to choose the largest credible earthquake and a suitable correlation for ground motion. In practice, through expert opinion, measured data are used, together with an empirical-statistical model to determine a design specification. Examined this way, this approach for the specification of the seismic hazard is deterministic only in the way the formal hazard analysis methodology is replaced with judgment and an answer determined. One of the major difficulties with a deterministic approach like that in Appendix A is that the protection it provides against the seismic hazard is not quantified and therefore can vary from site to site. Because of this, it is a poor tool for the comparative evaluation of different seismic design spectra.

2.2 PROBABILISTIC APPROACH

In contrast to the deterministic approaches discussed above, probabilistic approaches, even those with subjective input, can yield results whose margins can be quantified. However, just as deterministic models require subjective input, the state-of-the-art and available data in Eastern United States do not allow useful probabilistic models based solely on objective input.

Empirical-statistical methods using a conventional statistical model to make direct estimates of the future behavior of the parameter of interest have been developed for West Coast sites where substantial applicable objective data, such as real earthquake spectra, exist. Typically, the parameter is peak ground acceleration (PGA) at the site. If enough appropriate records are available for a given site, a response spectrum can be obtained by such statistical models.

This approach avoids theoretical assumptions required by first principle models. However, for all eastern sites the data are insufficient to make meaningful estimates of a low probability event. The method also usually fails to incorporate much other knowledge specific to the site (e.g., location of faults or other source regions) and variations in the seismicity of various nearby source regions. These factors are generally introduced by judgment.

The remaining sections of this report describe the probabilistic methodology developed to predict a uniform risk of exceedance for ground motion parameters (PGA, PGV, and spectral accelerations) in the EUS. This model uses available objective data supplemented with subjective input from selected experts. While suffering from many of the limitations described above, it does allow rational estimates of seismic hazard in the east.

As discussed below, the model's purpose is to allow comparative evaluation of seismic hazard at specific sites. This capability allows comparison of response spectra generated from many techniques including Appendix A to 10 CFR 100, with Regulatory Guide 1.60 spectra and Housner spectra; selected time histories applied to a specific site; and Newmark-Hall spectra.

2.3 SIMILARITY OF MODELS

Since all models developed thus far for the east suffer from the same major weaknesses, paucity of data and uncertainty as to the first principles, two general similarities result. First, subjective input, usually in the form of opinion from one expert or more is included to allow useable prediction of response spectra to be made. Second, the methods often have substantial overlap since analysts attempt to build from past ideas. For example, an analyst can combine the "deterministic" selection of peak ground acceleration of Appendix A to 10 CFR 100 with the spectral shape of scaled time histories for a specific site.

Likewise, an analyst can combine the probabilistic selection of peak ground acceleration and velocity with the Newmark-Hall spectra. In the first case, shape is determined by statistical analysis of historic records and in the second case, the shape is based somewhat on deterministically developed first principles. Therefore, since these methods may be combined in a number of ways, some overlapping of methods is inevitable.

For this study four methods were considered in some detail. Only one, the Uniform Hazard Method (UHM) is new in its use of subjective input and specific application. The others (Newmark-Hall spectra, Real and Scaled spectra) have been developed for some time. Therefore, their methodologies are not discussed in this report. These other three approaches to defining spectral shape can be combined with anchor points determined by the UHM. Obviously, other approaches to defining the anchor points are available also (e.g., the approach taken by TVA in the Sequoyah nuclear plant in which expert judgment was used to choose a maximum credible intensity which when converted to magnitude provided a basis for the selection of real time histories).

The Newmark-Hall approach to determining spectral shape addressed the major problem with other approaches, that of a lack of earthquake records in the appropriate categories, with a unique solution based more on first principles. The Newmark-Hall spectrum is typical of response spectra for nearly all types of ground motion and can be physically interpreted as frequency dependent. At the low frequency end the response approaches an asymptote corresponding to the maximum value of ground displacement. From first principles, a low frequency system corresponds to a heavy mass and light spring, so when the ground moves rapidly the mass does not have time to move so the maximum strain in the spring equals the maximum displacement of the ground. For a high frequency system the spring is stiff and the mass is light so when the ground moves the stiff spring forces the mass to follow the ground movement. Thus the mass has the same acceleration as the ground, so the maximum acceleration of the mass equals the maximum acceleration of the ground. These physical phenomena are exhibited by the response spectra line approaching the maximum ground acceleration line at the high frequency side of the graph. At intermediate frequencies there is an amplification of motion corresponding to the dynamical characteristics of the system. The high frequency part of the spectrum is scaled relative to the peak acceleration and the intermediate frequency range is scaled relative to the peak velocity. In this study both peak acceleration and peak velocity are determined by the UHM as a function of uniform probability of exceedence expressed in return period for a given site.

Virtually every approach to specification of design spectra requires the explicit or implicit use of a suite of real strong motion recordings to develop the spectrum, whether site-specific or generic. For example, the generic NRC Regulatory Guide Spectrum was developed by statistically averaging a suite of records covering a variety of site geologies, magnitudes, and distances. On the other hand, a probabilistic model uses these records more implicitly in, for example, the development of an attenuation relation. The approach to real and scaled time histories is complementary to the probabilistic approaches in that it involves explicit averaging of the records. The key element to this approach is the criteria for the selection of records. There is clearly a potential tradeoff here; the more site-specific the criteria, the smaller the suite of appropriate records and, therefore, the less statistical validity for the conclusions. The basic criteria, however, must be based on the subjective assessment of the class of earthquakes that dominate the hazard at eastern United States sites.

If it is believed that the principal hazard comes from the occurrence of relatively nearby intermediate earthquakes (e.g., Appendix A to 10 CFR Part 100) the criteria must explicitly account for this hypothesis. In addition, the criteria must account for the regional tectonics through, for example, the depth or focal mechanism of earthquakes. Finally, the criteria must account for characteristics of the site that could influence the hazard, most notably the site geology. While this approach is <u>direct</u> in that it does not require many of the sophisticated hypotheses required in probabilistic approaches (e.g., earthquakes being a Poisson process), the approach contains important data-based assumptions. For example, there are statistical biases contained in any suite of digitized strong motion records resulting from highest priority being given by the USGS and others to larger acceleration records at the expense of the small accelerations. Similarly, there is tremendous uncertainty in converting earthquake magnitudes to a common scale. Many times these assumptions are uncertain that an extensive sensitivity study is required, thus diluting the value of the results to a decision maker.

In general, the actual strong motion records can be used to develop two types of spectra. First, the records can be normalized by their peak acceleration with statistics on their spectral ordinates resulting in a statistical spectral shape. This spectrum can then be anchored at a peak acceleration determined separately, perhaps from a hazard analysis. Alternatively, the spectral statistics could be performed on the raw, unnormalized records, resulting directly in a site specific spectrum. The selection of the appropriate magnitude range for the records could be from a hazard analysis for the site. Therefore, both of these approaches can employ the Uniform Hazard Model developed in this report.

2.4 LIMITATION OF UHM IN DECISION MAKING

There are three major differences between the UHM approach and other approaches to estimating seismic hazard in the east. One is that UHM explicitly uses subjective input from experts. As discussed above, all approaches inevitably rely on such subjective input due to the lack of objective information, measured data and proven first principle models. However, the UHM is explicit in the way such input is used and weighed. In some ways, this is the most forthright approach since it allows for peer review and assures that the knowledgeable reviewer will recognize that the results are subjective probabilities, not scientific fact. A second major difference is the inclusion of all earthquake contributions, those from small earthquakes as well as large earthquakes. In many ways, this approach is more forthright since it presents a truer picture of the seismic hazard. However, it should be noted that in comparative evaluation of other approaches, or to satisfy legal requirements, consideration of only large earthquakes may be appropriate. The third major difference involves the spectral content of UHM approaches. Here, the spectral shape does not represent any one event or class of events. Since each spectral ordinate estimates the uniform hazard of exceedence from all sources, near and far earthquakes with attenuation uncertainties, it may not be the proper spectrum to be used in assessing structural resistance. This issue is discussed in some detail in Section 6.

Because of these considerations it is believed that the UHM is best used in comparative evaluation of other approaches to determine seismic hazard. For example, in the past many designs have been based on the "deterministic" approach of Appendix A to 10 CFR 100 to anchor a Housner spectral shape at peak ground acceleration. This shape was typically derived from several large western records and scaled to appropriate eastern peak acceleration. Currently, a similar approach is used except that the shape is determined by Regulatory Guide 1.60. This spectral shape is roughly the mean plus one sigma of a large number of scaled western records. The appropriateness of either of these approaches can be usefully evaluated by comparison with the four methodologies discussed above.

2.5 POTENTIAL ADVANCES IN METHODOLOGY

Additional probabilistic methodology development is expected in the near future as a result of NRC's Seismic Safety Margin Research Program. As part of this program, Monte Carlo type integration techniques are proposed to calculate the seismic hazard for a typical Eastern site. Additional development of subjective input is also planned. One strength of this proposed approach over the UHM in this study is the ability to preserve the effect of individual earthquakes throughout the hazard analysis process. This would allow additional sensitivity studies to explore model assumptions and improved capability in design applications.

Another interesting approach to seismic hazard analysis in the east would be to combine the recent development of first principle deterministic models with empirical-statistical analysis of western and European earthquake records. Substantial data are available for such statistical analysis, however, most have not been digitized to allow convenient analysis. In this way it may be possible to reduce the amount of subjective input needed to yield usable results.

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3.0 SUBJECTIVE INPUT FROM EXPERT OPINION

Previous sections in this report have shown that seismic hazard assessment for eastern U. S. sites always requires some degree of subjective input, either in the model assumptions, the input data or both. It is our opinion that this should be acknowledged and that, furthermore, the subjective input should be formally solicited using as much expert opinion technology as possible.

As described in Section 4.0, the Uniform Hazard Methodology for the assessment of the seismic hazard at EUS sites attempts to do this through the use of a questionnaire and an expert panel. The results of this solicitation are summarized in a separate companion report "Seismic Hazard Analysis: Solicitation of Expert Opinion."

The purpose of this section is to summarize the formalized approach used to generate subjective input for the Uniform Hazard Method. The concepts of expert opinion solicitation, its biases and various synthesis techniques, are discussed in Appendix A. We conclude the Appendix with an elaboration on the questionnaire used in this study and a discussion on the expert panel.

3.1 EXPERT OPINION AND EASTERN U. S. SEISMICS

The analysis of seismic hazard in the eastern United States presents several challenging problems that a probabilistic approach can answer, but only with expert opinion and subjective probabilities.

1. The central and eastern regions are notable for their low level of seismic activity somewhat uniformly distributed in space. It seems that minor to moderate earthquakes may occur in just about any location. Above this moderate background seismicity, a few restricted areas have experienced a few major earthquakes together with much above average continuous activity. Since the correlation between epicentral location and geological and geomorphocic features is generally extremely low, the determination of tectonic regions or seismic source boundaries is usually made subjectively. The introduction of experts'

opinions regarding the seismic sources appears to be the only way a credible tectonic model can be developed for the east. Although such input is not introduced in our model as a consensus, the procedure addresses this question at the final stage by synthesizing each expert's results using a method of self weighing.

2. The low rate of activity of these regions that are disturbed so rarely by major events does not provide a good basis for classical statistics applications. At the level of probability usually desired, classical statistics give results driven by the large uncertainties. Often the uncertainties result from two questions: (1) To what extent should the large events be treated as anomalies? (2) What are the possibilities for such events to occur elsewhere? As insufficient geological and seismological data are available to answer these questions, only experts' opinions can be used to shed a light on them. Subjective probabilities provide a rational way to include them in the analysis. In our model they will be introduced at three levels: rate of occurrence, distribution of magnitudes, and upper magnitude cutoffs.

3. The almost complete lack of instrumental recording in the east forces the analyst to work from intensity data. At the epicenter the data show a large scatter when correlated with magnitude; at the site, they contain much less information than a strong motion recording which explicitly provides the peak value as well as the frequency content of the shaking. Such limitations suggest that the development of attenuation relationships could greatly benefit from the additional input of qualified experts.

In conclusion, it appears that a seismic analysis in the east cannot be based on the historic data alone and that, at a minimum, the data would have to be modified to reflect certain judgments. The approach to the problem presented in this report provides:

- The explicit input from recognized experts
- The explicit weight that this additional information will have in the analysis
- The integration of these subjective opinions with the recorded data.

The credibility of the analysis can only profit from such an open and defensible approach which will allow peer review.

3.2 QUESTIONNAIRE FOR EASTERN U. S. SEISMICS

A questionnaire was developed to elicit expert opinion on seismicity and intensity attenuation in the eastern United States. Because it is difficult, or perhaps impossible, to precisely quantify such factors given the sparse historical record, expert judgment was considered crucial.

Subsequent analysis using the responses to this questionnaire is clearly not Bayesian since a formal Bayesian analysis would consider, independently, both subjective opinion and historical data. It would then rigorously combine them, each with their corresponding weight, to provide a "posterior" input to be used in the analysis. However, such an analysis implies independence between subjective opinion and data. Due to their inherent knowledge of historical seismicity and attenuation in the east, it was considered unreasonable to expect the experts to divorce themselves from these data while forming an opinion. Therefore, such an opinion is necessarily a "posterior" estimate and cannot be used in a formal Bayesian analysis without double weighting the data. What was asked, then, was that each expert consider the available seismic data in the eastern United States and temper this by his general experience in the region, possible similarities between the east and other regions, geologic and tectonic considerations, expert judgment and similar types of information. In other words, we asked that each expert was asked to be a "Bayesian processor."

In order to help the respondents in answering the questionnaire, we supplied them with seismicity data for various source zones in the east. These data were based on an integrated catalog of earthquake occurrences generated from various regional catalogs for the east. For each of the zones, they were supplied with (1) a listing of all earthquakes having epicentral intensities of IV or greater, and (2) a table giving the number of occurrences of earthquakes of each Modified Mercalli (MM) intensity unit from IV through XII.

The questionnaire was divided into five sections:

- Source Zone Configuration
- Maximum Earthquakes
- Earthquake Occurrence
- Attenuation
- Self Ranking

Certain redundancy was designed into the questionnaire to allow for cross-checking and establish consistency in the results. Even so, follow-up was necessary in certain areas to obtain usable results.

The responses to each question could be made in one of several ways, all of which could be converted to a usable format for analysis. These formats were:

- A best estimate only (fixed quantity)
- A range of values defined by lower and upper bounds with a uniform distribution
- A range of values defined by lower and upper bounds with a non-uniform distribution
- A written discussion

Additionally, in the Source Zone Configuration, each expert was provided with maps giving two possible seismic zonations to rate and modify as thought best.

The experts were asked to apply their specific area of expertise to nine sites.

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4.0 UNIFORM HAZARD METHODOLOGY

This section presents the methodology used to determine the uniform hazard spectrum (UHS). The section begins with a review of the philosophy of the approach followed by a detailed discussion of the methodology. Recall that part of the methodology involves the explicit use of expert opinion solicited through a questionnaire. Much of this section will be dedicated to describing how the expert opinions are interpreted and how input to the seismic hazard analysis is developed from the expert opinions.

4.1 PHILOSOPHY OF APPROACH

A seismic exposure portrays the distribution of the expected value of a ground motion parameter at a given site. The values are estimated for a selected probability of exceedence within a given period of interest. An exposure distribution can be generated for any ground motion parameter for which appropriate source effects, transmission effects, and site effects can be defined. A typical seismic exposure procedure consists of four parts.

- Seismic source geometry (zonation)
- Earthquake Occurrence Model
- Attenuation model
- Exposure evaluation model

Several procedures are available for evaluating seismic exposure (e.g., Cornell and Merz, 1974; Der Kiureghian and Ang, 1975; McGuire, 1976; Algermissen and Perkins, 1976; Shah and others, 1975; and Mortgat and others, 1977). Although all these procedures utilize the four models noted above, differences exist in the key assumptions and methodology for application of these models, which can result in significant variations in the estimates of seismic exposure.

The seismic exposure evaluation procedure used in the present study consisted of the following steps.

Seismic Source Geometry

- Define representations (zones) for source geometry.

Earthquake Occurrence Model

For each source in the eastern United States:

- Define location and magnitude range
- Define earthquake recurrence:
  - (a) mean rate of occurrence
  - (b) magnitude distribution

Attenuation Model

- Define applicable mean attenuation relationships
- Define uncertainty about mean values

Exposure Evaluation Model

- Define procedure for computation of probability of exceedence

4.2 SEISMIC SOURCE GEOMETRY

Commonly, the locations of the different seismic sources are determined by using recorded hypocentral positions of past earthquakes together with geological and seismological information. The spatial distribution of hypocenters is then divided into different sources as a function of their shape and seismicity. Three types of sources are commonly used to represent the seismicity of any region. They are the point, line and area source at constant depth under the surface of the ground. Future seismic activity is restricted to the source and the seismicity is assumed to be homogeneous over the whole source.

Since the shape and location of the sources may have a major influence on the final results, special care was taken in this study to obtain the best possible estimates of these characteristics.

Source Model

Area Sources

The seismicity of specific sources in the Eastern U.S. is generally scattered over a large area, most sources were therefore modeled as planes. Their boundaries were approximated by a series of straight lines (Figure 4-1). Since the activity is usually restricted to a narrow depth range, the planes were assumed horizontal.

Line Sources

Line sources are used to model regions where recorded hypocenters lie fairly well along a line at constant depth such as a known fault. The source can be broken up in several segments to satisfy geometric constraints (Figure 4-2). Since few active faults have been located with precision in the East, this model was only rarely used.

Tectonic Model

The concept fault-rupture model for seismic risk analysis was first proposed by Ang (1974) and further developed by Der Kiureghian and Ang (1975, 1977). The model is based on the assumption that an earthquake originates at the focus and propagates as an intermittant series of fault slips in the ruptured zone of the earth's crust. The maximum intensity of ground shaking at a site is determined by the slip that is the closest to the site (significant distance). In all cases the significant distance is shorter than the hypocentral distance as used by point source models.

Even though the computer code can accommodate such an approach, a point source model was used in the analysis since the attenuation relationship

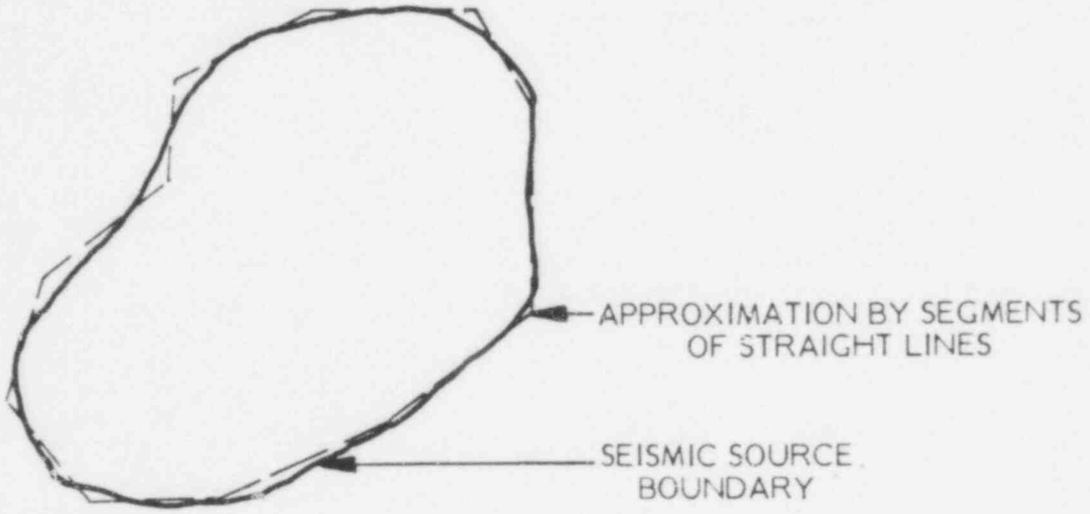

FIGURE 4-1

TYPICAL AREA SOURCE

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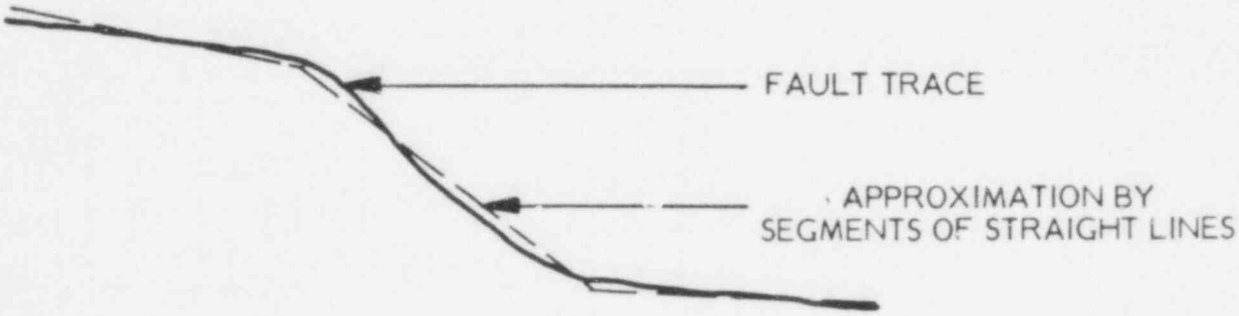

FIGURE 4-2

TYPICAL LINE SOURCE

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implicitly contained the concept of fault-rupture: they were developed based on intensity reports assuming that the epicentral intensity propagates undisturbed for some distance (function of epicentral intensity) before attenuating. To remain consistent with the definition of epicentral distance used in the development of these relations, all the seismic sources were located on the ground surface.

Expert Opinion

As discussed in Appendix A, base maps describing two possible seismic zonations of the eastern United States were provided to the expert panel. Each expert was asked to indicate his "degree-of-belief" in each source zone and source zone alternative. Two typical answers are presented in Figures 4-3 and 4-5. The following paragraphs describe the method used to incorporate this information in the analysis.

Case I (Figure 4-3)

The expert felt that source A could be modelled either by zone 1 or zone 2 or zone 3_a and 3_b with different degrees of belief (C_1, C_2, C_{3a} and C_{3b}, respectively). Since the "degree-of-belief" or credibility is defined as the chances for the seismicity within these zones to be restricted to the zones themselves without being allowed to "float" in the background seismicity of the entire region, the chance for source A to be modeled by either zone 1 or zone 2 or zone 3_a and 3_b (probability of existence of source A) is given by

$$C_A = 1 - (1-C_1)(1-C_2)(1-C_3)$$

where C_A is the source A credibility
C_3 is the average credibility between zone 3_a and 3_b .

C_A is generally not exactly 1.0, resulting in some "floating" earthquakes. One way to deal with this is to allow a number of earthquakes from source A to "float" anywhere in the eastern United States. This would, for example, allow

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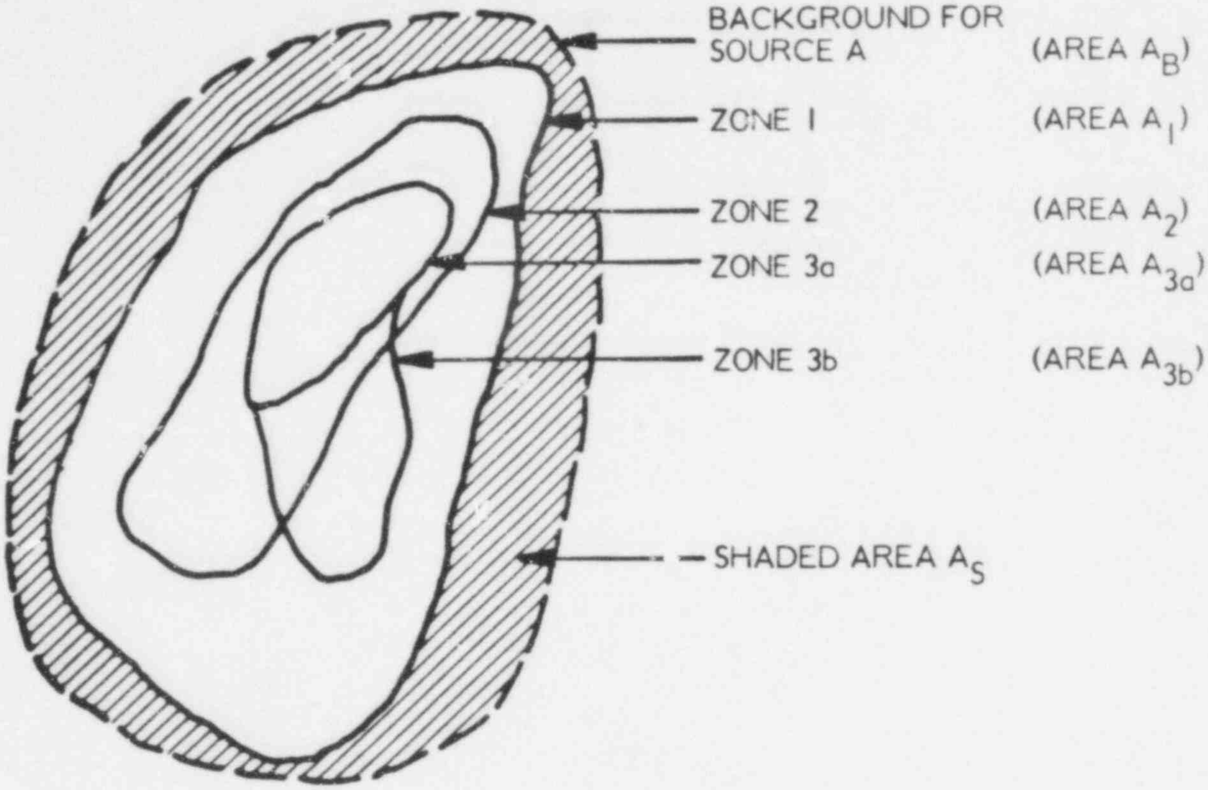

ZONE	CREDIBILITY	a
1	C_1	a_1
2	C_2	a_2
3a	C_{3a}	a_{3a}
3b	C_{3b}	a_{3b}

FIGURE 4-3

TYPICAL ZONE CONFIGURATION
ANSWER FROM ONE EXPERT FOR SOURCE A

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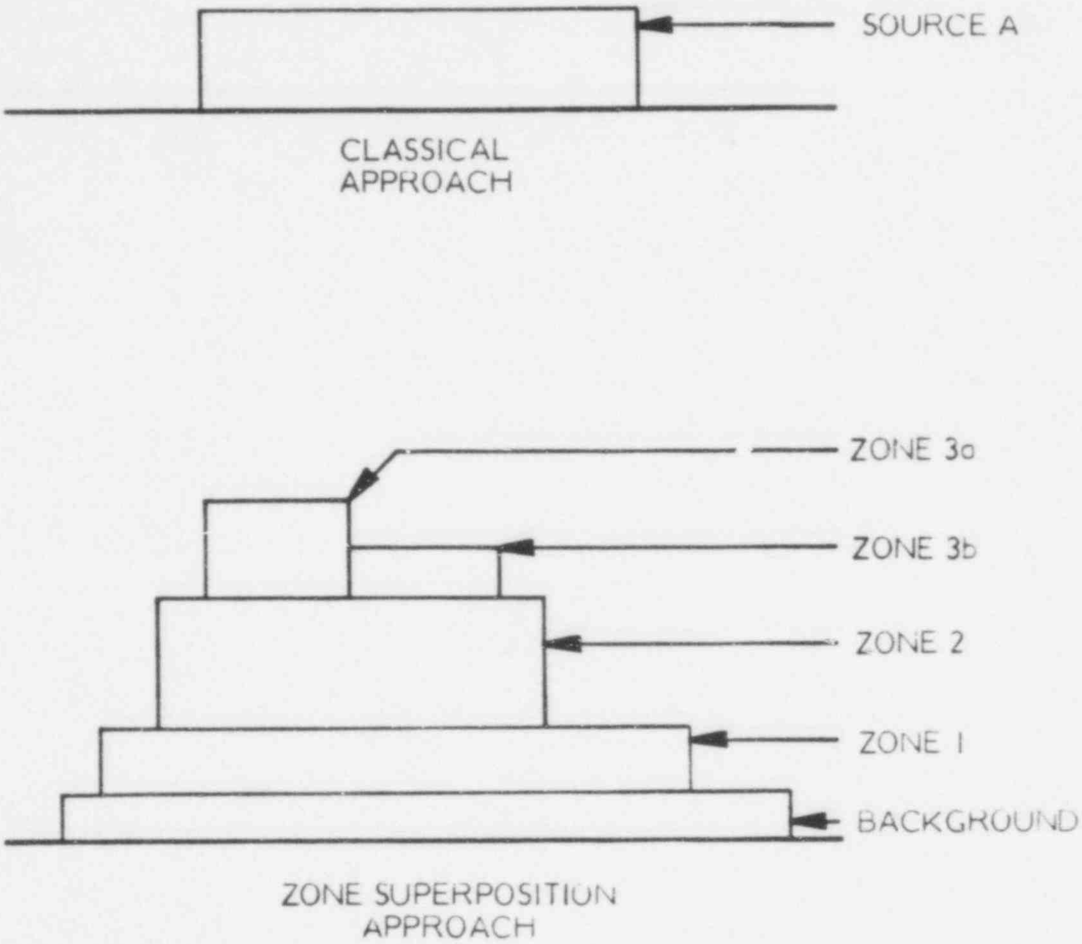

FIGURE 4-4

SEISMIC DENSITY SECTION FOR SOURCE A

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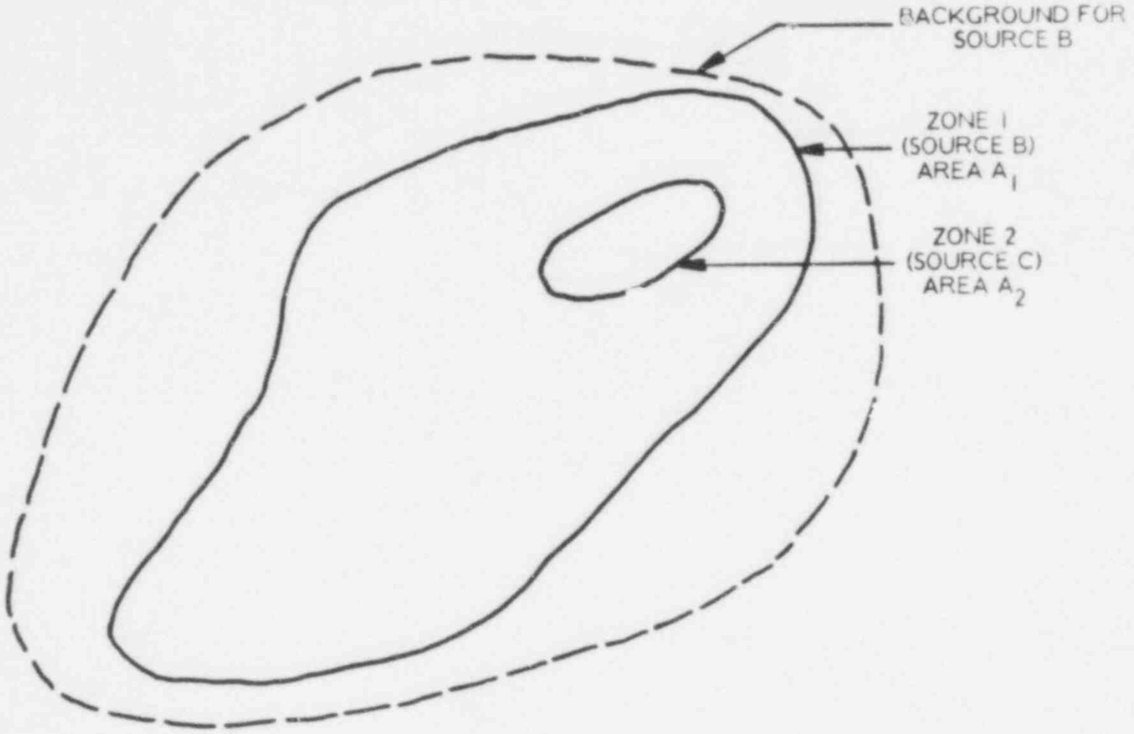

ZONE	CREDIBILITY	α
1	C_1	α_1
2	C_2	α_2

FIGURE 4-5

TYPICAL ZONE CONFIGURATION
ANSWER FROM ONE EXPERT FOR SOURCES B AND C

earthquakes from the New Madrid region to occur in Northern Illinois or earthquakes from the St. Lawrence Seaway to occur in the Piedmont. To avoid such an unrealistic assumption, a background restricting the "migration" of earthquakes was defined for source A. This background was approximately chosen as the envelope of the zonations provided by all the experts for source A. No credibility is assigned to the background and it automatically inherits all the earthquakes rejected from zone 1 through 3.

For each of the zones and the background, an "a" value, corresponding to the number of earthquakes greater than a given size, is determined following the steps presented in Appendix B. The values are a_1, a_2, a_{3a}, a_{3b} and a_B for the zones and the background. The problem consists now in distributing the seismicity among the zones. Again, the credibilities are used as a distributing factor. Assuming $a_1 > a_2 > a_3$ for the sake of the example

$$a'_1 = C'_1 a_1 + C'_1 (C'_2(a_1 - a_2) + C'_3(a_1 - a_3))$$

$$a'_2 = C'_2 a_2 + C'_2 (C'_2(a_1 - a_2) + C'_3(a_1 - a_3))$$

$$a'_3 = C'_3 a_3 + C'_3 (C'_2(a_1 - a_2) + C'_3(a_1 - a_3))$$

where:

a'_i is the number of earthquakes assigned to zone i assuming that $C_A = 1.0$

$$C'_i = \sum C_i/(C_1 + C_2 + C_3)$$

This implies that

$$\sum a'_i = a_1$$

In short, a_1 earthquakes have been distributed between zones 1, 2 and 3 as a function of their levels of activity (a_i) and credibilities (C_i).

