UCID-20421 Vol. 2

# SEISMIC HAZARD CHARACTERIZATION OF THE EASTERN UNITED STATES

## Volume 2: Questionnaires

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## Abstract

Volume 2 of this report contains the information given to the experts of the two panels (i.e. the Seismicity panel and the Ground Motion Model Panel). This information includes copies of the six questionnaires sent to the panel members.

The responses to questionnaires Q1,Q2,Q3 and Q4 are not specifically given in this Volume since they were not final. The reader may find a detail description of these responses in our interim report. In addition, questionnaire Q6, which is the feedback questionnaire to the Ground Motion Panel contains a complete summary of the responses to the previous questionnaire to the Ground Motion Panel.

The final set of responses, as they were used in the analysis, is presented in detail in Volume 1, of this report.

<u>VOLUME 2</u>

QUESTIONNAIRES
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## Description of Appendices in Volume 2

Volume 2 of this report contains the information given to the experts of the two panels (i.e. the Seismicity panel and the Ground Motion Model Panel). This information includes copies of the six questionnaires sent to the panel members. Although questionnaires Q1,Q2,Q3 and Q4 were documented in our interim report, Bernreuter et al. (1984), we also include them in this Volume for completeness.

The responses to questionnaires Q1,Q2,Q3 and Q4 are not specifically given in this Volume since they were not final. The reader may find a detail description of these responses in our interim report. In addition, questionnaire Q6, which is the feedback questionnaire to the Ground Motion Panel contains a complete summary of the responses to the previous questionnaire to the Ground Motion Panel.

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References

Bernreuter, D.L., Savy, J.B., Mensing, R.W. and Chung, D.H. (1984), Seismic Hazard Characterization of the Eastern United States: Methodology and Interim Results for Ten Sites, US NRC Report NUREG/CR-3756.

## Appendix A

## Questionnaires to the EUS Seismicity Panel

### A.1 Introduction

This appendix contains the complete text of the first three questionnaires sent to the EUS Seismicity Panel members. The first questionnaire (Q1) elicited the individual panel member's judgement about the zonation of the EUS. The second questionnaire (Q2), given in Section A.3, elicited the individual panel member's judgement about best estimates and the uncertainty in the following parameters:

- o The largest earthquake in each of the zones identified by the panel member in his/her answer to the first questionnaire.
- o The expected frequency or rate of earthquakes in each zone.
- o The magnitude (or intensity) recurrence relation for each zone.

In the third questionnaire (Q3), given in A.4, the experts were asked to provide a self weight which reflects how he/she perceives his/her level of expertise about his/her answers to Q1 and Q2.

The answers to the three questionnaires are summarized in A.5, Volume 1, Appendix A of this report.

## A.2 First Questionnaire-Zonation (Q1)

## 1. INTRODUCTION

### 1.0 Background

The purpose of this project, intiated by the U.S. Nuclear Regulatory Commission (NRC), is to "develop a seismic hazard characterization for the region of the United States east of the Rocky Mountains." One task of the project is to assess the seismicity of this region and to describe it in a form which can be used as input to a seismic hazard analysis. The seismic parameters of interest are:

- Seismo-tectonic zonation.
- Rate of earthquake occurrence.
- Distribution of earthquakes magnitudes.
- Largest earthquake, i.e. upper magnitude cutoff.

Because it is difficult, or perhaps impossible, to precisely quantify such seismic parameters using only the sparse historical record, expert judgement is crucial. Thus, a panel of experts has been assembled. The membership of the panel is:

Dr. Peter W. Basham

Professor Gilbert A. Bollinger

Dr. Michael A. Chinnery

Mr. Richard J. Holt

Professor Arch C. Johnston

Dr. Alan L. Kafka

Professor James E. Lawson

Professor L. Tim Long

Professor Otto W. Nuttli

Dr. Paul W. Pomeroy

Dr. J. Carl Stepp

Dr. Anne E. Stevens

Professor Ronald L. Street

Professor M. Nafi Toksoz

Dr. Carl M. Wentworth

As a member of the panel you have been selected based on your knowledge of the seismicity of all or part of the Eastern United States (EUS). We wish to thank you for your willingness to participate in the deliberations of the panel.

Some of you are familiar with the approach that we are taking as you participated in an earlier study. That study was limited to the assessment of the seismic hazard at the nine oldest reactor sites in the EUS. This study represents a generalization of the earlier study in that: (1) the approach is modified to incorporate methodology improvements suggested by our reviewers, and (2) the area to be dealt with is the entire EUS east of the Rocky Mountain front, including the offshore regions along the east and Gulf coastlines.

For those of you not familiar with our approach, we have enclosed the overview report from the previous study and give below a brief description of the elicitation process and analyses planned. The elicitation process will be in three stages. The first stage will be the elicitation of the seismo-tectonic zonation. This is the object of this questionnaire. You will be asked to describe a base map which identifies all potential source zones for the EUS. Since you may be uncertain about the existence and shape of some of the zones, you will be asked to provide plausible alternatives to individual features of your base map. From this information, a set of mutually exclusive zonation alternatives for the entire region can be derived. An appropriate subset of these alternative maps can be used to assess the seismic hazard at a specific site.

The second stage of this study, a questionnaire will be sent to you in order to elicit your opinion on the occurrence rate and magnitude distributions. Ideally, you should use your own set of historical seismicity data. However, if you desire, we will provide you such data in the form of a catalog of historic events. This catalog is described in Appendix 1. Specifically, for each zone in your base map as well as for the alternate zones, you will be given (1) a listing of all earthquakes in the zone having magnitudes greater than some pre-specified minimum, and (2) a table giving the number of earthquakes in the zone as a function of magnitude[1]. You will then be asked to respond to questions designed to elicit your opinion, in light of the data, regarding the earthquake occurrence rate, upper magnitude cut-off and magnitude distribution.

Your responses will then be combined and cross-checked to assure consistency in the results. Also, the results will be used to compute the seimic hazard at various locaions in the EUS. These hazard assessments will be made available to you in the third stage of the elicitation process so that you may assess the physical reasonableness of the seimic parameters elicited in the first two stages of our process.

The third stage of the process will start with a general meeting of the panel, and at that time you will have the opportunity to review results based on your input, as well as the results from the other panel members. In order to ensure anonymity, each panel member's results will be identified by some code which only that panel member will know. In addition, at the meeting we will discuss:

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1. We use the term magnitude as a general term referring to size, not as a specific measurement.

1. the models and approximations that we introduced to put your results into a form suitable for input into our hazard analysis;

2. the parameters which contribute the most to the uncertainty in the predicted seismic loading at the selected sites and to which the results are most sensitive; and

3. those areas which may need to be more carefully considered by the panel members.

After this meeting we will formally request that you revise your original responses if appropriate.

## 1.2 Description of the Seismic Hazard Analysis

Given source zone configurations and seismicity information from the first two questionnaires, along with an attenuation model, we can compute a hazard curve for any site in the EUS and any time period T. The hazard curve at a site is defined here to be the probability, P(A>a), that the maximum value of peak ground acceleration, A, induced at the site by earthquakes occurring within a T-year period exceeds the value a. Graphically, a typical hazard curve, plotted on a semi-logarithm scale, is given in Figure 1.1.

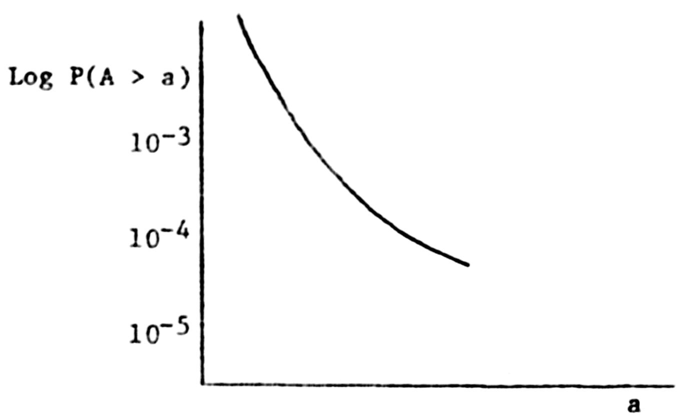


Figure 1.1 Typical Hazard Curve at a Site

To develop a hazard curve at a site, it will be necessary for us to adopt certain models to describe seismicity. From the responses to this questionnaire we will be able to develop a collection of maps (alternative source zone configurations for the EUS) for each expert. Given a map, we model the occurrence of earthquakes within each zone, where attention is restricted to earthquakes with magnitudes exceeding some pre-specified minimum, $M_m$. Following the standard hazard analysis practice, we assume that the occurrence of earthquakes can be approximated by a Poisson process.

You will be asked, in the second questionnaire, to estimate the space-time rate of occurrence, which is assumed constant within a zone, but which may vary from zone to zone. Given an earthquake, it is then necessary to model the magnitude distribution. You will be asked to model the magnitude-recurrence relationship for each zone and also to estimate the values of the parameters of the model (e.g., a linear model with an intercept and a slope as parameters). In addition, you will be asked your opinion about the existence of a physical upper bound on earthquake magnitudes. If you feel that you cannot give such an upper bound, or if you feel that the bound is so large as to be of no practical importance, then we will model the distribution of magnitudes with an upper limit equal to the largest observable value on your chosen measurement scale (e.g., XII on MMI scale). On the other hand, if you specify an upper magnitude cutoff, $M_u$, the range of the magnitude distribution will be restricted to the interval $[M_m, M_u]$. Your magnitude-recurrence model and your upper magnitude cutoff value will be combined to model the distribution of magnitudes for each zone.

Another essential ingredient in seismic hazard analyses is the attenuation model which relates peak ground acceleration at a site to earthquake magnitude and source-site distance. This portion of the project is not concerned with the choice of attenuation model. A second panel is being formed to assist in the selection of appropriate attenuation models and to estimate the parameters of the model.

The seismicity information for each expert is combined with the attenuation model to develop a "best estimate" hazard curve for each expert. Variations in the source zone configurations and uncertainty in the seismicity parameters will be combined to develop bounds for the hazard curve which reflect your level of confidence in your responses.

### 1.3 Discussion

Information about the seismicity in the EUS is available both in the form of recorded events (i.e., data) and in knowledge, held by individuals like yourselves, about the tectonic and geologic properties of the region which affect seismicity. Thus, it is appropriate to combine these two sources of information when characterizing seismic hazards in the EUS. Methods exist for analytically combining data with opinions, however, in this project we are relying on your abilities to assimilate the data with your knowledge in developing your responses to the questionnaires. Thus, we expect that you will review one or more catalogs of events, recognizing the shortcomings of the data (e.g., incompleteness of the catalogs). The data, in turn, should be combined with your general experience in the region, your knowledge of the geologic and tectonic features, similarities of the EUS with other regions, and other related information.

Throughout the questionnaires we will be asking you to associate a level of confidence to your responses. We will interpret your level of confidence to represent the degree to which you judge your knowledge, expertise, the historical data, etc., support a given response. In making this judgement we ask that you <u>not</u> be influenced by your level of expertise, for a given section of the EUS, relative to the other panel members. The latter measure of relative expertise (self-weighting) is only approproate when opinions from several individuals are combined to form a consensus. We will be eliciting such self-weights as a separate part of the elicitation process. To illustrate, suppose you are responding to a question about the existence of a zone in a section of the EUS for which you feel your level of expertise (self-weight) on a scale of 0.0-1.0 is 0.8. Based on your knowledge, review of past-events, etc., if you are 95 percent sure the zone should be identified, then your level of confidence in the existance of the zone is 0.95, not 0.95 x 0.8 = 0.76. [If you assign confidence of 0.76 to the zones existence, this implies that your confidence in its non-existence is 0.24, rather than 0.05].

We recognize the inherent difficulty of quantifying subjective judgement. However, substantial uncertainty is an unavoidable factor in assessing seismic hazard in the EUS. Until more data becomes available expert opinion about seismicity is an important source of information. It is widely accepted that subjective probability (i.e., in our terminology, level of confidence) is the uniquely appropriate means of quantifying uncertainty. Thus, eliciting your level of confidence is an attempt to assist you in sharpening and quantifying your opinions as well as to express your uncertainty. We encourage you to be as unbiased and complete as possible in responding to the questionnaire.

Although the goal is to describe the seismicity of the entire EUS, it is recognized that some of you will not feel comfortable in responding for the entire region. However, we urge you to supply zones for all regions if possible. Large uncertainties can be reflected in the range of alternatives presented and through the level of confidence associated with a response. We want to emphasize that, in addition to assessing the best estimate hazard curve and associated uncertainty for each expert, the intent of the project is not to obtain a consensus but to present the diversity of opinion among different experts. Therefore, we urge you to express your own knowledge and beliefs in your responses. Specifically, do not be reluctant to express unconventional and/or non-classical viewpoints.

If you feel that you cannot respond to our questions for certain regions of the EUS, this is acceptable. In that case respond only to the portion of the EUS for which you are knowledgeable. However, whatever portion of the EUS you respond to, we urge you to answer all questions.

## 2. SOURCE ZONE CONFIGURATION

### 2.1 Introduction

In this part of the elicitation process we are concerned with the specification of various seismic source zones. A zone is a region which has homogeneous seismic characterictistics in terms of rate of activity, magnitude disdtribution and upper magnitude cut-off. The intent of this section is to obtain the geographic boundaries of the major seismic zones and local tectonic features, e.g., faults, which should be considered in a seismic hazard analysis. The region to be considered is the Eastern United States and Southeastern Canada extending west to the Rocky Mountain front or roughly 104°W.

We will be asking you to draw a base map of the seismic source zones for the Eastern United States and Southern Canada on one of the maps provided . The base map should:

- o Identify all potential seismioc zource zones
- o Describe your "best estimate" of the boundaries of the zones.

It is recognized that you may have alternative views about the zonation other than your initial base map. Specifically, you may be uncertain about:

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

Thus, we will be asking you questions which will allow you to express such uncertainty.

We have provided several maps which can be used to indicate alternative source zone configurations. Please do not return your responses on any other working maps or even copies of the maps provided to you. In processing your responses, these maps will be digitized and therefore need to be all the same. If you need more maps, please do not hesitate to request them from us.

To assist you in interpreting and answering the questions for this part of the elicitation, we have included an illustration of the type of response we hope to derive from the questions in this section of the questionnaire. Please recognize that this illustration is not intended to reflect reality but only to illustrate the desired format for your responses. (In fact, the illustration was purposely done by a non-seismologist).

In the illustration, Figure A1 describes the base map, in response to Question 1-1. Each zone has been indexed. Indexing zones is necessary for later identification when one describes alternative configurations in response to later questions. In this illustration 15 zones were identified. Most of the zones are aras, except Zone 2 which is a line source. Table A1 illustrates the response to Question 1-2 on uncertainty in the existence of one or more zones identified on the base map. The zones identified in Table A1 are those for which the respondent was not sure about their existence, i.e., the need to identify a separate source zone different from the surrounding area. Two pieces of information are provided for each zone identified in Table A1:

- the respondent's level of confidence that a zone does exist

- if the zone is considered non-existent, the region must become part of another zone; this zone must be identified.

In the illustration, Zones 2, 3, 4, 5, 12, and 14 were considered potentially non-existent. The respondent's confidence in Zone 2 existing is 0.40 and if Zone 2 does not exist then that region becomes part of Zone 1. Similarly, the respondent has confidence 0.85 that Zone 3 must be identified as a separate source zone.

