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**SEISMIC HAZARD CHARACTERIZATION AT THE DOE
SAVANNAH RIVER SITE (SRS)
STATUS REPORT**

by

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Seismic Hazard Characterization of the Savannah River Site: A Status Report

I. Introduction

1.1 Background

The purpose of the Seismic Hazard Characterization project for the Savannah River Site (SRS-SHC) is to develop estimates of the seismic hazard for several locations within the SRS. Given the differences in the geology and geotechnical characteristics at each location, the estimates of the seismic hazard are to allow for the specific local conditions at each site. Characterization of seismic hazard is a critical factor for the design of new facilities as well as for the review and potential retrofit of existing facilities at SRS.

When dealing with facilities whose consequences of failure can impact both the public and on-site personnel, it is customary to perform two types of seismic hazard analyses. One analysis based on deterministic concepts such as the ones prescribed for commercial nuclear plants in NRC regulations (10CFR, Part 100, Appendix A), the other is based on probabilistic concepts which provide an estimate of the uncertainty in the form of a range or distribution of the hazard rather than a single point frequency estimate as is the case using deterministic techniques.

Frequency estimates with uncertainties are necessary when risk based or performance-based designs or reviews are conducted. In particular, this is the case for Probabilistic Risk Assessments (PRA). The PRA provides estimates of probabilities of experiencing certain types of events, such as probabilities of release of radioactive materials from a facility. It uses the probability distribution of the causative events, as an input, such as the probability distribution of the ground motion at the location of the facility.

The scope of the SRS seismic hazard characterization reported in this document is limited to the Probabilistic Seismic Hazard Analysis (PSHA). The goal of the project is to provide seismic hazard estimates based on a state-of-the-art method which is consistent

with developments and findings of several ongoing studies which are deemed to bring improvements in the state of the seismic hazard analyses.

An important component of this projects is in the interaction with these ongoing studies. The Lawrence Livermore National Laboratory (LLNL) team (the SRS seismic hazard team) working on the project is a participant, along with personnel from NRC and the commercial nuclear power industry, in several of these projects.

One of these ongoing projects, sponsored by the NRC/RES, involves the review and updating of the NRC regulations for the siting of Nuclear Power Plants (NPP), where methodologies and criteria are being developed for the design of future NPP's to be sited in the United States. Another project, in collaboration between the DOE, NRC and the Nuclear Power industry, represented by the Electric Power Research Institute - EPRI, (the resolution project) involves review of existing PSHA methodologies, an assessment of those methodologies and making recommendations and developing guidelines for performing the most appropriate and up to date PSHA, given a particular problem and set of resources.

One important goal of the SRS-SHC is to use a methodology which follows the guidelines and recommendations and is within the bounds and limitations that are anticipated to be produced by the Resolution Project.

1.2 Evolution of the Seismic Hazard Characterization of the Southeastern U.S.

In the early 1970's, the seismic hazard characterization of southeast U.S. became an important NPP licensing issue due to the uncertainty in assigning a maximum credible earthquake for that area of the country. The difficulty was in large part due to the fact that a large earthquake occurred in historic times (Charleston, 1886) but for which there are no observable geological indicators identifying the causative fault. One hypothesis is that earthquakes of the same type as the Charleston 1886 earthquake would occur only in the Charleston area. Another hypothesis is that, since no causative fault could be identified, such earthquakes could in fact occur in a much larger area extending possibly several hundred of kilometers both north and south as well as west of Charleston.

In 1982, the United States Geological Survey (USGS) sent a letter to the NRC regarding the uncertainties in defining seismic sources, in particular, the seismic source responsible for the 1886 event.

The USGS position was not to explain the 1886 earthquake, rather it emphasized the lack of conclusive evidence for any positive identification of the causative fault.

In 1982, the Eastern U.S. Seismic Hazard Characterization project, sponsored by NRC (Bernreuter et al., 1985, and 1989) and its equivalent, sponsored by EPRI, (EPRI, 1989) were the first attempts at using PSHA to incorporate all the uncertainties in the design and decision process. These methodologies are based on the basic hazard model developed by Cornell (1968).

The important elements of the PSHA methods are:

A. The Probabilistic Hazard Model

The physical processes underlying the occurrence and magnitudes of earthquakes and the attenuation of the ground motion between the earthquake source and the site, as well as the effects of local site conditions, are stochastic (random) processes. Thus, the assessment of the seismic hazard at a site is based on probability or frequency models. The basic hazard models include the following:

- (a) • The location of future earthquakes is modeled as a Poisson process with source zones (i.e., given an earthquake, the location is uniform within the zone) which represent areas where earthquakes with common frequency and magnitude characteristics occur.
- (b) • The temporal occurrence of earthquakes within a source zone is modeled as a Poisson process; the occurrence rate is an input based on historical seismicity data or other geological information.
- (c) • The distribution of earthquake magnitudes is generally modeled as a truncated exponential distribution and specified by a recurrence curve.

- (d) • Given an earthquake of a given magnitude at a given location, the ground motion measure at the site is modeled as a lognormal random variable. The mean of the log are then of the measure, as a function of location and magnitude, is given by a ground motion attenuation model.

Given specific values of the parameters of the frequency models in (a) thorough (d), the seismic hazard at the site is the probability of exceedance of the ground motion measure for a given duration of time, typically one year

B. Representation of Uncertainties in the Seismic Hazard Models

Given specific values of the parameters, e.g. occurrence rate of earthquakes within a source zone, of the hazard models, the seismic hazard is a deterministic frequency calculation, as described in A. However, due to limited historical data and a lack of information and knowledge, it is not possible to specify the values of the model parameters with certainty. Thus lack of certainty, or uncertainty, is recognized in PSHA's by specifying probability (uncertainty) distributions for the models and/or model parameters. For example, uncertainty in characterizing source zones is specified by alternative source boundaries; fault zone uncertainties are described by alternative boundaries or fault geometries. On the other hand, uncertainty in the occurrence rate is often represented by a probability distribution for the rate. Uncertainty, different from stochastic variation which is inherent to the physical processes is based on the current available historical data and information. Additional seismicity and or ground motion data, or research in seismology, geology, geophysics and tectonics can lead to better understanding of the underlying physical processes, thus, a reduction in the uncertainties of describing the stochastic models.