When C_A (probability of existence) is smaller than 1.0 the a'_i are modified as follows:

$$a''_i = C_A a'_i$$

The seismicity assigned to the background is made of:

- $(1-C_A)(a'_1 + a'_2 + a'_3)$ earthquakes allowed to occur anywhere over the whole background and

- $a_s = a_b - a_1$ earthquakes restricted to the shaded area of Figure 4-3.

As the background extends below the zones some seismicity adjustment is then introduced to avoid double counting of earthquakes.

- a_s is prorated to the whole background area as
  $a'_s = a_s A_b / A_s$

The total background seismicity becomes

$$a'_b = a_s A_B/A_s + (1-C_A)(\Sigma a'_i)$$

- $a_s \; A_1/A_B$ earthquakes are substrated from the three zones as $a'''_i = a''_i - C'_i \, a_s A_1/A_B$

Finally, since zone 3 is made of two zones, its seismicity is divided between them as a function of their level of activity

$$a'''_{3a} = a'''_3 \, a_{3a}/(a_{3a} + a_{3b})$$

$$a'''_{3b} = a'''_3 \, a_{3b}/(a_{3a} + a_{3b})$$

A typical seismic density section of source A is presented in Figure 4-4.

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This procedure, although somewhat cumbersome, has the advantage of modeling one source as a superposition of zones of different activity levels based on credibility. Furthermore, it replaces the abrupt seismic discontinuity of one source above the background by a stepwise decay and therefore reduces the sensitivity of the analysis to geometric source boundaries.

Case 2 (Figure 4-5)

The zonation presented in Figure 4-5 is somewhat simpler. The expert feels that source B should be modeled with zone 1 with a credibility C_1 and that localized higher seismicity justifies the consideration of source C modeled by zone 2 with credibility C_2.

In this case, the two zones are not alternative zonations to the same source but model two different sources. Hence the probability of existence is not computed and the two sources are treated independently:

$$a'_1 = C_1 \, a_1$$

$$a'_2 = C_2 \, (a_2 - a'_1 A_2 / A_1)$$

As C_2 approaches zero the additional influence of source C decreases until it is simply absorbed by Source B. The background is treated as in Case 1.

When the background covered a large number of complicated sources like in the north east, the earthquakes outside the zones (shaded area in Figure 4-3) were simply allowed to occur anywhere over the whole background. In all cases the conservation of earthquakes was strictly respected. In summary, our treatment of the zonation response from the expert panel reduced to Case 1, Case 2, or a combination between them.

4.3 EARTHQUAKE OCCURRENCE MODEL

The basic input parameters of the earthquake occurrence model are the magnitude range (upper magnitude cutoff) and the recurrence of earthquakes. In

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the following discussion, the size of earthquakes is expressed in terms of earthquake magnitude though MMI could be used as well.

With respect to earthquake data, the magnitudes are discretized every 1/4 of magnitude (M_i) or ½ MMI as it is commonly done in data recording. This representation permits the use of discrete models and has the advantage of getting away from data fitting which usually results in unacceptable uncertainties for the case of large magnitudes where the data is scarce.

Of course, continuous models can be useful for purposes of conducting robustness investigations and subsequent testing of sensitivity of results to parametric assumptions. There are certain other techniques that could be employed, such as extrapolation using "goodness of fit" criteria, but invariably all these approaches require some subjective judgement similar to that used in this study.

The development is done in three steps:

(1) Assuming that earthquake occurrences form a Poisson process with mean rate of occurrence independent of magnitude, a distribution is obtained on the number of occurrences for the time period considered.

(2) Given that an event has occurred, a distribution on the magnitude of events is determined from past data and subjective input. The process generating model can be asumed to be Bernoulli. The probability of success p_{M_i} corresponding to each trial is defined as the probability that the event that has occurred is of magnitude M_i. Thus the probability of failure $q_{M_i} = 1 - p_{M_i}$, at each trial is the probability that the event is not of magnitude M_i. The probability of having r events of magnitude M_i given that a total of n events have occurred can therefore be obtained using the binomial distribution.

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(3) The distribution of the number of events of each magnitude independently of the number of trials is obtained by combining steps one and two.

There are alternate statistical approaches which immediately come to mind. These include modeling of earthquakes of different magnitudes as a stream of Poisson events and use of Compound Poisson processes.

Although these alternate approaches do not eliminate subjectivity in the problem of extreme event estimation or upper magnitude cut-off determination, they are nevertheless, useful for cross-validation purposes in areas where sufficient quantities of data are presently available. Their application is, however, outside the scope of this study.

Earthquake Occurrence (Poisson Model)

It is assumed, once the seismic sources have been located, that earthquake occurrences on each source form a Poisson process with mean rate of occurrence independent of magnitudes. For earthquake events to follow the Poisson model, the following assumptions must be valid:

1. Earthquakes are spatially independent
2. Earthquakes are temporally independent
3. The probability that two seismic events will take place at the same time and at the same location approaches zero

The first assumption implies that the occurrence or absence of a seismic event at one site does not affect the occurrence or absence of another seismic event at some other site or the same site. The second assumption implies that seismic events do not have memory. The assumptions of spatial and temporal independence have been fairly well verified by data when aftershock sequences are removed, and are commonly accepted practices. The degree of dependence between events due to the dual mechanism of stress accumulation and release has not yet been determined with any amount of precision but the earth's "memory" appears to fade quite rapidly with time (Garner and Knopoff, 1974). The third assumption implies that for a small time interval more than one seismic event cannot occur on one source. This is a very realistic and good assumption which fits the physical phenomenon and has been used in many studies.

Thus, considering all the events of magnitude greater than an arbitrary lower bound, a distribution is obtained for the number of occurrences in a given period of time, Δt. The lower bound is chosen such that earthquakes of magnitude smaller than the one specified have a negligible damage potential and can thus be disregarded. This is done for each seismic source.

In its general form, the conditional Poisson law can be written as

$$p_N(n/\lambda) = \frac{e^{-\lambda t}(\lambda t)^n}{n!} \quad , \quad t > 0 \;;\; n \text{ integer} \geq 0, \qquad (4\text{-}1)$$

where

$p_N(n/\lambda)$ = probability of having n events in time period t, given λ
n = number of events
λ = mean rate of occurrence per unit of time

Thus if the mean rate of occurrence λ is known, the probability distribution function can be defined completely.

The parameter λ is obtained from the data and can be modified subjectively. In the present case, it is expressed as the mean rate of occurrence per year of earthquakes larger than magnitude 4.0. Using equation 4-1, the probability of any number of events on a source during the future time period can be obtained. As an example:

$$P(0) = \frac{e^{-\lambda t}(\lambda t)^0}{0!} = e^{-\lambda t} \qquad (4\text{-}2)$$

$$P(1) = e^{-\lambda t} \lambda t, \quad \text{etc.}$$

Since these outcomes are exhaustive and mutually exclusive, the condition $\sum_{n=0} p(n) = 1.0$ is satisfied. Two typical plots of these discrete distributions are given in Figure 4-6.

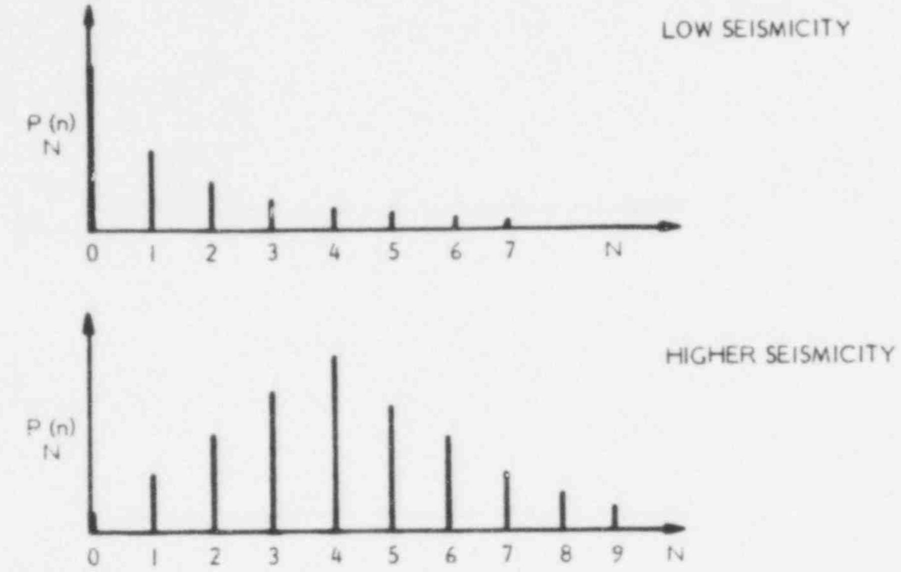
Bayesian Estimate of λ

More classical approaches exist for parameter estimation and corresponding confidence internal calculation for the Poisson model utilized in the study. The results of classical parameter estimation may then be compared with results obtained through Bayesian analysis.

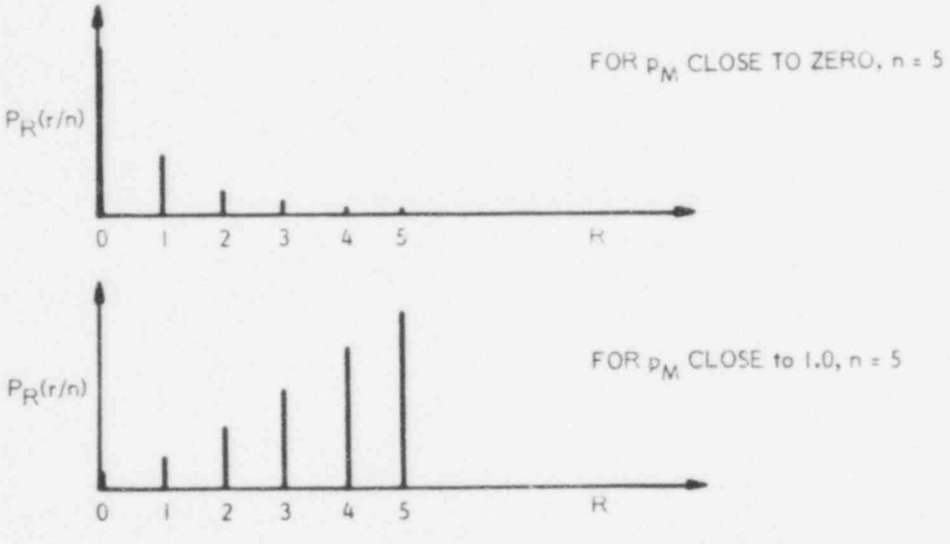
In this study, a Bayesian approach is used so that historical data and subjective information can be effectively combined and used in the analysis. If one assumes that the number of seismic events for a future time t folows a Poisson probability law, there is still uncertainty about the parameter λ, the mean rate of occurrence (Equation 4-1). Therefore, λ is treated as a random variable. The probabilistic information on λ can be obtained through historical data or from the subjective knowledge of the analyst. The subjective probability distribution on λ is called the prior distribution.

The concept of conjugate prior is used for analytical simplicity (Raiffa and Schlaifer, 1961). Therefore the prior distribution for the random variable λ is chosen as the gamma distribution with parameters λ' and ν'. Since the gamma distribution can fit a large variety of shapes this choice does not introduce any major limitations in the model.

Using the historical information, one can obtain the sample likelihood function for λ. The posterior distribution for λ can be obtained by combining the prior distribution and the sample likelihood function by means of Bayes' theorem.



(b) POISSON MODEL - TWO DISCRETE DISTRIBUTIONS FOR N



(a) BERNOULLI MODEL - DISCRETE PROBABILITY DISTRIBUTIONS FOR R

FIGURE 4-6

TYPICAL DISTRIBUTIONS FOR POISSON AND BERNOUILLI MODEL

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Let $f'_\Lambda(\lambda)$ be the prior probability distribution function for λ, and $L(\lambda)$ be the sample likelihood function for λ, then the posterior distribution $f''_\Lambda(\lambda)$ is obtained as

$$f''_\Lambda(\lambda) = N_1 L(\lambda) f'_\Lambda(\lambda). \tag{4-3}$$

where N_1 is a normalizing constant.

Note that the posterior distribution of λ is also gamma type.

In equation 4-1, the conditional probability on the number of events n is based on λ. The unconditional or the marginal distribution on n can be obtained by using equation 4-1 together with equation 4-3 and integrating over all λ's. Thus

$$p_N(n) = \int_0^\infty p_N(n/\lambda) f''_\Lambda(\lambda) d\lambda \tag{4-4}$$

which leads to

$$p_N(n) = \frac{\Gamma(n+\nu'')}{n!\Gamma(\nu'')} \cdot \frac{t^n \lambda''^{\nu''}}{(t+\lambda'')^{n+\nu''}}$$

for n integer ≥ 0

$\nu'' > 0$

$\lambda'' > 0$

$t > 0$

Equation 4-4 is called the marginal Bayesian distribution of n. This distribution, after taking into consideration the uncertainties on the mean rate of occurrence, gives the probability of the number of events above a predetermined lower bound M, in time period t.

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It should be emphasized that even though the mathematical model for earthquake occurrence follows a formal Bayesian approach, it was not used as such in the analysis. As described in Section 3.0, the experts were asked to formulate their opinion explicitly including the information contained in the data, hence in our analysis, all the prior distributions were assumed diffuse, and the input from the experts were considered as hard data. The resulting uniform hazard spectrum must therefore be considered as subjective probability.

Distribution of Magnitudes (Bernoulli Model)

A Bernoulli trial is used to model information on magnitudes. Given that an event has occurred, the probability that it is of any given Richter magnitude can be represented in terms of a Bernoulli trial. If the seismic event that has occurred is of the M_i under consideration, then the outcome of the Bernoulli trial is a success. Conversely, failure at each trial implies that the seismic event that has occurred is of M_i other than the one under consideration.

If p_{M_i} = probability of success at each trial corresponding to M_i

and $q_{M_i} = 1 - p_{M_i}$

= probability of failure at each trial,

then using the binomial law,

$$p_R(r_{M_i}/n, p_{M_i}) = C_n^{r_{M_i}} \, p_{M_i}^{r_{M_i}} (1-p_{M_i})^{n-r_{M_i}} \tag{4-5}$$

for an integer > 0

r_{M_i} integer; $0 \le r_{M_i} \le n$

$0 \le p_{M_i} \le 1$

where $p_R(r_{M_i}/n, p_{M_i})$ is read as the probability that r_{M_i} events M_i will occur out of a total of n events given that the probability of occurrence of M_i is p_{M_i} at each trial, and

$$C_n^{r_{M_i}} = \frac{n!}{r_{M_i}!(n - r_{M_i})!}$$

A different probability p_{M_i} is obtained for each M_i considered in the model. A similar equation is thus obtained for each of the other magnitudes. The probabilities p_{M_i} are mutually exclusive within the range of selected magnitudes for the different magnitudes; hence,

$$\sum_{\text{all } M_i} p_{M_i} = 1.0 \ .$$

As an example, for $M_i = 6$ and $n = 5$,

$$P \text{ (0 events of } M = 6 \text{ given 5 earthquakes)} = (1 - p_6)^5$$

$$P \text{ (1 events of } M = 6 \text{ given 5 earthquakes)} = 5 \times p_6 \times (1 - p)^4$$

$$P \text{ (5 events of } M = 6 \text{ given 5 earthquakes)} = p_6^{\ 5} \ .$$

It should be noted that

$$\sum_{r=0}^{n} p(r/n) = 1.0 \ .$$

The typical plots of the above distribution are shown in Figure 4-6.

Equation 4-5 represents the generating process for the number of events M_i. However, this information is conditional on the knowledge about p_{M_i}, the probability of success corresponding to M_i. To rationally incorporate the historical as well as subjective information on p_{M_i}, the parameter is treated as a random variable with the opportunity for a Bayesian formulation.

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Bayesian Estimate of p_{M_i}

In the classical approach, p_{M_i} is estimated from data by calculating proportions. Confidence intervals are then computed on those proportions utilizing techniques such as Chi-Squared bounding. Results could be compared with those based on Bayesian approach in areas where data is plentiful.

The conjugate prior distribution on p_{M_i} $(f'_p\,(p_{M_i})\,)$ is assumed to be beta type with parameters of η' and ξ'. Since the normalized beta distribution is bounded between 0 and 1 and fits a large variety of shapes, this choice does not introduce any major limitations in the model. A prior distribution of a similar form has to be assumed for each of the magnitudes considered.

The usual format of the available data indicates that among the n earthquakes observed on a given source, r_{M_i} were M_i. This information is used in the construction of the sample likelihood function. Noting that the generating process (Equation 4-5) is a binomial process, the sample likelihood function on p_{M_i} $(L(p_{M_i}/n,r_{M_i})$ is obtained.

The posterior distribution $f''_P(p_{M_i})$ is given by

$$f''_P(p_{M_i}) = N_1 L(p_{M_i}/n,r_{M_i})\, f'_P(p_{M_i}) \qquad (4\text{-}6)$$

where N_1 is a normalizing constant.

Note that the posterior distribution on p_{M_i} is also beta type.

In equation 4-5, the conditional probability on the number of successes r_{M_i} is based on p_{M_i} and n. The condition on p_{M_i} can be removed using equation 4-6 and integrating over all the values of p_{M_i} as follows:

$$p_R(r_{M_i}/n) = \int_0^1 p_R(r_{M_i}, p_{M_i}/n)\,dp_{M_i} \tag{4-7}$$

$$= C_n^{r_{M_i}} \left[\frac{\Gamma(\eta''_{M_i})}{\Gamma(\xi''_{M_i})\,\Gamma(\eta''_{M_i} - \xi''_{M_i})} \cdot \frac{\Gamma(\alpha_{M_i})\,\Gamma(\beta_{M_i} - \alpha_{M_i})}{\Gamma(\beta_{M_i})} \right]$$

for n integer > 0

r_{M_i} integer

$0 \le r_{M_i} \le n.$

where $\xi''_{M_i} = \xi'_{M_i} + r_{M_i}$

$\eta''_{M_i} = \eta'_{M_i} + n$

$r_{M_i} + \xi''_{M_i} = \alpha_{M_i}$

$n + \eta''_{M_i} = \beta_{M_i}$

The above expression is the distribution on the number of earthquakes of a fixed M_i given that n earthquakes have occurred. There is a similar distribution for each M_i considered.

Largest Earthquake (Upper Magnitude Cutoff)

The next step is to account for uncertainty in the specification of the upper magnitude cutoff.

The approach is general and can accomodate a wide range of assumptions. First, one subjectively (e.g., from expert opinion) determines the range of possible maximum magnitudes and a probability distribution, $p\ (M_u)$, over that range.

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$p(M_u)$ is discretized in ¼-magnitude bands and the probability for M_j to be the largest event is computed as $p'(M_{uj})$. The magnitude corresponding to the truncation of the upper tail distribution is M_m.

In a second step, the probability of occurrence (success) of magnitudes is modified to include the distribution on upper magnitudes. This is done by modifying the mean of the beta distribution as

$$ {}^{\mu}P'_{M_i} = {}^{\mu}P_{M_i} \sum_{j=i}^{m} P'(M_{uj}) \tag{4-8} $$

The parameter ξ''_i of the beta distribution can be computed since M''_i is kept constant. The ξ''_i are then renormalized such that the condition

$$ \sum_i \frac{\xi''_i}{M''_i} = 1.0 $$

is verified.

The independent treatment of magnitude distribution and upper magnitude cutoff is valid since for all experts solicited these two distributions are independent of each other.

It is clear that results are sensitive to choice of upper magnitude cut-off. Consequently, it is imperative that results from the selected subjective approach be compard with other techniques such as the use of combined prior distributions using various weighing schemes. The problem of subjectivity in judgement of upper value cut-off may never be overcome. However, the analyst must explore various statistical techniques for combining subjective input from experts to ensure that they produce consistency in results. The schedule contraints of this study requires that the consistency checks be restricted to certain data checks.

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Marginal Distribution on the Number of Magnitudes

The distribution of the number of events of each magnitude independently of the number of trials is obtained by combining steps (1) and (2).

$$p_R(r_{M_i}) = \sum_{n=0}^{\infty} p_R(r_{M_i}/n)p_N(n) \qquad (4\text{-}9)$$

$$= \sum_{n=0}^{\infty} C_n^{r_{M_i}} \frac{\Gamma(\eta''_{M_i})}{\Gamma(\xi''_{M_i})\,\Gamma(\eta''_{M_i} - \xi''_{M_i})}$$

$$\cdot \frac{\Gamma(r_{M_i} + \xi''_{M_i})\,\Gamma(n + \eta''_{M_i} - r_{M_i} - \xi''_{M_i})}{(n + \eta''_{M_i})}$$

$$\cdot \frac{\Gamma(n + \nu'')t^n \lambda''^{\nu''}}{n!\,\Gamma(\nu'')\,(t + \lambda'')^{n + \nu''}}$$

This distribution describes totally the seismicity of the source considered in terms of the two parameters magnitude (M_i) and number of occurrences (n).

The Bernoulli model has the advantage that the probability of occurrence of an earthquake of any given magnitude (p_{M_i}) can be established independently of other magnitudes. It also offers greater flexibility in the use of historical seismicity data and in combining it with subjective information through a Bayesian approach.

Expert Opinion

In sections two and three of the questionnaire, the experts provided information related to

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- Site of maximum earthquake
- Earthquake occurrence

The following paragraphs present how this information was utilized in the analyses. As mentioned in Section 3, we asked the experts to be the "Bayesian processor" and provide us with a "posterior" input.

Since the model is based on a formal Bayesian approach the historical data could not be used in the study without double counting them since they already had been included explicitly in the experts' answers. To prevent such a bias, all the prior distributions were chosen as diffuse and the only input used was the one provided by the experts.

Size of Maximum Earthquake

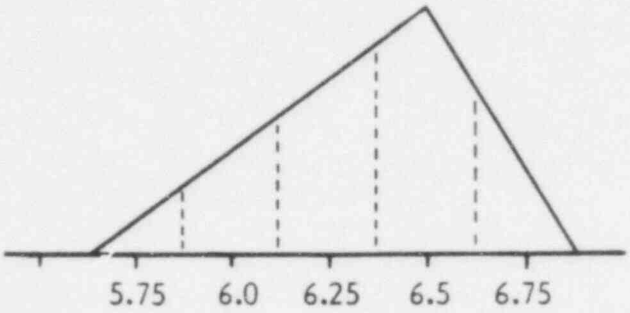
The largest earthquake to be expected to occur in each zone for a time period of 1,000 years was chosen as the upper magnitude cutoff in the analysis. This information was provided through specification of either one magnitude or a range of magnitude associated with a best estimate. When the upper magnitude cutoff was defined by one magnitude, say M_i, it was assumed that no event greater than that magnitude could occur and therefore $p_{M_{i+1}}$ was set equal to zero. When the upper magnitude cutoff was defined by a range of magnitudes, a triangular distribution was anchored over the range with its mode centered on the best estimate as shown in Figure 4-7. The $P(M_{uj})$ were obtained from that distribution and incorporated in the analyses as described in the previous section.

Earthquake recurrence

All experts choose to express the recurrence in terms of the well known linear relationship

$$\log N_c = a + b\,M \qquad (4\text{-}10)$$

	m_b
LOW BOUND	5.75
HIGH BOUND	6.75
BEST ESTIMATE	6.50



M_u	$P(M_{uj})$
5.75	.057
6.0	.171
6.25	.286
6.5	.352
6.75	.133

FIGURE 4-7

TYPICAL DISTRIBUTION OF MAXIMUM EARTHQUAKE

The slope b was expressed by the expert panel as a fixed value (i.e., 0.9) or a value associated with an uncertainty (i.e., 0.9 ± 0.1).

On many occasions the parameter a was not provided. In such cases, the a value was determined from the data itself corrected for homogeneity in time (Appendix B) and other information provided in the answer booklet, such as the return period of large events. In all cases, the recurrence relationship based on the expert's input was drawn together with the data as a consistency check. A typical plot is presented in Figure 4-8. The probability of success of each magnitude M_i given the occurrence of an event was then determined as

$$p_{M_i} = \frac{\Delta M_i}{\Sigma \Delta M_i} \qquad (4\text{-}11)$$

where ΔM_i is the number of events of magnitude M_i computed from the recurrence relationship and $\Sigma \Delta M_i$ is the total number of events of magnitude greater or equal to the smallest one of interest in the analysis.

Uncertainty in Recurrence Slope b

The uncertainty in the recurrence slope was modeled by the shape of the beta distribution describing the p_{M_i}. The beta parameters η'' and ξ'' were modified as follows to model the uncertainty. Given that one event greater than $M_i = 4.0$ has occurred and anchoring the slope at $M_i = 4.0$, the variation in M_i corresponding to magnitude 6.0 for the two bounding slopes was taken as two sigmas. This assumption is valid since most of the hazard is governed by those magnitudes in the analysis. Furthermore it implies that the uncertainty is larger for larger magnitudes, which is a valid assumption. Hence knowing the mean and the standard deviation for $M_i = 6$, the parameters η'' and ξ'' were computed as

$$\eta'' = \frac{\mu(1 - \mu)}{\sigma^2} - 1 \qquad (4\text{-}12)$$

$$\text{and} \quad \xi'' = \mu \eta''$$

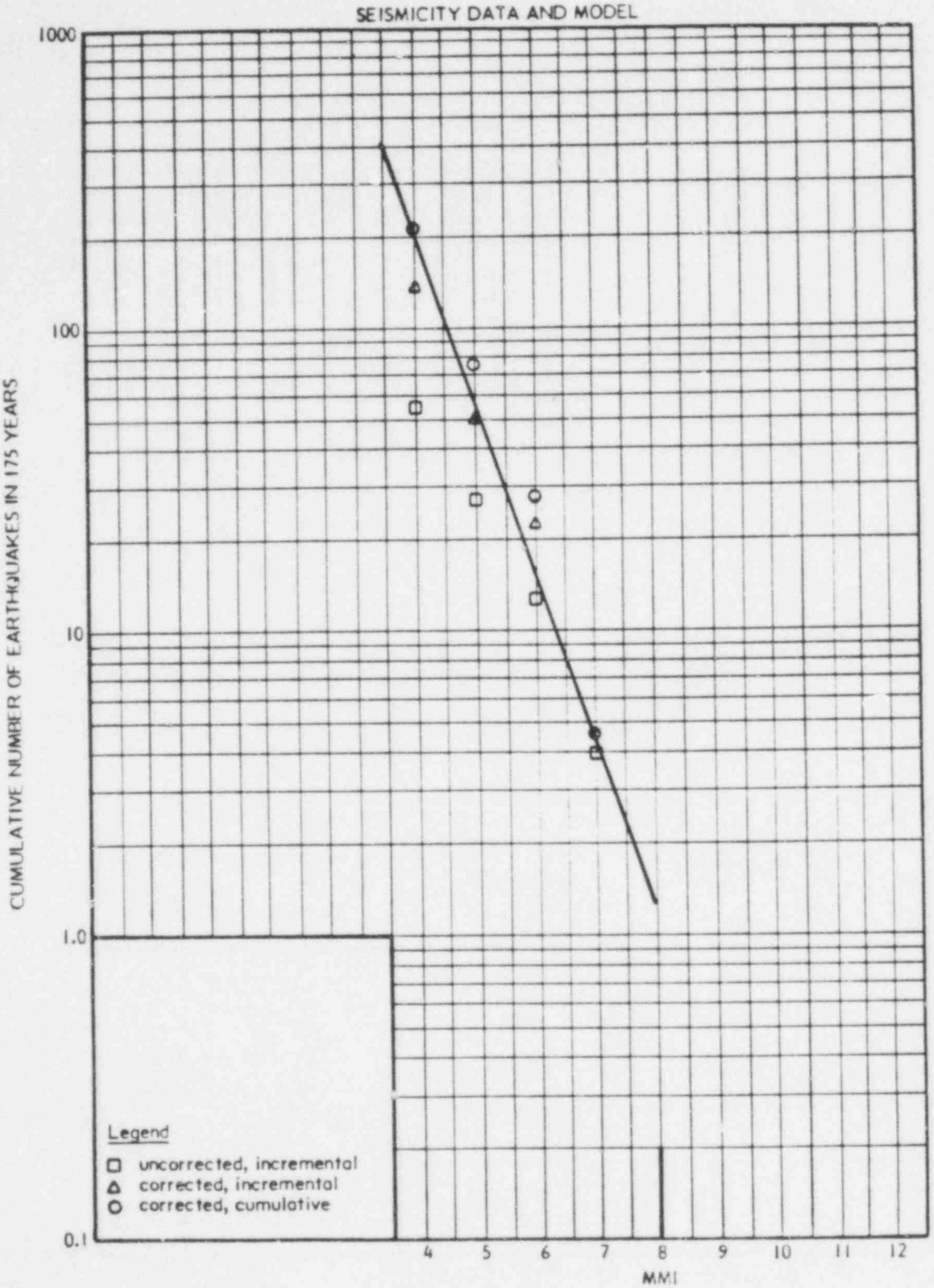


FIGURE 4-8

TYPICAL PLOT OF DATA, CORRECTED DATA
AND RECURRENCE RELATIONSHIP

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The same η'' was used for all magnitudes implying that the uncertainty increased with magnitude.

When only the mean of slope was provided, an insignificantly small uncertainty was assumed.

Uncertainty in Recurrence Intercept

This uncertainty is modeled by the parameters λ'' and ν'' of the gamma distribution. Since the data was based on 175 years, and the experts used the data explicitly to provide their input, the parameter λ'' was set to 175 which automatically sets the uncertainty.

4.4 ATTENUATION RELATIONSHIPS

The difficulty in quantifying attenuation in the Eastern United States (EUS) results from the almost complete absence of strong-motion data. Inferences thus must be made about the attenuation of ground motion in the East by studying systematic differences or similarities between the EUS and other regions of the world regarding information that is indirectly related to ground motion such as intensity data.

Introduction

As a preliminary attempt to focus on the problem of attenuation in the EUS, it is valuable to list evidence that may shed some light on the differences or similarities between ground motion attenuation in the EUS and the Western United States (WUS). For instance:

- MM intensity attenuates slower in the EUS than in the WUS, based on an abundance of historic intensity data.
- A comparison of ground motion data from the 1968 Illinois earthquake and nuclear blast data recorded in the EUS with similar data in the WUS suggests that the rate of attenuation of PGA in the far field may be the same for both regions.

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- There are higher propagation velocities at depth in the EUS than in the WUS.
- There are higher Q-values (lower damping) in the EUS than in the WUS.
- There is no low Q-zone in the upper mantle in the EUS.
- There are systematic differences among magnitude determinations between the EUS and WUS.

Some inferences concerning differences in ground motion characteristics between these two regions may be made from the above evidence. They can tentatively be quantified in terms of differences in frequency content, amplitude and duration of the motion.

- The relative damageability of ground motions in the far field as compared to the near field is greater in the EUS than in the WUS. This implies a relatively larger energy content and
  - (a) larger accelerations, or
  - (b) longer durations, or
  - (c) both (a) and (b)
- The relative contribution of body waves at the larger distances is greater in the EUS. This implies higher amplitudes and longer durations at distance.
- The EUS may be a more efficient propagator of surface waves than the WUS. This would imply relatively longer durations and larger long-period motions in the EUS.
- There may be fewer complexities in the transmission path in the EUS. This could explain in part the lower damping inferred in the EUS. It might imply less scattering of waves, making the EUS a relatively more efficient propagator of the higher frequency motions.
- Since there are more competent rocks at depth in the EUS, earthquake foci may be deeper. This might imply lower attenuation of ground motion as compared to the WUS at distances less than several focal depths. This would not explain differences in attenuation at greater distances.

- Source parameters relative to the "size" of an earthquake may be different in the EUS than in the WUS. The higher competency of the rock and lack of major well developed fault zones might imply higher stress drops and smaller source dimensions in the EUS.

It is interesting to note that some theoretical evidence (Campbell and Duke, 1974) suggests that source strength parameters (e.g., stress drop) and Q-values may not directly affect the rate of decay of ground motion values among regions. This shows that the energy content, which can be related to peak accelerations, is directly proportional to both stress drop and Q. This suggests that the rate of decay of acceleration may be merely a function of geometrical spreading.

Approach

It would seem that, aside from theoretically modeling, there is only one alternative to EUS attenuation, given the paucity of strong motion data and availability of intensity data. This approach consists of developing a model for the attenuationof site intensity using EUS intensity data and then to use existing EUS strong motion data in conjunction with data from the West to convert the site intensity into a ground motion parameter. The ground motion parameters chosen for this analysis are peak ground acceleration (PGA), peak ground velocity (PGV), and several spectral ordinates at frequencies ranging from 25 HZ to 0.5 HZ. In addition, the site intensity is also retained as an additional measure of the ground motion. As discussed elsewhere, we have calculated the seismic hazard at specific sites, using nine separate sets of input, corresponding to the data and opinion, provided by nine experts. Many of the experts preferred to deal with seismic hazard in terms of epicentral intensity, and our attenuation relation as described above is appropriate for use with these experts' input. Other experts preferred body-wave magnitude, and for these experts we factor out epicentral intensity as a parameter in the attenuation model using a correlation between body wave magnitude and epicentral intensity.

The strength of this approach is that it specifically models the EUS by explicitly incorporating EUS intensity attenuation. The only basic assumption is that site intensity-ground motion correlations are regionally independent.

One weakness of this approach has to do with apportioning an attenuation model into submodels. The uncertainty contained in each of the submodels increases the uncertainty in the final prediction (Cornell, et al, 1977), although at the present time there does not appear to be any rational alternative to this.