Responses to Question 1-3 on potential alternative boundary shapes for an individual zone or group of zones is illustrated in Figures A2 and A3 and Table A2. In this case, Zone 3 was considered to have two potential configurations; the elliptical shape on the original map and a triangular shape drawn on Figure A2. The respondent's confidence, conditional on the zone's existence, in the elliptical shape boundary was 0.6 and in the triangular boundary was 0.4. These are entered in Table A2. Also, in the illustration, alternative configurations for Zones 11 through 15 are drawn on Figure A2 as Zones 19 through 24. Finally, zones labeled 4 and 5 in the initial map were judged to have two additional boundary shapes. These are labeled 17 and 18 in Figure A2 and Zone 25 in Figure A3. Notice that in the latter alternative, the region originally described by two zones has been described by a single zone.

Although most of the source zones identified in the illustration represent areas, there are also relevant line and point sources, such as faults, which could be active or could otherwise serve to localize seismicity. It is important that you identify such line and point sources on your maps and treat them in your responses as another zone, indexing them, consider their existence/non-existence and possibly reshaping or relocating them on your alternative maps.

## 2.2 Questions

1-1 Using one of the maps provided, please draw your base map of potential source zones, along with their "best estimate" configurations, for the Eastern United States. Please index each zone identified on your map.

1-2 To express an uncertainty about the possible existence of an individual zone or cluster of zones, please record, by index number, in a table similar to Table A1, any regions which you are not certain should be identified as a zone. Indicate your level of confidence in its being a zone and indicate what zone that region will be part of if the zone does not exist.

1-3 To indicate possible alternative boundaries for an individual zone or cluster of adjacent zones, please isolate the zones you would like to reshape; provide as many alternative boundaries, on one or more of the maps provided, as you feel is necessary; and, in a table similar to Table 2, list the alternatives and give us an expression of your confidence (relative to the other alternative shapes for that zone or zones) in each alternative boundary shape.

As indicated in the Introduction we will provide, if you desire, a description of historical seismic activity relevant to your source zone configurations which you can use as a data base for responding to the questions on seismicity in the second stage of the elicitation process.

1-4 Do you desire to have us provide you a description of historical seismic activity in the EUS?

Yes ______ No _____

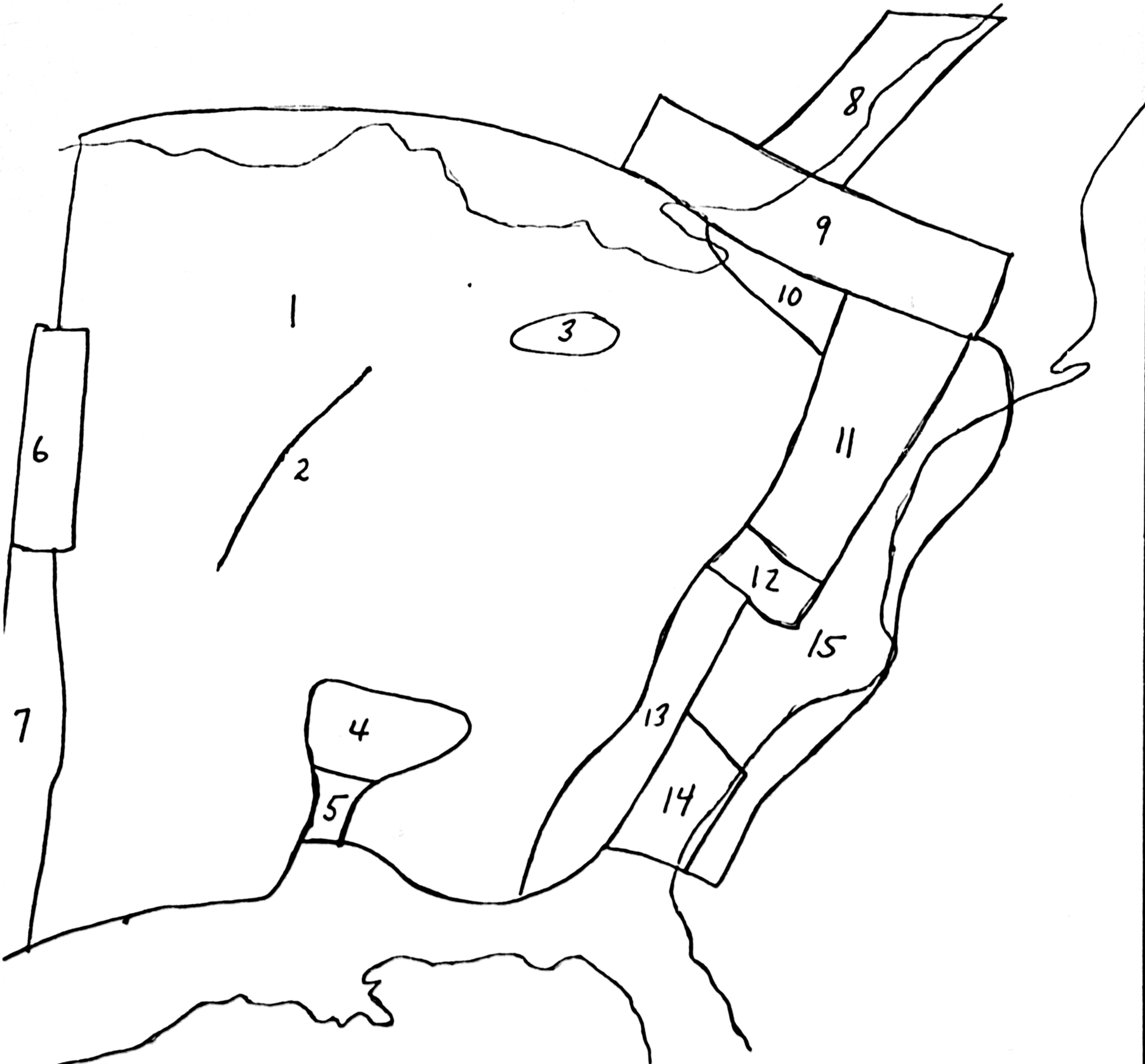


Figure A1. "Best Estimate" Source Zone Configurations

Table A1. Existence of Selected Zones

| Zone Index | Level of Confidence In Existence | Non-Existent Zone Becomes Part of Zone Number |
|---|---|---|
| 3 | 0.85 | 1 |
| 4 and 5 | 0.98 | 1 |
| 12 | 0.70 | 11 |
| 14 | 0.80 | 15 |

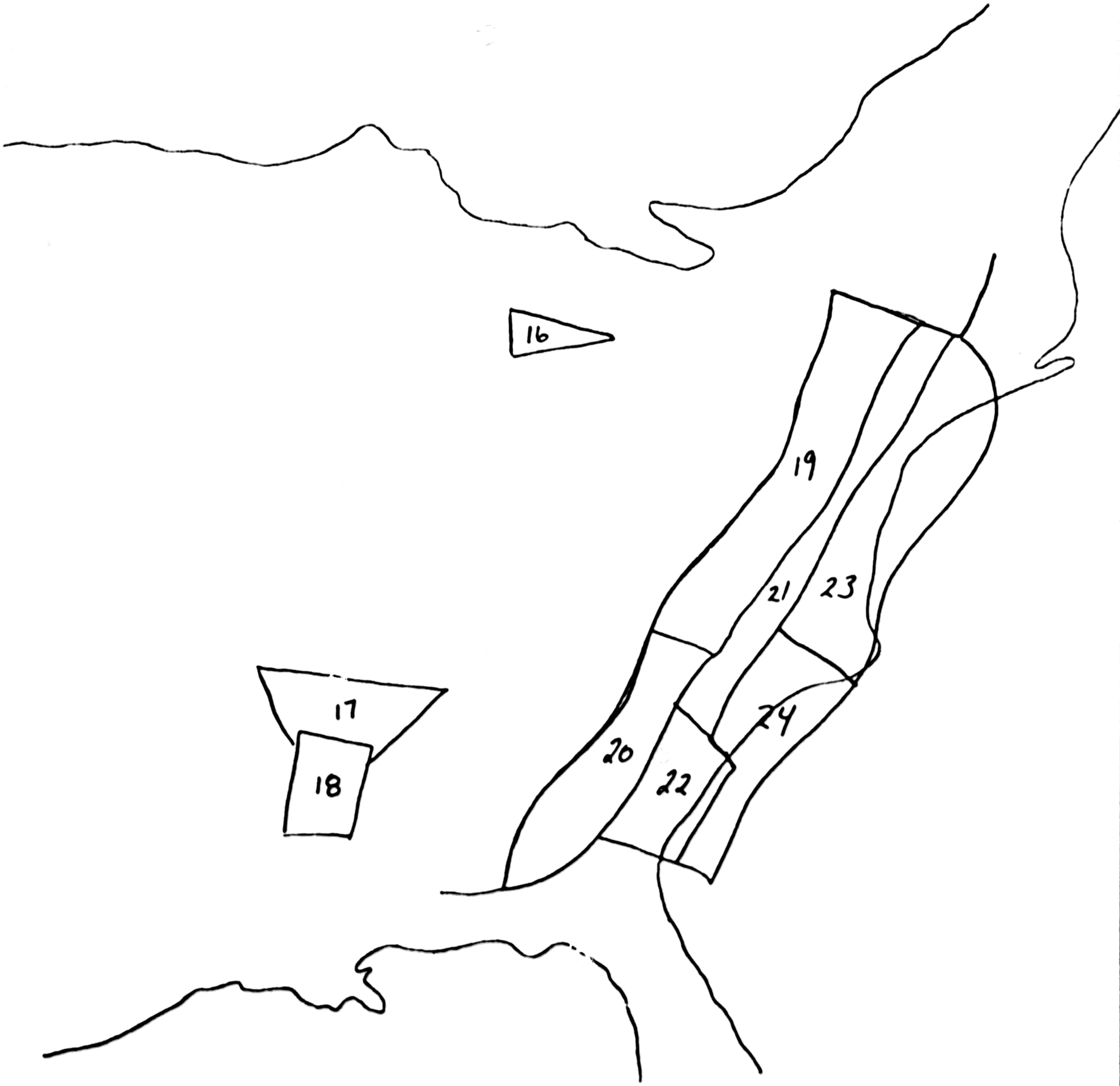


Figure A2. Alternative Source Zone Configurations

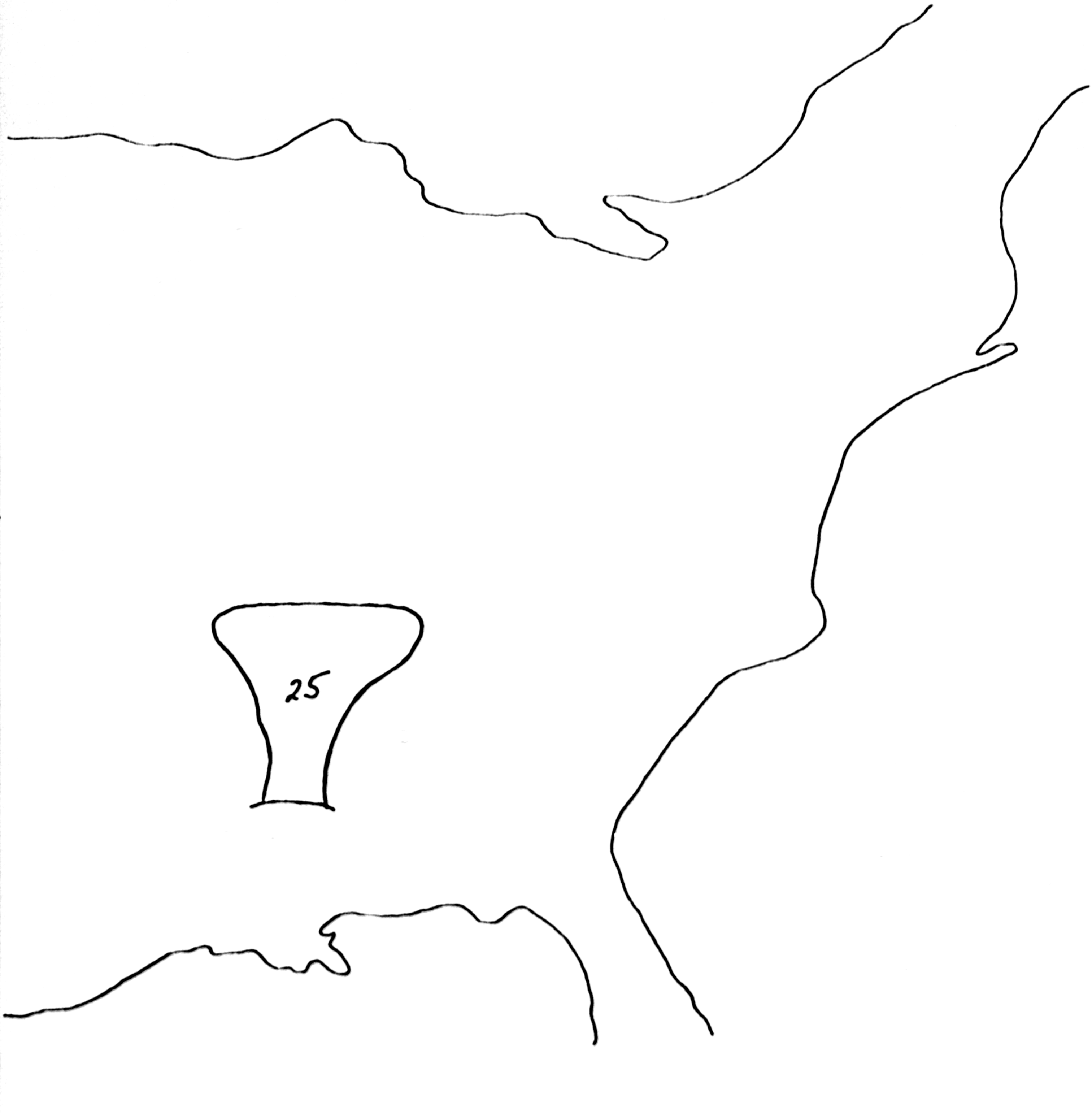


Figure A3. Alternative Source Zone Configurations

Table A2. Confidence for Alternative Boundaries

| Zone Index | Level of Confidence[1] In Boundary Shape |
|---|---|
| 3 | 0.6 |
| 16 | 0.4 |
| | |
| 4, 5 | 0.7 |
| 17, 18 | 0.15 |
| 25 | 0.15 |
| | |
| 11, 12, 13, 14, 15 | 0.7 |
| 19, 20, 21, 22, 23, 24 | 0.3 |

(1) Notice that for any specific region, the sum of the levels of confidence over alternative boundary shapes should be 1.0.

## A.3 Second Questionnaire: Seismicity Parameters (Q2)

## 1. EASTERN UNITED STATES SEISMICITY

### 1.0 Introduction

As part of the project to develop a seismic hazard characterization of the EUS, this questionnaire is designed to elicit your opinions about the seismicity of the source zones you identified in Questionnaire 1. For each of the zones[(1)] identified in your zonations of the EUS we will ask questions about:

- o The largest earthquake, i.e., upper magnitude cutoff
- o The expected frequency or occurrence rate of earthquakes
- o The magnitude-recurrence relation

We are returning to you digitized versions of the maps you developed for Questionnaire 1 as well as historical seismic data, if you requested this information.