Since the historical data is limited and knowledge of the physical processes is incomplete, assessments of the values of the hazard model parameters depends on individuals' interpretation of the data and information. Based on the same evidence, it is not unusual for several knowledgeable individuals, i.e., experts, to arrive at different models and/or values for model parameters. If inputs from several experts and/or teams of experts is used in

an analysis, the differences in interpretations adds to the uncertainty and must also be represented in the overall uncertainty. It is not uncommon, as a way to analyze the sensitivity of the seismic hazard estimate to different sources for uncertainty, to differentiate between these two sources of uncertainty, (1) the uncertainty of an individual due to limited evidence and (2) the uncertainty between individuals due to diversity of interpretations.

C. Seismic Hazard Assessment

As indicated in A, given specific model parameters, assessment of the seismic hazard is a deterministic analytical calculation. The result is a seismic hazard curve, i.e., the probability of exceedance of the ground motion measure as function of the value. With uncertain models and model parameters, as well as multiple experts, the result is a family of seismic hazard curves representing the uncertainty in seismic hazard assessment given the current evidence. The assessment uncertainty is often summarized by seismic hazard uncertainty bounds represented by the envelope of uncertainty fractiles, e.g. 15th and 85th fractiles, at each value of the ground motion measure. A typical seismic hazard curve, with uncertainty bounds, is given in Fig. 1.1 where the solid curve represents the 50th fractile envelope seismic hazard curve and the dashed lines are the uncertainty envelopes.

The assessment generally involves a large number of seismic hazard calculations and is often done by performing Monte Carlo sampling from the probability distributions of the uncertain models and/or model parameters.

The LLNL and EPRI methodologies were used to characterize the seismic hazard at 69 NPP sites (LLNL, 1989) and 49 sites (EPRI, 1989) east of the Rocky Mountains.

Both methodologies were used to provide probabilistic seismic hazard estimates for SRS. These were used to review and analyze existing facilities. They also were used in a PRA of the K-reactor.

The LLNL methodology was subsequently reviewed, improved and used for the seismic hazard characterization of the New Production Reactor site at SRS. This project was terminated in January 1992.

The present SHC project is a continuation of the SRS-NPR project recognizing that the potential application is across all of SRS. Additionally, this project has attempted to recognize the rapidly changing state-of-the-art seismic hazards techniques, particularly in the areas of expert elicitation and ground motion modeling.

An important aspect of this project has been the formation of a group to review the LLNL methodology and to provide recommendations for improvements which could be implemented quickly. This group, the Methodology and Analysis Review Committee (MARC), its function and recommendations are discussed in Section 2. In Section 3, the present LLNL methodology, is described. This is followed by a description of the actual process of modeling the seismicity (Section 4), ground motion attenuation modeling at the SRS (Section 5), and a brief description of the treatment of site specific conditions (Section 6).

In Section 7, the results of the seismic hazard calculations are presented. In addition, some comparisons with the 1989 EUS/NRC results, the NPR 1992 results, and results from an updated EUS, 1992 set of calculations are given.

2. The Methodology and Analysis Review Committee (MARC)

2.1 Purpose and Role of the MARC

The purpose of the MARC was to review the LLNL methodology, and provide recommendations for further improvements to satisfy the specific needs of the SRS-SHC project. The committee consisted of four members from DOE (Jeff Kimball), academia (Allin Cornell), industry (Kevin Coppersmith) and LLNL (Jean Savy).

The function and mode of operation of the MARC was to offer other analysts familiar with the LLNL method an opportunity to critically review and comment on the merits of the LLNL methodology, to draw on the experiences of other studies and combine these with their own expertise to propose improvements to the LLNL methodology.

2.2 Summary of the MARC Recommendations

The MARC identified four general areas for improvement to be addressed as part of the SRS effort:

(a) Seismicity Modeling

A new approach to characterizing the recurrence magnitude relation, proposed by LLNL, was reviewed. In this approach, modeling of the recurrence rates is defined by estimates of the actual rates of occurrence of several magnitudes (two values for the standard, i.e., Truncated Exponential model, and three values for the Characteristic model). In previous LLNL studies, the recurrence rates were characterized by estimates of the a - and b - parameter values of the Gutenberg-Richter/Truncated Exponential model.

The advantage of the new approach, referred to as the "seismicity frequency model", is that it provides a more effective way of assessing the uncertainty associated with the estimates of rates of earthquakes for large magnitudes. By contrast, the previous method occasionally resulted in artificially large uncertainties particularly for high magnitude and, as was demonstrated by M. McCann at the MARC meetings, it sometimes led to unacceptable estimates of the recurrence rates (Wingo, 1992).

(b) Ground Motion Modeling

New information on the differences in the characteristics of the sources and the propagation of the seismic energy in the earth's crust between Eastern and Western United States, as well as new techniques of modeling

ground motion led the committee to conclude that ground motion modeling was an area of potentially major improvements.

There is a general consensus in the earthquake engineering community that all the data available should be used to its maximum extent. At the same time, hybrid models (Physical/Statistical) such as the BLWN model, or even numerical models, are gaining favor. As these approaches are developed, there is more and more reluctance to rely on intensity data which contributed substantially to the development of the ground motion models in previous studies.

An equally important issue is the estimation of the random variability of the ground motion measure. This is often taken as the dispersion of the historical data about an estimated ground motion attenuation model. This issue is very complex. It does not only refer to the estimation of a statistical parameter, (such as the standard deviation of a distribution) but it also requires understanding the physical meaning of the random variation to be able to model it appropriately for use in the probabilistic hazard analyses. It was concluded by the MARC that the large variability on the estimates of the standard deviation (σ) associated with the ground motion mode in the SRS-NPR study (See fig. 2-1) was an important issue. Figure 2-1 shows the estimates of seven experts and the value recommended by LLNL for the analysis. It is believed that such dispersion in the estimate of σ shows that σ represents different things to different experts. This points out the need for refining the method of collecting estimates of this parameter. Thus, the MARC identified the expert elicitation component as a very important area to re-visit.

The overall conclusion of the MARC was that the assessment of the ground motion distribution model had to be entirely revised with an emphasis on characterization of the random uncertainty σ and the method of elicitation of ground motion models. It was recommended to have a workshop for the purpose of sorting out these issues and of developing a plan of action for resolving them.

(c) Elicitation and Documentation

The LLNL Methodology is based on using individual experts' interpretations to quantify the seismicity and ground motion uncertainties in the scientific community.

The goals of the elicitation process are:

- Provide unbiased estimates of the seismicity modeling parameters (including zonation and recurrence rates), and the ground motion distribution parameters.
- Accurately characterize the uncertainties associated with estimating the seismicity and ground motion models and model parameters.
- Provide the necessary documentation to support the parameter estimates and models selected by the experts.