The added uncertainty has a significant influence on the seismic hazard results and we are sure that greatly improved estimates of the seismic hazard could be obtained through additional work on this topic. When an attenuation model is derived directly from recorded ground motion, the statistical uncertainty usually corresponds to a one-standard deviation level corresponding to 1.6-2.0 times the mean. When the uncertainty in mean predictions of intermediate parameters, such as intensity, are rigorously included, this multiplicative factor becomes 2.0-2.9 (Cornell et. al, 1977). Clearly, a hazard analysis which integrates out to a 2 or 3 standard deviation ground motion is being driven by this multiplicative factor. While it has been outside the scope of this effort to address this uncertainty in detail, we feel that these uncertainties may be excessive. That is, in spite of their statistical formality, they are derived from data representing all possible earthquake types and all possible travel paths. The seismic hazard at a particular site is usually dominated by a particular type of earthquake (e.g., magnitude range, depth, focal mechanism, etc.), with a particular travel path. We believe that a detailed consideration of this would significantly reduce the attenuation model uncertainty. In the meantime, however, we are forced to rely on a formal statistical definition of the uncertainty. Consistent with the uncertainty contained in each of the submodels for attenuation, we use a value for dispersion or uncertainty of a multiplicative factor of 2.45. Since the data are generally assumed to be lognormally distributed, this is often expressed as a natural logarithm additive factor of ln (2.45) = 0.9. A further basis for this particular value is contained in the work done for TVA by Weston Geophysical Inc. (1978).

Another weakness is that the influence of site geology on the predicted site ground motion is more difficult to quantify when the intensity data is incorporated. In the past, several investigators have attempted to quantify site geology effects by including geology (e.g., soil, rock) as a parameter in the regression between ground motion and site intensity. The difficulty in this is that the majority intensity reports are reports for soil conditions at a location nearby to an accelerograph station. The conventional procedure has been to adjust the intensity report for the difference in location and to then associate this adjusted intensity with the recorded ground motion at the accelerograph site. At best this approach for characterizing site effects is circular and results in a systematic bias toward soil response. Our approach is similar to the one taken by Murphy and O'Brian (1977). Since almost all intensity data corresponds to soil intensity data, we assume that a correlation between site intensity and recorded ground motion will be most representative of soil, and that the intensity data alone are inadequate to quantify a corresponding model for rock. We feel that the best way to accurately define a rock model is through Western U.S. data for ground motion as a function of distance, magnitude, and site type. None of the intensity biasing problems discussed above exist for this data set, although we acknowledge there are potential biases such as building foundation effects (Boore, et. al, 1978). The data currently available are insufficient to resolve at this level of detail and we, in the end, rely on the overall "reasonableness" of the rock model as a last check. We present the detailed results on our treatment of site geology in a following section, following a summary presentation of the strong motion data base used for analysis.

Summarily, our approach to attenuation is to combine EUS intensity attenuation data with WUS instrumental data relating site intensity to a gorund motion parameter. When required for compatibility with a particular expert's input, epicentral intensity is converted to body wave magnitude. The resulting attenuation model is considered to be appropriate for soil sites. A scale factor is then developed for WUS data for each ground motion parameter to convert the soil prediction to a rock prediction.

4.5 SEISMIC EXPOSURE EVALUATION

Seismic exposure is evaluated by computing the level of a ground motion parameter at a site for a selected probability of exceedence. In the following discussion, maximum peak ground acceleration (PGA) is chosen as a parameter for illustrating the analytical framework. An identical procedure is used for any other parameter such as peak ground velocity (PGV) and spectral accelerations.

A typical seismic region contains a number of earthquake sources. The seismic exposure evaluation aims at combining the effect of all sources to provide an estimate of the probability of occurrence of at least one event of a given PGA within the time period of interest. By repeating the process for a number of PGA levels, a probability distribution function or cumulative distribution function for the PGA is developed at the site.

In this model the quantities M and PGA are discretized to equal step increments such that all the integration signs can be replaced by summations. Since the distance is a parameter in the attenuation relationships, the process of division of a source area A into smaller segments enables one to take into consideration the distance variation to the site from different parts of a large source. The size of the segments is chosen small enough such that the approximation from a continuous to discrete computation is acceptable. The seismicity within a source remains the same from segment to segment. If the mean rate of occurrence of earthquakes for the whole source is λ'', then the rate for a segment ΔA is

$$\lambda''' = \lambda'' \Delta A/A \qquad (4\text{-}14)$$

The distribution on the number of events for each segment is obtained from equation 4-4, where λ'' is replaced by λ'''. The conditional distribution on magnitudes given M events remains unchanged by the segmentation of the sources. The distribution of the number of occurrences of each magnitude is given by equation 4-7. The same distribution applied for any segment of the source. The distribution of the number of occurrences of each M increment can be presented under a matrix form that describes the total seismicity of the segment.

Only a finite number of different magnitude events can occur on the segment (from the largest to the smallest magnitude considered). The number of occurrences of any of these events is limited by the probability of occurrence associated with them. They are disregarded when this probability becomes negligible, say 10^{-8}. Hence, the total number of events is finite and can easily be handled under the summation signs.

Since the distance from the segment to the site is known, all the parameters of the attenuation relationships are determined.

For a given event M_j occurring on a segment and distance R_l from the site, the probability of obtaining a maximum acceleration a_i at the site is given by $f(a_i/M_j,R_l)$, which is the distribution of accelerations for a given magnitude and distance. This distribution is chosen to be lognormal.

<u>Contribution of One Segment</u>

The contribution to acceleration greater or equal to a_i of all events M_j occurring on the same segment is written as:

$$P(A \geq a_i) = pP(M_j) + \left[1 - (1 - p)^2\right] P(2M_j) + \ldots + \left[1 - (1 - p)^n \; P(nM_j)\right] \qquad (4\text{-}15)$$

where

$P(A \geq a_i)$ = probability of obtaining acceleration greater or equal to a_i at least once

$P(kM_j)$ = probability of k occurrences of event M_j with $k = 1, 2 \ldots n$

p = $P(A \geq a_i/M_j)$, probability of obtaining an acceleration greater or equal to a_i given an event M_j

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Setting $q = 1 - p$, the above expression can be rewritten:

$$P(A \le a_i) = P(\text{no } M_j) + \sum_{k=1}^{n} q^k \, P(kM_j) \qquad (4\text{-}16)$$

with n chosen such that $q^k P(nM_j)$ can be neglected.

The above discussion assumes independence among events. Hence, the contribution of all possible events can be combined as follows:

$$P(A \ge a_i)\Big|_{\text{one segment}} = 1 - \prod_{\substack{\text{all} \\ M_j}} \left[1 - P(A \ge a_i)_{M_j} \right] \qquad (4\text{-}17)$$

The whole range of magnitudes is covered starting with the largest one down to the smallest one that generates a noticeable effect at the site ($M_j \ge M_{min}$ as a function of distance). This eliminates the consideration of a large number of events.

Contribution of One or Several Sources

As the events are assumed independent from segment to segment, the contribution of each segment of a source is combined as in equation 4-13.

$$P(A \ge a_i)\Big|_{\text{one source}} = 1 - \prod_{\substack{\text{all} \\ \text{segments}}} \left[1 - P(A \quad a_i)\Big|_{\substack{\text{one} \\ \text{segment}}} \right] \qquad (4\text{-}18)$$

When several sources are considered, the same principle is applied for each source. Thus,

$$P(A \geq a_i) = 1 - \prod_{\substack{\text{all} \\ \text{sources}}} \left[1 - P(A \quad a_i) \Big|_{\substack{\text{one} \\ \text{source}}} \right] \qquad (4\text{-}19)$$

This expression gives the probability of occurrence at the site of at least one acceleration greater than a given level. A typical cumulative distribution function is shown in Figure 4-9.

Once a cumulative distribution function is established for a site, the seismic exposure can be determined for any desired probability of nonexceedence. Before discussing this process, the following definitions are presented:

PROBABILITY OF NONEXCEEDENCE	Probability of nonexceedence is the probability that a given level of ground motion will not be exceeded within the period of interest
PERIOD OF INTEREST	Period of interest is the assumed design life or useful life of a structure or project
RETURN PERIOD (RP)	Return period is the mean waiting time for an event of interest (assuming a Poisson law of occurrence of earthquakes)

Once a period of interest is selected, the acceleration corresponding to a given probability of nonexceedence or return period can be estimated by applying Bernoulli's binomial probability law, which states that if for independent trials, p is the probability of success at each trial, the probability of r successes in n trials is given by:

$$p_R(r/n) = C_r^n \, p^r (1 - p)^{n-r} \qquad (4\text{-}20)$$

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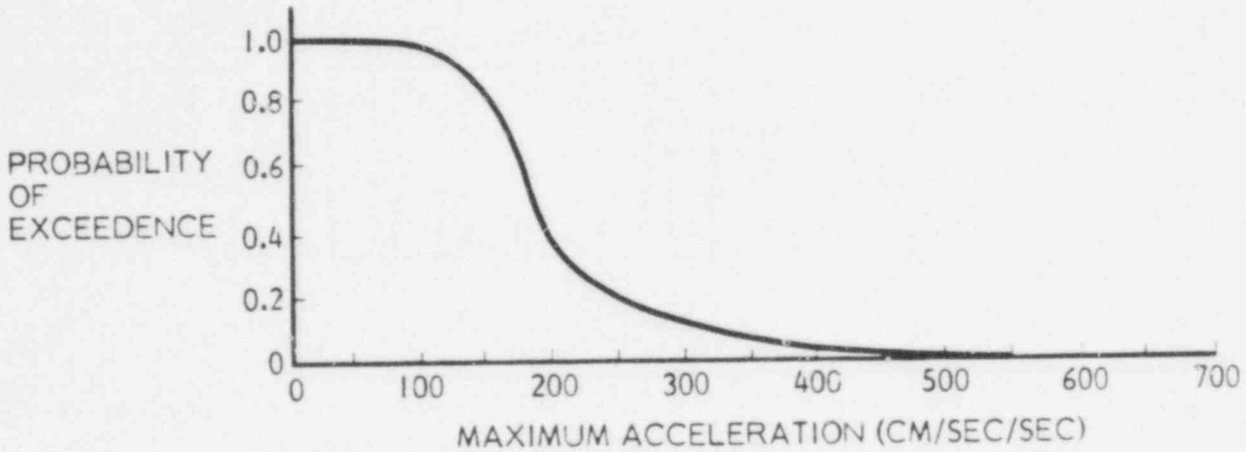

FIGURE 4-9

TYPICAL CUMULATIVE DISTRIBUTION FUNCTION
FOR PGA AT A SITE

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where n integer > 0; 0 < r < n; and

$$C_r^n = \frac{n!}{r!\,(n-r)!}$$

Thus, if the period of interest is 50 years and an acceleration corresponding to 200-year return period is desired for a site, we proceed as follows:

$$p(RP = 200 \text{ years}) = 0.005 \text{ per year}$$

Hence, the probability of at least one success in 50 years (trials)

$$= 1 - \text{probability (no success in 50 years)}$$

$$= 1 - p_R(0/50)$$

Here, n = 50 years and r = 0. Using equation 4-20,

$$p_R(0/50) = C_0^{50}\,(p)^0\,(1-p)^{50} = (1-0.005)^{50} = 0.778$$

Hence, probability of exceedence in 50 years = 1 - 0.778 ≈ 22%. The desired acceleration may be found from the CDF corresponding to a probability of exceedence = 22%.

Figure 4-10 gives a relationship between return period, period of interest, and probability of nonexceedence. Note that this shows that accelerations associated with 200 year return period have a 22% probability of being exceeded in 50 years. The relationship is general and can be applied to any situation based on the Poisson's law for mean rate of occurrence and the Bernoulli binomial law.

The following observations are useful in regard to the return period concept.

(1) A return period (RP) is the mean (or average) waiting time for an event of interest (assuming Poisson occurrence of events).

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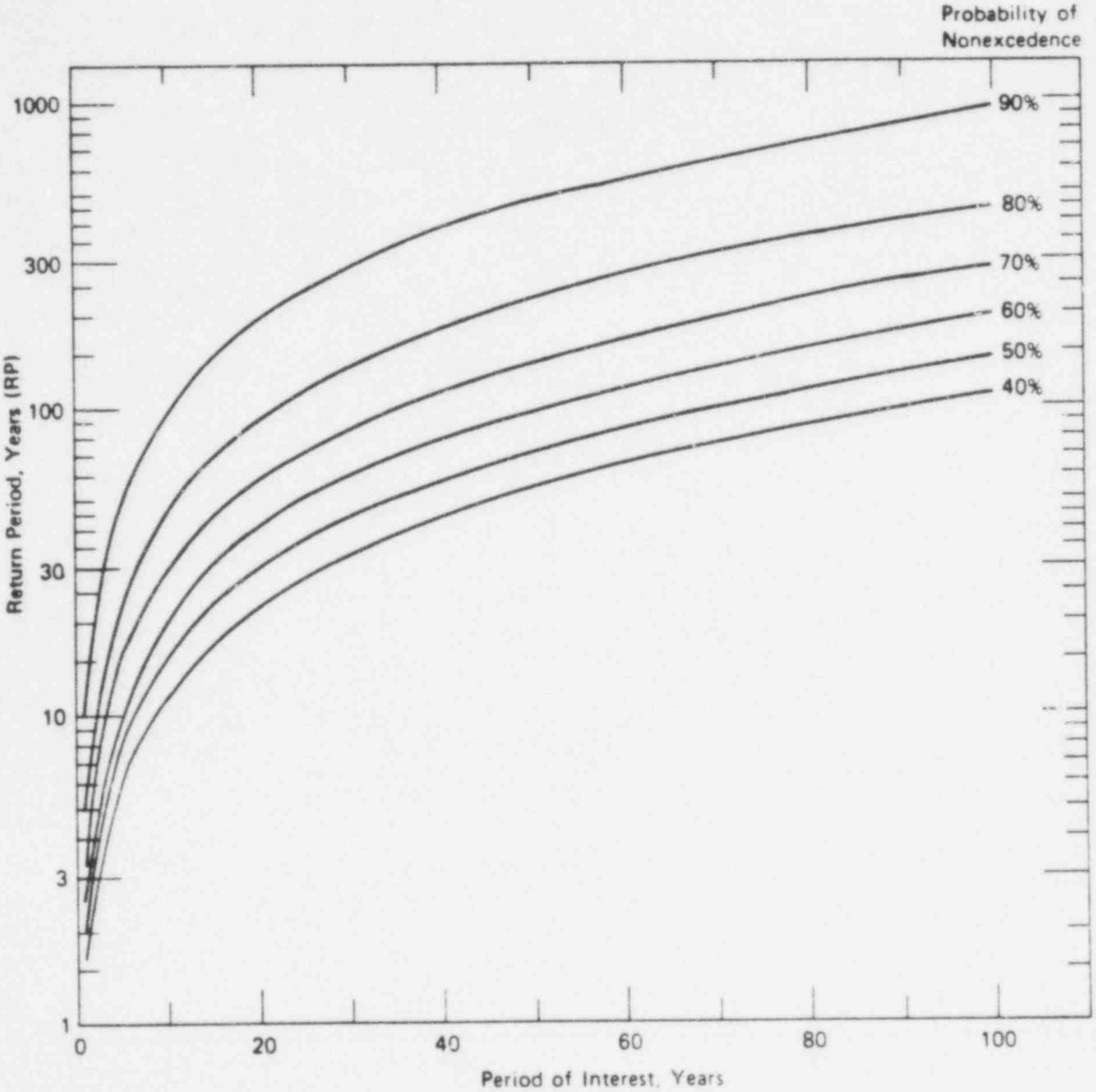

FIGURE 4-10

RELATIONSHIPS BETWEEN RETURN PERIOD, PERIOD OF INTEREST AND PROBABILITY OF NONEXCEEDENCE

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(2) The probability that an event corresponding to a return period RP will occur in any given year is given by p = 1/RP. Hence, for a return period of 500 years, p = 0.002.

(3) The probability that not a single event of the RP type will occur in RP years can be approximated by 1/e for large RP (RP ≥ 15), where e = 2.718. Thus, if return period is 100 years, the probability that in 100 years there will not be a single event producing the 100-year peak ground acceleration is given by $1/e \simeq 0.36$, or there is 64% chance that in 100 years there will be at least one event producing a 100-year peak acceleration or more.

A typical exposure plot of acceleration versus return period is presented in Figure 4-11.

Synthesis of Results

Different exposure evaluation at a site was obtained for each expert using his input only. The loading parameters considered were PGA, PGV, nine spectral ordinates of a 5 percent damping response spectrum (T = .04, .05, .08, .10, .20, .30, .40, 1.0 and 2.0 seconds) and Modified Mercalli Intensity. A typical set of spectra for the 1,000 year return period is shown in Figure 4-12. This approach has the advantage of providing the range of results corresponding to each expert as well as the distribution within that range. Moreover, a synthesis result can be obtained using the method of weighted averages.

In the questionnaire, the experts were asked to rank themselves on a scale from 0 to 10 regarding the confidence they had in their answer. For each zone considered three self-rankings were asked regarding zonation (R_z), upper magnitude (R_u) and recurrence (R_s).

These weights, together with the percentage of contribution of each zone to the exposure were used to reach the synthesis. For each expert, the weight of the source was computed from the self-ranking.

$$W_{ij} = \sqrt{R_{zij}^2 + R_{uij}^2 + R_{sij}^2}$$

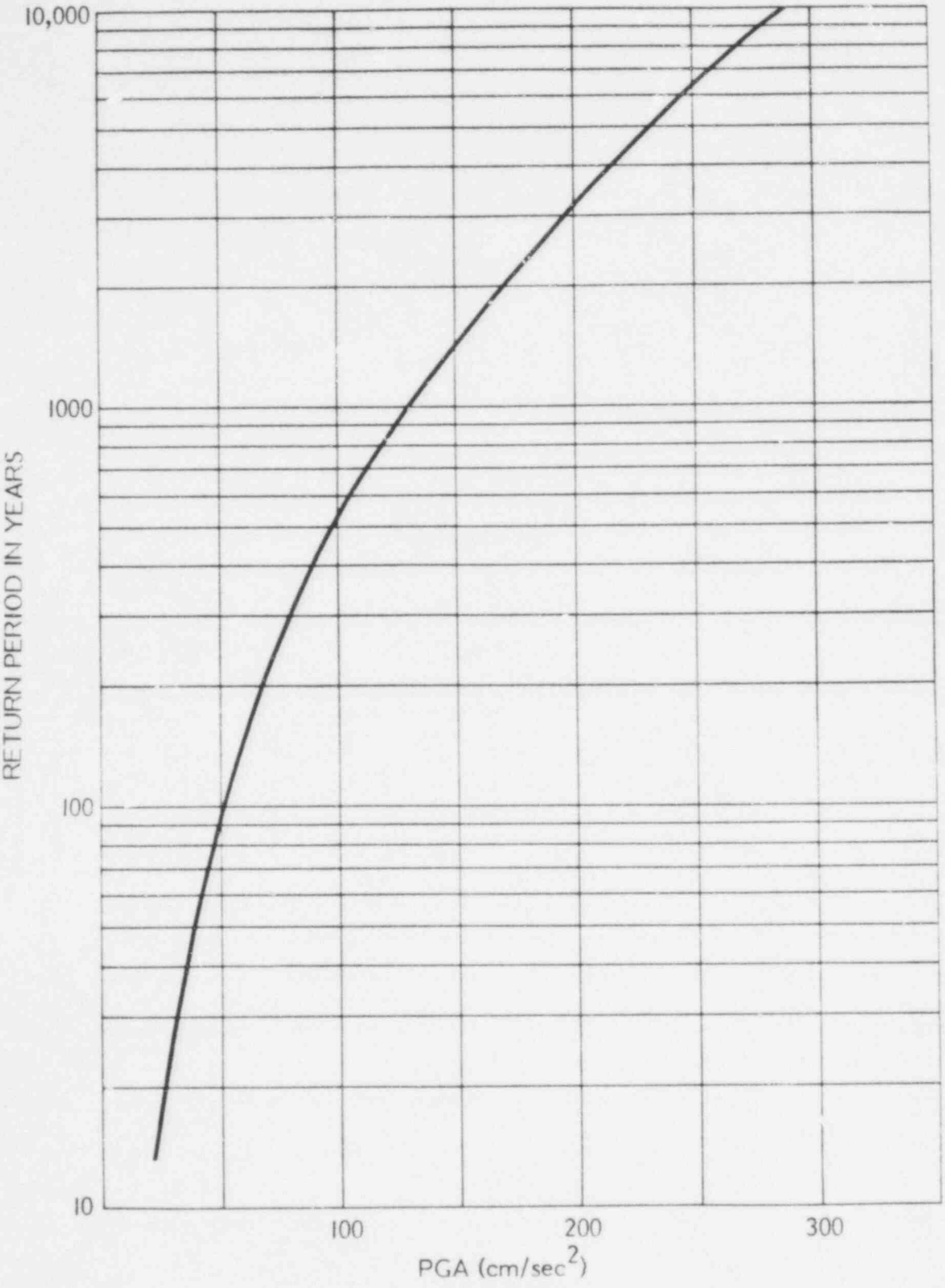

FIGURE 4-11

TYPICAL PLOT OF PGA VS. RETURN PERIOD

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ALL EXPERTS -- DRESDEN -- 1000 YEAR RETURN PERIOD

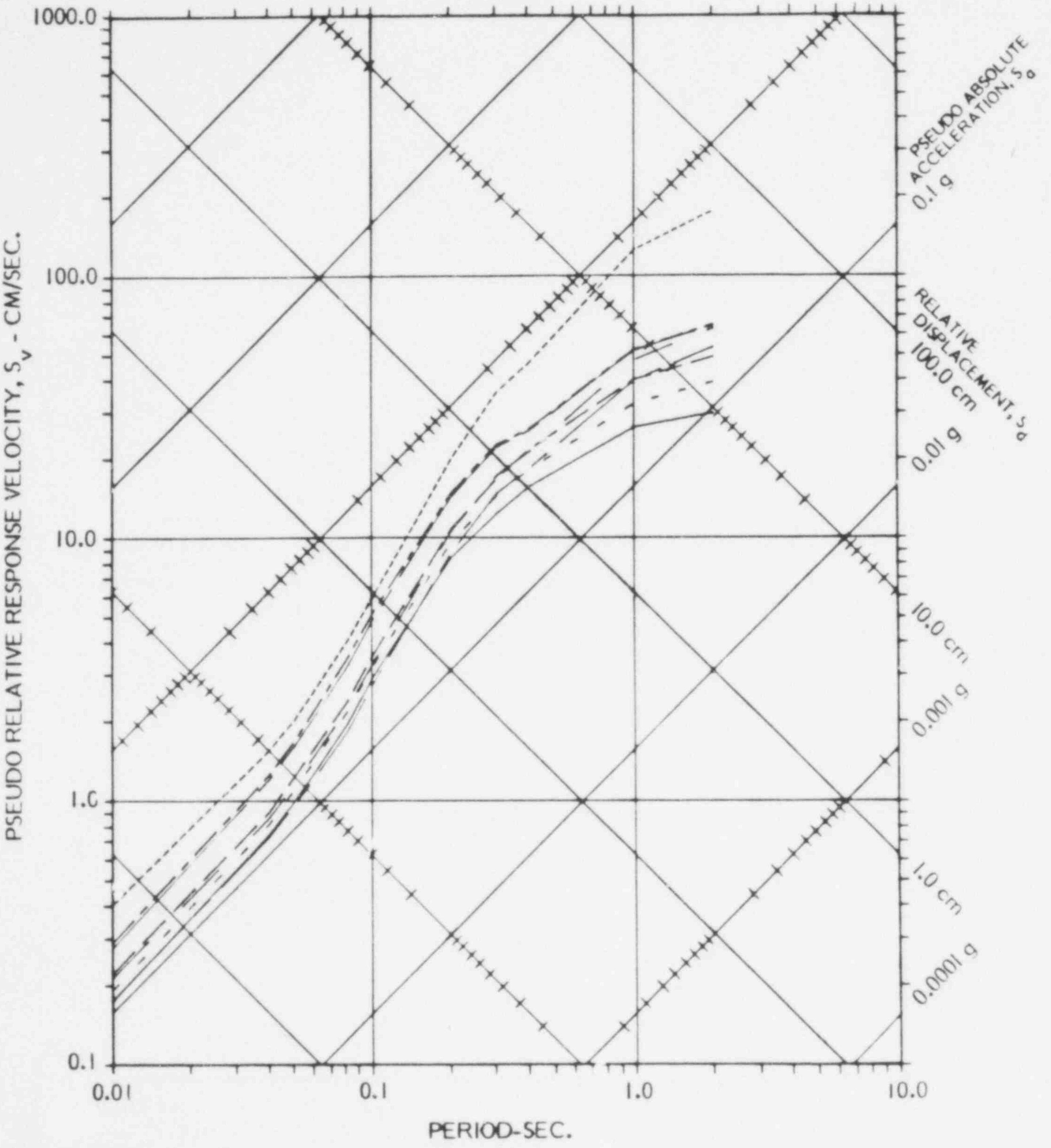

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FIGURE 4-12

TYPICAL SPECTRA AT A FIXED SITE CORRESPONDING TO EACH EXPERT

where i is the zone index
j is the expert index

For the return period considered, the contribution of each zone to the total exposure (p_{ij}) was determined for each expert. It should be noted that both the exposure and the zone contribution varies from expert to expert.

An example is given in Table 4-1. The contributing weight of each expert is computed as

$$E_j = \sum_i \rho_{ij} W_{ij}$$

The weighted average for a given parameter and return period is obtained as

$$L_{A_\nu} = \sum_j L_j E_j / \sum_j E_j$$

This process has to be repeated for each exposure parameter and return period. Figure 4-13 presents a typical spectrum synthesis.

TABLE 4-1

SOURCES WEIGHTS AND CONTRIBUTIONS FOR A GIVEN LOADING PARAMETER AND RETURN PERIOD

		Zone Index					
		1		2		i	
Expert	Exposure	Weight	Contribution (%)	Weight	Contribution (%)	Weight	C
1	L_1	W_{11}	p_{11}	W_{21}	p_{21}	p_{i1}	p_{i1}
2	L_2	W_{12}	p_{12}	p_{22}	p_{22}	W_{i2}	p_{i2}
.							
.							
.							
j	L_j	W_{1j}	p_{1j}			W_{ij}	p_{ij}

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EXPERT 11 -- 1000 YEAR RETURN PERIOD

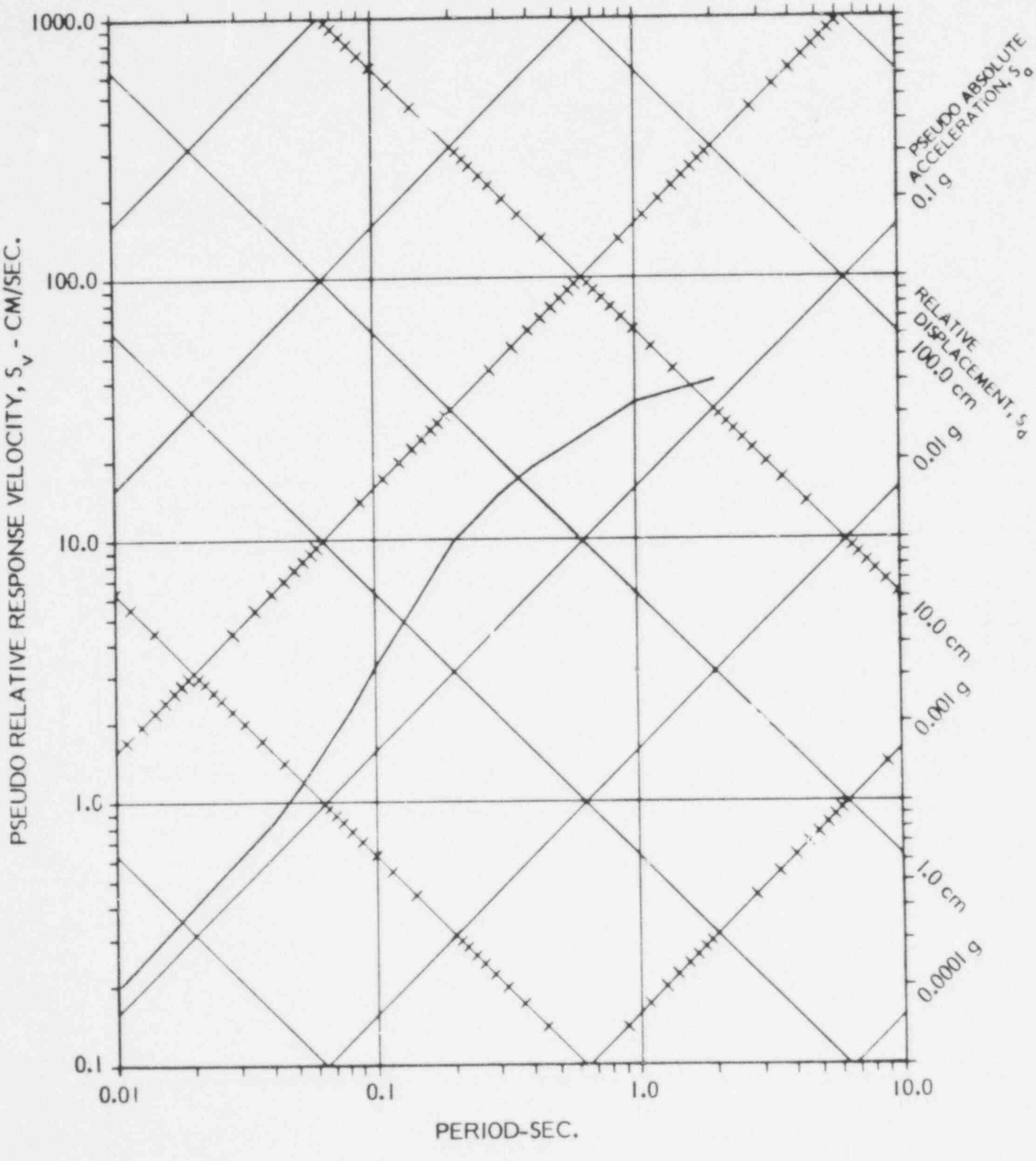

FIGURE 4-13

TYPICAL SYNTHESIS SPECTRUM

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5.0 ILLUSTRATION OF THE UNIFORM HAZARD METHODOLOGY

In order to illustrate the details of the various steps presented in the previous section, a typical rock site was selected in the Central Stable Region and one expert's opinion was processed for input into the analysis.

Application of the hazard procedure consists, in essence, of defining appropriate input parameters for the source zonation, the source seismicity model and the attenuation model, and using the exposure evaluation model to obtain expected values of ground motion parameters for various probability levels. Output from the exposure model is a cumulative probability distribution function (CDF) for each ground parameter.

5.1 PROBABILITY LEVELS OF EXPOSURE

In this example seismic exposure values are estimated for three return periods: 200, 1,000 and 4,000 years. In actuality, a cumulative distribution function was developed for each parameter so that values could be estimated for any return period desired.

5.2 SOURCE GEOMETRY

Required input consists of source location and geometry. As presented in the companion Expert Opinion Report, base maps describing two possible seismic functions of the eastern United States were provided to the experts. They were asked to indicate their "degree-of-belief" (credibility) in each source zone and source zone alternative by estimating the chances of the seismicity to be restricted within the zone boundaries. These zones were digitized to satisfy the input format required by the computer code. They are presented in Figures 5-1, 5-2 and 5-3.