In responding to questions about seismicity we expect that you will use one or more catalogues of historical events, either those of your own choosing or the catalogue we have supplied at your request. When using the catalogues to assess the future seismicity in the EUS it is important that you consider the validity and quality of the data as well as some potential shortcomings in using the recorded events to form your opinions. One issue you should consider is the potential incompleteness of the data. The completeness of a catalogue will depend on several factors, e.g., the length of recorded history, the population density and distribution during past events. Completeness is likely to vary between catalogues as well as between regions within a catalogue. It would be appropriate for you to correct for incompleteness when using the data to form your opinions. You should also be aware of potential inaccuracies in the location and size of the past events. In addition, aftershocks are a potential source of uncertainty when using historical data. Since our analysis is based on assuming earthquakes occur as a Poisson process, one might question the inclusion of aftershocks when using the data to assess seismicity. How to treat aftershocks is left to your discretion. Aftershocks have not been culled from the data in the catalogue we provided.

The extent to which you rely on the historical data to form opinions about the future seismicity of the EUS should be based on your judgements of the data. This may be based on your knowledge of the geologic and tectonic features of the area, similarities with other regions, theoretical considerations, results of studies available to you, and any other information you feel is related to the seismicity of the EUS. Thus, your responses to questions about seismicity should reflect your assimilation of the data with your knowledge and experiences relevant to the seismicity of the EUS and your evaluation of the historical record of seismicity in the various zones.

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(1) In using the generic term zone in this questionnaire, we are referring to all tectonic features (e.g., areas, faults) identified on your maps as potential sources of earthquakes.

For each seismic parameter used to characterize seismicity within a zone, e.g., the expected frequency of earthquakes, we will ask you to give your best estimate of the value of the parameter. In addition, we will ask you to give an interval of values for each parameter to which you associate a high degree of confidence. As discussed in the Introduction in Questionnaire 1, confidence is considered to reflect your state of knowledge regarding the seismic parameter conditional on the historical data, your knowledge about and experiences with the geologic and tectonic conditions in the EUS, and any other information relevant to the seismicity in the region. We do not ask you to associate a specific level of confidence with the interval because of the difficulty we expect you would have in distinguishing between similar confidence levels, e.g., distinguishing between 90 and 95 percent levels of confidence. However, in our analysis we will model your state of knowledge about a parameter by assigning a probability distribution to each seismic parameter. Your best estimate and confidence bounds will be used to estimate the parameters of the probability distribution. In this context we will associate a specific level (e.g., 95 percent) of confidence with your interval. This interval should represent a set of values, in which you are highly confident that it includes the true value of the parameter. The width of the interval should reflect the uncertainties you have about the seismicity within a zone.

We would like to emphasize that it is important, for the success of this project, that you respond to <u>all</u> questions for each of the zones identified in the first questionnaire. Thus, even if you are uncertain about one or more seismic property for a zone, we encourage you to express an opinion. Your uncertainty should be reflected in your responses to questions involving a statement of confidence. Moreover, even if you believe some seismic features (e.g., the magnitude-recurrence relation model) are similar for all zones, you should consider each zone individually in making your responses. For example, even if your best estimate of the slope of a linear magnitude-recurrence relation is the same for all zones, your uncertainty about this parameter may vary from zone to zone; one reason for this is that the quality and amount of historical data varies from zone to zone. This variation in uncertainty should be reflected in varying confidence bounds for the slope from zone to zone.

To help you understand the reasons for the questions we pose in this questionnaire as well as why we emphasize the need for you to respond to all questions, we will outline how the three items addressed in this questionnaire (frequency of earthquakes, upper magnitude cutoff, magnitude- recurrence relation) enter into the hazard analyses.

For this project, seismic hazard at a site is defined as the probability P(A a) that the peak acceleration A at the site exceeds the value a. That is, P(A a) is the probability that at least one earthquake occurs for which the peak acceleration at the site exceeds a. This probability is experessed per unit time, e.g., $2.8 \times 10^{-3}$ per year. The seismic hazard curve is frequently described by a plot of the logarithm of P(A a) versus a. (See Figure 1.1 in Questionnaire 1.) The peak acceleration at a site is assumed to be functionally related to earthquake magnitude and source-to-site distance.

Hence, the hazard $P(A > a)$ depends on the distribution of peak acceleration conditional on magnitude and source-to-site distance, as well as the distribution of magnitudes, integrated over relevant source zones. The upper magnitude cutoff is the parameter of the distribution of magnitudes which defines the largest possible earthquake for each zone. The expected frequency of earthquakes and the magnitude-recurrence relation are jointly used to describe the frequency of magnitudes between the specified minimum level $M_0$ and the upper magnitude cutoff $M_U$. Our hazard analysis methodology, similar to that used in the previous study, uses your inputs about the seismicity within a zone to estimate the expected frequency of earthquakes for a finite set of magnitude intervals spanning the range between $M_0$ and $M_U$. Assuming a Poisson model for the occurrence of earthquakes in each zone, we can integrate over the relevant zones to assess the seismic hazard at a site, conditional on the values of the seismic parameters.

We will combine your best estimate and interval estimates of the seismic parameters, along with your responses to the questions in Section 4, to specify a joint probability distribution for the seismic parameters. This distribution will be used to assess a best estimate hazard curve and bounds for the hazard curve which represent your uncertainties in the seismicity of the EUS. Details about the appropriate probability distributions and about how we will interpret your inputs to estimate these probability distributions are discussed in the respective sections of the questionnaire. A discussion of the precise method for assessing the seismic hazard at a site and propagating the uncertainties through the analysis are too complex to present in this introduction. Details for the complete seismic hazard analysis, including the procedures for propagating uncertainty through the analysis, will be presented for your review at the general meeting of the panel during the third stage of the elicitation process.

## 2. UPPER MAGNITUDE CUTOFF

### 2.1 Introduction

An important parameter of the magnitude distribution is the upper limit of the range of magnitude values. This limit corresponds to the largest magnitude that will occur given the current geologic and tectonic conditions within a zone. This part of the questionnaire is concerned with eliciting your opinions about this limiting magnitude value for each zone identified in your seismic zonation of the EUS.

When one considers the magnitude of the largest event that can occur in a source zone, one might imagine that this will depend on the time length to be considered. For example, if one considers periods of 150 years and 1,000 years, one might expect the magnitude of the largest event to be different for the two time periods. In fact, if one were able to record the magnitudes of all earthquakes within a source zone over two such time intervals it would not be unusual for the largest event in 150 years to be different than the largest event in 1,000 years. This would be true even if the tectonic and geologic conditions of the region remained constant over time, since the magnitude of the largest event in T years, $M_T$, is a random variable. Thus, values observed over the 2 time periods would be realizations from two distributions of values. It is true that the probability distributions of these random variables will depend on T. However, assuming that the seismic, tectonic, and geologic conditions of the region remain constant over time, the range of values, specifically the lower and upper limits of the distributions, will be the same for both distributions. Conceptually, the relationship between the distributions of the largest earthquake in 150, 500, and 1,000 years is shown in Figure 2.1. Notice that all three distributions have a common upper limit, denoted $M_U$. However, the probability that the largest earthquake has a magnitude close to $M_U$ decreases as the time period T decreases. This common upper limit is the parameter of interest in this section of the questionnaire.

The assumption that the range of values of the distribution of magnitudes is independent of time suggests, perhaps, that the value of the upper limit must include magnitudes of events which may occur as a result of potential long term changes in geologic and tectonic conditions. This is not the case for this project. In your responses, you should not consider the consequences of a change in tectonic conditions, for example, a change of the Atlantic margin to a subduction zone. The purpose of this project is to consider the seismicity of the region as it exists today and can be expected to exist in the near geological future.

The tectonic and seismic conditions currently existing within a zone will limit the magnitude of an earthquake, should an earthquake occur. This limiting value of magnitude, determined by the physical conditions within a zone, is the upper limit of the distribution of magnitudes. We refer to this parameter as the upper magnitude cutoff.

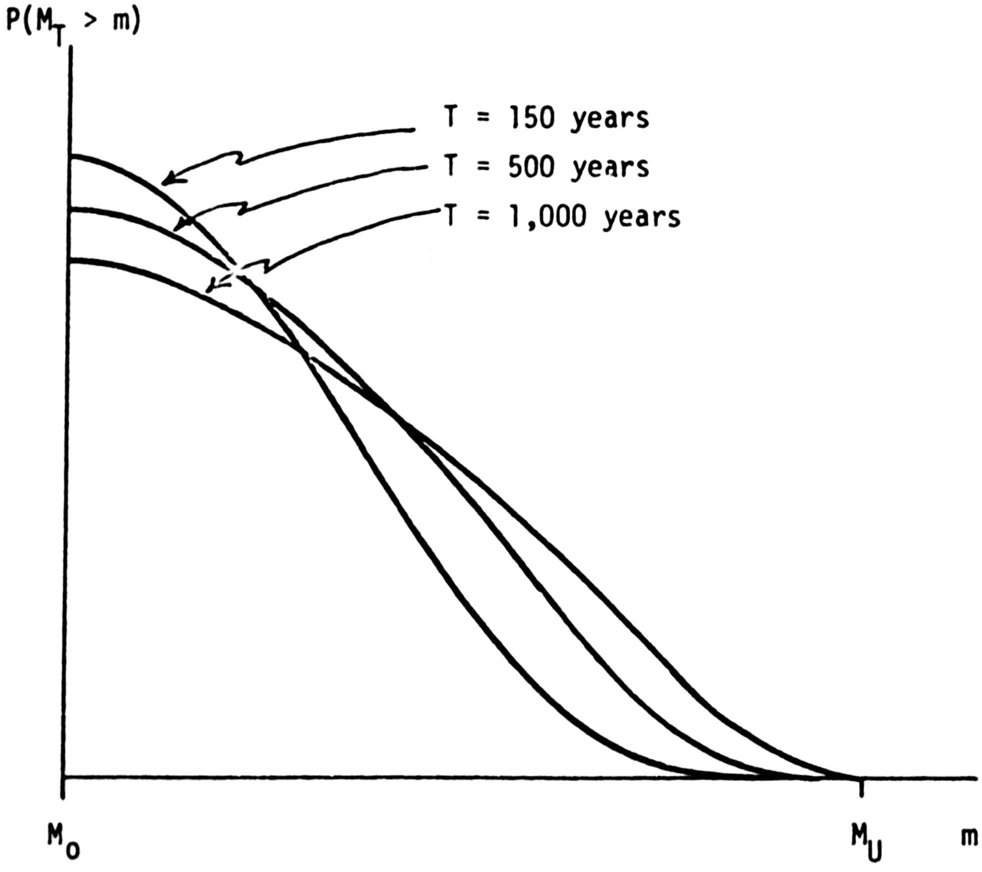


Figure 2.1 Probability that the Magnitude of the Largest Earthquake, $M_T$, in T Years Exceeds m.

Definition:

Upper Magnitude Cutoff, $M_U$ - the upper limit for the distribution of earthquake magnitude within a zone, given the current tectonic and seismic conditions.

If the current tectonic and seismic conditions were to remain stationary and the magnitudes of all earthquakes were recorded for a long time, the collection of magnitudes would form a distribution of magnitudes, the upper limit of which is the parameter $M_U$. The parameter $M_U$ should be distinguished from the random variable $M_T$ discussed above.

An important consideration in the assessment of the upper magnitude cutoff is the saturation properties of the measurement scales presently used to describe the magnitude of an earthquake. For example, the Modified Mercali Intensity (MMI) scale has an upper value of XII. Thus, no matter what the total energy (or moment) associated with an earthquake, its magnitude, when measured in MMI, can never exceed XII. Similarly, the energy (or moment) - magnitude relationship, when magnitude is measured in $M_{bLg}$ units, is described in Figure 2.2. Thus, when responding to questions concerning an upper magnitude cutoff, if one's response is expressed relative to observable magnitude values, the magnitude saturation value is an upper limit. On the other hand, when assessing the upper magnitude cutoff you may not want to be constrained by the saturation value. This can be done by expressing one's opinion in an alternative magnitude scale (e.g., in $M_s$). Alternatively, to avoid problems of changing magnitude scales (e.g., from $M_s$ to $M_{bLg}$) and the uncertainty of the relation between scales, you may want to continue the linear portion of the moment-magnitude relation beyond the saturation value (indicated by the dashed line in the figure). To allow you as much flexibility as possible in expressing your views about the upper magnitude cutoff, you should feel free to consider or not consider the saturation of the measurement scale in your responses. We do ask you, however, in Question 2-2 to indicate if you are limited by a saturation value.

In Question 2-4 we ask you to specify an interval for the upper magnitude cutoff $M_U$ to which is associated a level of confidence. This interval will be combined with your best estimate to describe your uncertainty about the value of $M_U$. In this description we will treat your best estimate as the most likely value (mode) and the endpoints of the interval as the limits of a triangular distribution similar to that shown in Figure 2.3. If you feel the triangular distribution does not adequately describe your uncertainty in the value of the upper magnitude cutoff, you should indicate an appropriate distribution in response to Question 2-5. Such a distribution can be expressed in terms of a density (relative frequency) function e.g., the uniform density function in Figure 2.4a, or in terms of a cumulative distribution function, e.g., the uniform distribution function in Figure 2.4b.