The MARC reviewed the general elicitation and documentation process designed in the SRS-NPR project and provided recommendations for pursuing and strengthening that process and bringing it to its conclusion in the context of the new project. The main recommendations were as follows:

- Pursue the elicitation and feedback of the updated experts zonation and seismicity models.
- Strengthen the pre-elicitation part of the experts' training and information gathering phase of the elicitation process. For that purpose, data analyses in order to provide additional data input to the experts prior to the feedback meetings.
- Strengthen the phase of the elicitation process involving the critical review of the models and parameters provided by the experts as their interpretations of the data. This includes using the data diagnostics tools (DDTS) developed in the SRS-NPR project and

adding several others such as analyses of historic and predicted rates of seismicity around the SRS.

- Revisit the ground motion elicitation process including the mode of aggregation of the experts' input. Perform a new round of ground motion elicitations of ground motion distribution with an emphasis on eliciting estimates of the random variety of the ground motion measure.

The recommendations of the MARC were folded into the scope of the SRS-SHC project and led to the present LLNL methodology which is described in the next section.

3. Outline of the LLNL PSHA Methodology

3.1 The Overall LLNL PSHA Methodology

The hazard model, described in the outline in Fig. 3-1, is intended to present the essentials of the LLNL approach with minimal discussion of the issues and considerations in developing the methodology. The current methodology is described here, and summarized in Figure 3-1. It includes all previous modifications and improvements added to the original NRC methodology since 1982, the modifications incorporated in the SRS-NPR study and the improvements based on the MARC recommendations.

3.2 The Hazard Model

Let G be the ground motion parameter, e.g., PGA, spectral velocity, and $SH(g)$ the seismic hazard as a function of g , the level of ground motion parameter G .

The seismic hazard at a given site is the probability that the ground motion parameter G exceeds some value g during a period of t years.

$$SH(g) \equiv P(\max. G \text{ in } t \text{ yrs} > g)$$

As it is customary in PSHA, such as the SRS study, the period of time is chosen as 1 year and is referred to as the annual probability of exceedance of g . Then,

$$SH(g) = 1 - P(\text{no } G > g \text{ in 1 year})$$

The area influencing the ground motion at the site is partitioned into "zones", and assuming independence of earthquake activity between zones,

$$SH(g) = 1 - \prod_{\text{zones}, k} P_k(\text{no } G > g \text{ due to earthquakes occurring in zone } k)$$

Assuming that earthquakes occur temporally within a zone as a Poisson process

$$SH(g) = 1 - \prod_k e^{-\lambda_{gk}}$$

where

$\lambda_{gk} \equiv$ expected frequency of earthquakes in zone k such that the ground motion at the site exceeds level g .

$$\lambda_{gk} = \lambda_{ok} P_k(G > g \mid \text{an earthquake such that its magnitude } M > m_0)$$

where

$\lambda_{ok} \equiv$ expected frequency of earthquakes in zone k such that $M > m_0$
 [Based on the assumption of only being interested in the contribution of earthquakes of magnitude m_0 or greater]

and

$$P_k (G > g | \text{ an } \dots M > m_0) =$$

$$\int_{m=m_0}^{M_{uk}} \int_r P_k (G > g | (m,r)) dH_k(m | m_0, M_{uk}) d(r) F_k(r)$$

where,

- $P_k (G > g | (m,r)) \equiv$ ground motion distribution given an earthquake of magnitude m at distance r from the site. Generally a lognormal distribution, the ground motion attenuation model specifies the mean of the logarithm of the ground motion measure.
- $H_k (m | m_0, M_{uk}) \equiv$ magnitude distribution, given an earthquake of magnitude $M > m_0$; M_{uk} denotes the largest possible magnitude in zone k ; specification of this distribution is an input.
- $F_k (r) \equiv$ spatial distribution of earthquakes within zone k expressed in terms of the distance r of the location from the site; this spatial distribution is assumed to be uniform over the zone.

3.3 Inputs for Probabilistic Seismic Hazard Analyses

3.3.1 Use of Experts' Scientific Interpretations: Selection and Elicitation

Inputs for the seismic hazard calculations are based on two basic principles:

- The inputs should be based on the scientific interpretations and judgments of individuals.
- The expected diversity and uncertainty in judgments regarding the seismic activity affecting the EUS and the subsequent ground motion given an earthquake should be recognized, accommodated and retained in the analysis.

Based on these principles, two panels, a Seismicity Panel (S-panel) and a Ground Motion Panel (G-panel), were formed to provide the required seismicity and ground motion inputs (see tables 3.1 and 3.2). Representation of a broad range of backgrounds, current employment and expertise provided the means of sampling the potential diversity of interpretations and judgments within the relevant scientific community. The role of the experts is shown in Fig 3.2. Selection of panelists was based on several criteria in addition to representation of diversity, including peer recommendation, professional activity within the relevant areas, relevant publications, availability to participate and interest in the project.

The process of selecting the S- and G-experts followed a formal set of rules designed to satisfy the needs of the project. This process comprises two phases:

Phase 1: Develop a pool of candidates, based on a set of generic criteria. This pool could include potentially many individuals, (e.g., several tens)

The criteria were developed by LLNL and consultants, and include consideration of the individuals background publications and general background.

Phase 2: Select, from the pool of candidates, those individuals who satisfy a series of criteria specifically developed for the task of estimating the seismic hazard for the SRS.

When deciding whether to use individual experts (LLNL, 1989) or several teams of experts (EPRI, 1989), one has to balance the plusses and minuses of each approach. Basically, it is common to disregard the two extreme approaches where experts are:

- answering questions individually without interaction with other experts.
- grouped into a single team where consensus is sought even at the detriment of a fair representation of diversity.

Neither the LLNL, 1989 nor the EPRI, 1989 studies are strict applications of these two extremes.

The LLNL approach is based on the philosophy that it is important that the inputs be the responsibility of single experts, rather than having that responsibility being shared among groups of experts within teams, even if all the members of the teams are identified and committed. The LLNL methodology has always recognized this fact, but it is in the SRS-SHC project that we firmly set the basic elements which satisfy all the requirements of this study as described earlier in Section 2 and repeated here:

- Provide an unbiased set of inputs
- Retain the diversity among experts

The LLNL method consists in using individual experts (the S- and G-experts) who are provided all the necessary support and help to enable them to be fully cognizant of all issues, alternatives and available data. A potentially preferred mode of operation in the future would be to ask each S- and/or G-expert to form his/her own team. The role of the members of a team would be solely to provide support to the S- (or G) expert who is the individual ultimately for the interpretation of the evidence and the models and parameter estimates given to the elicitors. The SRS-SHC elicitation was just short of being performed in this preferred manner. Each S and G expert was provided all the possible help that the LLNL analyst team and consultants could provide including responding to all specific request from the experts.