In presenting certain data and input, we will sometimes need to refer to a fractional value of intensity. These fractional values, which are a mathematical artifact of treating intensity as a continuous variable, will be referenced as, for

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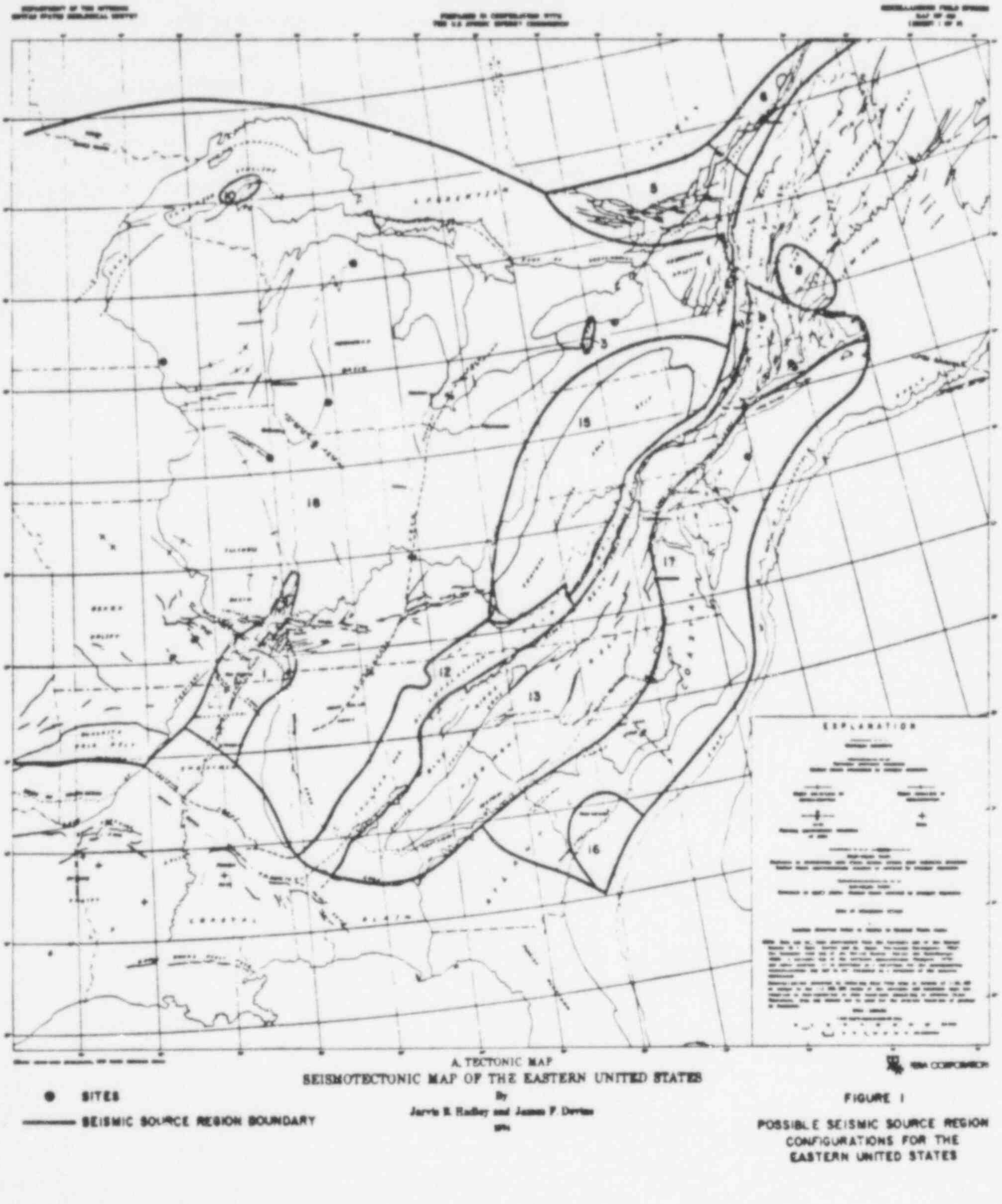

FIGURE 5-1

BASE MAP I

FIGURE 2

POSSIBLE SEISMIC SOURCE REGION CONFIGURATIONS FOR THE EASTERN UNITED STATES

FIGURE 5-2

BASE MAP 2

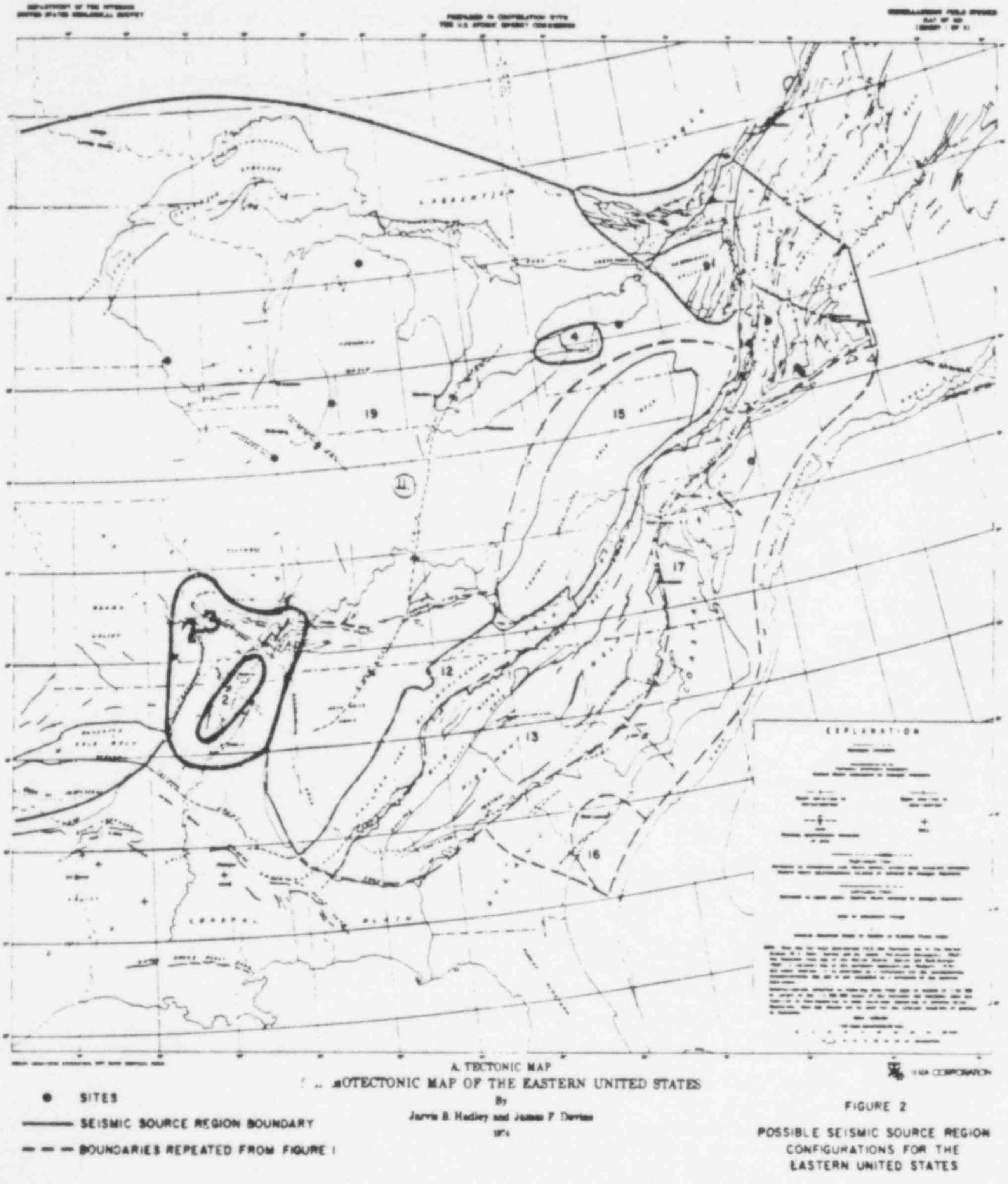

FIGURE 5-3

ZONATION MAP EXPERT 11

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example, VII½ for VII-VIII. Table 5-1 presents a list of all the zones provided by the expert. The first three columns give the zone number, the source name and zone area (km^2). Note that Zone 2 (base map) has been replaced by a modified zone by the expert. Column 4 gives the cumulative number of events greater than MMI IV¼ for a period of 175 years. The MMI IV¼ is used since only events of MMI greater than IV½ are considered in the analysis and a ½ intensity is adopted as an increment. The increments are centered at IV½, V, etc., and half the increment is considered on each side of the centered value. Hence, the increment bands are defined by IV¼, IV-3/4, V¼, etc. Appendix B on source seismicity describes how the cumulative number of events is obtained.

Column 5 gives this expert's degree-of-belief (credibility) in percent regarding each zone. The background zones have no credibility assigned to them as they have been defined as the envelope of all the zones presented by the entire expert panel.

Columns 6 through 8 give the self-ranking of the expert regarding the configuration, the upper magnitude cutoff and the recurrence in each zone.

5.3 SOURCE SEISMICITY

For each source, recurrence input parameters consisted of the following:

(a) The mean rate of occurrence, of earthquakes, for the period covering the data base 175 years

(b) Distribution of earthquake MMI

(c) A distribution on upper MMI cutoff

Mean Rate of Occurrence

This expert did not provide explicitly an "a" value for each of the zones. Therefore, a decision was to be made about where to anchor the slope of the recurrence to determine "a."

TABLE 5-1

INPUT FROM EXPERT 11
CENTRAL UNITED STATES

							Ranking		
Zone Number	Zone Name	Area (km^2)	Number of Events Greater Than MMI = IV½ in 175 Years	Slope MMI	Upper Magnitude Cutoff MMI	Credibility %	Function	Upper MMI	Recurrence
1	New Madrid	55,890	255	0.50 ± 0.1*	XI 1/2-XI 1/2-XII	60	9	8	7
2	New Madrid (Modified)	16,006	180		XI 1/2-XI 1/2-XII	85	9	8	7
23	New Madrid	98,506	160		VI 1/2-VII-VIII 1/2	80	9	8	7
10	Upper Keweenaw	5,713	14		VI 1/2-VII 1/2-VIII 1/2	20	6	6	4
11	Anna	2,986	35		VII 1/2-VIII 1/2-IX 1/2	80	9	7	7
	New Madrid Background Area	258,056	380		XI 1/2-XI 1/2-XII VI 1/2-VII 1/2-VIII 1/2	--	9	8	7
	Central Stable Region	1,463,550	185		VI 1/2-VII 1/2-VIII 1/2	--	8	6	6

The corrected data (Appendix B) was used to this effect together with indirect information such as return period for large events and the size of the two largest events for the period considered. The mean rate of occurrence for 175 years is shown in Figures 5-4 through 5-10.

Distribution of Earthquake Magnitudes

The distribution of earthquake magnitudes was given by the expert as the slope of the recurrence "b" = 0.5 ± 0.1. The uncertainty in the slope was modeled as described in Section 4.0. The parameter η'' of the beta distribution was obtained as follows: given that one event has occurred, the number of events in the MMI 8.5 increment corresponding to a slope of 0.4 is .009279, the number of events in the same MMI increment corresponding to a slope of 0.5 is .00438, and to a slope of 0.6 is .00197.

Hence $\sigma = .00365$, $\mu = .00438$ and $\eta'' = 326.1$. The ξ''_{M_i} are computed as the number of earthquakes in each intensity band out of a total of 326.1 greater than MMI = 4.25. This distribution is given in Table 5-2.

Upper Magnitude Cutoff

For a 1,000-year period of interest this expert specifies in Zone I upper magnitude cutoff range of m_b = 7.5-7.5-7.75. These are converted to MMI using the relation MMI = $2m_b - 3.5$ to remain consistent with the slope given in terms of MMI: XI½ - XI½ - XII. The triangular distribution fitted to this range gives the following probabilities for those MMI to be the largest ones

MMI	XI½	XII
$P'(M_{uj})$	.667	.333

The same procedure is applied to the other zones.

TABLE 5-2

DISTRIBUTION EARTHQUAKE MMI

MMI Band	Number of Events
4.5	142.7
5.0	80.3
5.5	45.1
6.0	25.4
6.5	14.3
7.0	8.03
7.5	4.51
8.0	2.54
8.5	1.427
9.0	0.803
9.5	0.451
10.0	0.254
10.5	0.143
11.0	0.0803
11.5	0.0451
12.0	0.0254

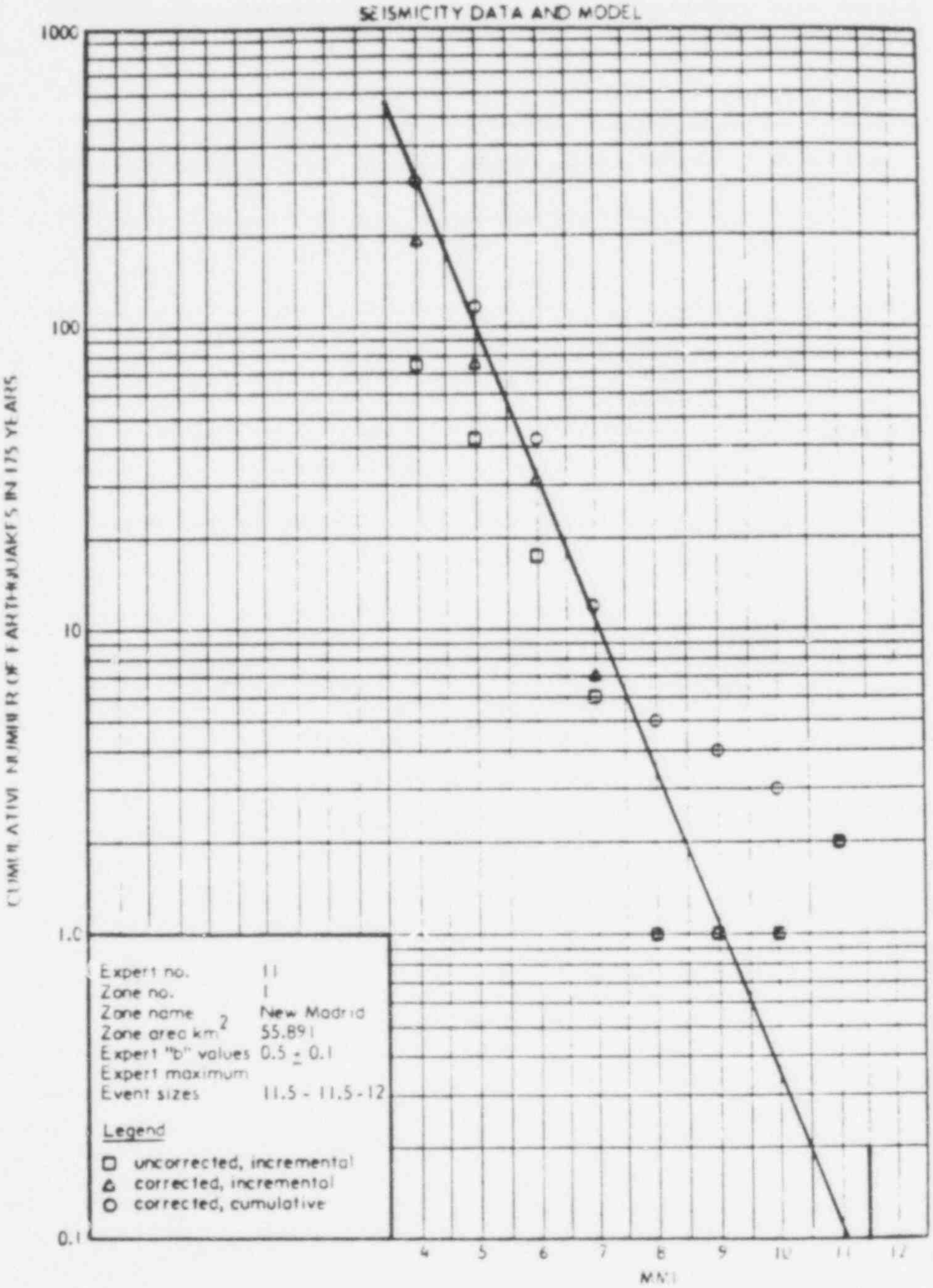

FIGURE 5-4

RECURRENCE RELATIONSHIP

EXPERT 11

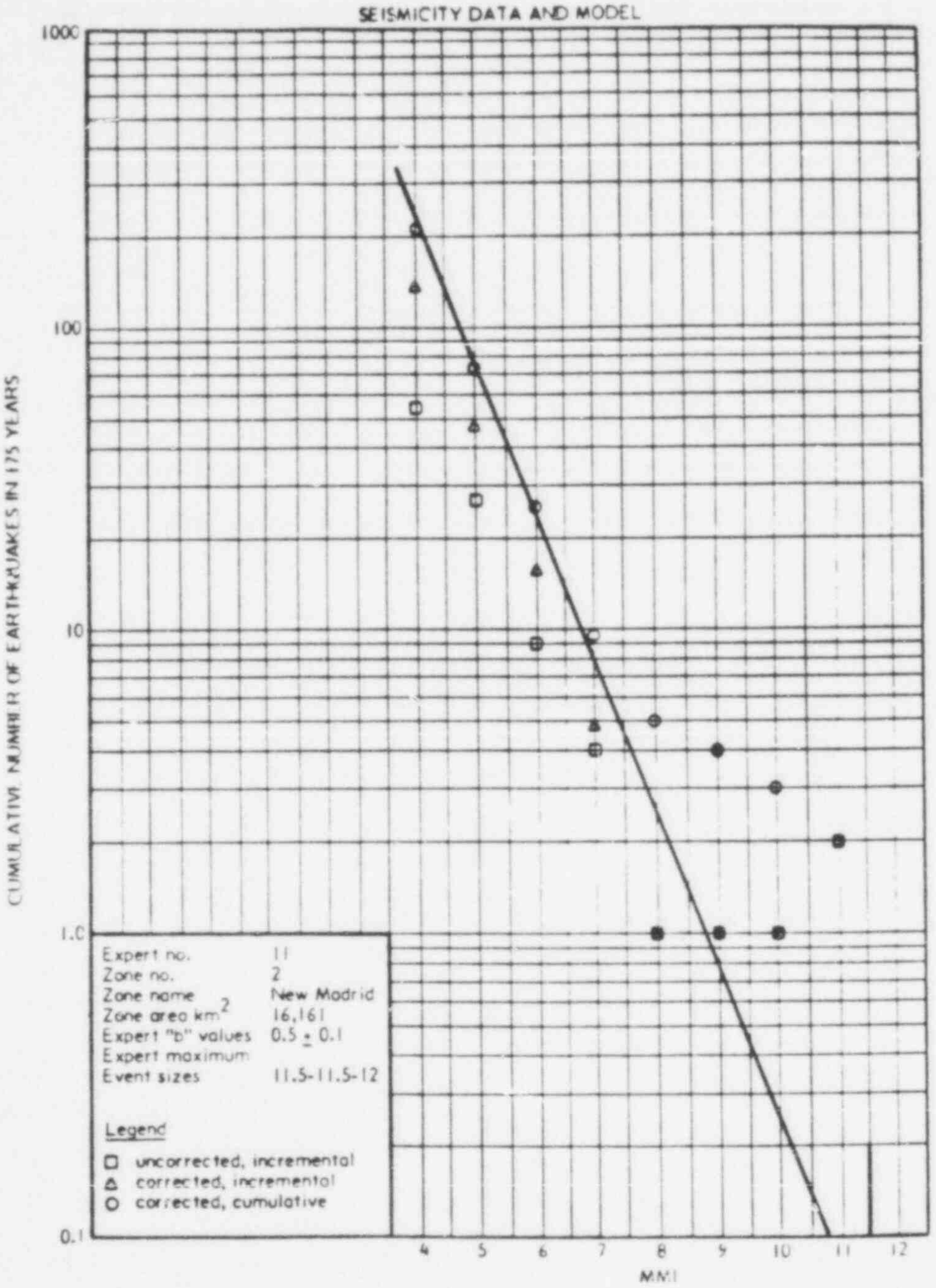

FIGURE 5-5

RECURRENCE RELATIONSHIP

EXPERT 11

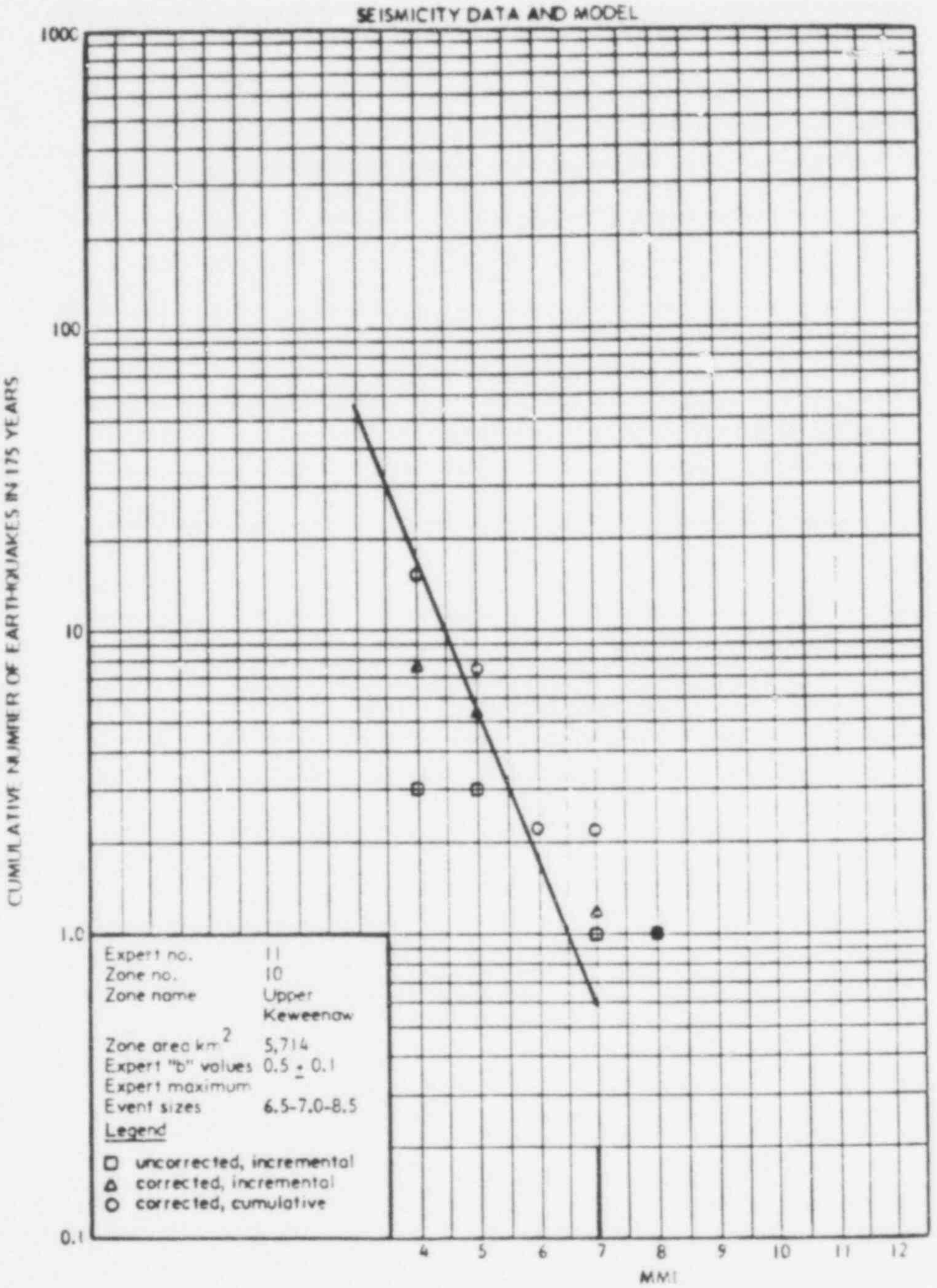

FIGURE 5-6

RECURRENCE RELATIONSHIP

EXPERT II

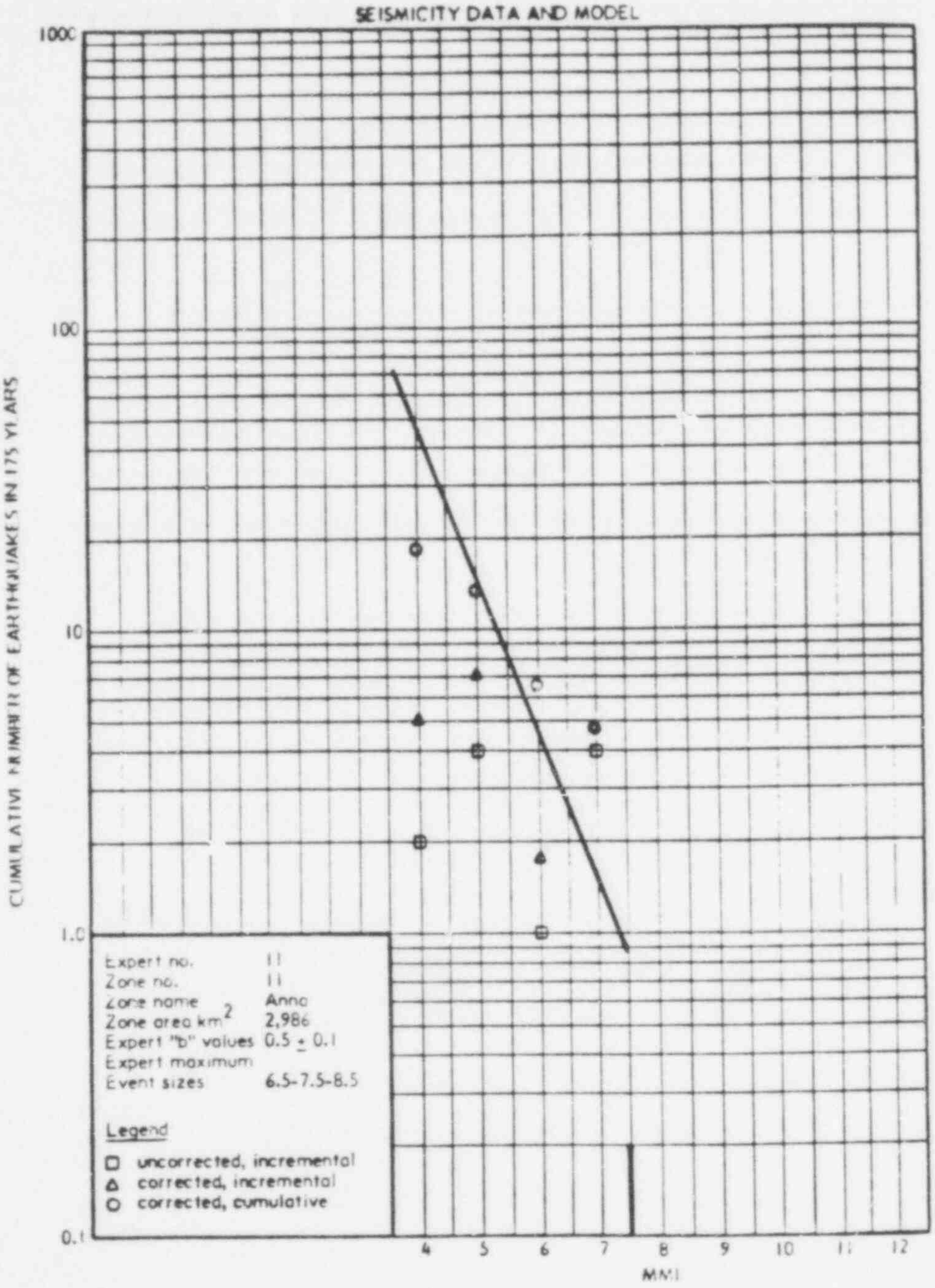

FIGURE 5-7

RECURRENCE RELATIONSHIP

EXPERT 11

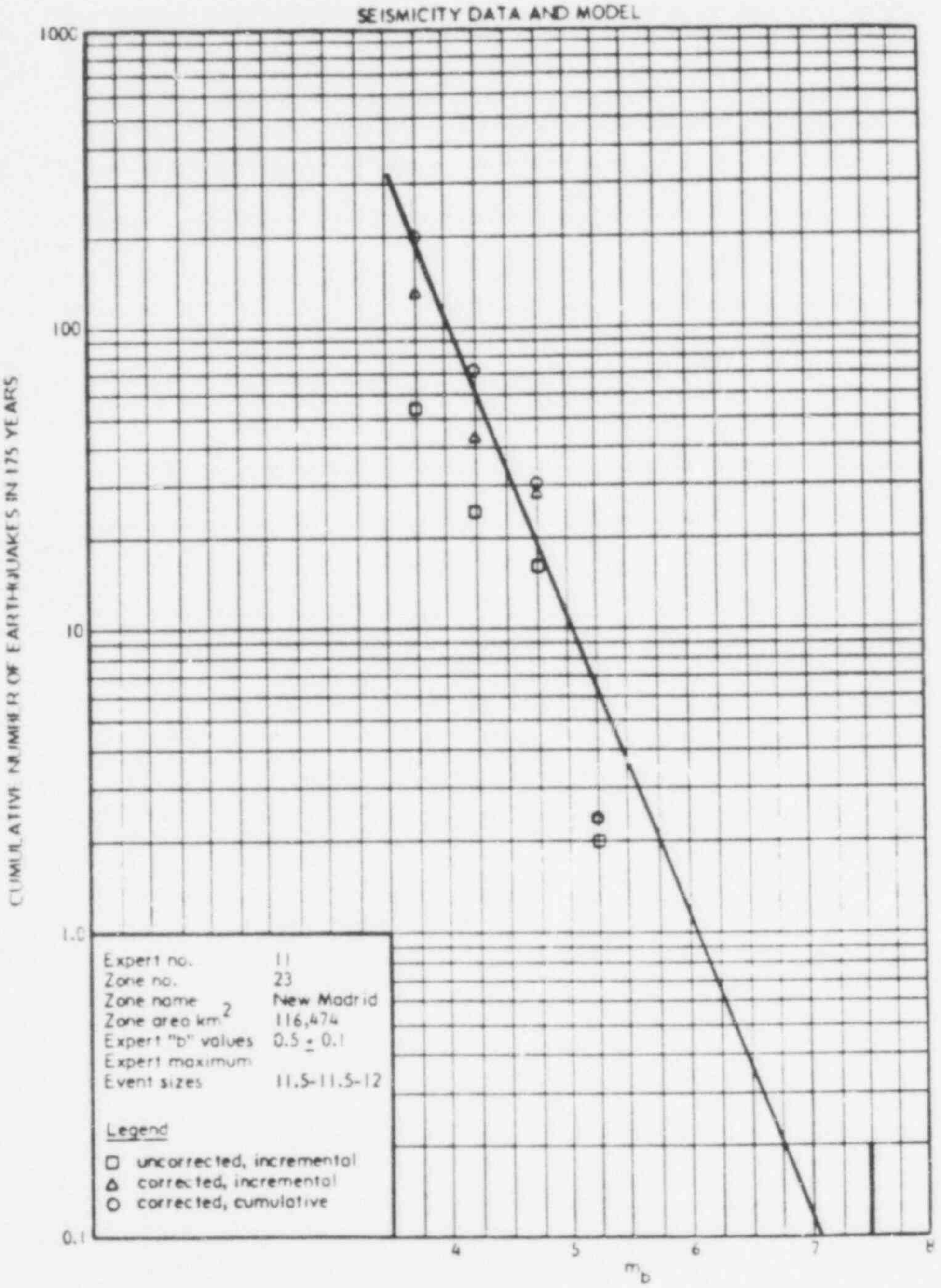

FIGURE 5-8

RECURRENCE RELATIONSHIP

EXPERT 11

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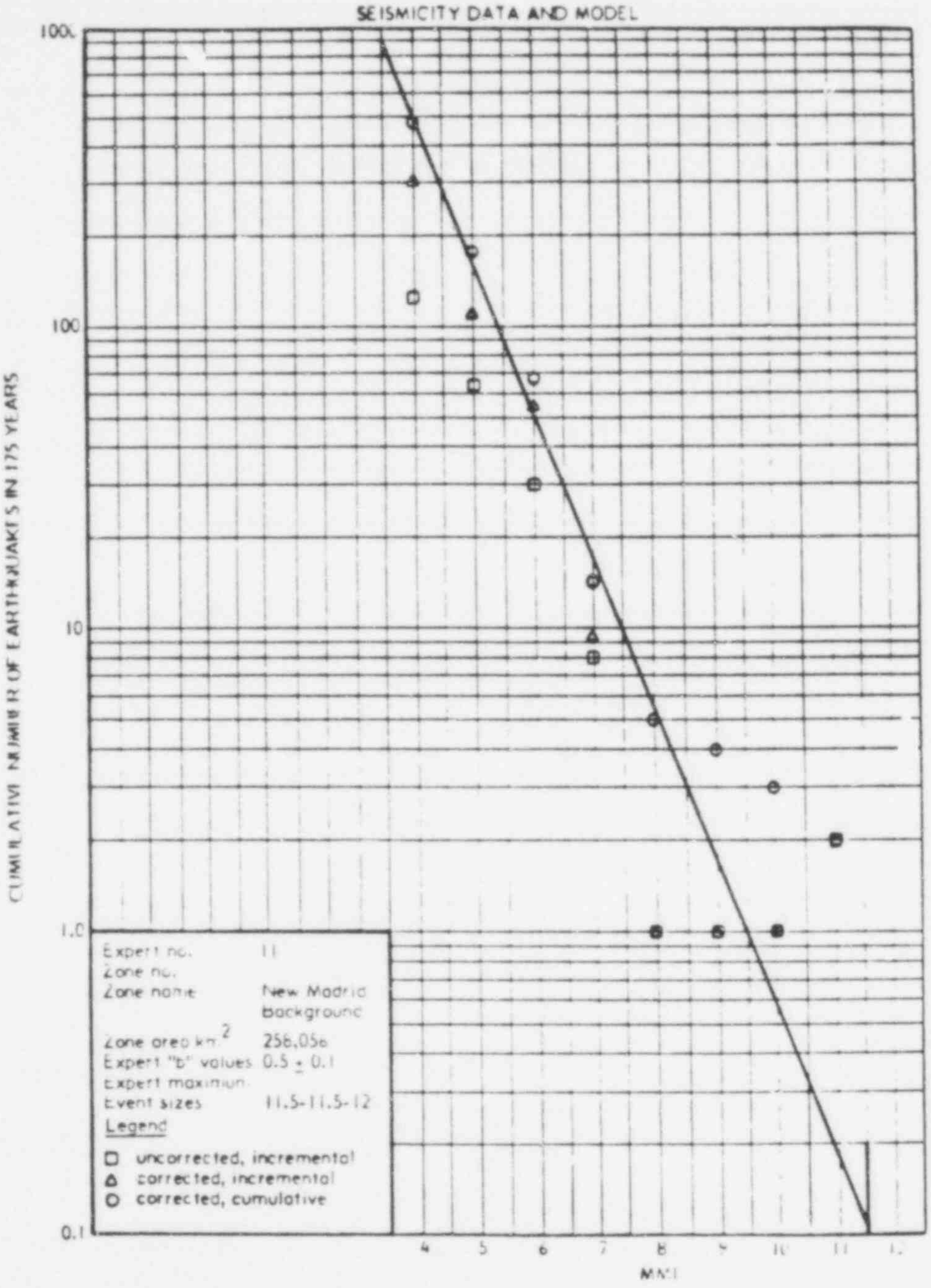

FIGURE 5-9

RECURRENCE RELATIONSHIP
EXPERT 11

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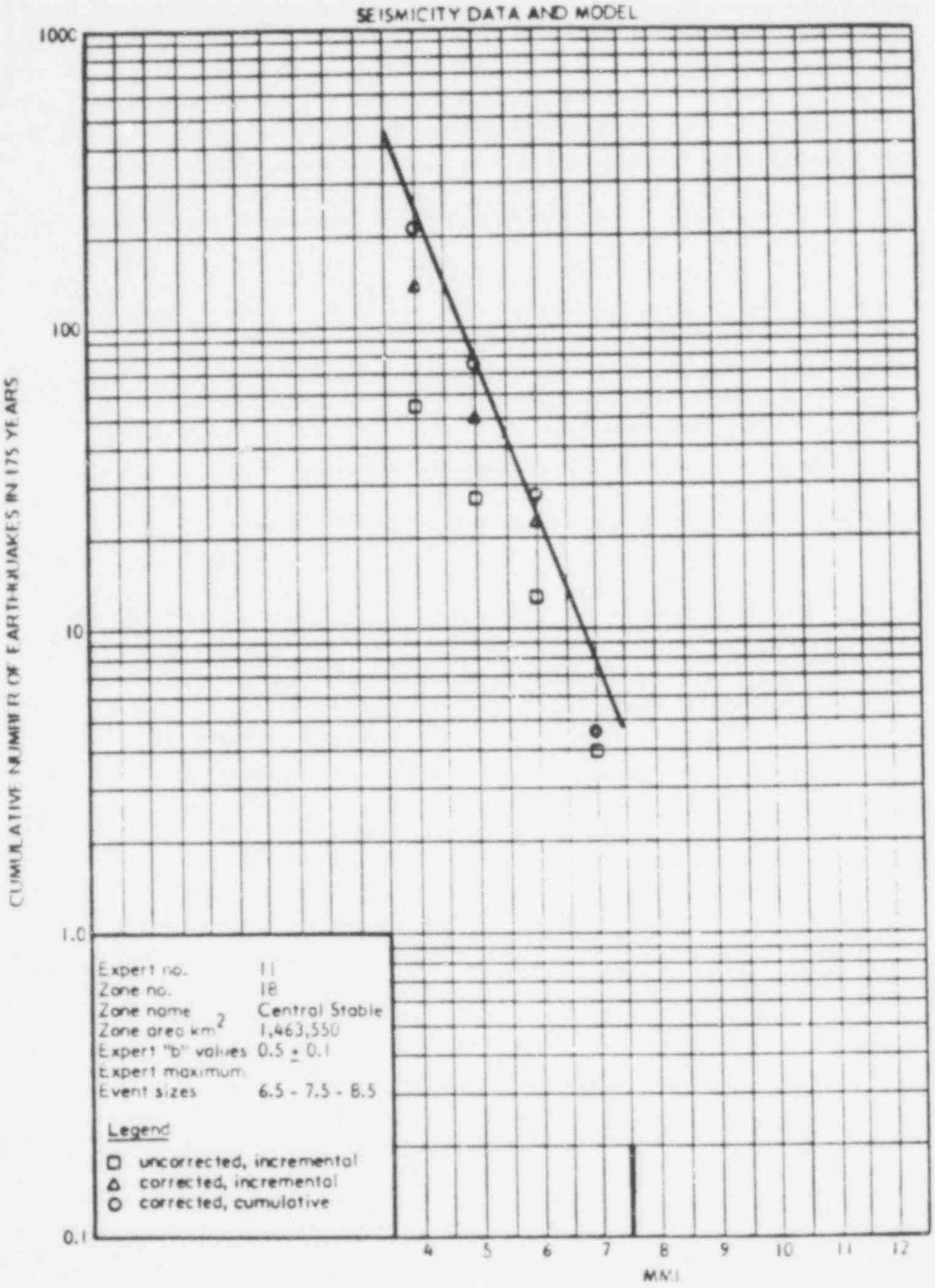

FIGURE 5-10

RECURRENCE RELATIONSHIP

EXPERT 11

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5.4 ZONE SUPERPOSITION

Following the procedure presented in Section 4.0, the seismicity is distributed among alternative zones as a function of credibility. The number of events greater than MMI IV¼ is referred to as "a" in the following paragraphs.