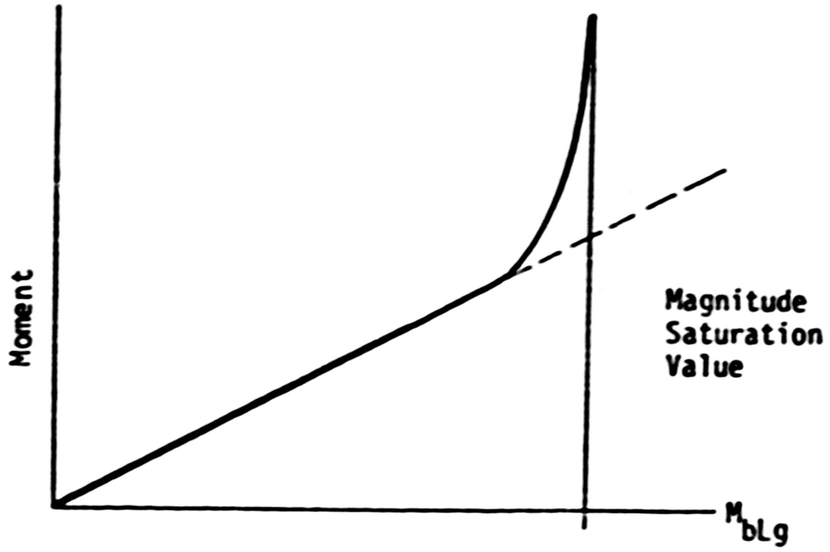


Figure 2.2 Moment - Magnitude Relationship

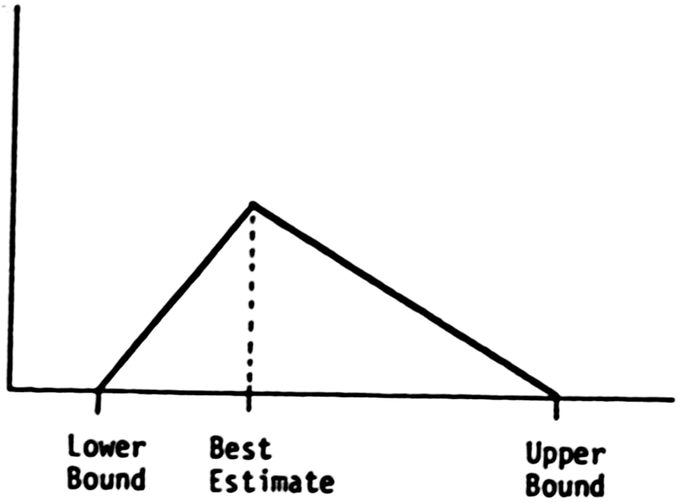


Figure 2.3 Triangular Density Function

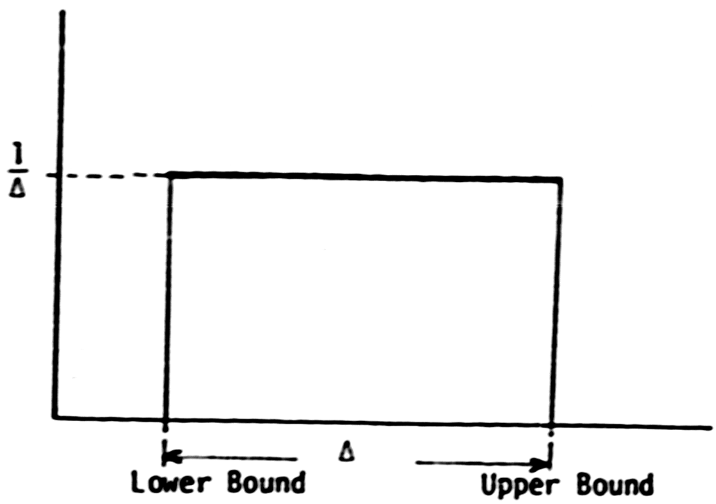


Figure 2.4a  Uniform Density Function

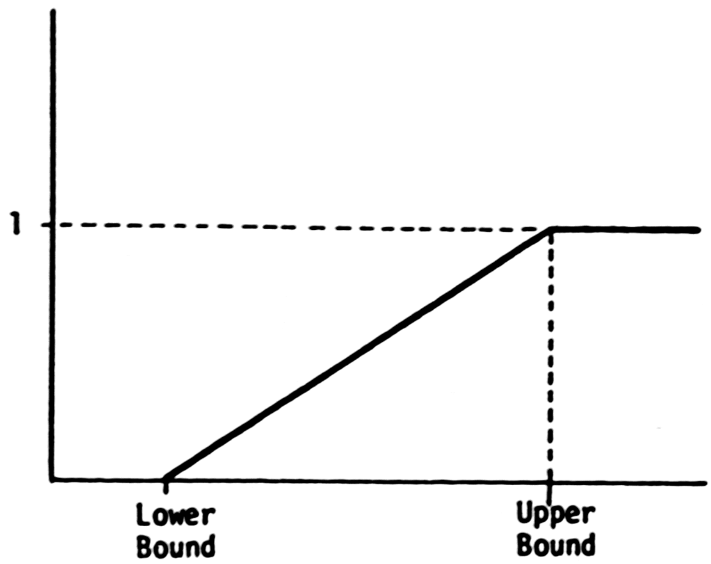


Figure 2.4b  Uniform Distribution Function

## 2.2 Questions

For each of the seismic source zones identified on your maps of the zonation of the EUS.

2-1 What scale of measurement (e.g., MMI, $M_{bLg}$, etc.) for earthquake magnitude will you use for your responses to questions about the upper magnitude cutoff? (Note: It is not necessary to use the same scale for all zones; indicate, separately, the scale you are using for each zone.)

2-2 Will you, in your responses concerning the upper magnitude cutoff, be constrained by the saturation value (e.g., XII on the MMI scale) on your chosen scale of measurement? If so, what is the saturation value?

2-3 Given the current tectonic and seismic conditions for each zone, give your best estimate (most likely value) for the upper magnitude cutoff $M_U$ for the distribution of magnitudes for the zone.

2-4 Give a lower bound $M_{UL}$ and an upper bound $M_{UU}$ for the value of the upper magnitude cutoff such that the range ($M_{UL}$, $M_{UU}$) is a reflection of your confidence in estimating the upper magnitude cutoff. As indicated in Fig. 2.2, the interval ($M_{UL}$, $M_{UU}$) will be treated as a 100% confidence interval for $M_U$.

2-5 Does the triangular distribution adequately describe your uncertainty in the value of the upper magnitude value? If not, please indicate an appropriate distribution.

## 3. EARTHQUAKE OCCURRENCES

### 3.1 Introduction

In this part of the questionnaire we elicit your opinions about the occurrence of earthquakes with magnitudes between a minimum magnitude $M_0$ and the upper magnitude cutoff in each of the source zones identified on your maps of the zonation of the EUS. For this project, the minimum magnitude, in MMI units, is $M_0$ = IV and, in $M_{bLg}$ units, is $M_0 = 3.75$. To elicit your opinions we ask you to respond to questions about:

1. The expected frequency (occurrence rate) of earthquakes with magnitude equal to or greater than $M_0$ within a zone.

2. The magnitude-recurrence relation within a zone.

We recognize that by requesting your opinions about the expected frequency and the magnitude-recurrence relation, we are potentially eliciting redundant information. Specifically, for a specific time period, if the magnitude-recurrence relation is applicable at $M_0$ then it can be used to estimate the expected frequency of earthquakes with magnitude equal to or greater than $M_0$. However, since the magnitude-recurrence model is usually derived from historical data, data which might be incomplete for magnitudes close to $M_0$, one might believe that the magnitude-recurrence model does not hold for all magnitudes. In this case, the two sets of questions are not redundant but provide needed inputs into the seismic hazard analysis. We further address the issue of the range of applicability of the magnitude-recurrence relation in Section 3.4.

By asking both questions, it provides you an opportunity to estimate the expected frequency by viewing the historical data from more than one perspective. For example, an estimate of the expected frequency can be based on only the number of earthquakes occurring over a period of time. On the other hand, the estimate from the magnitude-recurrence relation is influenced by the model used to fit the historical data. Thus, we have estimates of similar parameters based on different methods of analyzing the historical data. We recognize, of course, that you may choose to use entirely different procedures as a basis for your responses.

In any case, we request that you respond to questions about both expected frequency and the magnitude-recurrence relation. In doing such we hope that you will consider both questions separately and not derive the obvious response of one from the other. This permits us to treat your responses to both sets of questions equally in the seismic hazard analysis.

In responding to questions regarding the occurrences of earthquakes we expect you will use historical data on the seismic activity in the EUS, either your own data or the catalogue of historical events we have provided. Of course, when using this data to subjectively assess future seismicity in the EUS it is important that you use your judgment as to the validity, quality, and completeness of the data in determining how much you will rely on the data to form your opinions. If you are using the catalogue that we provided at your request, it should be recognized that no corrections for completeness have been performed on it nor have aftershocks been culled from the data. The analysis of the completeness of the catalogue and the use of aftershocks has been left to your discretion. Your judgments of the data may be based on geologic and tectonic considerations, similarities with other regions, theoretical considerations, results of your own studies or other studies available to you, or any other information which you feel influences the seismicity in the EUS.

We will ask you to provide your best estimate of the seismicity parameters and to express your uncertainty about each parameter by specifying an interval for the value of the parameter to which you associate a high degree of confidence. When modeling your uncertainty about the parameters in this section, the confidence interval is interpreted to be the set of values for which your personal confidence is 0.95 (i.e., a 95 percent level of confidence) that the true value lies within that range. As discussed earlier, the level of confidence reflects the degree to which you judge the data, tectonic and geologic conditions, etc., support a given response.

In the seismic hazard analysis, rather than imposing a parameteric model on the magnitude distribution, we take a nonparametric approach and base our analysis on the occurrence rate for each subinterval in a finite partition of the magnitude range ($M_0$,$M_U$). Your best estimates and confidence bounds for the seismic parameters are transformed into a best estimate and confidence bounds for the magnitude-recurrence relation using the functional form (e.g., linear) of the relation you supply. The best estimate and confidence bounds for the magnitude-recurrence relation will be used to specify the means, variances and covariances of the occurrence rates for the subintervals. These will, in turn, be used to determine the parameters of the joint distribution of the occurrence rates, which is modeled as a multivariate gamma distribution.

## 3.2 Magnitude Scale

When analyzing your responses to questions about earthquake occurrences it is important that the magnitude scale you use in making your responses be clearly identified. You are free to use whatever scale you feel permits you to best express your opinions about seismicity within a zone. The same scale need not be used for all zones. In Question 3-1 we ask you to identify the magnitude scales you will use in your responses about earthquake occurrences.

The seismic hazard analysis will be based on magnitudes in either the MMI or $M_{bLg}$ scales. Thus, if you use any other magnitude scale it will be necessary to transform the responses in your chosen scale to statements on either the MMI or $M_{bLg}$ scale. To make this transformation we will need to know the relationship between the magnitude scales you will be using and either MMI or $M_{bLg}$. To ensure the integrity of your answers, we ask you to describe this relation.

Also, the hazard analysis will involve several ground motion models, some of which involve intensities and some involving magnitudes. Thus, it is necessary for us to move between the epicentral intensity $(MMI)_E$ expressed in the MMI scale and $M_{bLg}$ scale. To do this we propose to use the relation

$$(MMI)_E = 2M_{bLg} - 3.5$$

If you do not feel that this is the best model for relating $(MMI)_E$ and $M_{bLg}$ measurements, you can indicate such in your response to Question 3-4.

Finally, the seismic hazard analysis is based on assessing the hazard at a site in the EUS due to earthquakes with magnitudes above a minimum level. For purposes of this project, the minimum magnitude, $M_o$, is either $(MMI)_E$ = IV or $M_{bLg} = 3.75$. In this analysis it is assumed, from a structural standpoint, the effect on a nuclear power plant of earthquakes of magnitude below IV or 3.75 will be insignificant and hence need not be taken into consideration. If you respond to questions about seismicity in other than the MMI or $M_{bLg}$ scales, it is important to identify the corresponding minimum level.

Questions

3-1 In your responses to questions about earthquake occurrences, please list all the magnitude scales you will use. Note: It is not necessary to use the same scale for all zones.

For any magnitude scale other than MMI and $M_{bLg}$ identified in Question 3-1, please

3-2 Describe the relationship between that scale and either the MMI or $M_{bLg}$ scale.

3-3 Indicate the minimum magnitude, $M_o$, below which the effect of the earthquake will be insignificant.

When transforming between $(MMI)_E$ and $M_{bLg}$ scale in our analysis we propose to use the relation

$$(MMI)_E = 2M_{bLg} - 3.5$$

3-4 Do you agree with this relation? If not, please indicate the relationship you believe is more appropriate.

## 3.3 Expected Frequency of Earthquake

An important parameter for characterizing the seismicity of a zone is the frequency with which earthquakes occur within the zone. Since a seismic hazard analysis is based on considering the effect of earthquakes having magnitudes or epicentral intensities greater than some minimum level, we are only interested in the occurrence of earthquakes with magnitude at the minimum level or greater. The questions in this part of the questionnaire are designed to elicit information about the expected frequency of earthquakes within a zone with magnitudes at or above the minimum level.

For purposes of this project the minimum magnitude, $M_O$, is either $(MMI)_E$ = IV or $M_{bLg}$ = 3.75. If you are responding to questions about magnitude in any other scale, e.g., in $M_s$ units, there is a corresponding minimum level below which the effect of the earthquake on a nuclear power plant will be insignificant.

The expected frequency can be expressed either in terms of the rate of occurrence within a zone per year, e.g., 0.313 per year, or the number of earthquakes expected to occur in a zone within a specified period of time, e.g., 47 in 150 years. The time period is left to your discretion. The period you use may depend on the catalogue of historical data you choose and your opinion about the completeness of the data. The same time period need not be used for all zones. We are interested in assessing the seismic activity in each zone under the geologic and tectonic conditions as they exist today and can be expected to exist in the near geological future. Thus, in using the historical data one must judge, in addition to the completeness of the data, how well past seismic activity reflects activity that may occur in the future under present conditions.

Questions

For each of the seismic source zones identified on your maps of the zonation of the EUS:

3-5 What scale of measurement for earthquake magnitude will you use for your responses to questions about the expected frequency of magnitudes greater than $M_O$?

3-6 Give your best estimate of the expected frequency, either in terms of the mean rate per year or the expected number in T years, of earthquakes with magnitude at or above $M_O$ occurring within the zone. Indicate the time period T.

Note: The expected frequencies should be expressed as the rate (number) per zone, not per unit area.

3-7 Give an interval which you believe, with a high degree of confidence, represents the possible values of the expected frequency.

### 3.4 Magnitude Distribution

Conditional on an earthquake of magnitude $M_O$ or greater occurring within a zone, the magnitude of the earthquake can be any value between $M_O$ and $M_U$, the upper magnitude cutoff. Thus, given that an earthquake occurs within a zone, its magnitude is the value of a random variable drawn from a distribution of magnitudes. The purpose of this part of the questionnaire is to elicit information which characterizes this distribution.

Several methods can be used to describe the magnitude distribution. Certainly, one simple method would be to list a set of distinct magnitude values along with the frequency or relative frequency corresponding to each magnitude. However, the method most often used is based on the magnitude-recurrence relation. This is a model for the relationship between the $\log_{10} N_m(T)$ and m for magnitudes between $M_o$ and $M_U$, where $N_m(T)$ is the number of earthquakes exceeding magnitude m in T years. Three such models, or magnitude-recurrence relations, are illustrated in Figure 3.1. The choice of the function , e.g., linear, quadratic, piecewise linear, as well as the values of the model parameters, e.g., a, b, c, characterize the magnitude distribution.

Another method for describing the magnitude distribution, which may be analogous to specifying a magnitude-recurrence relation, is to model the magnitude distribution in terms of a well known probability distribution, e.g., the exponential distribution. The choice of the distribution, e.g., exponential, as well as the values of the parameters of the distribution characterize the magnitude distribution. When using well known probability distributions it must be recognized that most probability distributions are defined over an infinite range, e.g., zero to infinity. Since the upper magnitude cutoff, $M_U$, is finite, it will be necessary to truncate the probability distribution at $M_U$ when using such models to describe the magnitude distribution.

Although any of these methods is adequate to describe the magnitude distribution, it is most convenient for our analysis to characterize the magnitude distribution in terms of the magnitude-recurrence relation. Thus, we encourage you to respond to Questions 3-8 through 3-16 which elicit information about the magnitude distribution in terms of the magnitude-recurrence relation. However, if you feel you can better characterize the magnitude distribution using another method then please use the alternative method. In any case, it is important that the magnitude distribution be completely characterized, i.e., both functional form and parameter values, for all zones.

Questions

Questions 3-8 through 3-16 are based on characterizing the magnitude distribution in terms of a magnitude-recurrence relation. If you are using an alternative method to describe the distribution of magnitudes, skip questions 3-8 through 3-16 and go directly to Question 3-17.

3-8 What scale of measurement (e.g., MMI, $M_{bLg}$) for earthquake magnitude will you use for your responses to questions about the magnitude-recurrence relation?

3-9 Will you, in your responses concerning the magnitude-recurrence relation, be constrained by the saturation value on your chosen scale of measurement? If so, what is the saturation value?