Although the initial elicitations of the scientific judgments of the experts were based on questionnaires and written responses, the current approach is to base the elicitations on personal interviews. The interviews are generally conducted by two or three individuals with backgrounds in seismic hazard analysis, expert elicitations and/or one of the relevant areas of expertise, seismology, geology, geophysics or ground motion modeling.

The interview process is designed to be as flexible as possible to help the experts to "feel comfortable" with the elicitation. The primary objective of the elicitations is to have the experts provide their inputs in a format that best reflects the

available scientific evidence and their state of scientific knowledge. The intent is to elicit all the required information at the interview session. However, the approach is to be flexible and accommodate experts who do not feel comfortable with providing all of their inputs at the time of the interview but desire more time to do additional work and/or thinking. In this situation, the initial interview concentrated on interacting with and educating the expert about the elicitation, the information being elicited and the format for their responses. The session included going through all the questions and having the expert give illustrative responses to provide us assurance that he/she understood the process, to clarify misunderstandings and to answer questions. The expert is then left to complete his/her inputs in a timely manner. In general, another round of interaction would take place, mostly by telephone.

The end product of the elicitations were the experts' expression of their probabilities about models, model parameters or (nonparametric) frequencies. An expert's probabilities are derived by asking the expert to give:

- a lower and upper bound for the model parameter or frequency representing their 0.05 and 0.95 probability percentile values.
- a "most likely" value (mode of their probability distribution) for the model parameter or frequency.

and to select a "shape (from a set of 7 different families of distributions) for their probability distribution. If the elicitation involves selection between models, e.g., zonations, the panelists' probability distribution is a discrete distribution over the collection of possible models.

In addition to the interview, the elicitation process includes considerable one-on-one interactions, and communications in addition to feedback, either in groups or with individuals, to assist the experts to review their inputs and give them the opportunity to make adjustments to their inputs if they deem it appropriate.

3.3.2 Description of Earthquake Activity in the Area Influencing Ground Motion at the Site

This is expressed in terms of,

- (1) Zonation maps
- (2) Seismicity models for each of the source zones in a zonation map.

(1) Zonation Maps:

A Zonation is defined as a partition of the entire area of interest into source zones, where a source zone is defined as a unique source of earthquakes, i.e., specific features; e.g., a fault or fault segment; or area zones associated with a geologic or geophysical condition conducive to earthquake activity such that the earthquake activity is homogeneous throughout the zone.

The specification of the zonation is based on eliciting from experts

- a. A "most likely" zonation, i.e., the zonation to which they assign their highest probability of it representing the sources of earthquake activity throughout the area.
- b. Alternative zonations based on either
 - i. specification of distinct alternate zonations
 - ii. alterations of the "most likely" zonation by
 - associating a probability of existence to any zone
 - altering the boundary of any zone or groups or zones, with appropriate probabilities

The term "existence" means that the specific source(s) are active and distinct from the surrounding source(s) in terms of seismicity. Any zonation involves one or more complimentary zones that are areas not included in distinctly specified zones; these are treated as any other zone.

Based on an expert's inputs, a catalog of zonations is developed for input into the seismic hazard calculations. A probability is associated with each zonation.

(2) Seismicity Models for the Source Zones:

Seismicity within each zone is based on eliciting probabilities for (kth zone)

- λ_{ok} - expected frequency (or its inverse, the expected return period) of earthquakes with magnitude at or exceeding the minimum magnitude, m_o below which there is no contribution to the probability of damage to the facility.

In practice the value of m_o is generally magnitude 5 for the commercial Nuclear plants, but could be lower, depending on the type of equipment the facility contains. For the SRS study, we chose $m_o = 5.00$ and will performed sensitivity analysis with $m_o = 3.75$.

- M_{uk} - upper magnitude cutoff, i.e. the largest possible magnitude supported by the source(s) within the kth zone.
- λ_{1k} - expected frequency (return period) of earthquakes with magnitude at or exceeding a magnitude m_{1k}
[generally, $m_{1k} = m_o + 0.75(M_{uk} - m_o)$]
- If a characteristic earthquake magnitude distribution is suggested by an expert, additionally,
 - m_{ckl}, m_{cku} - range of the magnitude of a characteristic earthquake (the magnitude is assumed to be uniform over the range). In general, the range has been represented by a lower bound value m_{ckl} and the upper magnitude cutoff, M_{uk}

- λ_{ck} - expected frequency (return period) of the characteristic earthquake

These inputs are based on the experts suggesting either the truncated exponential distribution or a characteristic earthquake distribution for the magnitude distribution. If other models are suggested, appropriate parameters would be identified and their values elicited.

An additional input to be elicited is the possibility of a limitation on the range of λ_{ok} , given λ_{lk} (or vice versa, the range of λ_{lk} , given λ_{ok}), which is a measure of the correlation (with respect to an experts' uncertainty) between λ_{ok} and λ_{lk} . Our current approach is to elicit a most likely value and a range for the "slope" of the magnitude-frequency "line" (assumed a straight line) between λ_{ok} λ_{lk} . (the most likely value is the "slope" of a line between the most likely λ_{ok} and λ_{lk} values). This information, combined with the bounds (distributions) for λ_{ok} , λ_{lk} are used to model a joint probability distribution for λ_{ok} , λ_{lk} in terms of a marginal probability for λ_{lk} and conditional probability distribution for λ_{ok} given λ_{lk} .

In summary, the elicited seismicity information are probability distributions for λ_{ok} , λ_{lk} and M_{uk} which are used to specify the distribution of earthquake magnitudes for each zone.

Combined with the zonations, this constitutes the seismicity portion of the inputs into the seismic hazard calculations.

3.3.3 Ground Motion Frequency Distributions

The ground motion inputs needed for probabilistic seismic hazard calculations are conditional frequency distributions for the ground motion at a site given earthquakes of magnitude m centered at distance " r " from the site. This information is elicited from the panel of ground motion experts (G-Panel). It is generally accepted by the ground motion community, and all our experts, that the conditional frequency distribution of ground motion (the random uncertainty) is adequately modeled by a log normal distribution.