New Madrid Region

This example is fairly similar to Case I, Section 4.0. Zones (7) 2 and 23 are treated together since they represent an alternative to Zone I from Table 5-1.

Zone	a	C
1	255	60
2	180	85
23	160	80
Background	380	--

Average credibility of Z_1 and $Z_{23} = (.8 + .85)/2 = .825$
Credibility of Z_1 or Z_2 and $Z_{23} = 1 - (.175)(.4) = .93$
$a_1 + a_{23} = 160 + 180 = 340.$

Distribution of seismicity between Z_1 and A_{2+23}

$$a_{2+23} = 340 + \frac{85 \times .6}{1.425} \times \frac{.825}{1.425} = 217.6$$

$$a_1 = 255 + \frac{85 \times .6}{1.425} \times \frac{.6}{1.425} = 122.4$$

Seismic density in background: outside Z_{2+23}

$$\frac{(380 - 340)}{258{,}056 - 114{,}512} = .000279$$

The number of events in background is .000279 x 258,856 = 71.9

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The number of events in Z_{2+23} belonging to the background is .000279 x 114,512 = 31.9

To prevent double counting of earthquakes, these 31.9 events are subtracted from Z_1 and Z_{2+23} as a function of credibility

$$a_{2+23} = 217.6 - 31.9 \times \frac{.825}{1.425} = 199.1$$

$$a_1 = 122.4 - 31.9 \times \frac{.6}{1.425} = 109.0$$

The seismicity is decreased as a function of the credibility of the New Madrid Source (probability of existence)

$$a_{2+23} = 199.1 \times .93 = 185.2$$

$$a_1 = 109.0 \times .93 = \underline{\underline{101.4}}$$

The seismicity is distributed between Z_2 and Z_{23} as a function of their activity

$$a_2 = \frac{185.2 \times 180}{340} = \underline{\underline{98.0}}$$

$$a_{23} = \frac{185.2 \times 160}{340} = \underline{\underline{87.1}}$$

The total number of earthquakes belonging to the background becomes

$$a_b = 71.9 + (199.1 + 109.0) \times .07 = \underline{\underline{93.5}}$$

We consider next the Central Stable Region. The seismic density in this region is

$$\frac{185}{1,463,550} = .000126 \text{ event/km}^2$$

Upper Keneenaw (Z_{10})

$$a_{10} = 14.$$

The number of events in this source belonging to Central Stable Region is

$$.000126 \times 5{,}173 = .72$$

$$a_{10} = (14.0 - .72) \times .2 = \underline{\underline{2.7}}$$

Since Z_{10} is a source of low activity with little effect on the site studied, no background is used for this zone.

<u>Attica (Z_{11})</u>

$$a_{11} = 35$$

The number of events in this source belonging to Central Stable Region is

$$.000126 \times 2{,}986 = .38$$

$$a_{11} = (35 - .38) \times .8 = \underline{\underline{27.7}}$$

The number of events in the Anna background is $34.6 - 27.7 = \underline{\underline{6.9}}$

<u>Central Stable Region</u>

$$a_c = 185. + 11.3 + .4 = 196.7$$

Normalizing for the area used in the analysis

$$a_c = \frac{196.7 \times 868{,}442}{1{,}463{,}550. + 2{,}986 + 5{,}713} = \underline{\underline{116.0}}$$

The final seismic input is presented in Table 5-3.

TABLE 5-3

CENTRAL U.S. - EXPERT NO. 11

Zone No.					
TERA	Expert	Zone Name	No. of Events ≥ 4.25 MMI in 175 Years	Slope MMI	Upper Magnitude Cutoff MMI
1		New Madrid	101.4	0.50 ± 0.1*	XI 1/2-XI 1/2-XII
2	20	New Madrid	98.0		XI 1/2-XI 1/2-XII
10		Upper Keweenaw	2.7		VI 1/2-VII-VIII 1/2
11		Anna	27.7		VI 1/2-VII 1/2-VIII 1/2
23	23	Mississippi	87.1		VII 1/2-VIII 1/2-IX 1/2
--		New Madrid Background	93.5		XI 1/2-XI 1/2-XII
--		Central Stable Region	116.0		VI 1/2-VII 1/2-VIII 1/2
--		Anna Background	6.9		VI 1/2-VII 1/2-VIII 1/2

---

* For all zones.

5.5 ATTENUATION MODEL

As described in Section 4.0, several relations were combined to produce a final attenuation relation of the form

$$\ln(GM) = C_1 + C_2 I_o + C_3 r + C_4 \ln(r)$$

The ground motion (GM) parameters were PGA, PGV, and PSA at nine frequencies between 25 Hz and 0.5 Hz. Figure 5-11 presents a graphical summary of the PGA attenuation model for various values of m_b.

5.6 EXPOSURE EVALUATION MODEL

Using the model presented in Section 4.0, the exposure is computed at the site for the loading parameters considered. Even though only three return periods are of direct interest, a complete cumulative distribution function is computed so that any return period can be obtained. Figure 5-12 presents a plot of PGA versus Return Period at the site. A Uniform Hazard Spectrum (5% damping) was determined by computing the spectral amplitudes at nine periods (.04, .05, .08, .10, .20, .30, .40, 1.0 and 2.0 seconds). This spectrum corresponding to a 1,000-year Return Period is presented in Figure 5-13.

5.7 SENSITIVITY ANALYSIS

The objective of this section is to emphasize the importance of a sensitivity study in any seismic hazard analysis. Recall that a seismic exposure analysis represents the combined effects of various parameters representing source zonation, source seismicity, attenuation, and seismic exposure evaluation models and the associated uncertainty. A sensitivity analysis can enhance the utilization of a seismic exposure evaluation because it provides an insight into the relative influence of various parameters and enables one to focus on the assumptions that require particular attention versus those that are relatively insignificant.

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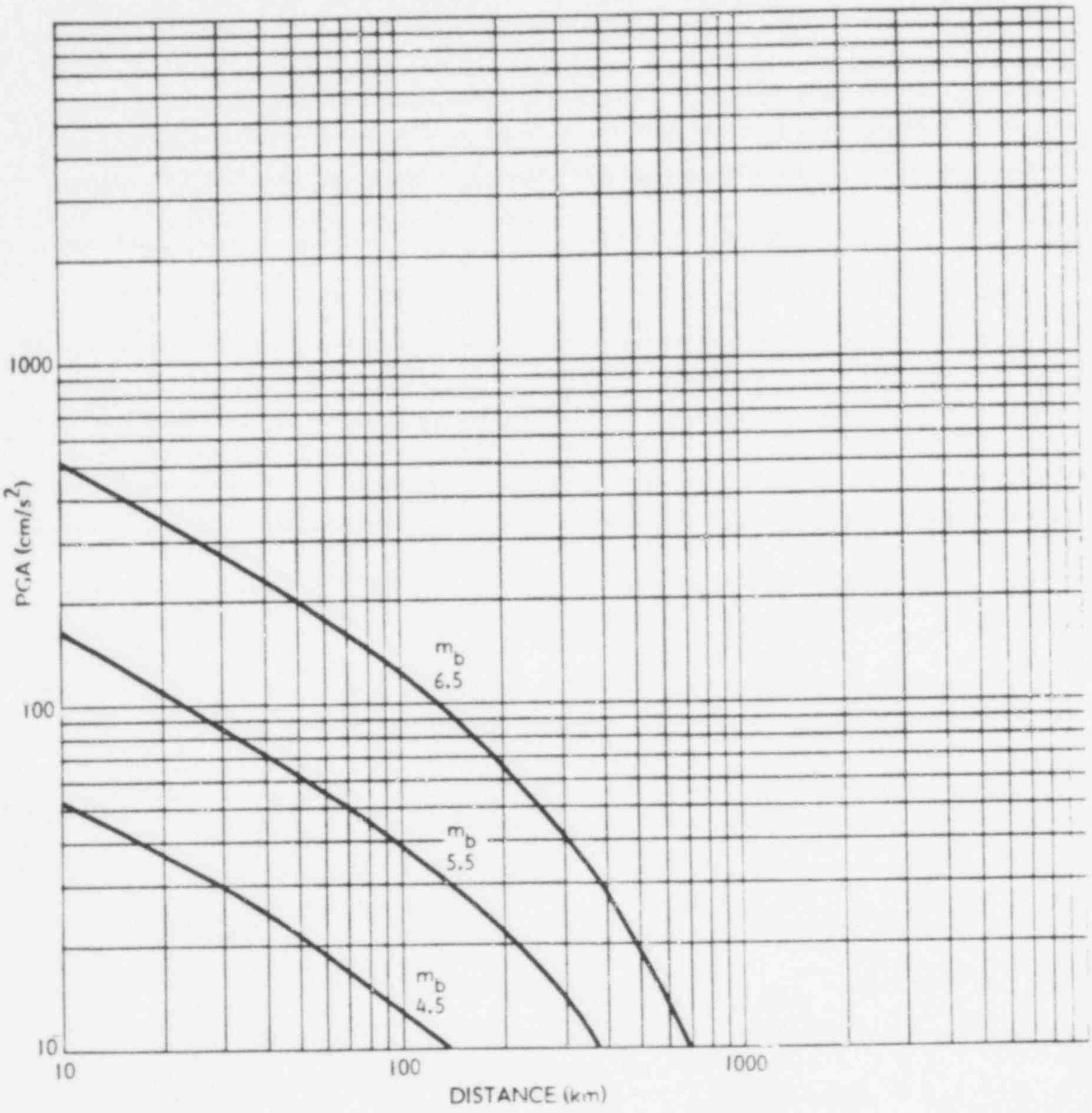

FIGURE 5-11

PEAK ACCELERATION ATTENUATION RELATIONS

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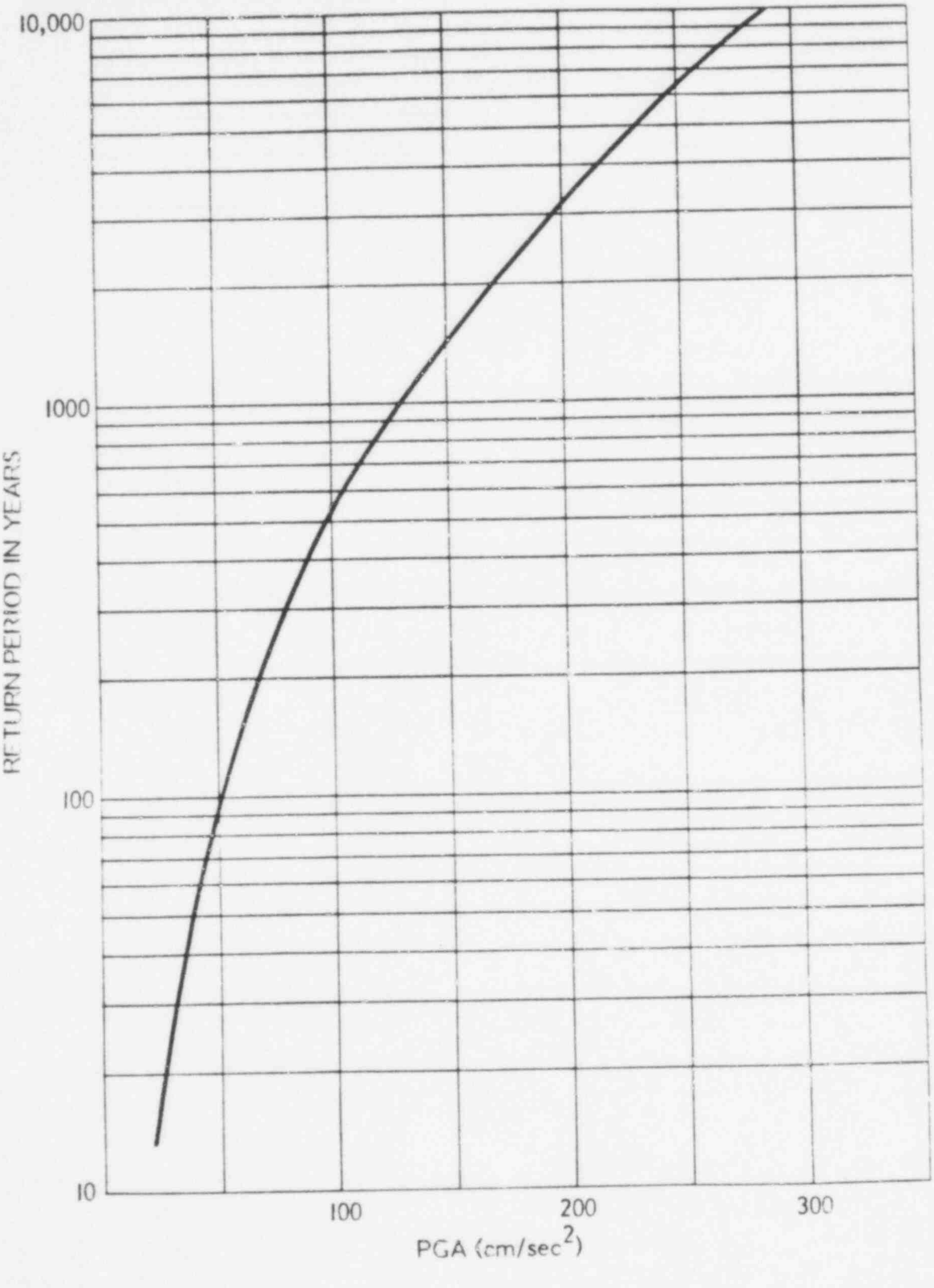

FIGURE 5-12

PLOT OF PGA VS. RETURN PERIOD
FOR EXPERT 11

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EXPERT 11 -- 1000 YEAR RETURN PERIOD

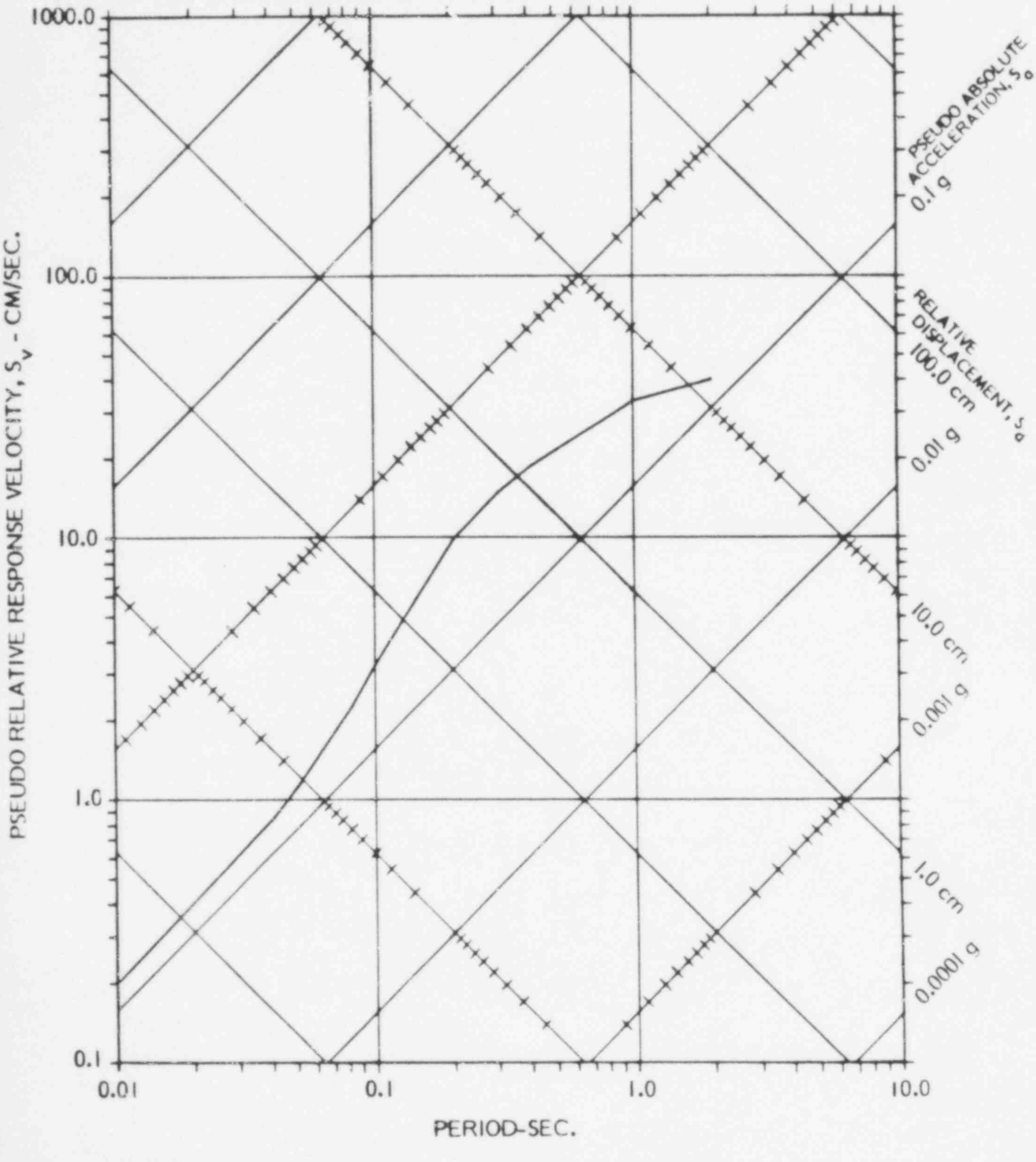

FIGURE 5-13

1,000-YEAR RETURN PERIOD UNIFORM
HAZARD SPECTRUM FOR EXPERT 11

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In this section we illustrate the importance of sensitivity studies by examining effects of the following parameters on seismic exposure at a sample site:

- Source zonation credibility
- Uncertainty associated with the earthquake mean rate of occurrence and magnitude distribution
- Upper magnitude cutoff
- Uncertainty associated with attenuation relationship and truncation of the distribution modeling this uncertainty

Sensitivity analyses were carried out for the same specific site and expert used above. Although this choice is representative of typical situations, conclusions from these analyses cannot unilaterally be extended to all experts and all sites. Influence of certain parameters such as source zonation credibility and upper magnitude cutoff vary significantly from case to case. Fortunately, they can often be inferred from the type of input and the location of the site with respect to zone boundaries. A complete sensitivity analysis represents a major undertaking beyond the scope of the present study. The following discussion of the results and qualitative comments, which may not be applicable to other sites and other experts, is presented only for illustration.

Source Zonation Credibility

As mentioned in Sections 4.4 and 5.4, the seismicity of overlapping zones was distributed between them as a function of their credibilities with the undistributed earthquakes being allowed to "float" in the source background. In this sensitivity analysis all credibilities are assumed to be 100 percent with no earthquakes lumped in the background. The equal hazard spectrum at the sample site is presented in Figure 5-14. Little difference is noticeable mainly because the two main contributing sources are the central stable region which underwent no change and the New Madrid region which is too distant to reflect small variations in boundary conditions. This result is typical of all experts for most sites in the Central Stable Region. In the northeast, the complexity of the

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100% SOURCE CREDIBILITY

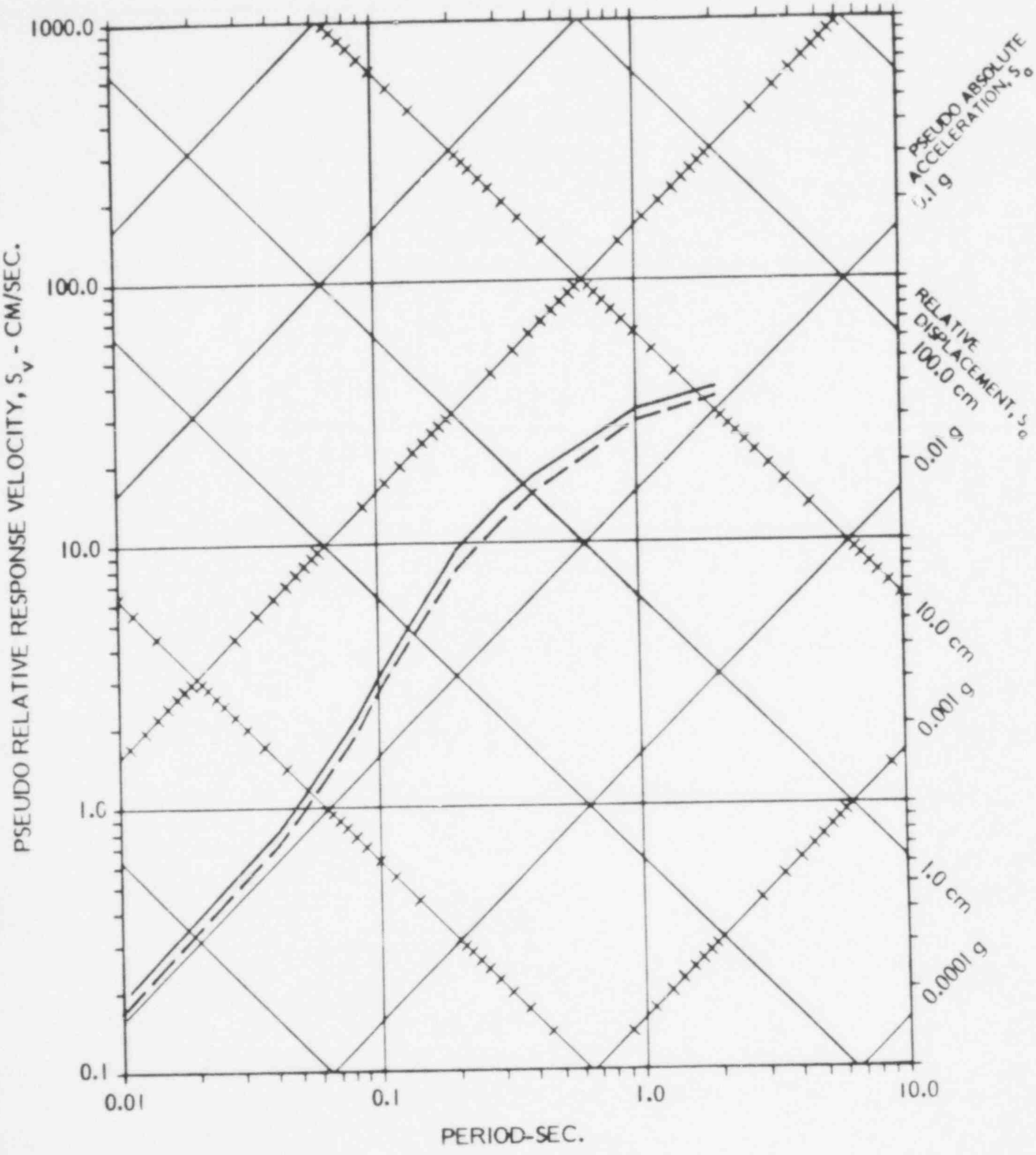

FIGURE 5-14

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zonation and the variations between experts would require a detailed study to determine the sensitivity of this parameter.

Seismicity Model Uncertainty

In this sensitivity analysis, the expected value of these parameters is kept constant and only the uncertainty about the mean is varied as modeled by the parameters of the gamma and beta distributions. The larger uncertainty increases the probability of a higher level of seismicity at the expense of a lower one. Hence, for a rather short return period the effect is not unique and depends upon the size of events governing the hazard.

Figure 5-15 presents the 1,000-year spectrum for a large increase in uncertainty. As the results show, there is both a decrease and increase of hazard as a function of the period. This effect is not surprising since different event sizes are dominant hazard contributors at different frequencies.

For longer return periods one expects a global increase which may become very significant. The 4,000-year spectrum showed a 30 to 50 percent increase over the whole spectrum. Such conclusions are generally applicable for other experts and other sites.

Upper Magnitude Cutoff

In this case the maximum earthquake has been changed for all sources to an MMI XII, implying that the largest possible earthquake can occur anywhere. Figure 5-16 presents the spectrum. The increase is substantial over the whole spectrum range (50 to 100 percent).

In general, such an increase is a function of two parameters: the upper magnitude cutoff specified by the expert for the sources governing the hazard and the magnitude distribution. For example, no change would occur for an expert who specifies MMI XII for all zones and a large increase would occur for an expert with a relatively low MMI cutoff for zones. These conclusions, of

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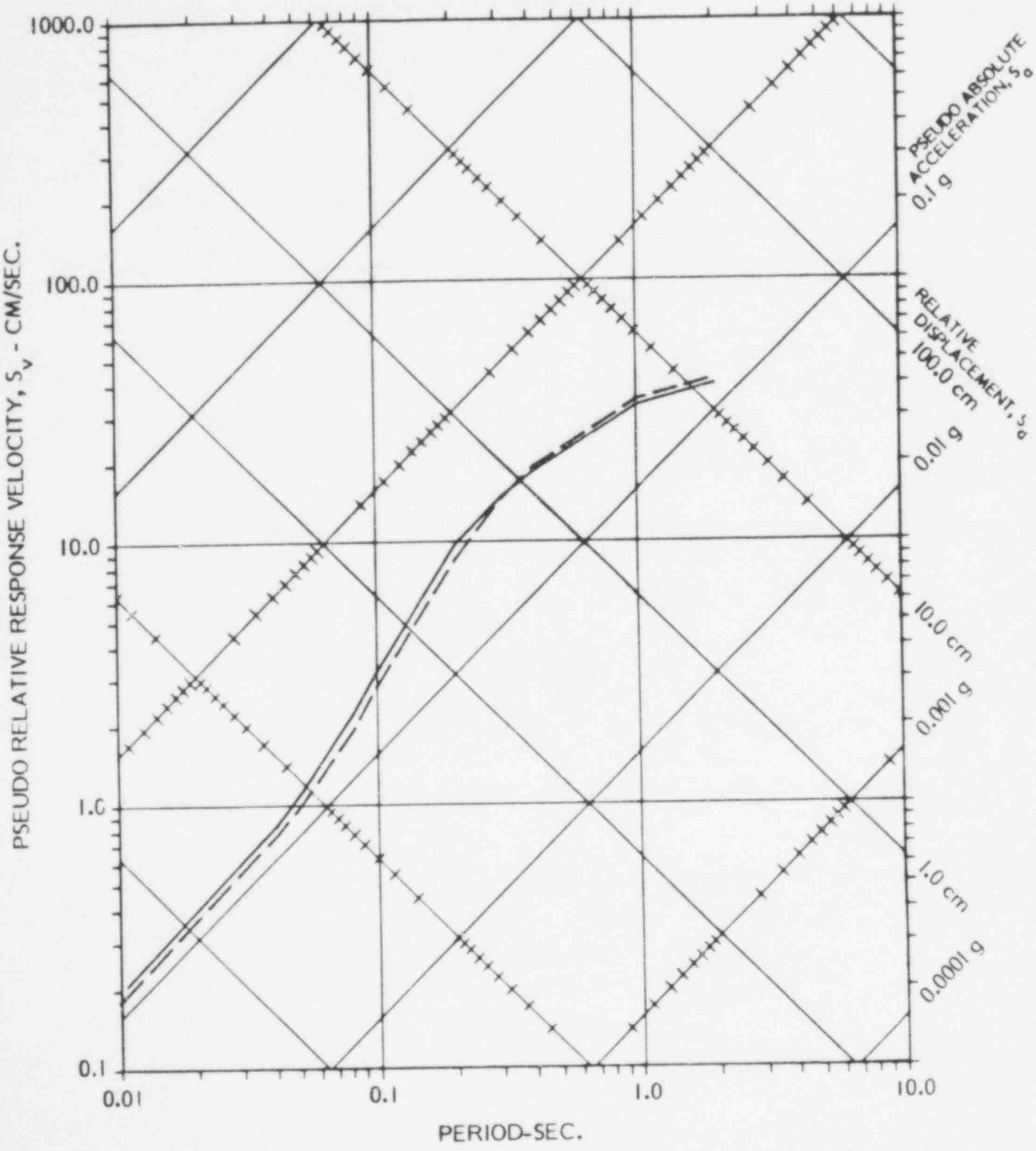
LARGE RECURRENCE UNCERTAINTY



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—— BASE

– – – SENSITIVITY

FIGURE 5-15

NO UPPER MAGNITUDE CUTOFF

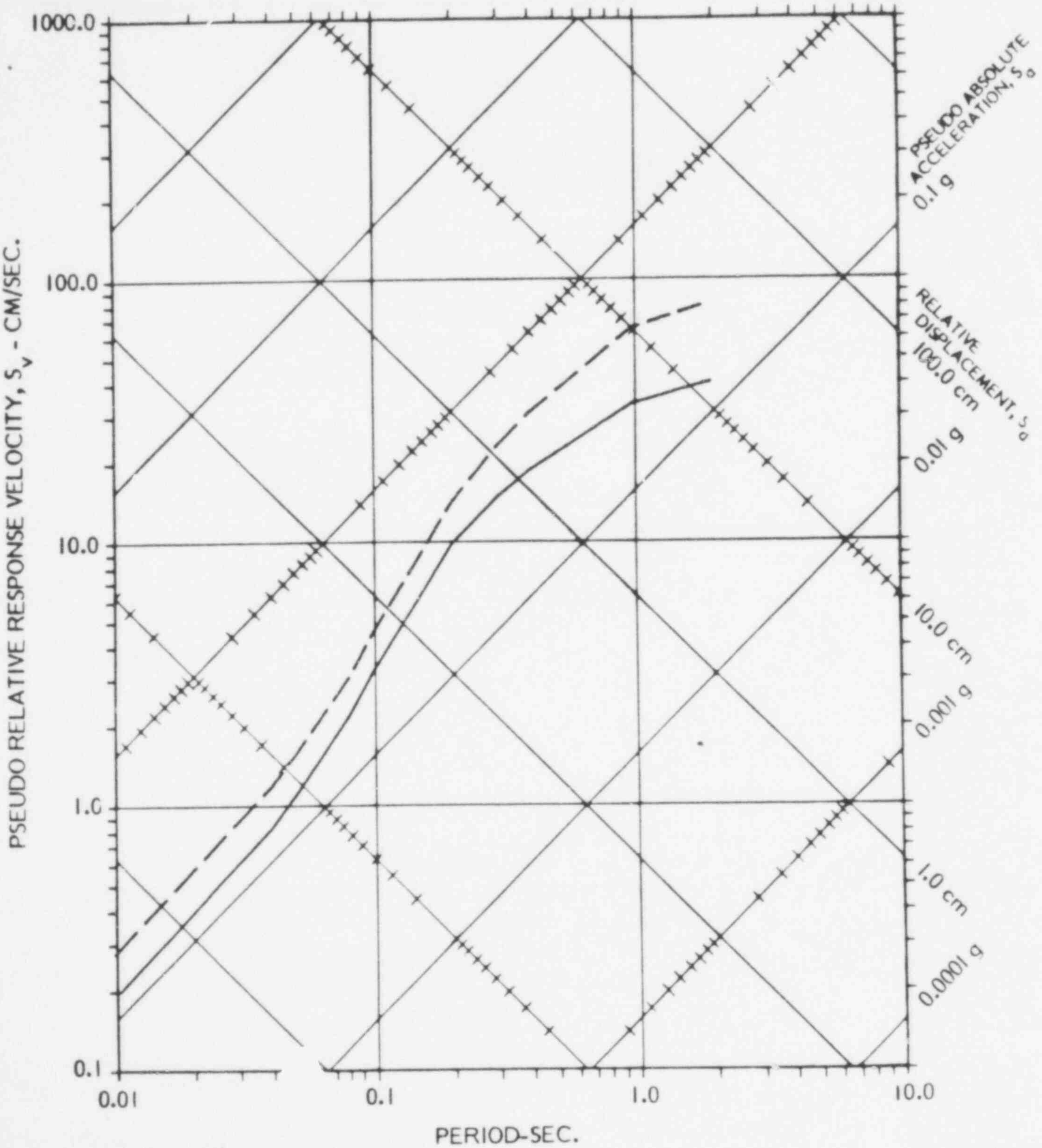

FIGURE 5-16

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course, are dependent on other parameters, notably the b-value. For example, the calculated hazard is relatively insensitive to changes in the upper magnitude cutoff if the expert's b-value is large.