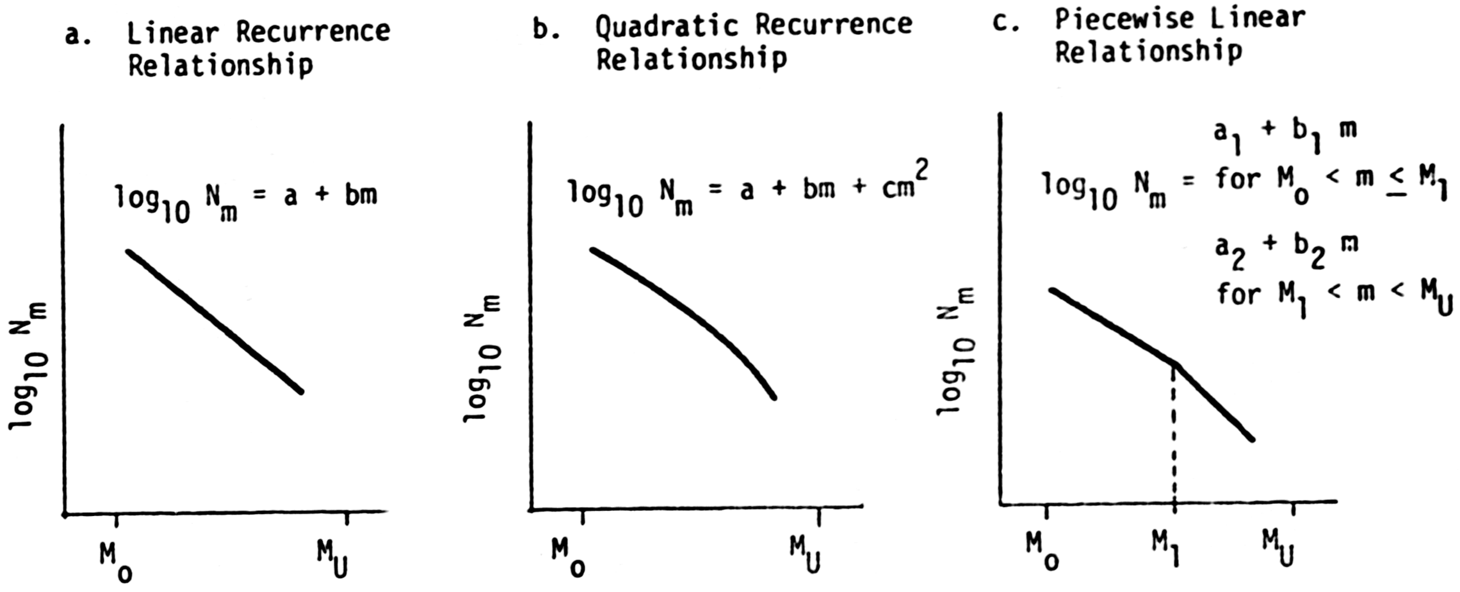


**Figure 3.1 Magnitude-Recurrence Relations**

In using the magnitude-recurrence relation to characterize the magnitude distribution it must be recognized that the model is an empirical relation based on historical data collected over T years. Since the entire magnitude range may not be represented in the historical data, the model derived from the data may not be applicable for all magnitudes between the minimum magnitude $M_o$ and your maximal upper magnitude cutoff $M_{UU}$. We ask you to identify the range of magnitudes, denoted $M_{LB}$, $M_{UB}$, in Question 3-14. This range may vary from zone to zone.

It is necessary for the seismic hazard analyses, however, to characterize the magnitude distribution for all magnitudes including the magnitudes between $M_o$ and $M_{LB}$ and between $M_{UB}$ and $M_{UU}$. Thus, it is necessary to extrapolate the magnitude-recurrence model beyond the range ($M_{LB}$, $M_{UB}$). You can indicate how this should be done by responding to questions 3-10 and 3-11. If you do not suggest a method we will extrapolate the magnitude-recurrence relation beyond $M_{LB}$ and $M_{UB}$ by a method based on assuring a continuous derivative at $M_{LB}$ and $M_{UB}$, a zero derivative at $M_U$ and a value at $M_o$, on the $N_m$ scale, equal to the expected frequency of earthquakes with magnitude equal to or greater than $M_o$, the minimum magnitude. A graphical illustration, assuming a linear magnitude-recurrence relation, is given in Figure 3.2. Note, the vertical scale in Figure 3.2(a) is $N_m$ rather than $\log_{10}N_m(T)$ and $\log_{10}N_m(T)$ in Figure 3.2(b). For each of the seismic source zones identified on your maps of the zonation of the EUS

3-10 Indicate the magnitude-recurrence model (e.g., linear, a + bm; quadratic, $a + bm + cm^2$) which, in your opinion, best represents the seismicity of the zone.

Notes: a. The same model need not be used for all zones.
b. If a piecewise model is chosen, part of the model is the specification of the "change points" e.g., $M_1$ in Figure 3.1c.

3-11 For the model chosen in Question 3-10 give your best estimate of the value of the parameters of the model (e.g., values of a, b, c).

3-12 Specify the time length, T, on which your estimates of the parameters identified in Question 3-11 are based.

3-13 Give an interval which you believe, with a high degree of confidence, represents the possible values for each parameter identified in your response to Question 3-11.

3-14 Specify the range of magnitude values, denoted ($M_{LB}$, $M_{UB}$), for which the magnitude-recurrence relation identified in Questions 3-10 and 3-11 is applicable.

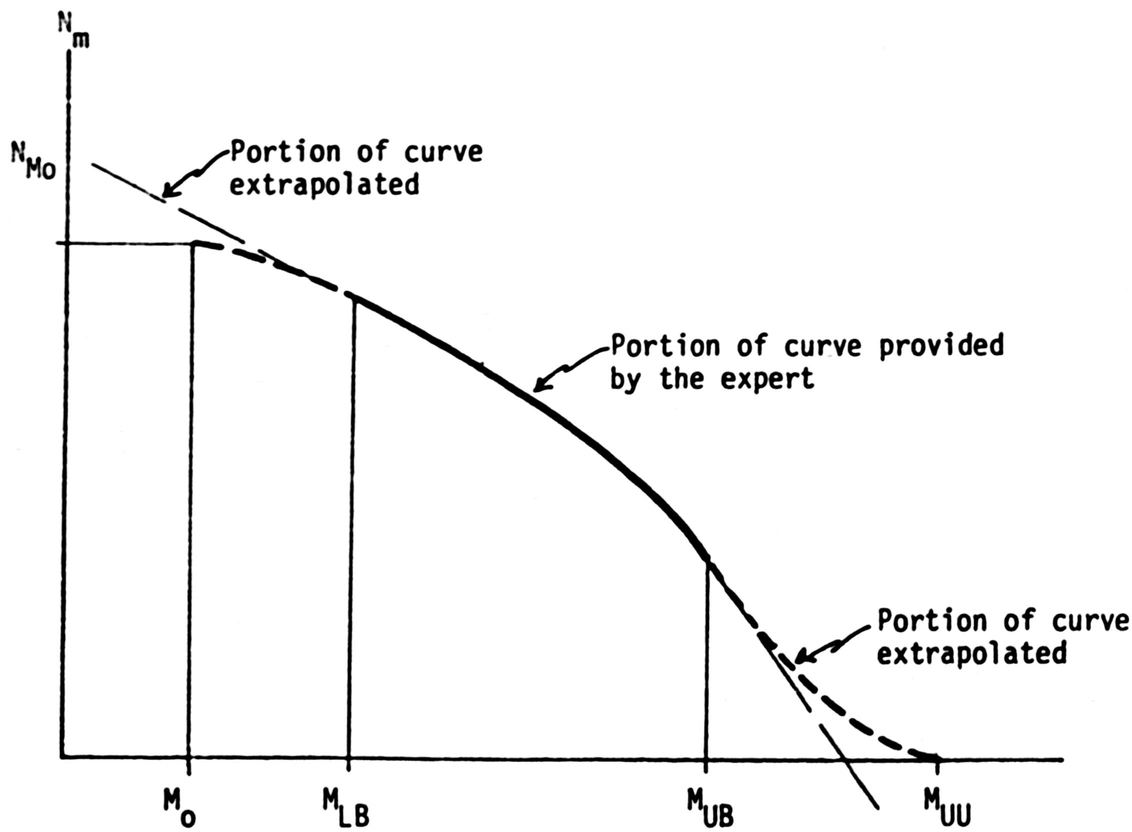


**Figure 3.2(a) Extrapolation of the Magnitude-Recurrence Relation in the Number of Event versus Magnitude Space.**

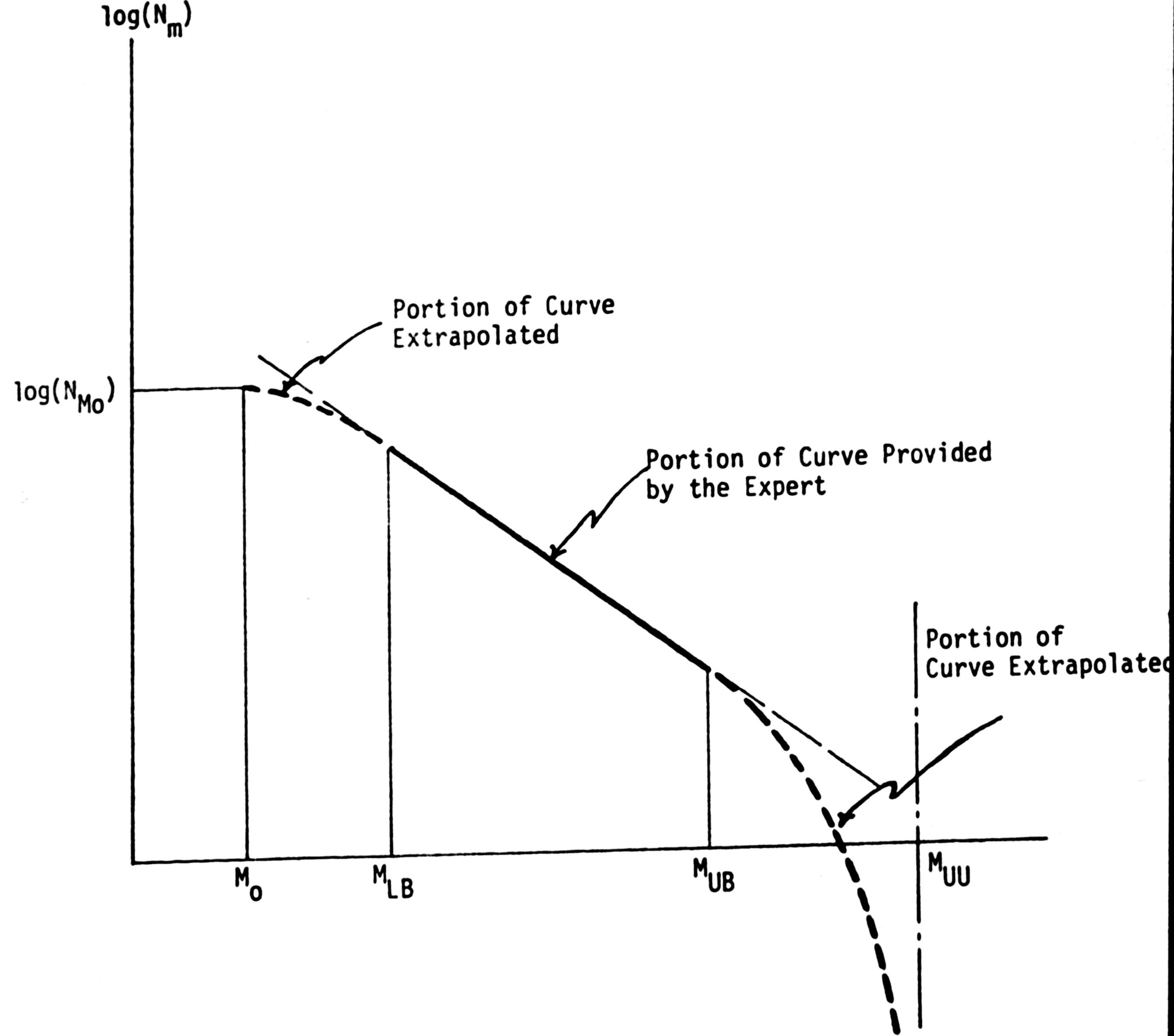


Figure 3.2(b) Extrapolation of the Magnitude-Recurrence Relation in the Logarithm of Number of Event versus Magnitude Space

If the range ($M_{LB}$, $M_{UB}$) does not coincide with the interval ($M_o$, $M_{UU}$) for some zones, it is necessary to extrapolate the magnitude-recurrence curve beyond ($M_{LB}$, $M_{UB}$) so that the frequency of earthquakes can be assessed for all magnitudes from the minimum magnitude $M_o$ to the maximal upper magnitude cutoff $M_{UU}$. Extrapolation of this curve in either direction is a matter of subjective opinion. We have suggested one method for extrapolating. However, you may prefer to suggest an alternative procedure. In that case our method of extrapolation would not be applied when we analyze your inputs. Of course, when extrapolating, two restrictions on the extrapolation procedure must be recognized. Specifically, the value of $N_m$ at $m = M_o$, the minimum magnitude, should equal the expected frequency of earthquakes with magnitudes equal to or greater than $M_o$ and the value of $N_m$ at $M_U$, the upper magnitude cutoff, should be zero. To indicate your method of extrapolation, please respond to Questions 3-15 and 3-16.

If the range ($M_{LB}$, $M_{UB}$) does not coincide with the interval ($M_o$, $M_{UU}$) for any zone and you have a method of extrapolation you feel is appropriate, please

3-15 Indicate how the magnitude-recurrence curve should be extended to magnitudes in the interval ($M_o$, $M_{LB}$).

3-16 Indicate how the magnitude-recurrence curve should be extended to magnitudes in the interval ($M_{UB}$, $M_{UU}$).

If you have responded to Questions 3-8 through 3-16 for all source zones, please skip the remaining questions in this section.

If you can better describe the magnitude distribution using another method (e.g., by a discrete or well known continuous probability distribution), please do so in the context of Questions 3-17 through 3-19.

3-17 What scale of measurement (e.g., MMI, $M_{bLg}$) for earthquake magnitude will you use in describing the probability distribution of magnitudes?

3-18 For each of the seismic source zones identified on your maps of the zonation of the EUS, specify a model for the probability distribution of magnitudes for that zone. Include in your specification your best estimate of any parameters in the model.

3-19 Give an interval which you believe, with a high degree of confidence, represents the possible values for any parameters identified in your response to Question 3-18.

## 4. EARTHQUAKE OCCURRENCE IN T YEARS

### 4.1 Introduction

As discussed in Section 2.1, the magnitude $M_T$ of the largest earthquake in T years is a random variable. the probability distribution of this random variable is a function of earthquake frequency and magnitude distribution. Thus, your opinions about the probability distribution of the largest earthquake in T years reflect your opinions about the distribution of earthquake magnitudes.

In eliciting your opinions about the probability distribution of $M_T$ we recognize that we are gathering more information than is absolutely necessary to analyze the seismic hazard at a site. However, use of redundant information increases the precision of our estimates and gives you the opportunity to assess seismicity from more than one perspective. We plan to develop the seismic hazard at a site based on (i) your responses to the questions in Sections 2 and 3, and (ii) your responses to Sections 2 and 3 combined with your responses to the questions in this section. This will give us an opportunity to share with you, when we discuss the output of the hazard analysis, the consequences of your assessing the seismicity of the EUS from alternative perspectives.

Since the probability distribution of $M_T$ is related to the seismic parameters discussed in Sections 2 and 3 it would be possible to derive responses to the questions in this section directly from your responses in the preceeding sections. We prefer you did not do this but again use the historical data, the tectonic and geologic conditions of the EUS, and other relevant information to develop your opinions about the probability distribution of $M_T$.

To gather information about the distribution of the magnitude of the largest earthquake we consider two time periods, T = 150 years, because it represents approximately the length of recorded history in some sections of the EUS, and T = 1,000 years, because it represents a somewhat extended length of time.