Assuming a log normal conditional frequency distribution, elicitation of ground motion information is based on eliciting the experts' probabilities about two distributional parameters, the conditional median, g_{50} , of the ground motion measure and the conditional standard deviation of the logarithm of the ground motion measure $\sigma_{\ln g}$.

The method outlined here for the development of the ground motion frequency distribution is different from previous methods used by LLNL in the sense that the aggregation of the G-experts input is done at the level of the input to arrive at a composite ground motion distribution rather than at the output hazard level. This important difference is described in detail in the Section 5 on ground motion modeling. The remainder of this section is based on our latest approach of aggregation at the input level.

From a computational point of view, ideally, the inputs are based on having the experts provide a set of rules for generating their probability distributions for g_{50} and $\sigma_{\ln g}$ for all (m,r) . Minimally, their probability distributions for the collection of (m,r) pairs used in the seismic hazard calculations are needed. In general, the experts have provided this information in terms of a weighted linear combination of the value of g_{50} derived from specified ground motion models and a distribution for $\sigma_{\ln g}$ which is piece wise homogeneous over ranges of magnitudes. Of course, an expert is not forced to provide an assessment for any (m,r) or range of (m,r) 's for which he/she is uncomfortable with providing such input.

In the previous Eastern U.S. studies, this information was elicited for hard rock sites in the Southeastern section of the EUS. Adjustments to the level of g_{50} for other types of soils and other sections of the EUS are currently derived from other sources.

The elicitation provides the information needed to develop a "joint" probability distribution for $(g_{50}, \sigma_{\ln g})$ for any (m,r) pair. It constitutes the ground motion portion of the inputs into the probability calculations (see Savy et al., 1993).

3.3.4 PSHA Calculations, Propagation of the Uncertainties

The elicited information for each expert member of the S-panel is:

- A family of zonations with probabilities
- Probability distributions (uncertainty distributions) for seismicity parameters λ_{ok} , λ_{lk} , and M_{uk} for each zone

and for each member of the G-panel the elicited information is:

- Probability distributions (uncertainty distributions) for ground motion parameters g_{50} and σ_{lng} for each (m,r) pair

The calculation phase of the PSHA is to combine this information to assess probability distributions for the seismic hazard $SH(g)$ for all values of g .

The first step in this process is to aggregate the uncertainty distributions for the ground motion parameters elicited from the ground motion panelists into a single joint conditional uncertainty distribution for (g_{50}, σ_{lng}) for each (m,r) pair based on equal mixing weights for each expert. These distributions are referred to as the "composite" joint conditional ground motion parameter uncertainty distributions (or the composite distributions). Derivation of the composite distribution is based on Monte Carlo sampling of the individual panelists' uncertainty distributions and is described in terms of

- the marginal conditional uncertainty distribution for g_{50} , given (m,r), expressed in terms of the fractiles of the uncertainty distribution. g
- conditional uncertainty distributions for σ_{lng} given the fractiles of g_{50} , i.e. given $g_{50,j}$ $j = 5, 15, 25, \dots, 95$, modeled as beta ($p, q; s_l, s_u$) distributions, where s_l, s_u are lower, upper bound for σ .

When using the composite distributions as sources of ground motion inputs for the seismic hazard calculations it is important that the functional correlation between the median ground motion g_{50} (the level of ground motion variability, as quantified by σ_{lng}) over magnitude and distance is retained in the calculations.

This is done by using the same fractile of g_{50} for all (m,r) and the same for $\sigma_{\ln g}$ (but possible at a different fractile level than g_{50}) for all (m,r) .

Development of uncertainty distributions for seismic hazard $SH(g)$ for all values of g is based on propagating the uncertainties using a Monte Carlo sampling of the uncertainty distributions of the zonations, seismicity parameters and ground motion parameters. Samples of the seismicity information derived from uncertainty distributions for each seismicity panelist are combined with samples of the ground motion parameters from the composite distribution to derive samples of seismic hazard curves $SH(g)$ over the range of g . These are aggregated so that composite uncertainty distributions for $SH(g)$ can be developed for each g . Although not currently evaluated, it would be easy to develop the correlation in the uncertainty in $SH(g)$ for pairs of g levels.

The output of the PSHA is generally described in terms of the envelopes of fractiles (or other distributional parameters, e.g., the expected values) of the uncertainty distributions of $SH(g)$ over the range of g .

3.4 Data Diagnostics Tools

The inputs provided by the experts is the most important element of the PSHA. Thus, it is necessary that the experts be provided with the available evidence, particularly the historical data, as well as an analysis of their inputs. To provide this, we developed a series of analysis tools referred to as Data Diagnostic Tools.

In a somewhat generic fashion, we lump together the analyses performed prior to the elicitations and those performed after the elicitation into a single class of Data Diagnostic Tools (DDT). The results of these analyses are used both to provide information and help to the experts, and to provide a way of reviewing the experts interpretations and elicited parameter estimates. They are also used to prepare the next feedback step in the analysis.

The information is collected from knowledgeable individuals and since no one knows the absolute truth, no one can judge the validity of competing scenario which can be defended on the basis of physical assumptions. However, one can devise a series of diagnostics which can point out inconsistencies in an expert's

input. These diagnostics can rely on first principles of physics and mathematics or on concepts of probability and statistics and make use of comparisons with widely accepted data sets.

The purpose of the data diagnostics is to uncover inconsistencies. These can arise due to misinterpretation of the data or misunderstanding of a specific theory by the expert, or can result from errors committed by the analyst in transcribing the expert's input into the analysts format. The diagnostics phase is not a peer review, but is a feedback to the experts that they can use for their review of their inputs. However, it can be used as input to such peer review which, as seen below, we propose to be performed.

3.4.1 Zonation and Seismicity (SDG)

These DDT's are designed to test the two components of a seismicity model:

- (1) the zonation models
- (2) the recurrence models

The essence of these tests is to determine the validity of the implied earthquake activity rates in an approximate way emphasizing the logic behind the numbers, their ranges rather than comparing single estimates strictly with historical data. The basic type of question that these DDT's attempt to answer is:

- Are we predicting the "right" number of earthquakes, at the "right places" and with the "right" magnitudes and characteristics?

Clearly, if the historical catalogues were complete, in time and space, and accurate as to the location of earthquakes, their types, and magnitudes, they would be sufficient to validate an expert's seismicity (i.e., zonation-recurrence). This is obviously not the case and for this reason, we cannot use statistical tests alone to assess the validity of a seismicity model. Deviations, based on judgment, must be allowed, provided reasonable explanations based on scientific arguments and data are given for these deviations.