Attenuation Uncertainty

In most hazard analyses the most sensitive parameters are the attenuation relationships used and the uncertainty associated with them. This characteristic applies for this study. Two sets of runs using the same mean attenuation emphasize this point:

- The log-normal distribution was truncated at 2 sigma on each side of the mean and runs were performed with three values of sigma (0.5, 0.7, 0.9)
- A constant value of sigma of 0.9 was used and the number of sigma was varied between 1, 2, and 3.

The results are presented in Figures 5-17 and 5-18. The variations are dramatic for both parameters. The dramatic effect of these two parameters can be demonstrated in yet another way. When a sigma of 0.9 is applied to a distribution truncated at 3 sigma, accelerations as high as 15 times the mean can be carried into the analysis. If the mean is 0.3g, say, the truncated acceleration for this hypothetical case would be 4.5g! This conclusion will apply to other experts and sites.

For a fixed number of sigmas, a variation of sigma has a multiplicative effect. Conversely, for a fixed sigma, the variation in the number of sigmas has an asymptotically decreasing effect since the added probability of exceedence decays as the tail of the log normal distribution.

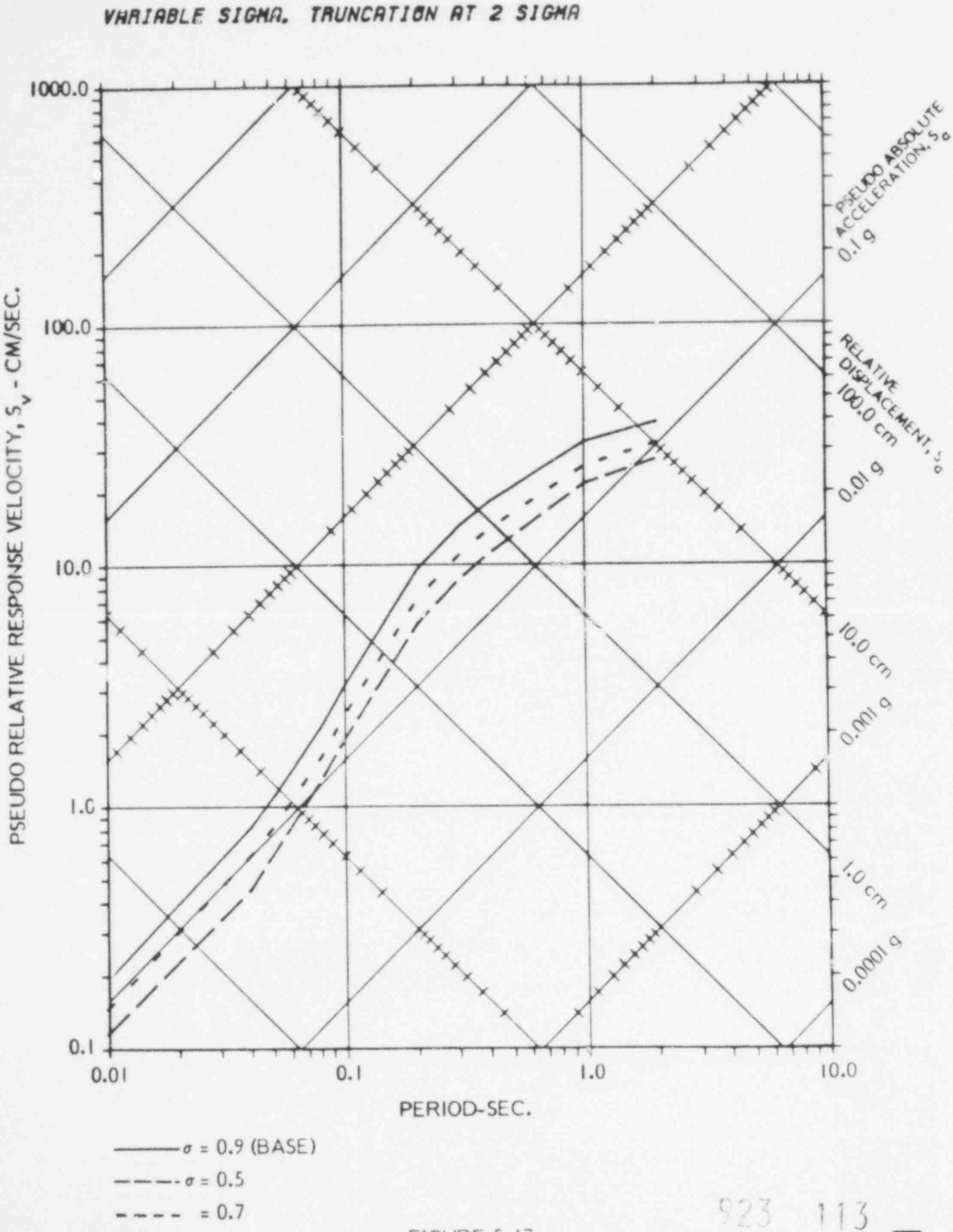

FIGURE 5-17

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VARIABLE TRUNCATION, SIGMA=0.9

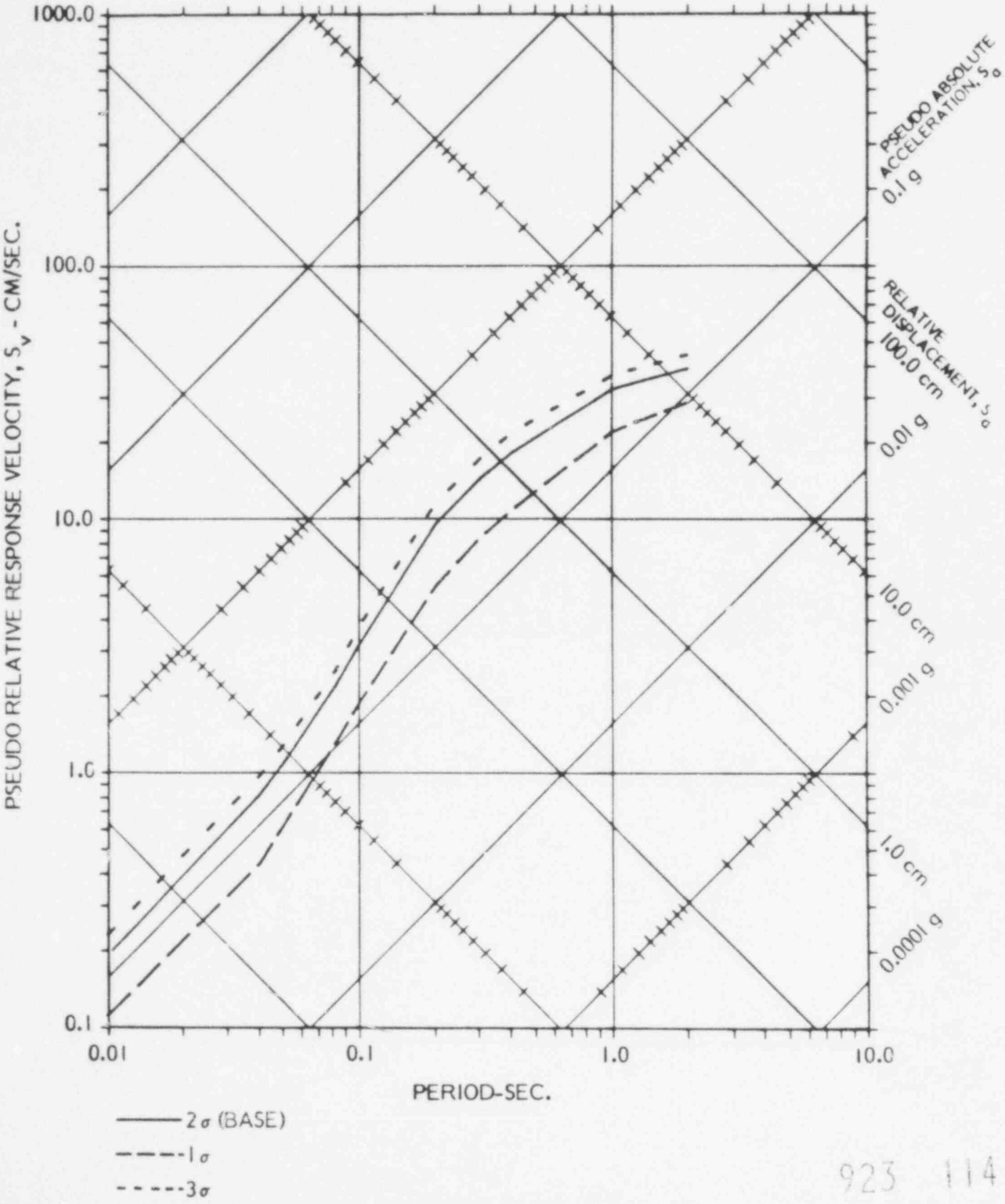

FIGURE 5-18

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6.0 UNIFORM HAZARD SPECTRUM

In order to understand how the uniform hazard spectra (UHS) can be used for design, it is important to consider the definition of UHS and study its implications. A uniform hazard spectrum is developed using probabilistic methods in such a way that each spectral amplitude has the same probability of being exceeded in a given period of time. In its development, each period is considered independently of another, and the spectral amplitude at one period is only weakly correlated with the spectral amplitude at another period. This comes about for the following reason: when developing the spectrum, predictions are made for one period at a time, say T_1. All the potential earthquakes contributing to the seismicity at the site are then considered using the seismicity, attenuation and exposure models, and their cumulative contribution to the loading at period T_1 is computed as a cumulative distribution function of the loading. The spectral acceleration versus return period plot (Figure 6-1) is then developed and the loading corresponding to the return period (RP) of interest (say 1,000 years) is used as the appropriate spectral amplitude for design at period T_1. The procedure is repeated for other periods within the frequency range of interest and the spectrum is built point by point.

It is important to realize that the contribution of each earthquake is introduced from the probability of exceedence aspect and not from the loading aspect. In other words, one asks the question: What is the probability that a fixed loading (at period T_1) will be exceeded by event 1 or 2 or 3 etc? The reversed question of contribution to a fixed loading from event 1, 2, 3 is not addressed. Figure 6-2 presents a typical uniform hazard spectrum for two levels of exceedence: 10 and 20 percent.

If we are interested in periods T_1 and T_2, the spectral amplitude corresponding to those periods indeed have the same probability of being exceeded due to all the earthquakes affecting the site. A spectrum developed based on other methods, such as statistics on number of records, might be biased by the data base which might not be representative of the distribution of events expected to occur at the site considered. Hence, such a spectrum will often contain a bias,

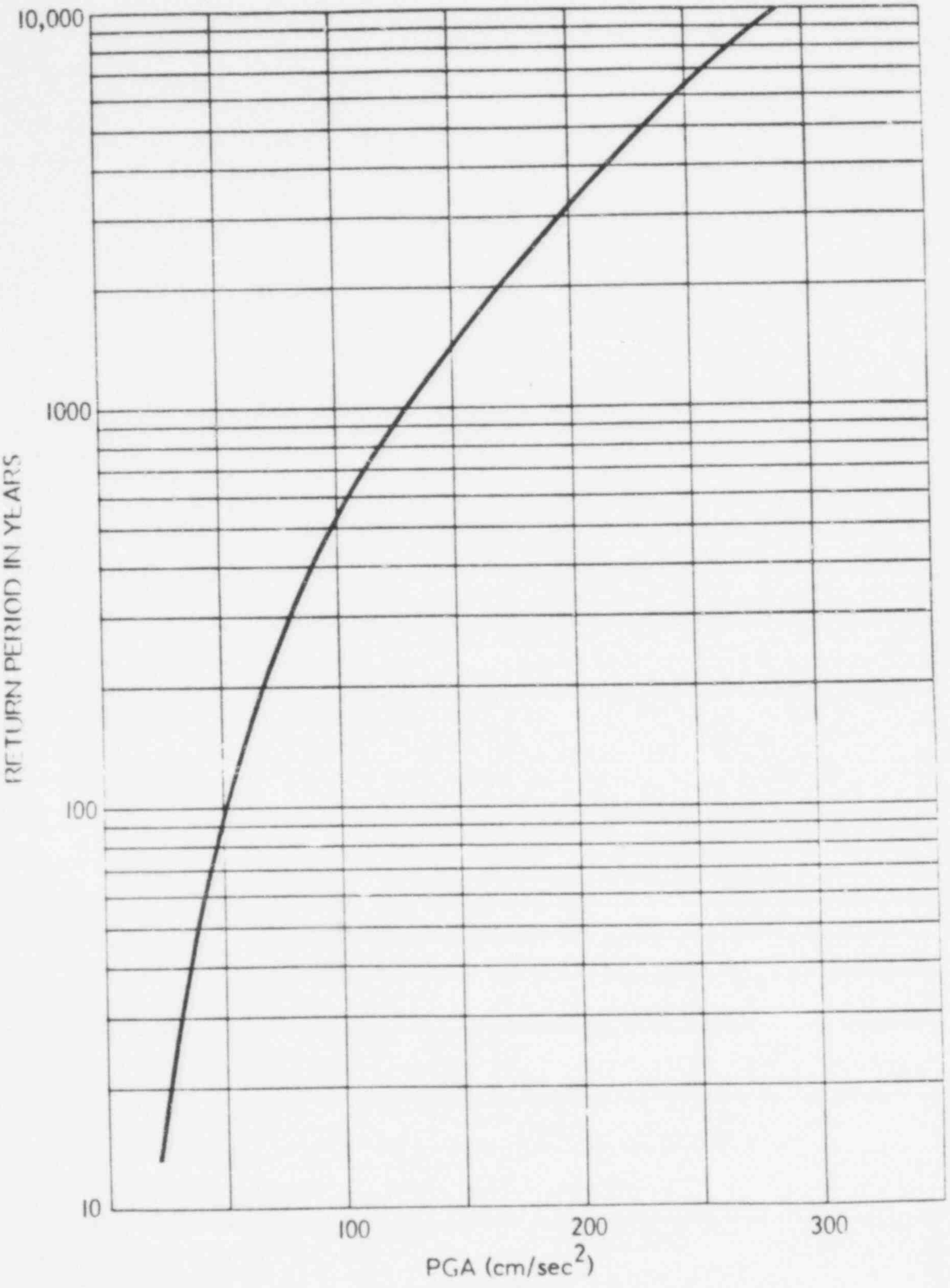

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FIGURE 6-1

SPECTRAL ACCELERATION VS. RETURN PERIOD
FOR PERIOD T_1

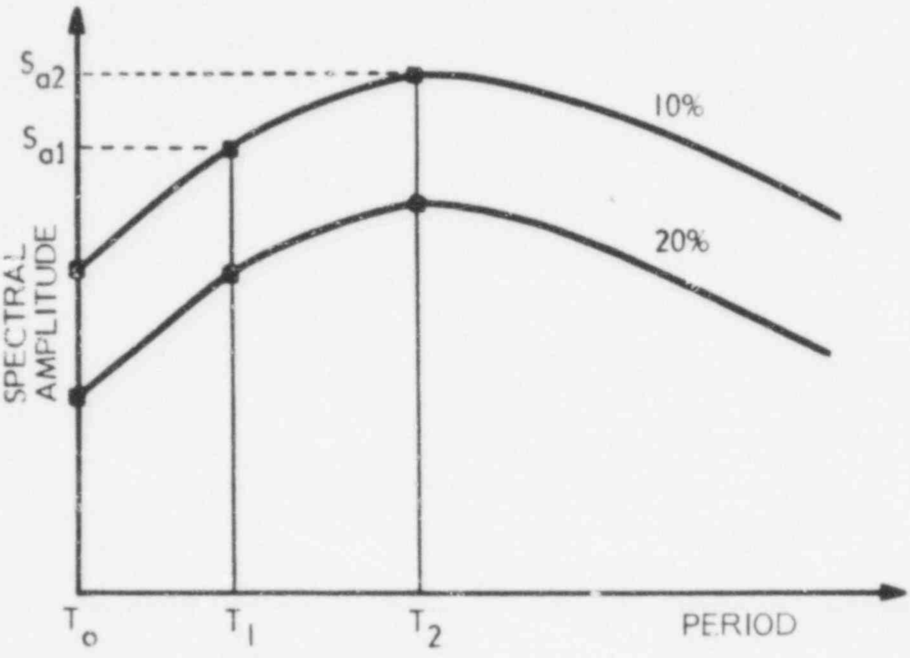

FIGURE 6-2

TYPICAL UNIFORM HAZARD SPECTRA
FOR 10% AND 20% PROBABILITY OF EXCEEDENCE

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either conservative or unconservative. If the data base consisted mainly of nearby events, but the site is expected to be subjected to distant events, the spectrum has a good chance of being overconservative in the high frequency range and underconservative for the long period. The uniform hazard spectra represent an improvement over this approach since they consider the same level of exceedence for each period. However it becomes apparent that since each period is treated independently of another, the notion of a specific spectral shape corresponding to a particular earthquake is lost in the process. The uniform hazard spectra represent an envelope of all the earthquakes affecting the site and any single type of event (with a specific shape) will always lie under it. The consequence of this point is illustrated below for a multi-degree of freedom system.

First, however, consider a single degree of freedom system. If one is interested in the loading at a single period T_1 independently of all the others, the UHS effectively provides the loading corresponding to the RP of interest since it represents, for that loading, the contribution from all earthquakes affecting the site. This would apply for the design of a system modeled by a single degree of freedom system, such as a piece of equipment.

On the other hand, when one is interested in designing for a multi-degree of freedom system, two characteristics enter the picture that make the UHS a very conservative, if not overconservative, design tool. For illustration, let us consider a two degree of freedom system with fundamental periods T_1 and T_2 ($T_1 > T_2$). The UHS amplitude corresponding to T_1 and T_2 are Sa_1 and Sa_2 respectively (Figure 6-2). As is well known, there is a high probability that the loadings Sa_1 and Sa_2 will not be felt by the structure at the same time, i.e., for a given event, the largest acceleration in the response time histories for periods T_1 and T_2 will not occur at the same instant. It is therefore conservative to add the loadings Sa_1 and Sa_2 as if their effect were cumulative. The square root of the sum of the square (SRSS) method of design qualitatively takes this into account by assuming that the global loading is on the average better represented by the vectorial sum of the individual modal loadings.

A much more important characteristic is that the UHS is an envelope of all events, and therefore it cannot be representative of any single event. If the structure is subjected to an earthquake rich in high frequency, the low frequency content of its spectrum will most probably be small. Conversely, if the event is distant and rich in low frequency its spectrum will most probably have little energy in the high frequency range. In other words the spectral amplitudes Sa_1 and Sa_2 will not be felt by the structure for any single event. Since the structure will only have to resist one earthquake at a time, using Sa_1 and Sa_2 in a model superposition analysis is overconservative.

The goal is therefore to design for <u>event specific uniform hazard spectra</u> (ESUHS): spectra that correspond to the types of earthquakes that can be felt at the site. There is obviously a large number of such spectra and it is unreasonable to want to consider each of them independently. On the other hand, the previous arguments imply that it is overconservative to use only the envelope of all the ESUHS.

From an engineering point of view, it appears reasonable to consider only a few types of spectra, for example: rich high frequency content, intermediate, and rich low frequency content. Since the purpose is now to obtain a number of uniform hazard spectra resulting from the sorted contribution of different types of earthquakes, it is necessary to determine the parameters that govern the shape of earthquake spectra in order to assign the contribution of each event to the correct ESUHS.

In a probabilistic hazard analysis, the spectral shape is determined by the attenuation relationships used to transfer the loading information from the generating source to the site. Carrying the discussion for two periods of interest, the attenuation relationship is of the type:

$$Sa_{M,R} = \frac{b_{11} e^{b_{21},m}}{R^{b_{31}}} \qquad \text{a} \quad {}_1$$

$$Sa_{M,R} = \frac{b_{12} e^{b_{22} M}}{R^{b_{32}}} \qquad \text{at } T_2$$

The spectral shape (ratio of Sa_1 to Sa_2) for a fixed distance and magnitude is determined by the parameters b_{11} and b_{12}, while the spectral shape variation (variation of Sa_1 to Sa_2 ratio) with distance and magnitude is governed by the constants b_{21}, b_{22}, b_{31}, and b_{32}. As shown in Figure 6-3, distance is an important parameter since the ratio Sa_1 to Sa_2 varies significantly with it, whereas it only varies marginally with magnitude (Figure 6-4). Hence as a first approximation, a good separator for spectral shapes is distance and only the cumulative exposure from earthquakes within a distance band should be continued to produce an ESUHS. From Figure 6-3 one sees that three distance bands would be appropriate: from Zero to D_1, where $Sa_1 > Sa_2$ and approximately constant, from D_1 to D_3 where the average ratio $Sa_1/Sa_2 > 1$ and finally distances greater than D_3, where Sa_1/Sa_2 is less than one and relatively stable. A more crude approximation would use only two distance bands: from 0 to D_2 ($Sa_1 > Sa_2$) and greater than D_2 ($Sa_1 < Sa_2$).

In order to remain consistent with a global hazard corresponding to a chosen RP, one cannot simply design for the most critical ESUHS at that RP. One has to consider the additional contribution of the others. One approach based on design is presented in the following paragraph.

Let us consider the two periods of interest T_1 and T_2 and assume that the earthquakes susceptible of affecting the site analyzed can be broadly sorted (based on distance) in two types of spectral shapes. For each distance band and period a spectral amplitude versus RP plot is obtained. Figure 6-5a presents separately the spectral amplitude at T_1 corresponding to the nearby and distant earthquakes and a combination of both. Figure 6-5b presents the same curves for period T_2.

Using the modal superposition method, one can determine a load versus RP curve for each ESUHS (Figure 6-6c, $D < D_2$ and $D > D_2$). Assuming independence between both ESUHS, the global load versus RP is obtained (Figure 6-5c, $D > 0$).

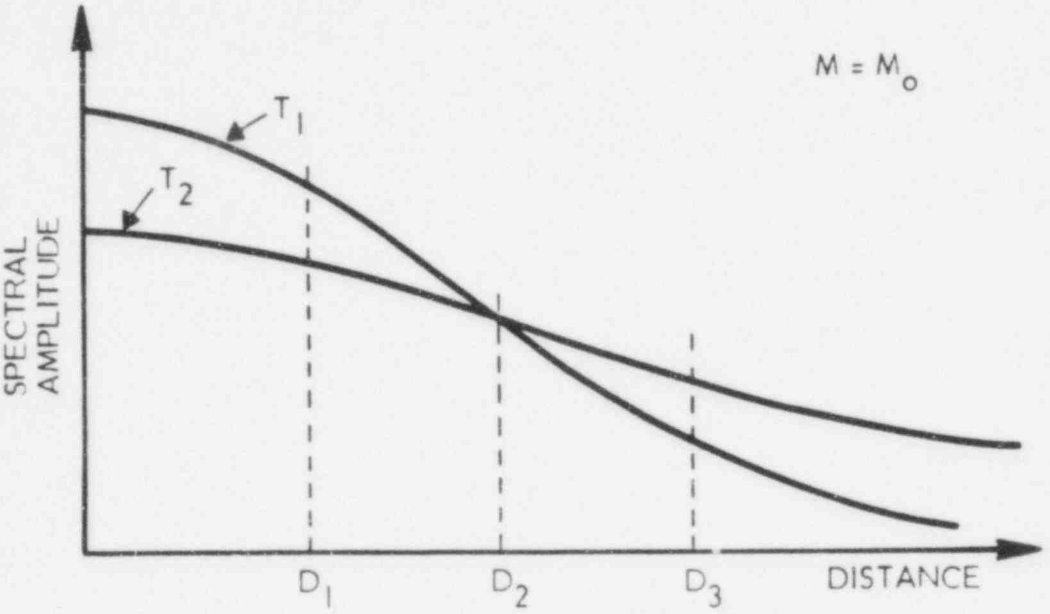

FIGURE 6-3

TYPICAL ATTENUATION OF S_{a1} AND S_{a2} WITH DISTANCE (FIXED MAGNITUDE)

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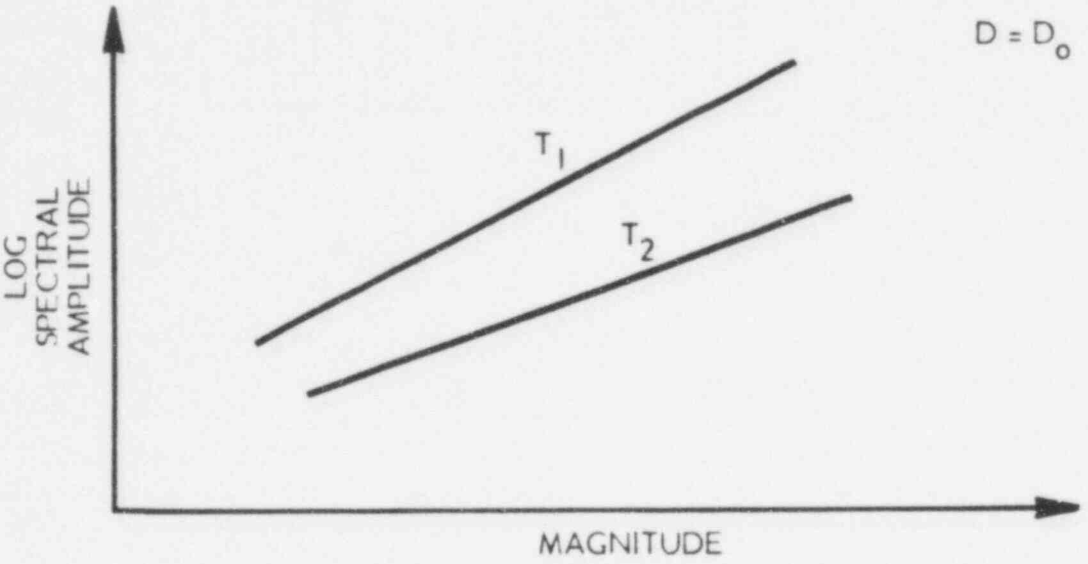

FIGURE 6-4

TYPICAL VARIATION OF S_{a1} AND S_{a2} WITH MAGNITUDE
(FIXED DISTANCE)

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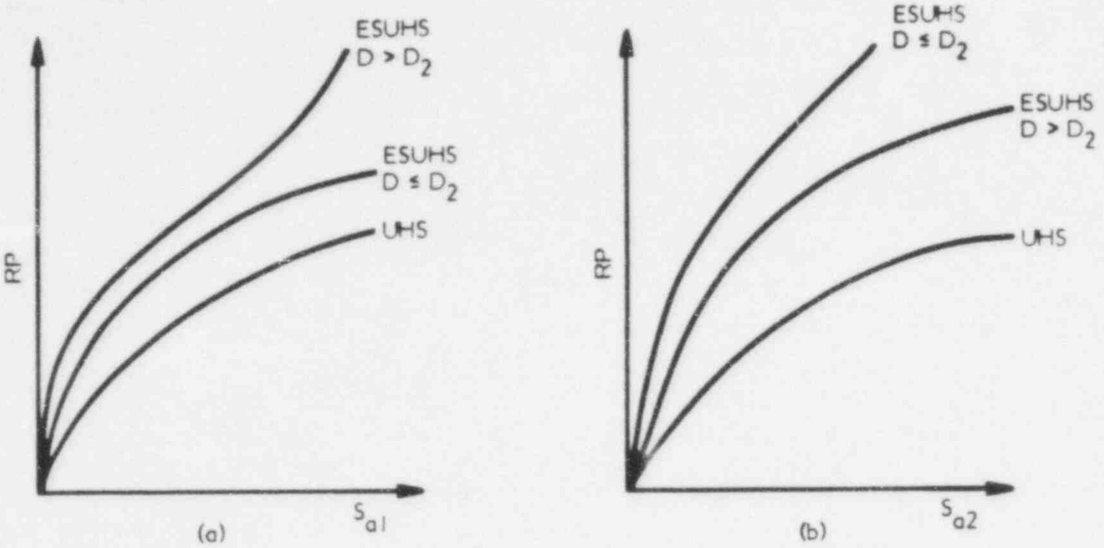

$$L_i = \sqrt{\left(P_1\; S_{a1}\Big|_{RP_i}\right)^2 + \left(P_2\; S_{a2}\Big|_{RP_i}\right)^2}$$

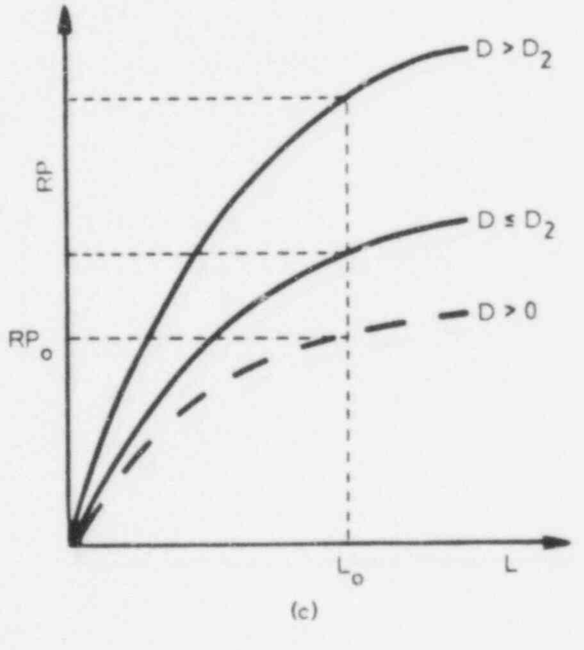

FIGURE 6-5

DETERMINATION OF DESIGN LOAD FROM TWO ESUHS

This curve presents in terms of a design parameter the global contribution of both nearby and distant earthquakes to the hazard at the site. The load corresponding to RP_o on this last curve represents the design value to be used for design. One can see that it corresponds to different RP for each ESUHS load curve.

This approach, which is structure dependent, represents a more rational attempt to take into account the specific spectral shape of earthquakes felt at the site. It removes some of the overconservatism implicit in the UHS method.

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APPENDIX A

SOLICITATION OF EXPERT OPINION

A.1 MODES OF JUDGMENT

Modes of judgment are the methods by which people assess uncertainty. They use intuitive assessment procedures that are often based on cues of limited reliability and validity. Three common features of these modes of judgment are worth noting (Spetzler and von Holstein, 1974):

- Generally people are not aware of the cues their judgments are based on
- Controlling the cues people base their judgments on is difficult
- People can be made aware of biases and make a conscious attempt to control them

It is convenient to divide the modes of judgments into the four categories of representativeness, availability, adjustment and anchoring, and unstated assumptions.

Representativeness is the tendency to assign the probability of an event according to the degree of similarity it has with a broader group of events from which it is issued. Often a simple event is given more weight than it should because it is well defined and considered representative while the whole population carries more generalized information. The biases resulting from representativeness can often be reduced or eliminated by structuring the problem in more detail (Spetzler and von Holstein, 1974).

Availability refers to how easily occurrences can be brought to mind. For instance, present or recent occurrences or information that made a strong impression at the time it was presented are more available than occurrences from a long time ago or that did not make a strong impression. One may assess the risk of heart attack among middle-aged people by recalling such occurrences

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among one's acquaintances, and often such information will be given more weight than it should because it is still vivid in one's memory. Such bias can usually be removed by conditioning the subject and forcing him to broadly survey his information base before starting the scaling.

The subject often adjusts his responses to further questions according to the first or most available piece of information. Typically the subject's adjustments will be insufficient and lead to a central bias. Such a phenomenon is called anchoring. Anchoring often occurs when the starting point is given to the subject, or when he is first asked a question which he considers very important (such as a mean value), to the extent that he bases the remainder of his answers on those. Such biases can be reduced by covering a wide range of values at the beginning, or by eliciting answers which cannot be correlated.

If there is room for unstated assumptions, the subject will, consciously or not, restrict himself to particular cases with which he feels more at ease, or he will implicitly disregard situations that he feels are too far-fetched to need consideration. Therefore, his probability distribution will not reflect his total uncertainty. This obstacle can be removed by properly structuring the problem and making sure that conditional probabilities are explicitly stated.