As discussed previously, the distribution of $M_T$ depends on the seismic parameters identified in Sections 2 and 3. A critical parameter is the largest magnitude possible, i.e., the upper magnitude cutoff $M_U$. In Section 2 we elicited your best estimate as well as an interval ($M_{UL}$, $M_{UU}$) for the upper magnitude cutoff. Since it would be impossible for you to respond to the questions in this section for all values of $M_U$ in the range ($M_{UL}$, $M_{UU}$), we ask you to respond conditional on your best estimate, denoted $M_U$ in the questions. Also, since your responses are conditional on $M_U$, you should respond to the questions in this section in the same scale of measurement as $M_U$.

## 4.2 Questions

Please respond to Questions 4-1 or 4-2 or both, and 4-3.

For each of the seismic source zones identified on your maps of the zonation of the EUS:

For T = 150 years and T = 1,000 years.

4-1 Give an estimate of the probability that the magnitude $M_T$ of the largest earthquake in T years equals or exceeds m, conditional on your best estimate $M_U$ of the upper magnitude cutoff, i.e., estimate

$$P\left\{M_T \geq m \mid \hat{M}_U\right\}$$

for (a) $m = \hat{M}_U - 1$, (b) $m = \frac{M_o + \hat{M}_U}{2}$, and (c) $m = M_o + 1$

4-2 Give an estimate of the median $M_T(.5)$ for the magnitude of the largest earthquake in T years, conditional on $M_U$. That is, estimate the value $M_T(.5)$ such that

$$P\left[M_T \geq \hat{M}_T(.5) \mid M_U\right] = P\left[M_T \leq M_T(.5) \mid \hat{M}_U\right] = 0.5$$

Information about earthquake frequency is also reflected in statements about the number of earthquakes with magnitudes exceeding a specific value. This is addressed in the next question.

4-3 Give an estimate of the expected value of the number of earthquakes of magnitude m or greater in T years, $N_m(T)$, conditional on your best estimate $\hat{M}_U$, for

(a) $m = \hat{M}_U - 1$, (b) $m = \frac{M_o + \hat{M}_U}{2}$, and (c) $m_o = M + 1$.

## 5. DEPTH OF EARTHQUAKES

### 5.1 Introduction

As described by attenuation models, the hazard at a site depends on the magnitude of an earthquake as well as the distance of the site from the earthquake source. The source-to-site distance, for some models, is a function of the surface distance of the site from a source as well as the depth of the hypocenter at the source. Thus for some models, in general, the deeper the expected depth of an earthquake, the greater the correction in the surface distance in the attenuation. In this section we elicit your opinions about the expected depth of an earthquake within each zone.

### 5.2 Questions

For each of the seismic source zones identified on your maps of the zonation of the EUS:

5-1 Which of the following best describes the distribution of depths at which earthquakes will occur within the zone. Earthquakes within the zone will occur:

a. at approximately the same depth throughout the entire zone

b. at only a small set of depths

c. within a "continuous" range of depths.

5-2 Give your best estimate of either

a. the single depth value

b. the set of depths and the percentage of activity attributable to each

c. the range of depths and a probability distribution describing the relative activity at depths throughout the range.

If your response to Question 5-1 is either b or c,

5-3 Do you believe that the depth at which an earthquake will occur within the zone will depend on the magnitude? If yes, what function best describes the relation between depth D and magnitude M (e.g., linear, $D = a + bM$; power function, $D = aM^b$)?

## A.4 Third Questionnaire: Weights (Q3)

# Lawrence Livermore National Laboratory

NUCLEAR SYSTEMS SAFETY PROGRAM

July 20, 1983
EG-83-62/1034u

Professor Gilbert A. Bollinger
604 Newman Lane
Blacksburg, Virginia 24060

SUBJECT: "Self Rating" Questionnaire
EUS Seismicity Modeling Panel
Seismic Hazard Characterization of the EUS

Dear Gil:

Enclosed please find the subject "Self Rating" questionnaire and answer sheet (three pages in all). It is important to the success of the project that you complete this questionnaire and return it to me as soon as possible. We will then incorporate your self-rating into our computational chain in strict confidence.

We are making steady and good progress in our project objectives. You will soon be informed about the extent of our progress and the time and place of our "Feedback Meeting" in October, 1983.

Thank you very much for your immediate attention, and have a good summer.

Sincerely yours,

Dan

Dae H. Chung
Principal Co-Investigator

DHC/sa

Enclosure

PS: If you have not yet submitted your bill, please send it to me indicating your consulting time. Danny



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## SELF RATING

### 1.0 Introduction

We have been receiving your responses from Questionnaire 2 and are in the final stages of developing the software to translate your opinions regarding the zonation and seismicity of the EUS into descriptions about the seismic hazard at selected sites. We want to again express our appreciation for your participation in this project.

As part of the elicitation process, we have asked you to give us your (a) best estimate of the seismic parameters (e.g., zonation, occurrence rate, upper magnitude cutoff, etc.) as well as (b) a range of values to which you associate a degree of confidence. In this context we consider confidence to reflect the degree to which you judge the historical data, your knowledge and experiences with the geologic and tectonic conditions in the EUS, and other relevant information to support a given response.

In the discussion (Section 1.3) in Questionnaire 1, we specifically pointed out that in questions involving a statement of confidence you should not be influenced by your level of expertise relative to the other members of the panel. Thus, we are able to develop a hazard curve with bounds for each individual which reflects the degree of confidence (or level of uncertainty) associated with the responses of that individual.

However, in addition to the hazard curve developed from the responses of each expert, it is important that we combine the hazard curves over all members of the panel to develop (a) a "best estimate" hazard curve which reflects the "best estimate" responses of the entire panel and (b) bounds for the hazard curve which reflect not only the uncertainties of the individual members but also the diversity of opinions between members of the panel. We propose to combine the best estimate hazard curves from each member and the uncertainty information by a weighted averaging procedure. To do this, of course, we need to determine an appropriate set of weights.

Although there are several weighting schemes (e.g., equal weights, LLNL derived weights), one set of weights, consistent with what was done on the previous (SEP) elicitation, is based on your appraisal of your expertise, i.e. self rating. We recognize some of the weaknesses and difficulties in eliciting and using self rating and we are investigating alternative weighting techniques. However, most weighting techniques are subjective and thus involve some of the same problems as self rating. Overall, we believe self rating to be a viable means of developing weights for combining the hazard curves for all members of the panel. Thus, we would ask you to self rate yourself with regard to your level of expertise about the geologic, tectonic and seismicity of the EUS.

In contrast to the previous elicitation when you were asked to self rate yourself with regard to (a) zone configuration, (b) maximum earthquake and (c) earthquake recurrence for each zone, our weighting method only allows for a single weight, i.e. a single weight which simultaneously reflects your expertise with regard to zonation and seismicity. However, we do recognize that you may feel your level of expertise is not the same for the entire EUS. Thus, we have partitioned the EUS into four regions.

- Northeast
- Northcentral
- Southeast
- Southcentral

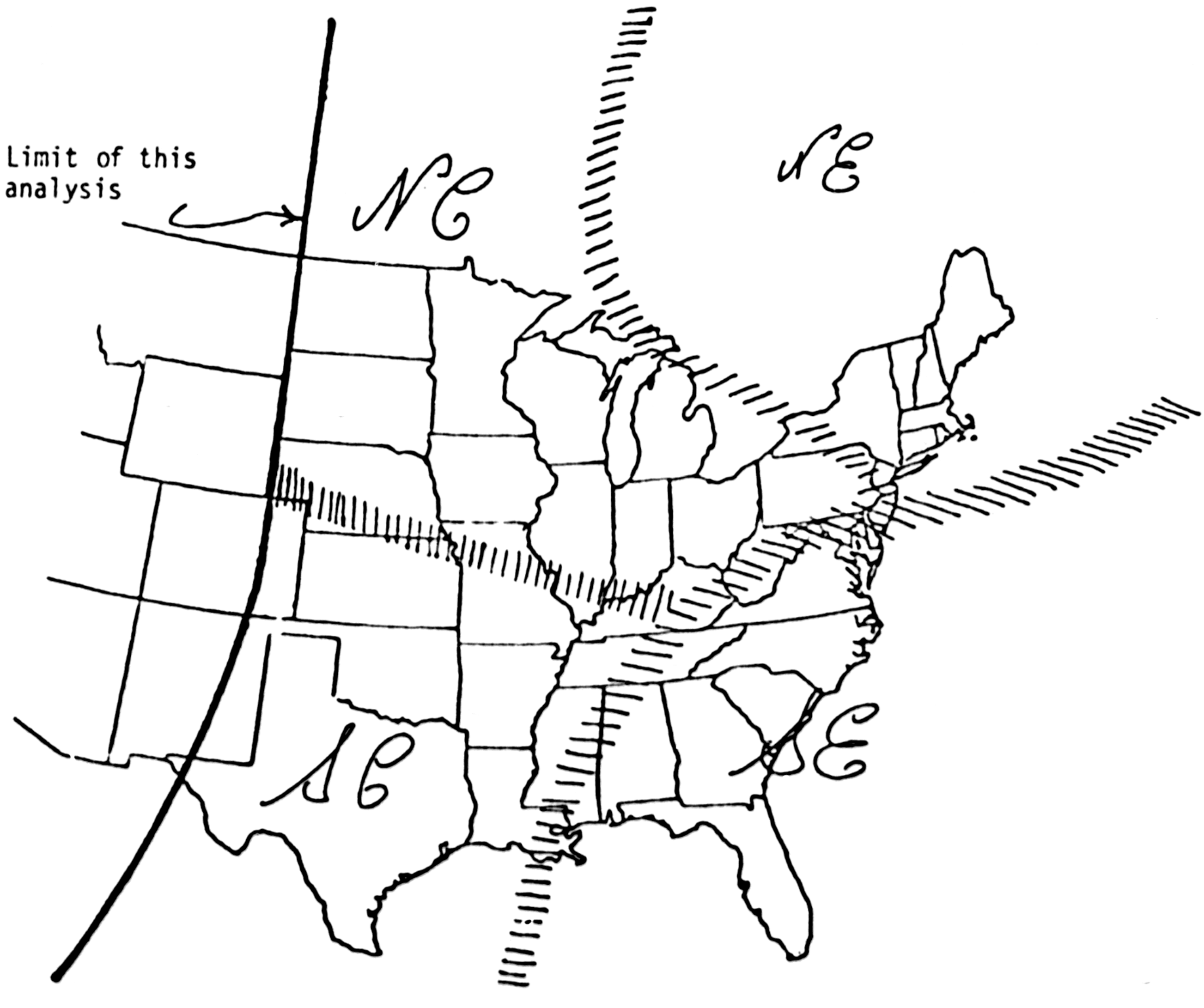
which have been labeled regions I-IV on the included map. The boundaries of the regions are also described in the following questionnaire. We would like you to self rate yourself for each of the four regions. We will combine your rating in the four regions to develop a single weight for the hazard based on your responses. The combination is based on the likelihood of the risk being initiated in a zone within each region.

In appraising your level of expertise in each of these regions, we ask that you use a 1-10 scale where low values indicate a low level of expertise and high values a high level of expertise. An integer value is not necessary, although not more than one decimal place (e.g. 7.3) is appropriate.

## 2.0 Question

For each of the four regions identified below, please indicate your level of expertise with regard to the geologic, tectonic and seismic characteristic within the region.

| REGION | SELF RATING |
|---|---|
| I. Northeast | ________ |
| II. Northcentral | ________ |
| III. Southeast | ________ |
| IV. Southcentral | ________ |




Identification of four regions of the Eastern U. S. based on a compilation of the seismic zonation expert maps developed in this study, combined with a map of $Q_o$-contours from Singh & Herrmann (1983).

## A.5 Summary of the Experts' Responses

This section contains in a summary form the following seismicity experts' input:

- o Digitized versions of the map(s) provided by the expert with each zone numbered with the expert's index system.
- o Table A2 for each expert gives the response to Question 3 of the first questionnaire about alternative zones and any additional comments required for the second questionnaire.
- o Table A3 for each expert keyed to the map zones gives the responses to the third questionnaire (self weights), the responses to Question 2 of the first questionnaire giving the probability of existence of the primary source zones and the responses to the second questionnaire.

Although the layout of Table A3 for each expert is reasonably self-explanatory, some explanation is helpful. The first line gives the expert number and his self weights for the four regions shown in Figure 2.4. Then follows the data for each zone. Two zone numbers are given for each zone, the number keyed to the map is the map index number (i.e., the zone index provided by the expert). For each zone the probability of existence is given (response to Question 2 of the first questionnaire). In some cases the probability of existence is listed as "ALTBDY." This indicates that this zone is an alternative shape for some primary zone. Reference must be made to Table A2 to determine which zones replace and which zones are replaced as well as the level of confidence in the alternative set of boundaries.

All experts chose to work in either $m_{bLg}$ or MMI and all but Expert 6 chose the recurrence model as

$$\log n = a - b\ (M \text{ or } I_0) \qquad \text{(A-1)}$$

Expert 6 chose a bi-linear model for some zones.

The second line of the data for each zone indicates whether the expert is using magnitude or intensity for his measure of earthquake energy for the zone in question. The range of validity of Eq. (A-1) is also given (Question 3-14). As discussed in the second questionnaire and in Appendix D, it is necessary to extrapolate beyond this range for some zones. The next line gives the best estimate of the upper magnitude cutoff $M_U$ and its interval $M_{UL}$ and $M_{UU}$. In most cases the experts expressed $M_U$ in either the $m_{bLG}$ or MMI scales. The few exceptions are given in the second table as well as the equation used to convert to either the MMI or $m_{bLg}$ scales. The next line gives the response to questions 3-6 and 3-7 of the second questionnaire. N is the number of events per year greater than $m_{bLg} = 3.75$ or MMI = 4, depending upon the magnitude scale used for the zone in question. The last two lines provide the response to questions 3-11 and 3-13 (a and b values and range) on a per year basis.

It should be noted that the experts felt that modeling the distribution for $M_u$ as a triangular distribution (Question 2-5) was acceptable. Table A.1 summarizes either the responses or where each response to the first three questionnaires can be found.

## Table A.1

### Summary of Responses or Where Response to Each Question can be Found

**First Questionnaire-Zonation**

(Q 1-1) See digitized maps for each expert in Fig. A1 to A20.

(Q 1-2) The probability of existence of each primary zone is given in the Table A3 for each expert. The zone(s) that a zone with probability less than one becomes part of (the host zone) of is given in the Table A2 for each expert.

(Q 1-3) Alternative boundaries are also given in the second table for each expert.

**Second Questionnaire--Seismicity Parameters**

(Q 2-1) Experts generally used $m_{blg}$ or MMI except where noted in Table A2 for each expert.

(Q 2-2) Generally not a problem or experts extrapolated the $m_{bLg}$ scale beyond saturation. Any exceptions are noted in the second table for each expert.

(Q 2-3 and 4) Given in Table A3 for each expert.

(Q 2-5) Triangular distribution acceptable to all experts.

(Q 3-1) All experts used either $m_{bLg}$ or MMI.

(Q 3-2) Where applicable given in Table A2 for each expert.

(Q 3-3) Panel members generally agreed with the choice of $M_o$.

(Q 3-4) Only two panel members (Nos. 1 & 10) provided their own relationship between epicentral intensity and magnitude. These relations are given in the Table A2 for experts 1 & 10.

(Q 3-5) The experts gave their estimate of N in the same scale they used for the magnitude-recurrence relationship. This is given in the Table A3 for each expert for each zone. Note that some experts used different scales for different zones.