The following is a brief description of the diagnostics which, at the present time, are envisioned to be done (labeled with a star "*" in the list below) or were performed (labeled with a plus, "+" in the list below) on the expert's inputs. Some of these are described in more details in section 4 on the SRS seismicity elicitation.

For simplicity and consistency with previous documents developed for and by the MARC, we use here the same identification where SDG stands for seismicity diagnostic and GDG stands for ground motion diagnostic.

- SDG1(+) Analyst makes judgment based on plot of each expert's zone historical seismicity for several time periods (presently 28 yrs, 59 yrs and 288 yrs), and superimpose the expert's model, an its associated uncertainty, on the plotted uncorrected data.
- SDG2(+) Plot the above data corrected for incompleteness, using several alternative methods of correction (i.e., Standard Stepp's technique, probabilistic technique using models of probabilities of detection).
- SDG3(+) Simulate regional catalogues of historical events using the expert's models, including the uncertainty in the zonation and recurrence models. Generate best estimate catalogues and catalogues with uncertainty. Compare the simulated catalogues with observed historical catalogues using statistical techniques.
- SDG4(+) Perform checking, review and audit of every single step in the transcription of the expert's input to the analysis format. This is an internal task, very time consuming which, in our view, has a high rate of return (i.e., we find bugs in the data!)
- SDG5(*) Perform a critical review of the scientific content of the expert's input. The review is performed by one or more individuals familiar with the scientific issues. For example, line fault consistency with strain, slip rate, etc.... The experts' assumptions is reviewed by the LLNL team prior to the one-on-one interview to determine issues that will be brought up, documented, clarified and/or resolved at the

interview. This is to be performed by a small group of experts in the field, not directly involved in the present study. Their input to the LLNL team will be used to formulate the content of future planned knowledge dissemination and feedback workshops and one-on-one interviews. If still "unusual" per the LLNL team opinion, the issues are reviewed later by peer review group.

- SDG6(*) Perform test hazard calculations and sensitivity analyses to show the important contributors. These analyses assess the relative contributions of the zones, of the different magnitude ranges, distance ranges, and modeling assumptions based on the best estimate hazards.
- SDG7(*) Display and review additional information from the uncertainty calculation, such as the percent contribution of the other remaining parameters to the final hazard. (upper magnitude cutoff, recurrence models uncertainty on the frequencies, etc.)
- SDG8(*) Provide the above information (SDG-6 and SDG-7) for the mean and variance of the hazard.
- SDG9(*) Plot the distribution of the hazard for several ground motion values, for all g.m. experts combined and for each one at a time.
- SDG10(*) Perform a historical analysis, emphasizing comparison with results from S-experts.

3.4.2 Ground Motion Modeling DDT's. (GDG)

In the elaboration of GDG's, the important question to answer is:

For a given location, source type and energy level earthquake, are we modeling "right" the probability distribution of the ground motion at a selected location?

Again, as for the seismicity case, comparison with an adequate catalogue of ground motion data would provide an objective evaluation of any ground motion attenuation model. This is obviously not the case; due to the lack of good quality

catalogue which would be recognized and accepted by the engineering and scientific community. Thus we believe that the first step to any diagnosing of g.m. models is a catalogue development task. This is unfortunately a big task which will require substantial effort and substantial time and is not in the scope of this project.

Regardless of their weaknesses to, we can use several catalogues, compare the models to the data in those catalogues and use judgment to evaluate the models.

The following are the diagnostic tests to be performed on the expert's inputs: (a "+" means that this item was performed a "*" means that it is proposed).

- GDG1(+) Plot each model and compare it with the catalogue data, visually.
- GDG2(*) Calculate the residuals of the predicted curve with the various catalogues, i.e., including the various measure of magnitudes, distance for some critical events, such as Saguenay. Include USGS data on explosion test if possible.
- GDG3(*) Create an artificial catalogue, for a single G-expert, by considering his entire set of models and their respective weights. Develop a statistic to assess the goodness of fit by comparing the artificial and empirical catalogues. This item is described in more details in Section 5 because we now develop a composite model of ground motion attenuation.
- GDG4(+) Perform checking, review and audit of every single step in the transcription of the experts' input to the analysis format. This is an internal task.
- GDG5(*) De-aggregate SHA results per class of ground motion spectra models.

The aggregated Uniform Hazard Spectra (UHS) have lost an important part of the information on the correlation between the spectral values at the various frequencies, i.e., the UHS spectral

shape is a "soup" made of several possible spectral shapes — Band limited white noise Brune Spectrum model, empirical models, Newmak Hall type models, or other analytical models. The de-aggregation, per model class, gives some additional insights since the results are not contained in the class-to-class uncertainty. For each class, the spectral shapes are expected to remain close to the average spectral shape of the class.

- GDG6(*) Historical analysis emphasizing comparison between the various ground motion models and classes of ground motion models.
- GDG7(*) Perform a critical review of the scientific content of the experts' input. This is to be done by a small group of experts not directly involved in the present study. Their input to the LLNL team will be used to formulate the content of future knowledge dissemination workshops, feedback meeting and interviews.

And for the diagnostics more specifically applied to the composite ground motion modeling, two types of diagnostic tools have been developed to assist the ground motion experts in their review and evaluation of their inputs. The first type consists of a series of descriptive tools for evaluating the experts' inputs about the median ground motion. These are designed to make comparisons between the median ground motions as predicted by a collection of attenuation models, the usual basis for the experts' assessment of the median ground motion, or to compare the experts' uncertainty estimates of the median ground motion relative to the historical data. These tools are:

- GDG8(+) Descriptions of the uncertainty distributions for the median ground motion for individual experts
- GDG9(+) Descriptions of the composite uncertainty distributions for the median ground motion

The second set of tools is designed to describe how the level of ground motion (random) variability affects the prediction of ground motion. These can be used to compare an expert's assessment of the level of random variation, in terms of the

value of the standard deviation σ_{In} , with the assessments of others and with the historical data. These tools are:

GDG10(+) Plots of any ground motion frequency fractile (or frequency level of exceedance), e.g., g95, based on a collection of attenuation models

GDG11(+) Descriptions of the uncertainty distributions of any ground motion frequency fractile for individual experts

GDG12(+) Descriptions of the composite uncertainty distribution for any ground motion frequency fractile

4.0 Elicitation of the Zonation and Seismicity Models

4.1 Development of the Seismic Zonation Maps

A fundamental step in hazard analysis for the PSHA is partitioning the regions of interest (i.e., regions covered by a circle of approximately 250 to 300 km centered on the SRS) into seismic source zones. Several approaches are possible in the elaboration of a spatial model of earthquake occurrences. The most common approach used in the western U.S. is based in identifying prominent features (such as fault traces) to which historic earthquakes can be associated. Thus it is relatively straight forward to build a spatial model of earthquake occurrences by delineating areas where the events associated with a given feature will occur in the future. Unfortunately, it is difficult to associate historic events to specific geologic or tectonic features in the EUS. We asked our S-experts to make use of the available geophysical, tectonic, geologic, and historic data to identify zones which are potential sources of earthquakes. In this technique, the contribution of every observable parameter (such as the direction and value of tectonic stresses, gravity anomalies, magnetic flux, geologic features, seismicity etc.) is subjectively evaluated in terms of how much support it provides to the hypothesis of a given zone being a potential source of earthquakes in the future.