A.2 BIASES

Biases are discrepancies between the expert's answers and his real knowledge. Such discrepancies can take several forms and can be either conscious or unconscious.

- Displacement biases consist of a translation of the whole distribution function either upward or downward but with no change in the shape.
- Variability biases consist of a variation in the shape of the distribution function. The bias can result either in a tighter distribution (central bias) or in a broader distribution (more uncertainty) than is justified by the expert's state of knowledge. These discrepancies are often a mixture of both biases unless the subject consciously modifies his answers in accordance with a well-defined pattern.

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The sources of bias can be divided into two categories--motivational or cognitive--both of which can be either conscious or unconscious.

- When obeying motivational biases, the subject influences the decision in his favor by modifying his answers. For example, he might reduce the uncertainty beyond what his knowledge would allow him because he feels that an expert in his position is expected to talk about this subject with a high level of confidence. In other cases, an expert might broaden the uncertainty to influence the decision one way or another.
- Cognitive biases are systematic adjustments introduced by the way the expert formulates his judgment. For example, one expert may give more weight to the last piece of information he has acquired simply because it is fresher in his mind.

A.3 SCALING TECHNIQUES

The goal of the encoding session is to obtain an accurate representation of the experts' judgment on a well-defined parameter of uncertainty. This judgment will be sought not only on the "most probable value" or on the expected value of the distribution, but also, when possible, on the entire probability distribution.

A judgmental probability distribution is encoded in a session between the expert whose judgment is being encoded and the analyst conducting the interview. In the present case, the questionnaire was sent to each expert, followed by a personal interview and additional questioning to resolve inconsistencies or other problems.

It is convenient to divide the different stages of scaling sessions into three steps.

- Pre-conditioning - the expert is conditioned to think fundamentally about his judgment and to avoid cognitive biases

- Scaling - the judgment is quantified in probabilistic terms
- Verifying - the responses obtained in the scaling are checked for consistency

The purpose of pre-conditioning is to pinpoint biases that might surface during the scaling and to force the subject to think about how he makes his judgment. This step will reveal the information which seems to be most available, the anchors which are being used and the assumptions which are being made.

It is during the scaling session that the subjective probability associated with the quantities of interest are obtained from the expert. Scaling methods can be sorted in different ways since they differ in several aspects, such as in the properties of the scale (ordinal, interval, ratio), the nature of the response (direct, indirect), the nature of the uncertain quantity (probability, value, both: P, V or PV methods), the experimental procedures, etc. Each of these aspects can be used to classify the scaling methods.

For the purpose of this study, we believe it is useful to sort them as follows:

Ordinal Questioning (Indirect or Direct Response Technique)

In the indirect response technique, to be used during interview, the subject is asked to choose between two or more alternatives. The choices are then repeatedly adjusted until he feels indifferent about choosing between them. The level at which indifference is reached can be translated in terms of probabilities (P methods) or values of the variable being scaled (V methods). In the case of the external reference process, one alternative is expressed in terms of the uncertain quantity and the other in terms of a familiar reference event. When the external reference is used, it is important that the expert be familiar and at ease with this external reference. References can be of two types: either a standard list of events of fixed probabilities or graphic displays such as the probability wheel or the probability segment. The internal reference process, on the other hand, uses alternatives defined in terms of the same value scale. For example, the subject is asked to choose between two possible ranges of values of the uncertain quantity.

In the direct response technique, the subject is asked to assign a probability corresponding to a given value (P method) or to assign a value corresponding to a given probability (V method).

Graphs

By graphing his subjective input, the subject provides both the probability and value of the uncertain quantity. He graphs this subjective input either by directly drawing the CDF or by giving a number of pairs of points from which a curve can be drawn.

Semantic Variables

This method requires that the scaling be done in two phases. First, the expert characterizes the event in terms of descriptors he is familiar with (such as "likely," "most probably," "rare," etc.) and then he must encode these descriptors in quantitative terms himself. This last step is necessary because the quantitative meaning of the verbal labels is extremely subjective (Lichtenstein and Newman, 1967). Although this method may be useful when the quantities of interest have no ordinal value scale, it is not thought practical for this project.

Finally, in the verifying phase of the session, judgments are tested for consistency. Since feedback and cross-checking play an important role in the process interviews are highly recommended to complete the procedure.

A.4 QUESTIONNAIRE FOR EUS SEISMICS

A questionnaire was developed to elicit expert opinion on seismicity and intensity attenuation in the northeastern region of the United States. Because it is difficult, or perhaps impossible, to precisely quantify such factors given the sparse historical record, expert judgment was considered crucial. The opinions were used in an analysis of seismic hazard.

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In order to help the respondents in answering the questionnaire, we supplied them with seismicity data for various source zones in the East. These data were based on an integrated catalog of earthquake occurrences generated from various regional catalogs for the East. For each of the zones they were supplied with (1) a listing of all earthquakes having epicentral intensities of IV or greater, and (2) a table giving the number of occurrences of earthquakes of each Modified Mercalli (MM) intensity unit from IV through XII. This data is presented in Appendix B to this report.

The following points were emphasized:

- The level of confidence the respondents associated with their answers would be explicitly considered. Therefore, since their input would undergo filtering and weighting when combined with the opinion of other experts, they were asked not to feel reluctant to express non-classical viewpoints.
- Nine sites were specified for analysis and the experts were asked to concentrate their effort on regions whose seismicity might affect these sites, leaving in the background those regions whose contributions would be negligible.
- Answers were to be based on general experience, geologic and tectonic considerations, as well as available data.
- The questionnaire was designed to contain redundancy, which was necessary for cross-checking and for establishing consistency in the results. The experts were asked not to try to produce answers consistent with earlier answers, or to backfigure from previous answers, since this would defeat the purpose of the redundancy.
- The experts were asked to concentrate on their areas of expertise and to focus on the part of the questionnaire with which they felt most comfortable.
- They were asked to attempt answers to all questions and to skip questions only if they felt uncomfortable with the format of the question or if they had no confidence in their ability to answer. Large uncertainties would be reflected in the range of values presented and through the confidence the experts associated with their response.

The questionnaire was divided into the following five sections:

- Source Zone Configuration
- Maximum Earthquakes
- Earthquake Occurrence
- Attenuation
- Overall Level of Confidence

In the Source Zone Configuration section, we were concerned with the specification of various areas or regions that appear to be unique in their potential to generate earthquakes. In particular, we were seeking the definition of regions within which the experts felt future earthquake activity would be homogeneous. As a point of reference, we provided maps giving two possible seismic zonations of the eastern United States. We asked the experts to carefully review these figures and to indicate where they thought there might be inadequacies by modifying, deleting and adding zones. The experts were asked to indicate their "degree-of-belief" in each source zone and source zone alternative by estimating the chances that seismicity within these zones is part of the background seismicity of the entire region. We also asked them to identify any localized tectonic structures that might be important to the seismic hazard of nearby sites and to indicate their "degree-of-belief" in the activity at these sites.

In the Maximum Earthquake section, we first addressed the question of determining the size of the largest event that, in the experts' opinions, could be expected to occur in each of the source zones for a given time period in the future. Since extrapolation of results from short time periods to very long ones is controversial, due to possible long-term variations in seismicity and other parameters, we explicitly considered two distinct time periods. The first one was chosen to be 150 years, this being generally on the order of our time period of interest and approximately equivalent to the length of recorded history in the East. The second time period was chosen to be 1,000 years, since such a period covers most non-catastrophic perturbations in seismic activity and leaves out the

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uncertainties associated with the extremely long-term geological variations outside the scope of the questionnaire.

The experts were also asked to consider the largest event that they might expect to occur within the current tectonic framework in each source zone without specifying any time period. It was emphasized that they should base their answers not only on the recorded data, but also on their feelings about:

- Whether the past history is a good estimator of the true state of nature
- Whether the future activity is likely to be similar or different from the past
- Whether this feeling could be based on any external source of information such as tectonics, theorectical studies, similarity with other regions in the world, or simply educated judgment.

The Maximum Earthquake section was divided into two parts. In the first part, we considered the size of the largest event expected to occur in a zone. In other words, knowing that a certain number of earthquakes will occur, we were interested in determining the size of the largest one and the uncertainty associated with that size. In the second part we considered the <u>return period</u> of the largest event.

The Earthquake Occurrence section considered the occurrence of earthquakes within the next 150 years for each source zone. Occurrences were expressed either in terms of the number of earthquakes expected to occur within that period (for example: 47 in 150 years) or as the mean rate of occurrence per year (i.e., 0.313 per year). The experts were asked to subjectively assess the <u>future</u> seismicity in the East based on the available data and their judgment as to the validity, quality and completeness of these data to represent the true seismicity in the East. To aid in their decision-making, we presented an accompanying seismicity booklet of earthquake occurrence data for the source zones presented in the zonation maps. These data included (1) a listing, in descending order of intensity, of all earthquakes having epicentral intensities IV or greater and (2) a table giving the number of occurrences of earthquakes of each MMI unit from IV through XII. These data were not "corrected" for completeness, but rather represented the latest generally available information on locations and sizes of recorded or felt events.

The limited strong motion data in the East can be supplemented by inferring, from theoretical or experimental information, the difference in peak acceleration and velocity ground motion between the eastern United States and the western United States, and correspondingly modifying the Western attenuation relations and intensity-ground motion correlations to make them applicable in the East. The section on Attenuation was intended to provide general information concerning the validity of existing attenuation relationships and ground-motion correlation for use in the eastern United States. Attenuation data were not specifically provided for this task; rather, we asked the experts to rely on their inherent knowledge of eastern United States attenuation.

In order to obtain a measure of the overall confidence the experts had in their answers, the final section asked them to rate, on a scale of 1 to 10 (10 being the highest), their confidence in their responses to the different sections of the questionnaire and in the various source zones. In this way, a synthesis or partial synthesis could be reached among the experts through weighted average procedures based on <u>self-assigned</u> levels of confidence.

The responses to each question could be made in any one of several ways, where all could be converted to a usable format for analysis. Acceptable answers were:

- A best estimate only (fixed quantity)
- A range of values defined by lower and upper bounds and associated with a uniform distribution
- A range of values defined by lower and upper bounds and associated with a non-uniform distribution
- A written discussion

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A.5 THE EXPERT PANEL

An obvious keystone to any expert opinion solicitation is the selection of the expert panel. The criterion used for this project was simple; employ as many as possible of the best experts in EUS seismology. Thirteen experts were contacted and their availability determined. Of these, only ten were able to complete the questionnaire. These experts, listed by region, were:

Dr. Robert Herrmann
Dr. Otto Nuttli
Dr. Ronald Street
Dr. Gilbert Bollinger
Dr. Edward Chiburis
Dr. Michael Chinnery
Dr. Richard Holt
Dr. Paul Pomeroy
Dr. M. Nafi Toksöz
Dr. Marc Sbar

APPENDIX B

DATA CORRECTION

It has been observed that the completeness of earthquake records varies with time. In the past, due to low population density and lack of interest in earthquake activity, only large events were recorded. With increased instrumental coverage, intermediate and lesser earthquakes were recorded with more frequency, thus suggesting an apparent increase in seismic activity with time which biases the statistics applied to the uncorrected data. Evaluation of the completeness of the available earthquake record is an important step in the analysis of data.

One alternative is to confine the analysis to subintervals of the record that are complete for the earthquakes of interest. The objection to this approach is that, as the sample interval becomes short, meaningful statistical averages of large earthquakes cannot be obtained because of their infrequent occurrences (Benjamin, 1968). Accordingly, as the sample becomes shorter the range of events that one has to work with becomes more restricted. In order to overcome these difficulties, we shall use a subinterval of the historical record which is adequate for establishing mean frequencies of the largest recorded earthquake. We shall then adjust for incomplete reporting. To determine the nature and degree of incompleteness, we shall use the procedure presented by Stepp (1971).

We must first determine the subinterval of the data base in which the mean rates of occurrence are stable for each intensity class. The mean rate of occurrence can then be determined from the interval of complete data for each intensity class. A complete treatment of the approach is given in the above reference.

Assuming that the earthquake occurrence in each intensity class can be represented by a Poisson distribution, the standard deviation of the process

$$\sigma_I = \sqrt{\lambda_T}/\sqrt{T}$$

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(where λ_T is the mean rate of occurrence of events of intensity I over the time period T)

behaves as $1/\sqrt{T}$ in the subinterval in which the mean is stable.

The ratio is given as $\lambda_T = N_I/T$, where N_I is the cumulative number of earthquakes having intensity I in the time interval T.

For a stable mean rate of occurrence in time, σ should plot versus T (on a log-log graph) as a straight line with slope -0.5. Departure of the data from this behavior is explained by incomplete reporting of earthquakes or by older data being incorporated into the sample. Hence, from the above analysis, we may create an artificially homogeneous data sample by carefully evaluating the intervals over which earthquake in different intensity classes are completely reported. For each intensity class, the interval must be long enough to establish a stable mean rate of occurrence and short enough to not include intervals in which the data are incompletely reported.

Since the data cover a large geographical area, for which the period of complete recording is not expected to be similar, the analysis was applied to two subregions: the central stable region, including the New Madrid area, and the East. The periods of complete recording are given in Table B-1 together with the scaling factor to be applied to a time period of 175 years.

A typical graph for data correction is plotted in Figure B-1. First, the incremental uncorrected data is plotted as squares. It is then corrected by multiplying it by the corresponding scaling factor to obtain a homogeneous data sample for 175 years (triangles). Finally, the cumulative number of earthquakes is plotted (circles). These are used together with other information to anchor the slope "b" when the expert does not explicitly provide an "a" value for the region considered (Section 5.0).

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TABLE B-1

CORRECTION RATIOS TO 175 YEARS

		Central U.S.	Eastern U.S.
Stable Years	MMI	Ratio	Ratio
70	IV	2.5	2.5
100	V	1.75	1.75
100	VI	1.75	1.75
150	VII	1.17	1.17
200	VIII	1.0	0.88
200	IX	1.0	0.88
200	X	1.0	0.88
200	XI	1.0	0.88

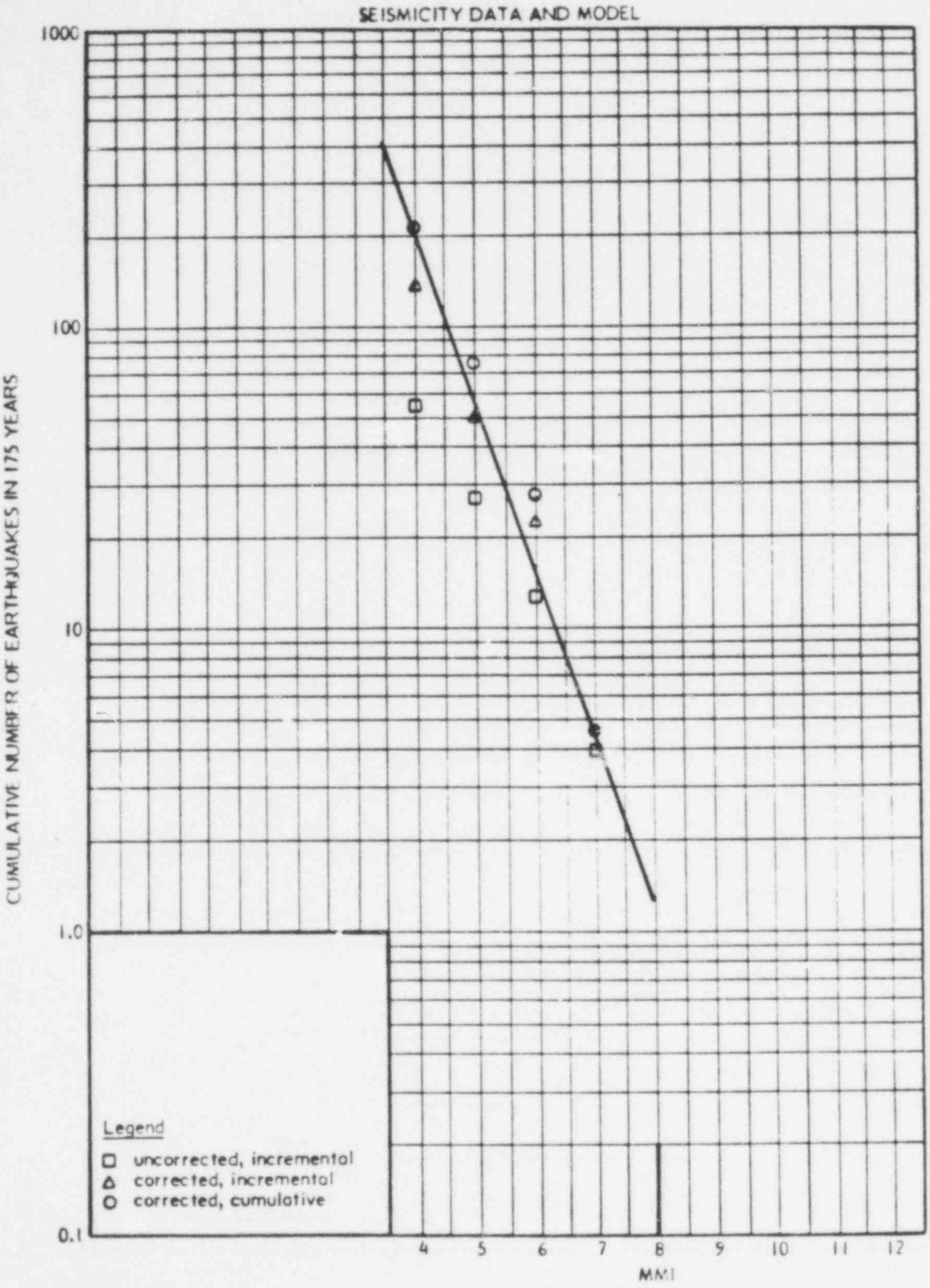

FIGURE B-1

TYPICAL PLOT OF DATA, CORRECTED DATA AND RECURRENCE RELATIONSHIP

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APPENDIX C

BIBLIOGRAPHY

Aggarwal, Y. P., and L. R. Sykes, "Earthquakes, Faults, and Nuclear Power Plants in Southern New York and Northern New Jersey," Bulletin of the Seismological Society of America, Vol. 200, 1978.

Aggarwal, Y. P., J-P. Yang, and E. Cranswick, "Seismological Investigation in the Adirondacks and Environs," Abstract, Geological Society of America, Vol. 9 (in press), 1977.

Aki, K., "Analysis of the Seismic Coda of Local Earthquakes as Scattered Waves," Journal of Geophysical Research, Vol. 74, pp. 615-631, 1969.

Aki, K., "Scaling Law of Earthquake Source Time Function," Geophysics Journal, Vol. 31, pp. 3-25, 1972.

Aki, K., "Maximum Likelihood Estimate of b in the Formula log N = a-bM and Its Confidence Limits," Bull. Earthq. Res. Inst., Vol. 43, pp. 237-239, 1965.

Albert, R. L., E. F. Chiburis, and R. K. Frohlich, "Intensity and Magnitude Determination of the Portsmouth, Rhode Island, Earthquake of March 11, 1976," Earthquake Notes, Vol. 47 (1976), p. 3.

Algermissen, S. T., "The Problem of Seismic Zoning," Building Practices for Disaster Mitigation, Building Science Series 46 (1973), National Bureau of Standards, U. S. Dept. of Commerce, pp. 112-125.

Algermissen, S. T., "Seismic Risk Studies in the United States," Fourth World Conf. Earthq. Engr., Vol. I, Sec. A-1 (1969), pp. 14-27, Santiago, Chile.

Algermissen, S.T., and D.M. Perkins, "A Probabilistic Estimate of Maximum Acceleration in Rock in th Contiguous United States", U.S. Geological Survey Open File Report 76-416, 1976.

Ambraseys, N. N., "Maximum Intensity of Ground Movements Caused by Faulting," Fourth World Conf. Earthq. Engr., Vol. I, Sec. A-2 (1969), pp. 154-171, Santiago, Chile.

Anderson, J., "A Dislocation Model for the Parkfield Earthquake," Bulletin of the Seismological Society of America, Vol. 64, (1974), pp. 671-686.

Ang, A. H-S., "Probability Concepts in Earthquake Engineering," Applied Mechanics in Earthquake Engineering, AMD-vol. 8, W.E. Iwan, Editor, ASME, pp. 225-229, 1974.

Arias, A., "A Measure of Earthquake Intensity in Seismic Design for Nuclear Power Plants," R. J. Hansen, Editor, M.I.T. Press, Cambridge, Massachusetts (1970).

923 139

Arnold, P., E. H. Vanmarcke, and G. Gazetas, "Frequency Content of Ground Motions During the 1971 San Fernando Earthquake," Department of Civil Engineering, M.I.T., (1976), Cambridge, Mass., R76-3.

Barosh, P. J., "New England Seismotectonic Study Activities During Fiscal Year 1977," Weston Observatory, Boston College, NUREG/CR-0081, RGA (Prepared for U. S. Nuclear Regulatory Commission).

Barosh, P. J., Coordinator, "New England Seismotectonic Study Activities During Fiscal Year 1977," U. S. Nuclear Regulatory Commission, Contract No. AT(49-24)-0291, May 1978.

Bernreuter, D., "Estimates of the Epicentral Ground Motion in the Central and Eastern United States," Sixth World Conference on Earthquake Engineering, (1977), New Delhi.

Bernreuter, D. L., "An Overview of the Relations Between Earthquake Source Parameters and the Specification of Strong Ground Motion for Design Purposes," Lawrence Livermore Laboratory, UCRL-79982, 1977. (Presented at second meeting of the group of experts on Reference Ground Motions in Nuclear Safety Assessments, Rome, Italy, Oct. 14, 1977).

Berrill, J. B., "Site Effects During the San Fernando, California, Earthquake," 6th WCEE 2-101 (preprint)(1977), p. 432.

Blume, J. A., "Engineering Intensity Scale Data for the 1971 San Fernando Earthquake," 6th W.C.E.E., 2-375, p. 729.

Blume, J. A., "Earthquake Ground Motion and Engineering Procedures for Important Installations Near Active Faults," Third World Conference on Earthquake Engineering, Vol. III, Sec. IV (1965), pp. 53-69, Auckland, New Zealand.

Blume, J. A., R. L. Sharpe, and J. S. Dalal, "Recommendations for Shape of Earthquake Response Spectra," Directorate of Licensing, U. S. Atomic Energy Commission, John A. Blume and Associates (1973), San Francisco.

Bollinger, G. A., "Re-Interpretation of the Intensity Data for the 1886 Charleston, S.C., Earthquake," U. S. Geological Survey (1977), Prof. Paper 1028.

Bollinger, G. A., "A Catalog of Southeastern United States Earthquakes 1754 through 1974," Virginia Polytechnic Institute and State University, Blacksburg, Virginia, 24061, Research Division Bulletin 101, Department of Geological Sciences, 1975.

Bollinger, G. A., "Seismicity of the Southeastern United States," Bulletin of the Seismological Society of America, Vol. 63 (1973), pp. 1785-1808.

923 140

Bollinger, G. A., "Historical and Recent Seismic Activity in South Carolina," Bulletin of the Seismological Society of America, Vol. 62 (1972), pp. 851-864.

Bollinger, G. A., "Seismicity of the Central Appalachian States of Virginia, West Virginia, and Maryland--1758 through 1968," Bulletin of the Seismological Society of America, Vol. 59 (1969), pp. 2103-2111.

Bollinger, G. A., and M. G. Hopper, "The Earthquake History of Virginia, 1900-1970," Department of Geological Sciences, Virginia Polytechnic Institute and State University (1972), Blacksburg, Virginia.

Bolt, B. A., and R. A. Hansen, "The Upthrow of Objects in Earthquakes," Bulletin of the Seismological Society of America, Vol. 67, No. 5 (1977), pp. 1415-1427.

Bolt, B. A., "San Fernando Rupture Mechanism and the Pacoima Strong-Motion Record," Bulletin of the Seismological Society of America, Vol. 62, No. 4, p. 1053.

Bolt, B. A., "Duration of Strong Ground Motion," Proceedings of the Fifth World Conference on Earthquake Engineering, No. 292 (1973), Rome, Italy.

Boore, D.M., W.B. Joyner, A.A. Oliver III, and R.A. Page, "Estimation of Ground Motion Parameters," U.S. Geological Survey, Circular 795, 1978.

Boston Edison Company Summary Report Geologic and Seismologic Investigations Pilgrim Unit 2, Boston Edison Company, Docket No. 50-471, 1976a.

Boston Edison Company, "Epicentral Location of," Boston Edison Company, 1976b.

Brazee, R., "Analysis of Earthquake Intensities With Respect to Attenuation, Magnitude and Rate of Recurrence," NOAA GPS, 1976, N65DC-2.

Burton, P. W., "A Tectonic Parameter Characteristic of Regional Seismic Risk," Abstract, Cordilleran Section, Geological Society of America, Boulder, Vol. 9, No. 4 (1977), 394. (Presented at 72nd annual meeting of the Seismological Society of America, April 5-7, 1977, Sacramento, California)

Busch, K. A., and U. Wagner, "Comparison of Artificial and Natural Earthquake Time History Functions with Regard to their Floor Response Spectra," Trans. 4th Int'l Conf. on Struct. Mechanics in Reactor Technology, Aug. 15-19, 1977, San Francisco, Vol. K(a), Paper K4/14.

Bycroft, G. N., "The Effect of Soil Structure Interaction on Seismometer Readings," Bulletin of the Seismological Society of America, Vol. 68, No. 3, pp. 823-844, 1978.

Campbell, D. L., "Investigation of Stress Concentration Mechanism for Intraplate Earthquakes," Journal of Geophysical Research Letters, Paper 820481, 1978.

Campbell, K.W., and C.M. Duke, "The Use of Seismotectonics in the Bayesian Estimation of Seismic Risk", School of Engineering and Applied Science, UCLA, 1977.

Canitez, N., et al., "Source Mechanism Interpretation, Surface Waves, Body Waves, Static Displacements, Strain Fields, San Fernando, California," Journal of Geophysical Research, Vol. 77, No. 14, p. 2583.

Caputo, M., "A Mechanical Model for the Statistics of Earthquakes, Magnitude, Moment, and Fault Distribution," Bulletin of the Seismological Society of America, Vol. 67, No. 3, pp. 849-861, 1977.

Chadwick, G. H., "Large Fault in Western New York," Geological Society of America Bulletin, Vol. 31, pp. 117-120, 1920.

Chinnery, M. A., and D. A. Rogers, "Earthquake Statistics in Southern New England," Earthquake Notes, Vol. XLIV, No. 304 (1973).

Cody, W., "Regional Tectonic Synthesis of Northwest New England and Adjacent Quebec," Geological Society of America, Memo 120, pp. 1-181, 1969.

Collins, J. D., "The Probabilistic Significance of Earthquake Prediction," Bulletin of the Seismological Society of America, Vol. 67, No. 1, Letter to the Editor (1977).

Cornell, C.A., H. Banon, and A.F. Shakal, "Seismic Motion and Response Prediction Alternatives," School of Engineering, MIT, 1977.

Cornell, C. A., and H. Merz, "Seismic Risk Analysis of Boston," Jour. Struc. Div., Proc. Am. Soc. Civil Engineers, Vol. 107, pp. 2027-2043, 1974.

Cosentino, P., V. Ficarra, and D. Luzio, "Truncated Exponential Frequency-Magnitude Relationship in Earthquake Statistics," Bulletin of the Seismological Society of America, Vol. 67, No. 6, pp. 1615-1623, 1977.

Crosby, I. B., "The Earthquake Risk in Boston," Journal of the Boston Society of Civil Engineers, Vol. 10 (1923), pp. 421-430.

Crouse, C. B., "Horizontal Ground Motion in Los Angeles During the San Fernando Earthquake," Egle. Eng. & Struct. Dyn., Vol. 4, No. 4, p. 333.

Der Kiureghian, A., and A. H-S. Ang, "A Line Source Model for Seismic Risk Analysis", Struct. Res. Series 419, Univ. Ill. at Urbana-Champaigne, Urbana, 1975.

Der Kiureghian, A., and A. H-S. Ang, "A Fault Rupture Model for Seismic Risk Analysis", Bull. Seism. Soc. Am. 67, 1173-1194, 1977.

Der, Z. A., and T. W. McElfresh, "The Relationship Between Anelastic Attenuation and Regional Amplitude Anomalies of Short-Period P Waves in North America," Bulletin of the Seismological Society of America, 67 (1977), pp. 1303-1317.

Devane, J. F., and R. J. Holt, "The Seismic History of Massachusetts," Economic Geology in Massachusetts, (1967), Graduate School, University of Massachusetts, pp. 373-377.

Docekal, J., "Earthquakes of the Stable Interior, with Emphasis on the Midcontinent," Diss. University of Nebraska, Vols. I and 2, 1971.

Donovan, N. C., and A. E. Bornstein, "The Problems of Uncertainties in the Use of Seismic Risk Procedures," Dames and Moore, Report No. EE77-4. (Presented at ASCE Fall Conv. and Exhibit, San Francisco, California, Oct. 17-21, 1977).

Donovan, N. C., "A Statistical Evaluation of Strong Motion Data Including the February 9, 1971, San Fernando Earthquake," Proceedings of the Fifth World Conference on Earthquake Engineering, No. 155 (1973), Sess. 4A, Rome.

Duke, C. M., et al, "Effects of Site on Ground Motion in the San Fernando Earthquake," 6th W.C.E.E., 2-93, p. 423, 1977.

Eppley, R. A., Earthquake History of the United States, Part I: Stronger Earthquakes of the United States, U. S. Coast & Geodetic Survey (1965).

Espinoza, A. F., and A. Lopez-Arroyo, "Earthquake Instrumental Intensity From Strong Ground Motion Records, San Fernando Earthquake," 6th W.C.E.E., 2-237, p. 722.

Espinoza, A. F., "Particle-Velocity Attenuation Relations: San Fernando Earthquake of February 9, 1971," Bulletin of the Seismological Society of America, Vol. 67, No. 4, pp. 1195-1214, 1977.

Esteva, L., "Seismicity Prediction: A Bayesian Approach," Fourth World Conference on Earthquake Engineering, Vol. I, Sec. A-I (1969), pp. 172-184, Santiago, Chile.

Evernden, J. F., "Magnitude Determinations at Regional and Near-Regional Distances in the United States," Bulletin of the Seismological Society of America, Vol. 57 (1967), pp. 591-639.

Evernden, J. F., "Seismic Intensities, 'Size' of Earthquakes and Related Parameters," Bulletin of the Seismological Society of America, Vol. 65, No. 5, pp. 1287-1313, 1975.

923 143

Faccioli, E., "Site-Dependent Probability Distributions for Peak Ground Motion Parameters in Strong Earthquakes," Inst. de Ingenieria, Univ. Nac. Autonoma de Mexico (1977), Publ. E-24.

Fisher, J. A., D. J. Leeds, and W. J. Murphy, "Seismo-Tectonic Relationships of the New Madrid, Missouri, Region," Paper presented at the meeting of the Seismological Society of America (1970).

Fisher, J. A., and F. L. Fox, "The Seismicity of Massachusetts," Economic Geology in Massachusetts, Graduate School, University of Massachusetts (1967), pp. 379-390.

Fletcher, J. B., and J. G. Anderson, "First Strong-Motion Records from a Central or Eastern United States Earthquake," Bulletin of the Seismological Society of America, Vol. 64, No. 5, pp. 1455-1466, 1974.

Fletcher, J. B., M. L. Sbar, and L. R. Sykes, "Seismic Trends and Travel-Time Residuals in Eastern North America and Their Tectonic Implications," Geological Society of America Bulletin, in press 1978.

Fletcher, J. B., and L. R. Sykes, "Earthquakes Related to Hydraulic Mining and Natural Seismic Activity in Western New York State," Journal of Geophysical Research, Vol. 82, pp. 3767-3780, 1977.

Fox, F. L., "Seismic Geology of the Eastern United States," Assoc. Eng. Geol. Bull., Vol. 7, pp. 21-43, 1970.

Fox, F. L., and C. T. Spiker, "Intensity Rating of the Attica (N.Y.) Earthquake of August 12, 1929--A Proposed Reclassification," Earthquake Notes, Vol. 48, No. 4, pp. 1-2.

Garner, J. K., and L. Knopoff, "Is the Sequence of Earthquakes in Southern California, with Aftershocks Removed, Poissonian?" Bulletin of the Seismological Society of America, Vol. 64, No. 5, pp. 1363-1367, 1974.

Gordon, D. W., T. J. Bennett, R. B. Herrmann, and A. M. Rogers, "The South Central Illinois Earthquake of November 9, 1968, Macroseismic Studies," Bulletin of the Seismological Society of America, Vol. 60, pp. 953-971, 1970.

Gupta, I. N., "Attenuation of Intensities Based on Isoseismals of Earthquakes in Central United States," Earthquake Notes, Vol. 47, No. 3 (1976), pp. 13-20.

Gupta, I. N., "Precursory Reorientation of Stress Axes Due to Vertical Migration of Seismic Activity," Journal of Geophysical Research, Vol. 80, No. 2, pp. 272-273, 1975.

Gupta, I. N., and O. W. Nuttli, "Spatial Attenuation of Intensities for Central U. S. Earthquakes," Bulletin of the Seismological Society of America, Vol. 66, No. 3, pp. 743-751, 1976.

923 144

Gutenberg, B., "Earthquakes in North America," Science, Vol. III (1950), pp. 319-324.

Guzman, R. A., and P. C. Jennings, "Determination of Design Spectra for Nuclear Power Plants," ASCE Nat'l Struct. Engr. Convention, April 14-18, 1975, New Orleans, La., Preprint 2508.

Gzovsky, M. V., "Tectonophysics and Earthquake Forecasting," Bulletin of the Seismological Society of America, Vol. 52 (1962), pp. 485-505.