(Table A.5-1 - continued)

| | |
|---|---|
| (Q 3-6 and 7) | These values are given in Table A3 for each expert and have been normalized to per year basis using the period T given by the expert. |
| (Q 3-8) | Same as (Q 3-5) |
| (Q 3-9) | Saturation of magnitude scale not generally a problem except where noted in Table A2 for each expert. |
| (Q 3-10) | Only Expert 6 departed from the linear magnitude-recurrence model (Eq. A.5-1) and chose a bilinear model. |
| (Q 3-11 and 13) | These values are given in Table A3 for each expert. The "a" values have been normalized to events per year basis. |
| (Q 3-14) | The range $M_{LB}$, $M_{UB}$ for which the model given by Eq.(A.5-1) is given in Table A3 for each expert. |
| (Q 3-15 and 16) | Experts agreed with our proposed approach for extrapolation of the magnitude-recurrence relation. |

The questions in Section 4 of the seismicity question have not yet been encoded. These will be provided in our final report.

# APPENDIX B

## Earthquake Catalogs

The basic information for the seismic data base used in this study was developed for NUREG/CR-1577: An Approach to Seismic Zonation for Siting Nuclear Electric Power Generating Facilities in the Eastern U.S. This catalog is discussed in detail in NUREG/CR-1577. A brief description is provided below along with the changes we have introduced:

1. WES-A catalog of seismic events in the northeastern United States and adjacent areas compiled by Prof. Chiburis of Western Observatory of Boston College, Weston, Massachusetts. The catalog consists of information on 2,567 events which occurred from 1534 through 1977. The areal coverage of the catalog is approximately 38°N to 60°N and 48°W to 81°W.

2. BOL-A catalog of seismic events in the southeastern United States and adjacent areas compiled by Prof. Bollinger of the Virginia Polytechnic Institute and State University at Blacksburg, Virginia. The catalog consists of information on 667 events which occurred from 1698 to 1974. The areal coverage of the catalog is approximately 31.5°N to 39.7°N and 76.2°W to 88.0°W.

3. SEU-A catalog of seismic events in the southeastern United States and adjacent areas published by the Southeast United States Seismic Network and edited by Prof. Bollinger. The catalog consists of information on 33 events which occurred from 1977 to 1978. The areal coverage of the catalog is approximately 32°N to 39.6°N and 78°2W to 89.3°W.

4. SLU-A catalog of seismic events in the central United States and adjacent areas compiled by Prof. Nuttli of Saint Louis University, St. Louis, Missouri. The catalog consists of information on 1,113 events which occurred from 1811 to 1975. The areal coverage of the catalog is approximately 30°N to 48°N and 80°W to 104°W.

5. EQH-A catalog of seismic events in the east and central United States and adjacent areas provided by Mr. Von Hake of the National Geophysical and Solar-Terrestrial Data Center, NOAA, Environmental Data Service in Boulder, Colorado. The catalog is a subset of the input data to the Earthquake History of the United States and consists of 926 events which occurred from 1638 to 1977. The areal coverage of the catalog is approximately 24°N to 50°N and 66°W to 106°W.

6. EUS-A catalog of seismic events in the east and central United States and adjacent areas provided by Mr. Tarr of the United States Geological Survey, Golden, Colorado. The catalog is itself a composite of many of the above catalogs and consists of 2,248 events which occurred from 1534 to 1974. The areal coverage of the catalog is approximately 29°N to 50.2°N and 65.8°W to 96.4°W.

7. To make the data set complete in Canada, we added the Canadian Earthquake Epicenter File to 1980 which covers Canada and adjacent areas of the northern U.S. provided by Dr. Peter Basham and Dr. Anne Stevens of the Department of Energy, Mines and Resources. This catalog is itself a composite of some of the above catalogs as well as Canadian sources such as Earth Physics Branch, Department of EMR, University of British Columbia, etc. Only the Canadian data sources were retained.

The basic data from all of the above catalogs were merged. Because of the space and time overlap between the different catalogs, this resulted in multiple entries for the majority of the earthquakes listed. To edit the catalog, the following criteria were applied.

1. The entry from the local investigator was considered the most reliable and therefore, retained in the listing (e.g., for an event in southern Illinois, the SLU entry was retained while for an event in southern New Hampshire, the WES data were used).

2. In border regions (e.g., between the SLU and BOL areas and SLU an WES areas), the SLU data were accepted.

3. For remaining events, if there was an EQH listing, that data was retained.

4. There was a significant number of events ramaining with a listing in the EUS catalog only. Each of these events was examined separately. If the evidence indicated that the event should have been contained in other catalogs (e.g., an intensity VII in a populated area) and it was not, the earthquake was removed from our composite catalog. This still left a number of EUS events, (usually low intensity) the existence of which could not be confirmed. These events were retained in the catalog.

5. For the northeastern U.S., we adopted the magnitude estimates developed by Street and Lacroix (BESSA, Vol. 69 pp. 159-176) and changed the appropriate entries in the catalog.

APPENDIX C

# DEVELOPMENT OF EASTERN UNITED STATES GROUND MOTION MODELS LAWRENCE LIVERMORE NATIONAL LABORATORY

## 1.0 BACKGROUND

We use the term Ground Motion Model to identify the equation used to estimate the ground motion at a particular site as a function of the "magnitude" of seismic energy released by an earthquake, the appropriate distance between the site and the source of energy released, and some factor to account for local site conditions. Typically, the ground motion model takes the functional form:

$$\ln(GMP) = C_1 + C_2\,E + C_3A(R) + C_4\,S + (\text{Error term}) \quad (1\text{-}1)$$

where GMP = ground motion parameter of interest; e.g., PGA or PGV
$C_i$ = constants
E = measure of seismic energy release - usually some magnitude measure or epicentral intensity.
R = appropriate distance measure
A(R) = attenuation term - typically $A(R) = \ln R - C_5R$
S = site factor term, e.g., S = 0 soil
= 1 rock

The error term accounts for the fact that the ground motion at a site due to a specific earthquake is a random variable, being affected by many more parameters than can be represented in a mathematical model such as Eq. (1-1). For example, the ground motion generating potential of an earthquake may be governed by dynamic stress drop and the area of release of energy in addition to the earthquake magnitude. Furthermore, ground motion is likely to be affected by the radiation pattern as well as "fine" details of the local site geologic column. Thus, the model in Eq. (1-1), less the error term, is intended to represent the "expected" or average ground motion at a site and the error term accounts for the random variation about that average value attributable to specific earthquakes.

In addition to the inherent random variation in ground motion about the average value, another source of uncertainty associated with ground motion models is attributable to the choice of parameters included in the model and the data base used to estimate the values of the coefficients $C_1, \ldots C_4$ in Eq. (1-1). These uncertainties, which we call modeling uncertainties, contribute to the uncertainty associated with the hazard analysis methodology. Modeling uncertainties are discussed in more detail in Section 2.4.

The ground motion model and the associated magnitude of the random variation have a direct effect on the hazard analysis. The estimates of the probability of exceedance are strongly correlated with the ground motion model. Changes in the model significantly affect the estimates of the hazard at a site. Thus, it is important that we select the most appropriate ground motion models for use in the hazard analysis.

The development of a ground motion model for the Eastern United States (EUS) is a difficult task for several reasons:

- There are few data on strong ground motion from EUS earthquakes.

- It is generally agreed that one cannot make direct use of a ground motion model developed from the Western United States (WUS), as data from a number of different sources indicate that the attenuation of seismic energy in the EUS is much different from that in the WUS.

- Recent work by Nuttli (1983b) suggests that the seismic source spectrum scales differently for EUS earthquakes than for WUS earthquakes.

In spite of these difficulties, given the paucity of strong ground motion data in the EUS, it is necessary to make use of WUS ground motion data and models and make corrections for the known differences between the WUS and EUS. The ground motion parameters (GMP) chosen for this analysis are the horizontal components of peak ground acceleration (PGA), peak ground velocity (PGV), and several spectral ordinates (SA) at frequencies ranging from 0.5 to 25 Hz.

In our earlier program for the Systematic Evaluation Program (SEP) we took what might be termed a "best estimate" approach; i.e., for a given site we developed a single best estimate hazard curve for each expert of the EUS Seismicity Panel. In keeping with this approach we only sought a best estimate model from our first EUS Ground Motion Panel. We did not achieve this objective and in the end we handled the ground motion model in an ad hoc fashion, primarily relying on sensitivity studies to demonstrate differences between models.

In our current effort, one of our objectives is to incorporate the improvements suggested by our reviewers into our overall approach. Two of the main areas for improvement are in the treatment of uncertainty and the manner in which the ground motion model is treated. This time we are concerned not only with a best estimate hazard curve but a detailed study of the uncertainty in the estimate of the hazard. We also want our results to be suitable for use in performing probabilistic risk assessments (PRA). Suitable input for a PRA requires a complete specification of the uncertainty in the hazard curve.

To achieve these objectives, it is necessary to put the current EUS Ground Motion Model Panel on the same footing as the EUS Seismicity Panel. This requires the identification and weighting of all ground motion models for the EUS which the Panel members deem sufficiently reliable to be included in the analysis.

Because it is possible to develop a large number of different models, we have attempted to provide in this report a framework for selecting from all possible models those which we feel are sufficiently reliable or credible to be used in the hazard analysis. To assist us in choosing the most appropriate models we ask the panel (see questionnaire, Section 7) to provide several pieces of information. For the short term, we ask you to select from seven categories of already existing models the best model in each category and to provide your relative degree of belief in each. We also ask you to select from all the models the one which, in your opinion, provides the best overall estimates for the EUS. (Note: These models can change regionally.) For the long term, if in your opinion some new model could be developed or existing models improved by some additonal work, we ask you to provide a prescription of how to develop your "best estimate model" (or models if several are almost equally likely in your judgment). We may also have overlooked some models that you feel should be included. These should be added. In the feedback phase we will ask you to provide weights for all models. We will also address how best to deal with local site effects. Initially, we had planned to address this issue in this document, however, it would appear best to delay it until after the USGS workshop in July.

When making selections there are several considerations regarding how the models will be used that may affect choice and ranking of the various ground motion models. The first consideration is the choice of strong-motion components. Since our study is concerned with the horizontal components of ground motion, we have excluded any models based on the vertical component. In fact, there are very few such models available. Because there are two horizontal components, one must decide how they are to be used in the analysis. Models can be developed using the maximum or minimum component, the mean of the two components, the vector combination of component , or both components. In our analyses we will be using the mean of the parameters established from the two horizontal components . Since it is relatively simple to relate predictions based on other definitions to estimates of the mean, the particular definition used should not affect your choice or ranking of models. However, your choice of the value of uncertainty to be associated with these predictions should take this into consideration. The use of the mean of the two horizontal components has been found to result in a smaller standard error than the use of either the maximum component or both components.

The second consideration is the definition of the source-to-site distance. The way the hazard analysis is performed, earthquakes are essentially modeled as point sources at the surface of the earth. This is consistent with the definition of epicentral distance. Therefore, ground motion models utilizing epicentral distance as the measure of source-to-site distance are the most appropriate models to be used with the hazard code. A problem arises when a ground motion model uses a distance measure other than epicentral distance. Three such models, two by Campbell (1981b, 1982) and one modified from Joyner and Boore (1981), referred to as the SSMRP model, are offered for your consideration. Their use of closest distance to the fault rather than epicentral distance has substantially reduced the standard errors associated with these models. While this suggests that models based on fault distance are better predictors of strong ground motion than epicentral models, one must consider their use before making such a decision. For example, such models, when used with a hazard analysis based on epicentral distance, will tend to underestimate the ground motion expected at the site for distances close to the source (see Appendices C-B and C-C for a more complete discussion). This should be kept in mind when selecting and ranking the various ground motion models and when specifying an appropriate value for the uncertainty to use in the analyses. If the panel members feel the use of epicentral sources in the hazard code is a severe limitation to their selection of the best models, they are asked to indicate this in the questionnaire.

The last consideration is in regards to the strong-motion parameter to be used. The parameter of interest for our study is pseudo-relative velocity representing frequencies of 0.5 to 25 Hz (periods of 0.04 to 2 sec.). However, there are very few EUS ground motion models available that predict this parameter directly. The current state-of-practice is to develop response spectra from peak acceleration and/or peak velocity and standard spectral shapes. For this reason, we require ground motion models based on peak acceleration and peak velocity. Because there are fewer velocity models than acceleration models, the unavailability of certain models may also affect your choice of the "best model" in a particular category. Each of these parameters will be ranked separately. Several factors will have to be considered when selecting and ranking spectral models. One factor is whether the model is based on a regression of individual ordinates or based on a spectral shape. A second factor is the relative appropriateness of the various spectral shape models. Another factor is whether the spectral shape model requires estimates of both peak acceleration and peak velocity and whether both are available.

In Section 2 we describe the framework we have selected to categorize the different ground motion models. In Section 3 we provide a generic evaluation of the different categories defined in Section 2. In Section 4 we provide specific examples and comparisons between the acceleration models. In Section 5 we discuss velocity and spectral models. In Section 6 we discuss the available EUS strong-motion data. Section 7 contains the questionnaire.

## 2.0 INFERRING EASTERN U.S. GROUND MOTION

There are at least three general approaches that could be used to develop EUS ground motion models:

1. Those that use site intensity as an intermediate variable (I),

2. Those that use ground motion measurements directly (D), and

3. Theoretical modeling (T).

### 2.1 Intensity Based Models

This category includes all models developed in a formal manner by combining a MM intensity-attenuation relation, such as

$$I_s = C_1 + C_2 I_o + C_3 \ln R + C_4 R \tag{2-1}$$

with a relation between site intensity ($I_s$) and various ground motion parameters (e.g., PGA), to get a relation between GMP, source size and distance.

For each intensity-attenuation relation there are a number of different ways that the relation between site intensity and ground motion parameters can be developed and combined with the intensity-attenuation relation. To organize our discussion we will sort all such approaches into one of five basic methods:

(I-1) No weighting
(I-2) Distance weighting
(I-3) Magnitude weighting
(I-4) Magnitude and distance weighting
(I-5) Semi-empirical

The following discussion will briefly describe each of these approaches and the basic assumptions required for each. We will also attempt to describe the inferences involved in these assumptions regarding the prediction of ground motion in the EUS. The reader may then compare these inferences regarding EUS ground motion with what he believes to be the true conditions prevailing in the EUS to help him decide which models are more appropriate.

Method I-1 (No Weighting). This method simply relates site intensity to ground acceleration, ground velocity, and/or the response spectrum, as obtained from existing strong ground motion records. Thus,

$$\begin{aligned} I_s &= F(I_o, R) && \text{based on EUS data} \\ GMP &= G(I_s) && \text{based on WUS data} \end{aligned} \tag{2-2}$$

This method assumes that ground motions are the same for the same site intensity in both regions, regardless of the size or distance associated with this intensity. Thus, differences in the attenuation of $I_s$ between the two regions (i.e., differences in the relation $I_s = F(I_0,R)$) require that predictions of GMP in the EUS for fixed $I_s$ be associated with predictions in the WUS based on data obtained at shorter distances or from larger magnitudes. This will result in ground motion models for the EUS that predict higher amplitudes than similar models in the WUS for similar magnitudes and distances. Because this approach results in predictions in the EUS that represent WUS data of higher magnitudes or shorter distances, inferences regarding the effect of this approach on spectral shape and duration of strong ground motion in the EUS are not clear. While higher magnitude data will be associated with longer durations and relatively higher low frequency content, data obtained at shorter distances will be associated with shorter durations and relatively greater high frequency content. This would imply that on the average predictions of GMP in the EUS will probably be associated with ground motions of about the same duration and spectral content as those in the WUS.