The source zones are assumed to be areas of seismicity such that all potential earthquakes occurring within the area have the same characteristics such as constant spatial and temporal occurrences and identical maximum magnitudes.

The zonation maps were first elicited in a multi-phase process, as shown also in Fig. 3-1.

Phase 1. Identification of the issues of importance to the final hazard in the development of zonation maps. This phase was performed by the LLNL team in close collaboration with its consultants and by communicating with the S-experts. The result of the phase was used to select the subjects to be discussed at the workshop on knowledge dissemination.

Phase 2. A three day knowledge dissemination workshop was organized to present all the issues to the S-experts, allow them and other knowledgeable individuals from academia, the U.S.G.S., the SRS staff and members of the Nuclear Power industry, to present their views, their interpretation of the data, and to ensure a common basis of knowledge. In addition a brief training in the use of probabilities and use of expert opinion was presented by an expert in the field of elicitation of experts opinion (i.e., Prof. Ralph Keeney). The methodology, charter, and expectation from the experts were discussed in detail.

Phase 3. A questionnaire was developed by the LLNL team and its consultants, including a review by Prof. R. Kenney and was sent to the experts who were given a minimum of two months to answer the questions. During this time, the LLNL team provided support to the experts on a as needed basis, in the form of training meeting, telephone discussion exchange of literature or data, or documentation.

In the questionnaires on zonation the S-experts of the PSHA were asked to use a two step process to define their source zones. They were first asked to provide a map of the source zones which they

believed were likely to be the sources of future earthquakes, each source identifying a region where earthquakes with common "characteristics" occur. This zonation map was referred to as their preferred map, based on all the information available to them. In a second step they were asked to express their uncertainty in their zonation by assigning degrees of belief to the need to identify (i.e., on the existence of) each zone in their preferred map. They also could provide alternative source zone boundaries, again with appropriate degrees of belief.

Based on this type of information, all the possible combinations of zonations were generated for each S-expert, as described in Section 1.2. The degrees of belief were combined to compute a probability for each map. This probability distribution represented the experts uncertainty in the zonation of the EUS. For each S-expert the set of discrete probability distribution of the maps was used in the Monte Carlo simulation.

The SRS is located in South Carolina at the border between South Carolina and Georgia near the town of Aiken to the north, Augusta to the north west, Allendale to the south east and Barnwell to the east. See fig. A1.1. the region around the site is of medium seismicity, as shown in fig. A1.2 and seems to be concentrated at least 200 km north west of the site, for the historically recorded seismicity.

The difficulty, common to all of the eastern U.S. sites lies in the fact that observable seismic features are very difficult to identify and for the most part inexistent. As a result, the S-experts have to rely on other types of data which can lead to many possible interpretations of the seismotectonics in and around the sites region. This fact is evidenced by the diversity of seismic zonation maps provided by our S-experts reflecting their belief in the physical possibility of many possible scenarios.

Two main features dominate this analysis and were invariably considered by all the S-experts.

The first one is really a "non-feature" since it is the assumed location of areas of possible occurrence of earthquakes of the type (magnitude 6.5 to 7.5) which occurred around the city of Charleston (SC) in 1886. Considerable efforts have been spent by academia, the industry and the USGS to identify which actual existing physical feature might have been responsible for the 1886 earthquake. This issue is very important in helping the S-experts decide how they will draw their boundaries of an areal zone describing where such earthquakes might possibly occur in the future.

Unfortunately the entire body of information has not led to conclusive determination of where exactly the 1886 earthquake occurred. Based on epicentral intensity values, as shown on fig. A1.3, it appeared that the origin of the earthquake was close to Charleston, probably within 20 km west or north west of the city. In its attempt to clarify this issue and constrain such possible earthquakes to a limited area around Charleston, the USGS performed extensive works and research and concluded, in 1982, that it did not have the necessary data to categorically affirm that "Charleston 1886 type" earthquakes could occur only around Charleston.

Since that date, additional work has been done, which yet has not led to definitive conclusions, including the recent work in re-evaluation previous intensity data (see figs A1.4 and A1.5) or using the SPOT imaging satellite information system to identify possible lineaments on the earth surface (Talwani, 1991), would tend to confirm the existence of a physical feature.

Given the large magnitude of this possibly "wandering" earthquake, the issue of its location is very important for the PSHA, and given the multitude of possible interpretations by the S-experts, in the form of many possible scenarios, this is a dominant issue as to the level of uncertainty associated with the zonation and seismicity of the region.

The second issue of importance is the seismotectonic state of the small area around the SR site itself (on-site). Fig. A1.6 shows a detail of the SR site with the boundary of the triassic Dumbarton basin and the location of the Pen Branch fault which has been confirmed by the latest field investigation but which has not been found to be active. Because the Vogtle Electric NPP located at the boundary of

the SR site, near the Savannah river has been subject to a licensing process in the early 1980's, enormous amount of geologic and geophysical data has been developed for this region. In addition, the DOE has been investigating a number of facilities on the SR site to review its seismic safety and perform seismic upgrades when necessary to ensure a level of safety similar to that of NPP's.

In this extensive field work, many geologic features have been identified, few of them capable of producing damaging earthquakes at the SRS. Although it is not clear at this point how different these features are from other similar features in the coastal plain.

In the recommendation for GSG work at SRS a large portion of the effort was concentrated on resolving the nature of the Pen Branch fault as well as possibly the Charleston issue. A substantial amount of studies have already been performed, such as deep reflection geophysic studies and high resolution studies to locate the faults, as well as a good amount of neotectonic studies to clarify the nature, size and possible origin of the Charleston type of earthquakes. All the available results are known to our S-experts.