Hadley, J. B., and J. F. Devine, "Seismotectonic Map of the Eastern United States," U. S. Geological Survey Report, MF-620, 1974.

Hamilton, A. C., "Seismic Regionalization of Eastern Canada," Proc. Symposium on Design for Earthquake Loadings, pp. II-1 to II-23, McGill University, Montreal, Canada (Sept., 1966)

Hanks, T. C., "The Faulting Mechanism of the San Fernando Earthquake," Journal of Geophysical Research, Vol. 79, No. 8, pp. 1215-1229, 1974.

Hashizume, M., and N. Tange, "Source Parameters of the June 13, 1967, Earthquake near Lake Ontario, New York State," Canadian Journal of Earth Sciences, Vol. 14, pp. 2651-2657, 1977.

Hasselman, T. K., J. D. Chrostowski, and J. H. Wiggins, "A Bayesian Approach for Mapping Earthquake Intensity," Presented at ASCE National Convention, Oct. 17-21, 1977, San Francisco, California.

Hays, W. W., S. T. Algermissen, A. F. Espinosa, D. M. Perkins, and W. A. Rinehart, "Guidelines for Developing Design Earthquake Response Spectra," Construction Engr. Res. Lab. (CERL) (1975), Tech. Rept. M-114.

Hays, W. W, and T. J. Bennet, "Time Dependent Spectral Analysis of Ground Motion," Presented at fall annual meeting of the AGU, December 4-7, 1972.

Heigold, P. C., "Notes on the Earthquake of September 15, 1972, in Northern Illinois," Illinois State Geological Survey, Environmental Geology Notes, No. 59, 1972, 15 p.

Heinrich, R. R., "A Contribution to the Seismic History of Missouri," Bulletin of the Seismological Society of America, Vol. 31 (1941), pp. 187-224.

Herrmann, R. B., "Surface Wave Generation by Central United States Earthquakes," Ph.D. Dissertation, Saint Louis University, 1974.

Herrmann, R. B., "A Student's Guide to the Use of P and S Wave Data for Focal Mechanism Determinations," Earthquake Notes, Vol. 46, p. 4, 1975.

Herrmann, R. B., "The Use of Duration as a Measure of Seismic Moment and Magnitude," Bulletin of the Seismological Society of America, Vol. 65, pp. 899-913, 1975.

Herrmann, R B., "A Seismological Study of Two Attica, New York, Earthquakes," Bulletin of the Seismological Society of America, Vol. 68, No. 3, pp. 641-652, 1978.

Herrmann, R. B., and G. W. Fischer, "Theoretical Seismogram Constraints on some Crustal Velocity Models in the Central United States," Pageoph (in press), 1978.

Herrmann, R. B., G. W. Fischer, and J. E. Zollweg, "The June 13, 1975, Earthquake and its Relationship to the New Madrid Seismic Zone," Bulletin of the Seismological Society of America, Vol. 67, No. 1, pp. 209-218, 1977.

Herrmann, R. B., and B. W. Mitchell, "Statistical Analysis and Interpretation of Surface-Wave Anelastic Attenuation Data for the Stable Interior of North America," Bulletin of the Seismological Society of America, Volume 65, pp. 1115-1128, 1975.

Herrmann, R. B., and O. W. Nuttli, "Ground-Motion Modelling at Regional Distances for Earthquakes in a Continental Interior, I. Theory and Observations," Earthquake Engineering and Structural Dynamics, Vol. 4, pp. 49-58, 1975.

Herrmann, R. B., and O. W. Nuttli, "Ground Motion Modelling at Regional Distances for Earthquakes in a Continental Interior, II. Effect of Focal Depth, Azimuth and Attenuation," Earthquake Engineering and Structural Dynamics, Vol. 4, pp. 59-72, 1975.

Hershberger, J., "A Comparison of Earthquake Accelerations with Intensity Ratings," Bulletin of the Seismological Society of America, Vol. 46 (1956), pp. 317-320.

Hodgson, E. A., "Industrial Earthquake Hazards in Eastern Canada," Bulletin of the Seismological Society of America, Vol. 35 (1945), pp. 151-174.

Hodgson, J. H., "There are Earthquake Risks in Canada," Canadian Consulting Engineer, Vol. 7, pp. 42-51, 1965.

Hopper, M. G., and G. A. Bollinger, "The Earthquake History of Virginia, 1774 to 1900," Department of Geological Sciences, Virginia Polytechnic Institute and State University (1971), Blacksburg, Virginia.

Horner, R. B., A. E. Stevens, H. S. Hasegawa, and G. Leblanc, "The Maniwaki, Quebec, Earthquake of July 12, 1975," Abstract, Earthquake Notes, Vol. 46, p. 48, 1975.

923 146

Horner, R. B., A. E. Stevens, H. S. Hasegawa, and G. Leblanc, "Focal Parameters of the July 12, 1975, Maniwaki, Quebec, Earthquake--an Example of Intraplate Seismicity in Eastern Canada," Bulletin of the Seismological Society of America, Vol. 68, No. 3 (June, 1978), p. 619.

Housner, G. W., "Engineering Estimates of Ground Shaking and Maximum Earthquake Magnitude," Fourth World Conference on Earthquake Engineering (1969), Vol. I, Sec. A-1, pp. 1-13, Santiago, Chile.

Housner, G. W., and P. C. Jennings, "Generation of Artificial Earthquakes," Journ. Engr. Mech. Div., Proc. A.S.C.E., Vol. 90 (1964), pp. 113-150.

Howell, B., "Seismic Regionalization in North America Based on Average Regional Seismic Hazard Index," Bulletin of the Seismological Society of America, Vol. 64, No. 5, pp. 1509-1528, 1974.

Howell, B. F., Jr., and T. R. Schultz, "Attenuation of Modified Mercalli Intensity with Distance from the Epicenter," Bulletin of the Seismological Society of America, Vol. 65, No. 3, pp. 651-665, 1975.

Iwasaki, T., and T. Katayama, "Statistical Analysis of Strong-Motion Earthquake Response Spectra," Proc. U. S. - Japan Seminar on Earthquake Engineering Research with Emphasis on Lifeline Systems, Japan Society for the Promotion of Science, Nov. 8-12, 1976, Tokyo, pp. 59-77.

Jennings, P. C., G. W. Housner and N. C. Tsai, "Simulated Earthquake Motions for Design Purposes," Proceedings of the Fourth World Conference on Earthquake Engineering (1969), Vol. I, Sec. A-1, pp. 145-160, Santiago, Chile.

Jungels, P. H., and G. A. Frazier, "Finite Element Analysis of the Residual Displacement for an Earthquake Rupture: Source Parameters for the San Fernando Earthquake," Journal of Geophysical Research, Vol. 78, No. 23, pp. 5062-5083, 1973.

Kanamori, H., "Long-Period Ground Motion in the Epicentral Area of Major Earthquakes," Tectonophysics, Vol. 21 (1974), pp. 341-356.

Kelleher, J. and J. Savino, "Distribution of Seismicity Before Large Strike Slip and Thrust-Type Earthquakes," Journal of Geophysical Research, Vol. 80, No. 2, pp. 260-271, 1975.

Kelleher, J., J. Savino, H. Rowlett, and W. McCann, "Why and Where Great Thrust Earthquakes Occur Along Island Arco," Journal of Geophysical Research, Vol. 79, pp. 4889-4899, No. 32, 1974.

King, K. W., and W. W. Hays, "Comparison of Seismic Attenuation in Northern Utah with Attenuation in Four Other Regions of the Western United States," Bulletin of the Seismological Society of America, Vol. 67, No. 3, pp. 781-792, 1977.

923 147

King, P. B., "Tectonics of Quaternary Time in Middle North America," *The Quaternary of the United States*, Princeton University Press (1965), pp. 831-870.

Krishna, J., A. S. Arya, and K. Kumar, "Determination of Isoacceleration Lines by Sliding and Overturning of Objects," *Proceedings of the Fifth World Conference on Earthquake Engineering* (1973), No. 158, Sess. 4A, Rome.

Kubo, T., and J. Penzien, "Characteristics of Three-Dimensional Ground Motions Along Principal Axes, San Fernando Earthquake," 6th W.C.E.E., Vol. 2, 2-107, p. 439, 1977.

Kuribayashi, E., T. Iwasaki, Y. Iida, and K. Tuji, "Effects of Seismic and Subsoil Conditions on Earthquake Response Spectra," *Proceedings of the Fifth World Conference on Earthquake Engineering* (1973), No. 74, Sess. 2C, Rome.

Lammlein, D. R., M. L. Sbar, and J. Dorman, "Microearthquake Reconnaissance of Southeastern Missouri and Western Tennessee," *Bulletin of the Seismological Society of America*, Vol. 61 (1971), pp. 1705-1716.

Leblanc, G., and G. Buchbinder, "Second Microearthquake Survey of the St. Lawrence Valley near La Malbaie, Quebec," *Canadian Journal of Earth Sciences*, Vol. 14, pp. 2778-2789, 1977.

Leblanc, G., A. E. Stevens, R. J. Wetmiller, and R. DuBerger, "A Microearthquake Survey of the St. Lawrence Valley near La Malbaie, Quebec," *Canadian Journal of Earth Sciences*, Vol. 10, pp. 42-53, 1973.

Leeds, D. J., "The Design Earthquake," in *Geology, Seismicity and Environmental Impact*, Ed. D. E. Moran, et al. Assoc. of Engr. Geol., Special Publication, October, pp. 337-347, 1973.

Liu, S. C., "Evolutionary Power Spectral Density of Strong-Motion Earthquakes," *Bulletin of the Seismological Society of America*, Vol. 60 (1970), pp. 891-900.

Liu, S. C., and D. P. Jhaveri, "Spectral Simulation and Earthquake Site Properties," *Journal Eng. Mech. Div., Proc. A.S.C.E.*, Vol. 95 (1969), EM5, pp. 1145-1168.

Loughlin, J. S., "Earthquake of Western New York, August 12, 1929," (Boston, Mass: Associated Factory Mutual Fire Insurance Companies, Sept. 14, 1929).

Mateker, E. J., "Earthquakes in Missouri," *Washington University Magazine* (St. Louis, Mo.), Vol. 39 (1968) pp. 46-51.

McClain, W. C., and O. H. Myers, "Seismic History and Seismicity of the Southeastern Region of the United States," Oak Ridge National Laboratory, Oak Ridge, Tennessee, Report No. ORNL-4582 (1970).

923 148

McGuire, R. K., "Adequacy of Simple Probability Models for Calculating Felt-Shaking Hazard, Using the Chinese Earthquake Catalog," Submitted to Bulletin of the Seismological Society of America, 1978.

McGuire, R. K., "Effects of Uncertainty in Seismicity on Estimates of Seismic Hazard for the East of the United States," Bulletin of the Seismological Society of America, Vol. 67, No. 3, pp. 827-848, 1977.

McGuire, R.K., FORTRAN Computer Program for Seismic Risk Analysis: U.S. Geological Survey Open-File Report 76-67, 1976.

McGuire, R. K., "A Simple Model for Estimating Fourier Amplitude Spectra of Horizontal Ground Acceleration." Manuscript submitted to: Bulletin of the Seismological Society of America, March 1977.

McGuire, R. K., "The Used Intensity Data in Seismic Hazard Analysis," 6th W.C.E.E., p. 709, 1977.

Merriam, D. F., "History of Earthquakes in Kansas," Bulletin of the Seismological Society of America, Vol. 46 (1956), pp. 87-96.

Merz, H. A., and C. A. Cornell, "Seismic Risk Analysis Based on a Quadratic Magnitude-Frequency Law," Bulletin of the Seismological Society of America, Vol. 63, No. 6, pp. 1999-2006, 1973.

Milne, J. A., "A Catalogue of Destructive Earthquakes A.D. 7 to A. D. 1899," British Association Reports (1911), pp. 649-740.

Milne, W. G., and A. G. Davenport, "Distribution of Earthquake Risk in Canada," Bulletin of the Seismological Society of America, Vol. 59, pp. 729-754, 1969.

Milne, W. G., "Earthquake Epicenters and Strain Release in Canada," Canadian Journal of Earth Science, Vol. 4 (1967), pp. 797-814.

Milne, W. G., "Earthquake Activity in Canada," Proceedings of Symposium on Earthquake Engineering, University of British Columbia, Vancouver, Canada (1965), pp. II-47 to II-63.

Mitchell, B. J., "Radiation and Attenuation of Rayleigh Waves from the Southeastern Missouri Earthquake of October 21, 1965," Journal of Geophysical Research, Vol. 78, pp. 886-899, 1973.

Mohraz, B., "A Study of Earthquake Response Spectra for Different Geological Conditions," Bulletin of the Seismological Society of America, Vol. 66 (1976), pp. 915-935.

Moneymaker, B. C., "Earthquakes in Tennessee and Nearby Sections of Neighboring States--1926 to 1950," Journal of the Tennessee Academy of Science, Vol. 33 (1958), pp. 224-239.

Moneymaker, B. C., "Earthquakes in Tennessee and Nearby Sections of Neighboring States--1901 to 1925," Journal of the Tennessee Academy of Science, Vol. 32, (1957), pp. 91-105.

Moneymaker, B. C., "Earthquakes in Tennessee and Nearby Sections of Neighboring States--1851 to 1900," Journal of the Tennessee Academy of Science, Vol. 30 (1955), pp. 222-233.

Moneymaker, B. C., "Some Early Earthquakes in Tennessee and Adjacent States (1699 to 1850)," Journal of the Tennessee Academy of Science, Vol. 29 (1954), pp. 224-233.

Mortgat, C.P., T.C. Zsutty, H.C. Shah, and L. Lubetkin, "A Study of Seismic Risk for Costa Rica," Technical Report No. 25, The John A. Blume Earthquake Engineering Center, Department of Civil Engineering, Stanford University, April 1977.

Murphy, J. R., and L. J. O'Brien, "The Correlation of Peak Ground Acceleration Amplitude with Seismic Intensity and Other Physical Parameters," Abstract, Earthquake Notes, 47(4):14 (1977). (Paper presented at 48th annual meeting of the Seismological Society of America, Eastern Section, University of Michigan, Ann Arbor, Oct. 21-22, 1976.

Murphy, J. R., A. H. Davis, and N. L. Weaver, "Amplification of Seismic Body Waves by Low-Velocity Surface Layers," Bulletin of the Seismological Society of America, Vol. 61, No. 1, p. 109, 1971.

Murray, G. F., "Dislocation Mechanism--The Parkfield 1966 Accelerograms," Bulletin of the Seismological Society of America, Vol. 63, No. 5, p. 1537, 1973.

Narayana, R. I., and K. T. Sundara, "A Non-Stationary Random Process Model for Earthquake Accelerograms," Bulletin of the Seismological Society of America, Vol. 59 (1969), pp. 1163-1188.

Necioghi, A., and O. W. Nuttli, "Source Ground Motion and Intensity Relations for the Central United States," Earthquake Engineering and Structural Dynamics, Vol. 3, No. 2, p. 111, 1974.

Neumann, F., Earthquake Intensity and Related Ground Motion, University of Washington Press (1954), 77 pp.

Neumann, F., "Ground Amplitudes and Periods Associated with Earthquake Intensity," Modification of original statement issued as a Supplement to Quarterly Engineering Seismology Bulletin, MSP-75, 4th Quarter 1950 (1951).

Newmark, N. M. (Consulting Engr. Services), "A Study of Vertical and Horizontal Earthquake Spectra," prepared for Directorate of Licensing, U. S. Atomic Energy Commission, U. S. Government Printing Office, WASH-1255 UC-11 (1973).

Newmark, N. M., "Interpretation of Apparent Upthrow of Objects in Earthquakes," Proceedings of the Fifth World Conference on Earthquake Engineering, (1973), No. 294, Sess. 6D, Rome.

Nuttli, O. W., "Seismic Hazard East of the Rocky Mountains," ASCE National Struct. Engr. Meeting, Cincinnati, Ohio, April 22-26, 1974. Preprint No. 2195.

Nuttli, O. W., "Magnitude, Intensity and Ground Motion Relations for Earthquakes in the Central United States," Proc. Intl. Conf. Microzonation for Safer Construction Research and Applications, Vol. 1, pp. 307-318, 1972.

Nuttli, O. W., "The Mississippi Valley Earthquake of 1811 and 1812, Intensities, Ground Motion and Magnitudes," Bulletin of the Seismological Society of America, Vol. 63, pp. 227-248, 1973.

Nuttli, O. W., "Seismic Wave Attenuation and Magnitude Relations for Eastern North America," Journal of Geophysical Research, Vol. 78, pp. 876-885, 1973.

Nuttli, O. W., "State-of-the-Art for Assessing Earthquake Hazards in the United States: Design Earthquakes for the Central United States," National Technical Information Service, U. S. Department of Commerce, January, 1973.

Nuttli, O. W., "Magnitude-Recurrence Relation for Central Mississippi Valley Earthquakes," Bulletin of the Seismological Society of America, Vol. 64, pp. 1189-1207, 1974

Nuttli, O. W., and J. E. Zollweg, "The Relation Between Felt Area and Magnitude for Central United States Earthquakes," Bulletin of the Seismological Society of America, Vol. 64, No. 1, pp. 73-85, 1974.

Oliver, J., and B. Isacks, "Seismicity and Tectonics of the Eastern United States," Abstract, Earthquake Notes, Vol. XLIII (1972), No. 1, p. 30.

Page, R. A., J. A. Blume, and W. B. Joyner, "Earthquake Shaking and Damage to Buildings," Science, Vol. 189 (1975), No. 4203, pp. 601-608.

Page, R. A., P. H. Molnar, and J. Oliver, "Seismicity in the Vicinity of the Ramapo Fault, New Jersey-New York," Bulletin of the Seismological Society of America, Vol. 58 (1968), pp. 681-687.

Patton, H. "A Note on the Source Mechanism of the Southeastern Missouri Earthquake of October 21, 1965," Journal of Geophysical Research, Vol. 81, No. 8, pp. 1483-1486, 1976.

Pollack, H. N., F. J. Mark, S. G. Henry, D. Williams, and D. Brewster, "The Anna, Ohio, Earthquake Zone Seismic Network," (Ann Arbor, Mich.: Dept. of Geology and Mineralogy, University of Michigan).

923 151

Raiffa, H., and R. Schlaifer, "Applied Statistical Decision Theory", Harvard University, Boston.

Rankin, D. W., "Studies Related to the Charleston, South Carolina, Earthquake of 1886--A Preliminary Report," Geological Survey Professional Paper 1028, United States Government Printing Office, Washington, Department of the Interior, 1977.

Rascon, O. A., and M. Chavez, "On an Earthquake Simulation Model," Proceedings of the Fifth World Conference on Earthquake Engineering, Vol. 2 (1973), pp. 2899-2913, Rome.

Rascon, O. A., and C. A. Cornell, "A Physically Based Model to Simulate Strong Earthquake Records on Firm Ground," Fourth World Conference on Earthquake Engineering, Vol. I (1969), Sec. A-1, pp. 84-96, Santiago, Chile.

Reiter, L., and M. E. Monfort, "Variations in Initial Pulse Width as a Function of Anelastic Properties and Surface Geology in Central California," Bulletin of the Seismological Society of America, Vol. 67 (1977), pp. 1319-1338.

Richardson, R. M., and S. C. Solomon, "Apparent Stress and Stress Drop for Intraplate Earthquakes and Tectonic Stress in the Plates," Pure Appl. Geophys., Vol. 115, pp. 317-331, 1977.

Richter, C. F., "Seismic Regionalization," Bulletin of the Seismological Society of America, Vol. 49 (1959), pp. 123-162.

Richter, C. F., "An Instrumental Earthquake Scale," Bulletin of the Seismological Society of America, Vol. 25, pp. 1-32, 1935.

Roberts, E. B., and F. P. Ulrich, "Seismological Activities of the U. S. Coast & Geodetic Survey in 1949," Bulletin of the Seismological Society of America, Vol. 41 (1951), pp. 205-220.

Saragoni, G. R., and G. C. Hart, "Simulation of Artificial Earthquakes," Int. Jour. Earthq. Engrg. Struct. Dyn., Vol. 2 (1974), pp. 249-267.

Saragoni, G. R., and G. C. Hart, "Time Variation of Ground Motion Frequency Content: Characterization and Relevance," Proceedings of the Fifth World Conference on Earthquake Engineering (1973), No. 156, Sess. 4A, Rome.

Sbar, M., Y. P. Aggarwal, and L. Sykes, "Study of Earthquake Hazards in New York and Adjacent States," U. S. Nuclear Regulatory Commission, Washington, D.C., sponsored by New York State Energy Research and Development Authority, 1977.

Sbar, M., J. Armbruster., and Y. P. Aggarwal, "The Adirondack, New York, Earthquake Swarm of 1971 and Tectonic Implications," Bulletin of the Seismological Society of America, Vol. 62, pp. 1303-1317, 1972.

923 152

Sbar, M. L., R. R. Jordan, C. D. Stephens, T. E. Pickett, K. D. Woodruff, and C. G. Sammis, "The Delaware-New Jersey Earthquake of February 28, 1973," Bulletin of the Seismological Society of America, Vol. 65, pp. 85-92, 1975.

Sbar, M. L., J. M. W. Rynn, F. J. Gumper, and J. C. Lahr, "An Earthquake Sequence and Focal Mechanism Solution, Lake Hopatcong, Northern New Jersey," Bulletin of the Seismological Society of America, Vol. 60, pp. 1231-1243, 1970.

Sbar, M. L., and L. R. Sykes, "Contemporary Compressive Stress and Seismicity in Eastern North America: An Example of Intra-Plate Tectonics," Journal of Geophysical Research, Vol. 84, pp. 1861-1881, 1973.

Sbar, M. L., and L. R. Sykes, "Seismicity and Lithospheric Stress in New York and Adjacent Areas," Journal of Geophysical Research, Vol. 82, pp. 5771-5786, 1977.

Schaefer, S. F., and R. B. Herrmann, "Seismic Risk Analysis Applied to the Central United States," Earthquake Notes, Vol. 48 (1977), No. 4: pp. 35-43.

Scott, R. E., "The Calculation of Horizontal Accelerations from Seismoscope Records," Bulletin of the Seismological Society of America, Vol. 63, No. 5 (1973), p. 1637.

Seed, H. B., R. Murarka, J. Lysmer, and I. M. Idriss, "Relationships of Maximum Acceleration, Maximum Velocity, Distance from Source, and Local Site Conditions for Moderately Strong Earthquakes," Bulletin of the Seismological Society of America, Vol. 66 (1976), pp. 1323-1342.

Seed, H. B., C. Ugas, and J. Lysmer, "Site-Dependent Spectra for Earthquake-Resistant Design," Earthquake Engineering Research Center, Report EERL 74-12, University of California, Berkeley (1974).

Seed, H. B., and I. M. Idriss, "Rock Motions Accelerograms for High Magnitude Earthquakes," Earthquake Engineering Research Center, University of California, Berkeley, Report EERC 69-7 (1969).

Shah, H.C., C.D. Mortgat, A. Kiremidjian, and T.C. Zsutty, "A Study of Seismic Risk for Nicaragua," Part I, The J.A. Blume Earthquake Engineering Center, Report No. 11, Dept. of Civil Engr., Stanford University, January 1975.

Shakel, A., and M. N. Toksöz, "Earthquake Hazard in New England," Science, No. 195 (4274), pp. 171-173, 1977.

Shlien, S., and M. N. Toksöz, "Frequency-Magnitude Statistics of Earthquake Occurrence," Earthquake Notes (Eastern Section of the Seismological Society of America), Vol. 41, pp. 5-18, 1970.

923 153

Shoja-Taheri, J., and B. A. Bolt, "A Generalized Strong-Motion Accelerogram Based on Spectral Maximization from Two Horizontal Components," Bulletin of the Seismological Society of America, Vol. 67, No. 3, pp. 863-876, 1977.

Simmons, G., "Our New England Earthquakes," Weston Geophysical, Westboro, Mass., 1978.

Smith, W. E. T., "Basic Seismology and Seismicity of Eastern Canada," Proc. Symp. on Design for Earthquake Loadings, McGill Univ., Montreal, Canada (1966), pp. I-1 to I-43.

Smith, W. E. T., "Earthquakes of Eastern Canada and Adjacent Areas, 1534-1927," Publications of the Dominican Observatory, 26 and 32 (Ottawa, Canada: Department of Mines and Technical Surveys, 1962).

Smith, W. E. T., "Earthquakes of Eastern Canada and Adjacent Areas, 1928-1959," Pub. Dom. Obs. Ottawa, Vol. 32, pp. 87-121, 1966.

Stauder, W., M. Kramer, G. Fischer, S. Schaefer, and S. T. Morrissey, "Seismic Characteristics of Southeast Missouri as Indicated by a Regional Telemetered Microearthquake Array," Bulletin of the Seismological Society of America, Vol. 66, No. 6, pp. 1953-64, 1976.

Stauder, W., and O. W. Nuttli, "Seismic Studies: South Central Illinois Earthquake of November 9, 1968," Bulletin of the Seismological Society of America, Vol. 60, pp. 973-981, 1970.

Street, R. L., "Scaling Northeastern United States/Southeastern Canadian Earthquakes by the Lg Waves," Bulletin of the Seismological Society of America, Vol. 66, pp. 1525-1538, 1976.

Street, R. L., and R. B. Herrmann, "Some Problems With Using Magnitude Scales for Eastern North American Earthquakes," Earthquake Notes, Vol. 47, p. 3, 1976.

Street, R. L., R. B. Herrmann, and O. W. Nuttli, "Earthquake Mechanics in Central United States," Science, No. 184, pp. 1285-1287, 1974.

Street, R. L., R. B. Herrmann, and O. W. Nuttli, "Spectral Characteristics of the Lg Wave Generated by Central United States Earthquakes," Geophysics Journal, Vol. 41, pp. 51-63, 1975.

Street, R. L., and F. T. Turcotte, "A Study of Northeastern North American Spectral Moments, Magnitudes, and Intensities," Bulletin of the Seismological Society of America, Vol. 67, No. 3, pp. 599-614, 1977.

Sykes, L. R., "Intraplate Seismicity, Reactivation of Pre-existing Zones of Weakness, Alkaline Magnetism, and Other Tectonism Post Dating Continental Fragmentation," Journal of Geophysical Research Reviews, 8RO530, 1978.

Taylor, S. R., and M. N. Toksoz, "Crustal Structure in New England," Earthquake Notes, Vol. 49, 1978.

Thatcher, W., "A Note on Discrepancies Between Local Magnitude (M_L) and Microearthquake Magnitude Scales," Bulletin of the Seismological Society of America, Vol. 63, pp. 315-319, 1973.

Tong, W-H, B. Schumacker, C. A. Cornell, and R. V. Whitman, "Seismic Hazard Maps for Massachusetts," Seismic Design Decision Analysis, Internal Study Report No. 52, Dept. of Civil Engineering, M.I.T., 1975.

Trifunac, M. D., "Preliminary Empirical Model for Scaling Fourier Amplitude Spectra of Strong Ground Acceleration in Terms of Earthquake Magnitude, Source-to-Station Distance, and Recording Site Conditions," Bulletin of the Seismological Society of America, Vol. 66 (1976), pp. 1343-1373.

Trifunac, M. D., "Analysis of Strong Earthquake Ground Motion for Prediction of Response Spectra," Intern. J. Earthq. Engr. and Struct. Dyn., Vol. 2 (1973), pp. 59-69.

Trifunac, M. D., "A Method for Synthesizing Realistic Strong Ground Motions," Bulletin of the Seismological Society of America, Vol. 61 (Dec., 1971), pp. 1739-1753.

Trifunac, M. D., and A. G. Brady, "Correlation of Peak Acceleration, Velocity and Displacement with Earthquake Magnitude Distance and Site Conditions," Earthquake Engineering and Structural Dynamics, Vol. 4, No. 5, p. 455, July-Sept., 1976.

Trifunac, M. D., and D. E. Hudson, "Analysis of the Station No. 2 Seismographic Record--1966, Parkfield, Calif., Earthquake," Bulletin of the Seismological Society of America, Vol. 60, No. 3, p. 785, 1970.

Trifunac, M. D., and D. E. Hudson, "Analysis of the Pacoima Dam Accelerogram San Fernando, California, Earthquake of 1971," Bulletin of the Seismological Society of America, Vol. 61, No. 5, p. 1393, 1971.

Trifunac, M. D., "A Three-Dimensional Dislocation Model for the San Fernando, California, Earthquake of February 9, 1971," Bulletin of the Seismological Society of America, Vol. 64, pp. 149-172, 1974.

Trifunac, M. D., and B. Westermo, "A Note on the Correlation of Frequency-Dependent Duration of Strong Earthquake Ground Motion with the Modified Mercalli Intensity and the Geologic Conditions at the Recording Stations," Bulletin of the Seismological Society of America, Vol. 67, No. 3, pp. 917-927, 1977.

Udwadia, F. E., and M. D. Trifunac, "Characterization of Response Spectra Through the Statistics of Oscillator Response," Bulletin of the Seismological Society of America, Vol. 64 (1974), pp. 205-219.

Udwadia, F. E., and M. D. Trifunac, "Damped Fourier Spectrum and Response Spectra," Bulletin of the Seismological Society of America, Vol. 63 (1973), pp. 1775-1783.

Ulrich, F. P., "Zones of Earthquake Probability in the United States," Building Standards Monthly, Vol. 17 (1948), No. 3, pp. 11-12.

United States Atomic Energy Commission, "Design Response Spectra for Nuclear Power Plants," Regulatory Guide 1.60, Revision 1, December, 1973.

Wallace, R. E., "Time-History Analysis of Fault Scarps and Fault Traces--A Longer View of Seismicity," 6th W.C.E.E., 2-409, p. 766, 1977.

Werner, S. D., and H. S. Tsao, "A Study of Vertical Ground Response Spectrum Shapes," Agbabian Associates, El Segundo, Calif. (1977), SAN/1011-114 (Prepared for Energy Research and Development Adm., Div. of Reactor Development and Demonstration).

Werner, S. D., "Evaluation of Earthquake Ground-Motion Characteristics at Nuclear Power Plant Sites," Proceedings of the U. S. National Conference on Earthquake Engineering, E.E.R.I., June 18-20, 1975, Ann Arbor, Mich., pp. 462-473.

Werner, S. D., "Evaluation of Earthquake Ground Motion Characteristics at Nuclear Plant Sites," Agbabian Associates, El Segundo, Calif. (1975), SAN/1011-107. (Prepared for Energy Research and Development Adm., Div. of Reactor Development and Demonstration).

Werner, S. D., and H. S. Tsao, "Investigations of Vertical Ground Motion Characteristics for Nuclear Plant Design," Agbabian Associates, El Segundo, Calif. (1975), SAN/1011-108. (Prepared for Energy Research and Development Adm., Div. of Reactor Development and Demonstration).

Werner, S. D., and H. S. Tsao, "Statistical and Probabilistic Considerations in Defining Seismic Input Criteria," Agbabian Associates, El Segundo, Calif., (1975), SAN/1011-104. (Prepared for Energy Research and Development Adm., Div. of Reactor Development and Demonstration).

Weston Geophysical Inc., "Justification of the Seismic Design Criteria used for the Sequoyah, Watts Bar, and Bellefonte Nuclear Power Plants," Supplemental Report: Prediction of Strong Motions for Eastern North America on the Basis of Magnitude to the Tennessee Valley Authority, 1978.

Wetmiller, R. J., "The Quebec-Maine Border Earthquake, 15 June 1973," Canadian Journal of Earth Sciences, Vol. 12, pp. 1917-1928, 1975.

Whitham, K., W. G. Milne, and W. E. T. Smith, "The New Seismic Zoning Map for Canada, 1970 Edition," The Canadian Underwriter, June 15, 1970.

Whitcomb, J. H., J. D. Garmany and D. L. Anderson, "Earthquake Prediction: Variation of Seismic Velocities Before the San Fernando Earthquake," Science, No. 180, pp. 632-635, 1973.

Whitman, R. V., and J. N. Protonotarios, "Inelastic Response to Site-Modified Ground Motions," J. Geot. Engr. Div., ASCE, 103 (GT10): pp. 1037-1053 (1977).

Wiggins, J. H., Jr., "Construction of Strong Motion Response Spectra from Magnitude and Distance Data," Bulletin of the Seismological Society of America, Vol. 54 (1964), pp. 1257-1269.

Willis, D. E., and J. T. Wilson, "A Note on the Anna, Ohio, Earthquake of July 26, 1968," Earthquake Notes, Vol. 41, p. 3, 1970.

Wilson, J. T., "A Comparison of Isoseismal Maps with Accelerations Calculated from Specified Earthquake Sources," Abstract, Trans. Am. Geophys. Union (1972), Vol. 53, p. 447.

Woolland, G. P., "Tectonic Activity in North America as Indicated by Earthquakes in the Earth's Crust and Upper Mantle," Pembroke Hart, Editor, Geophysical Monograph 13, AGU, 1969.

Yecgulalp, T. M., and J. T. Kuo, "Stctistical Prediction of the Occurrence of Maximum Magnitude Earthquakes," Bulletin of the Seismological Society of America, Vol. 64, No. 2, pp. 393-414, 1974.

York, J. E., and J. E. Oliver, "Cretaceous and Cenozoic Faulting in Eastern North America," Geological Society of America Bulletin No. 87, pp. 1105-1114, 1976.

Young, G. A., H. S. Tsao, and A. Der Kiŭreghian, "Problem Areas in the Application of Seismic Hazard Analysis Procedures," Agbabian Associates, El Segundo, Calif. (1976), SAN/1011-101. (Prepared for Energy Research and Development Adm., Div. of Reactor Development and Demonstration).

923 157