Method I-2 (Distance Weighting). This method relates the ground motion parameter to site intensity and distance, assuming that the ground motions are the same for a similar site intensity and distance in the two regions. Thus,

$$I_s = F(I_0,R) \quad \text{based on EUS data} \qquad (2\text{-}3)$$
$$GMP = G(I_s, R) \quad \text{based on WUS data}$$

This method, which can be called "distance weighting," requires that predictions of GMP in the EUS for fixed $I_s$ and R be associated with predictions in the WUS based on data obtained from larger magnitude earthquakes in order to accommodate differences in the attenuation of $I_s$ between the two regions. This will result in ground motion models for the EUS that predict higher amplitudes than similar models in the WUS for similar magnitudes and distances. Because this approach results in predictions in the EUS that represent WUS data of similar distances but higher magnitudes, we may infer that EUS predictions will be associated with ground motions having longer durations, greater low frequency content, and about the same amount of dispersion as WUS predictions at the same magnitude and distance. The enhanced low frequency content will result in a "broader" predicted response spectrum in the EUS.

Method I-3 (Magnitude Weighting). This method relates the ground motion parameter to site intensity and magnitude, assuming that the ground motions are the same for a similar site intensity and magnitude in the two regions. Thus,

$$I_s = F(I_0,R) \quad \text{based on EUS data} \qquad (2\text{-}4)$$
$$GMP = G(I_s, M) \quad \text{based on WUS data}$$

This method, which we refer to as "magnitude weighting," requires that predictions of GMP in the EUS for fixed $I_s$ and M be associated with predictions in the WUS based on data obtained at shorter distances in order to accommodate differences in the attenuation of $I_s$ between the two regions. This will result in ground motion models for the EUS that predict higher amplitudes than similar models in the WUS for similar magnitudes and distances. Because this approach results in predictions in the EUS that represent WUS data of similar magnitudes but shorter distances, we may infer that EUS predictions will be associated with ground motions having shorter durations, greater high frequency content, and less dispersion than WUS predictions at the same magnitude and distance. The enhanced high frequency content will result in a "narrower" predicted response spectrum in the EUS.

Method I-4 (Magnitude and Distance Weighting). This method relates the ground motion parameter to site intensity, magnitude and distance. Thus,

$$I_s = F(I_o, R) \quad \text{based on EUS data} \qquad (2\text{-}5)$$
$$GMP = G(I_s, M, R) \quad \text{based on WUS data}$$

This method requires the assumption that the ground motions are identical for the same $I_s$, M, and R in the WUS and EUS. Thus, in order to accommodate differences in intensity attenuation between the two regions, predictions of GMP in the EUS will be associated with WUS data exhibiting higher than average site intensities for a given magnitude and distance. These data will tend to be associated with relatively rare properties of the source, path or site that result in higher than normal amounts of damage. This will result in ground motion models for the EUS that predict higher amplitudes than similar models in the WUS for similar magnitudes and distances. This method infers that EUS predictions will be associated with ground motions of either higher amplitudes, longer durations, enhanced frequency content, or some combination of these as compared to WUS predictions. Because this approach results in predictions in the EUS that represent WUS data at similar distances, they will represent ground motions having similar dispersion characteristics.

Method I-5 (Semi-Empirical). All of the above methods are based on a formal substitution of the results of a regression analysis between the GMP and site intensity (using WUS data) into a relation between site intensity, epicentral intensity and distance (EUS data) to get a relation between GMP, epicentral intensity and distance for the EUS. There are alternative approaches; e.g., Nuttli and Herrmann (1978) used Method I-4 but included a free parameter which they evaluted using judgment and some EUS ground motion data. Battis (1981) assumed that the ground motion in the epicentral region would be similar in all regions for earthquakes of the same epicentral intensity, and that PGA at the limit of the felt area is equal to 6 $cm/sec^2$.

## 2.2 Direct Models

Under this category we include all the approaches that derive ground motion models directly from the data without the use of site intensity as an intermediate variable. For the WUS, typical models of this class are those developed by Joyner and Boore (1981) and Campbell (1981a). Unfortunately, for the EUS there isn't sufficient data to perform such regression analyses. Thus, for the time being, one must resort to a semi-empirical approach to arrive at a model for the EUS.

There are many possible ways of developing semi-empirical models. For ease of discussion we separate them up into two major subcategories, D-1 and D-2. Category D-1 includes all those models where it is assumed that the ground motion "near" the source of energy release is the same in the EUS and WUS, and that at larger distances the differences in the ground motion between the two regions is due solely to differences in anelastic attenuation. Nuttli (1979) and Campbell (1981b) have developed models based on this assumption.

Category D-2 includes those semi-empirical models for which it is assumed that, in addition to differences in anelastic attenuation between the EUS and WUS, the ground motion scales differently in the EUS than in the WUS with source size (i.e., the basic source parameters of the earthquake are on the average different between the two regions). Nuttli's most recent models (Appendix A) fall into this category.

## 2.3 Theoretical Models

This category includes the approaches that rely on numerical modeling techniques, making use of some simple or complex theoretical model to compute the ground motion at a site. Examples of models in this category are: Herrmann and Goertz (1981), Savy (1979, 1981), and Apsel et al. (1982). This is a very large category which undoubtedly would have a number of subcategories. However, at this time it does not appear to us that any of the methods or results are sufficiently advanced to use in the type of hazard analysis required for this project. Although such methods show promise, they are not yet advanced to a state that one can use them without excessive computation costs. In addition, in view of the lack of correlation between earthquakes and known tectonic structures in the EUS, it is not possible to develop with any degree of accuracy the necessary source parameters for such models. Thus, in what follows, very little will be said about theoretical models and such models will not be included unless specifically proposed by one of the Panel members.

## 2.4 Modeling Uncertainties

Given an earthquake of magnitude M and distance R from a site, the ground motion model represents a statistical description of the ground motion at a site. In the case of an earthquake, the actual motion of the site is not likely to be exactly as predicted by the model. Although there are several reasons for this, they can be summarized as follows:

- The model is only a mathematical representation of the physical world which cannot capture all of the details of reality. It is unlikely that all relevant parameters have been included in the model. Furthermore, the values of the coefficients in the model are based on a limited sample of earthquakes. Thus, for a specific earthquake, the model cannot be expected to predict the exact ground motion value. Since for the EUS the coefficients are determined by use of data from other regions and/or theoretical or semi-empirical considerations, there is an added degree of uncertainty in modeling EUS ground motions.

- Even if the mathematical model was an exact representation of ground motion characteristics, it only represents an average or expected motion at a site for a specified magnitude and distance. Due to random variations in source, path, and site characteristics, it cannot predict the actual ground motion for a specific earthquake.

Both types of variation contribute to the uncertainty in predicting the ground motion for a specific earthquake. We believe it is important to distinguish between these uncertainties which we label modeling and random. The latter variation is, of course, the inherent random variation that occurs in the physical world. In the hazard analysis this type of variation is recognized by assuming that the ground motion has a distribution about the predicted value. We describe this distribution, in our hazard analysis, by a lognormal distribution, the median of which is estimated by the ground motion model. A complete specification of the distribution requires some measure of the variation in the ground motion parameter about its median value. A convenient way of expressing this variation is in terms of the standard deviation of the natural logarithm of the GMP. However, data necessary to assess this variation (i.e., ground motion data at the same location from several earthquakes of similar magnitude and distance from the site) are not available for the EUS. Thus, it is necessary to elicit expert opinion about this variation. The former variation is what we call modeling uncertainty. It arises because we have very limited data sets and an imperfect understanding of the functional form and parameterization of the ground motion model. This uncertainty will be included by the use of several ground motion models together with subjective weights assigned by panel members.

## 3.0 EVALUATION OF APPROACHES

### 3.1 General Discussion

Of the many possible models that can be developed, which one is "best"? The absence of actual data makes it impossible to give an unqualified answer. Thus, we must rely on expert judgment to help us select the best models.

At least three major factors must be considered when developing an EUS ground motion model. These three factors represent differences between the EUS and WUS relative to:

1. Regional attenuation of strong ground motion,
2. Scaling of ground motion with earthquake magnitude, and
3. The variability in ground motion between earthquakes of the same magnitude introduced by source, path and site effects.

The selection and ranking of ground motion models from those available should be based in part on an assessment as to how well they account for the above items. For example, all of the general approaches outlined above include differences in regional attenuation but in different ways. The approaches which use intensity data make the assumption that strong ground motion in the EUS attenuates at a rate proportional to that of intensity, this proportion being the same as that in the WUS. The semi-empirical approaches generally introduce a correction based on regional measurements of the attenuation of low energy seismic waves.

Evaluation of the general approaches outlined above is difficult because it is possible to develop many specific models for each class. However, there are some general comments that can be made which may be of use in comparing one model to another.

### 3.2 Intensity Based Models

We noted that there were at least five possible methods which use intensity to make estimates of the ground motion. However, in general, there seems to be no method free of theoretical deficiencies for using intensity data from the WUS to estimate ground motion in the EUS. One problem is that, in estimating one random variable (z) from another (x), introduction of a third random variable (y), used as an intermediary, results in both a bias in the mean estimate of z and a larger modeling uncertainty in estimating z than would be the case if z were to be estimated directly from x. In the case of estimating ground motion, the procedure of estimating site intensity from epicentral intensity, then estimating ground motion amplitudes from site intensity, results in amplitudes that are less dependent on earthquake size and distance than would be the case if ground motion were to be estimated directly. Such procedures can work well if there is a strong correlation between the variables. Such does not appear to be the case. This is not surprising as the intensity scale was not developed with such correlations in mind.

inclusion of a distance or magnitude term in the correlations of GMP to site intensity ($I_s$),

$$GMP = C(I_s, R) \tag{3-1}$$

or

$$GMP = C(I_s, M) \ , \tag{3-2}$$

tends to increase the dependence of GMP on M and R (i.e. it affects the relationships in the correct manner), making such correlations appear to be better than relationships of the type GMP = $G(I_s)$. However, inclusion of M or R does not ensure that unbiased estimates will be made. In fact no intermediary parameter can do that, unless it is perfectly correlated with the first parameter (in this case $I_s$) or with the last (GMP).

For the intensity based approaches, regional scaling of ground motion with earthquake magnitude is primarily accounted for by the way site intensity at some distance R scales with epicentral intensity, the regional relation between epicentral intensity and magnitude, and, as discussed in Section 4 (see Eq 4-19), how the various GMPs are related to site intensity. This last factor ($I_s$ GMP relation) is of concern because it is obtained from data in the WUS. The magnitude weighting approach introduces a secondary correction for magnitude scaling; however as discussed in Bernreuter (1981), this additional weighting is not introduced to account for regional differences in scaling of ground motion with magnitude, but rather help account for regional differences in attenuation and the fact that the same intensity occurs at much greater distances for large earthquakes as compared to smaller earthquakes. Battis (1981) argued that making the assumption that ground motion was the same in different regions at the same epicentral intensity allows for a regional correction for scaling with magnitude to be introduced through the relation between magnitude and epicentral intensity.

### 3.3 Direct Models

The most reliable ground motion model to use in a seismic hazard analysis, at least at this time, would be one obtained by direct regression on the data. For such results to be valid, one needs sufficient data from a number of earthquakes to be able to obtain reliable estimates for the coefficients of the model. Such data are not currently available in the EUS, requiring a semi-empirical approach to develop such models.

Semi-empirical models D-1 and D-2 are difficult to assess as a group because many diverse assumptions can be made. Many of the semi-empirical models introduce a correction for regional attenuation based on regional measurements of the attenuation of low energy seismic waves. In general, such models have a higher rate of attenuation at larger distances than the intensity based models. Most such models rely heavily on strong motion data from WUS earthquakes.

One key element in our classification is the question of the differences in average source parameters between EUS and WUS earthquakes and the implication this has on ground motion. The basis for such differences is discussed by Nuttli (1983a b). The impact of these hypothesized differences lies in the way GMP scales with magnitude. Semi empirical approaches in category D 2 introduce a regional correction for scaling of ground motion with magnitude. These corrections are generally based on theoretical considerations.

### 3.4 Other Factors

For several of the proposed categories we need to know the magnitudes of the earthquakes in the EUS and WUS on a scale which allows them to be directly compared at frequencies of 1 Hz and greater. The $m_b$ scale appears to be well suited for this, but there are problems. First, the $M_L$ scale rather than the $m_b$ scale is commonly used for WUS earthquakes. Furthermore, $m_b$ values for WUS earthquakes, as determined by the USGS, are often unreliable because they are usually based on P-wave amplitudes at distances of less than 2500 km. At these short distances two problems must be faced: the large variati n of P-wave amplitude due to variations in upper-mantle structure and the known difficulties with the Gutenberg-Richter calibration function. (The latter problem can be reduced by using the Veith-Clawson calibration function used by DARPA.) For the larger WUS earthquakes ($m_b > 5.5$), there are sufficient P-wave observations at distances greater than 2500 km to overcome these proble is. But some seismologists who have studied the amplitudes of P waves from underground nuclear explosions at the Nevada Test Site conclude that anomalous upper-mantle structure causes $m_b$ values for WUS events to be underestimated by about 0.3 $m_b$ units. Using such data, Chung and Bernreuter (1981) and Herrmann a d Nuttli (1982) conclude that the two scales ($m_b$ in the EUS and $M_L$ in the WUS) are approximately equivalent in the $M_L$=5 range. Using standard measurements, an $M_L$ of about 5.0 for a WUS earthquake would be comparable to an $m_b$ of about 4.6 for an EUS earthquake.

In addition to the corrections for differences in regional attenuation and magnitude scaling, there may be a need to correct for possible regional differences in the variability in ground motion between earthquakes of the same magnitude. This random variability arises due to differences in the rupture process, complexity of the travel path, and local site geology. For example, there is some evidence that earthquakes of the same magnitude are more similar in mid-plate areas, such as the EUS, than along plate margins. If this is true, we would expect to see less source induced random variability in the ground motion in the EUS than in the WUS. In addition, the travel path is certainly less complex in the EUS than along plate margins which would also lead to less variability. For this study the variability in the estimate of the ground motion for a given magnitude and distance is generally measured by the standard deviation of the natural logarithm of the parameter, $\sigma_{\ln GMP}$. Thus, for the EUS ground motion model we might expect contributions of source and propagation path variability on $\sigma_{\ln GMP}$ to be smaller than for the WUS. However, there are not sufficient data in the EUS to evaluate such an hypothesis.

The value of $\sigma_{lnGMP}$ is a measure of the total uncertainty including the fact that the data used to develop the ground motion model was obtained from a number of different sites with very different site geology. There have been only a few studies which have attempted to sort out the relative contribution to the variability in the ground motion from these factors (Bernreuter, 1979, McCann and Boore, 1982). At this stage we are only addressing standard "rock" and "soil" sites. Nevertheless, it should be kept in mind that, in general, near-surface rock is more competent (e.g., higher $V_s$, $V_p$, $\rho$) in the EUS than in the WUS. Also the soils in many areas of the EUS are significantly different (e.g., Glacial Deposits) than those at sites that make up the existing strong motion data base. These factors need to be kept in mind when providing estimates for $\sigma_{lnGMP}$ in the question- naire. As noted in the introduction, we will address shallow soil sites and other anomalous site conditions as special cases.