Aside for clearly including a Charleston type zone in their zonation maps large areal zone or small ones around Charleston, all the expert modeled the relative seismic quiescence around the site. Most experts had a zone associated with the Dumbarton basin and few of them believed in the seismic potential of the on-site faults, albeit with a small degree of belief.

The S-experts interpretations of the available data is shown in Appendix A in the form of the zonation maps fig A2.1 to A2.9.

4.2 Seismicity and Upper Magnitude Cutoff

Section 4.2 gives a brief description of the techniques which were first used in the standard type of analyses and it describes the latest LLNL technique used in this project. A summary of the S-experts' seismicity parameter used in this analysis is given in Appendix B of this report.

4.2.1 The Standard Approach for Recurrence Modeling

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

$$\text{Log}_{10}N = a - bm \text{ (or } I), \quad (4.1)$$

where the seismicity parameters a and b are constant for a given seismic source zone, m denotes magnitude, and I if the epicentral intensity. Generally, Eq. (4.1) is modified to account for the fact that every seismic zone is believed to be only capable of producing earthquakes with magnitudes (or intensities) bounded above by some maximum value (called the upper magnitude cutoff, M_U).

In the seismicity questionnaire, the experts were asked to model the seismicity of the EUS by providing the a , b , and M_U values for each of the zones they identified in their maps. They were asked to provide a preferred value (the value which they believe is the most likely to represent the true state of nature) and a range of values which represented their uncertainty in estimating the values of these parameters. This information was used to develop probability distributions which in a first set of calculations (June 1, 1990) were used in the Monte Carlo simulations.

4.2.2 LLNL's Approach for Recurrence Modeling

The recurrence laws modeled by the Gutenberg-Richter curves ($\text{Log } N(m) = a - bm$) give quantitative estimates of two fundamental aspects of earthquake occurrences.

1. It gives a prediction of the total number of events greater than some magnitude, and
2. it describes the relative number of events of each possible magnitudes.

In the Gutenberg-Richter Law, the "a" parameter sets the overall level of the curve, to give the total number of events greater than the nominal zero magnitude. The "b" parameter gives the relative proportion of each magnitudes hence, completely defining the negative exponential probability density function of the magnitude ($f_M(m)$ used in the seismic hazard model).

The S-experts' expertise is more on the knowledge and understanding of the physical process and the identification of scientific evidence and information which constitute their body of knowledge and it would be characterized as "substantive" knowledge.

When asked to quantify an expert's state of confidence about particular theories (i.e., on SRS-SHC project, about his proposed tectonic, or parameter values for the seismicity models) it is not uncommon to observe differences, sometimes great differences, between the ability of the expert to describe physical phenomena and give analytical models and scenarios and his ability to quantify relative likelihood for these phenomena and scenarios.

An expert who is trained and experienced in the use of probability as a language with which to express a state of confidence or state of knowledge, in Winkler and Murphy's works (1978), is considered "normatively" good.

This issue of calibration of expert opinion is paramount in the elicitation process for our seismic hazard analysis at the SRS. After much analyses, reviews of inputs in our previous NRC (eastern U.S.) studies and even in the responses of the S-experts to the first questionnaire on seismicity the MARC concluded that our modeling of the S-experts' uncertainty in the recurrence of earthquake did not appropriately model their state of knowledge with respect to their uncertainty in the recurrence of earthquakes. This is due primarily to the fact that we may have been asking the wrong questions. Those questions were probably relying too much on normative aspects rather than purely substantive aspects. The main consequence of this problem has been, in some cases, model of uncertainty which lead to (subjectively judged) inconsistencies with the observed data and also to physically unrealistic frequency predictions of moderate to large magnitude earthquakes (see Wingo, 1992).

It is important to recognize that this is a departure from our previous work. In the EUS-NRC study we did not emphasize estimates of the tail of the distribution of the hazard, including mean values which because of skewness in the hazard probability distribution are associated with high percentiles (70 to 90%).

Thus, we improved our methodology by focusing on questions dealing with material the S-experts are more familiar. To update the elicitation for the SR site, we generated an additional questionnaire entitled "Refinement on the Modeling of the Uncertainty of the Recurrence Curves".

The purpose of the elicitation remains a characterization of the S-experts' uncertainty in $N(m)$. Now, instead of asking them questions about their uncertainties on the a and b -values, we asked the experts questions about their uncertainty about $N(m)$ for two values of the magnitude m_0 and m_1 (three values for characteristic models).

Figure 4.1 summarizes the new additional input that we need from the experts. $N_L(m)$ and $N_U(m_0)$ are respectively the lower and upper bound on the number per year, of events greater than magnitude m .

4.2.3 Final Feedback on Seismicity

4.2.3.1 Preparation of the Feedback

An important effort was made to provide the experts with a array of analysis results based on the data diagnostics described in Section 3.

These analysis are centered on two purposes:

- (1). Analyze the existing seismicity data to help the S-experts understand, in an absolute sense, the earthquake process in the southern US.

One important aspect of this element of the information developed was to identify and display the uncertainties inherent in the process of estimating seismicity rates. This part is described in more details in the section 4.2.3.2 below.

The results of this effort were presented in the form of a multitude of tables and plots of estimates of rates versus magnitude, for a variety of

conditions and parameter values that the S-experts might have chosen, some of them having been selected by the S-expert himself prior to starting the analysis.

- (2). Compare the available S-experts' models interpretation obtained at the end of the latest elicitation, described in Section 4.2.2 with the existing data. This task was performed by: first providing plots and tables of the S-experts models super-imposed on those developed in (1) above, secondly, we used a method developed by Jack Benjamin Associates for the study of the K-reactor at SRS. In this method, the input from the S-experts is used to develop an artificial model of the seismicity in the area around the site. The results are compared with the catalogs of seismicity and displayed in a variety of ways to help the S-experts.. Section 4.2.3.3 describes this method in more details.

4.2.3.2 Analysis of Historical Earthquake Data

To ensure that everyone has access to an analysis of the historical earthquake data, we sent the S-experts the results of several analyses of the historical data for each of the zones they identified for the first phase Seismic Characterization of SRS Project. This information and/or other pertinent materials was put at their disposal in preparation for our visit when we feedback elicited their opinions about the seismicity for each zone.

This information contained sets of plots of the raw data, in log frequency of exceedance per year, as a function of magnitude. Also included in the plots were:

- the frequency of exceedance versus magnitude curve based on the S-expert's most likely estimates based on their previous assessments of seismicity
- similar curves based on their lower and upper bound assessments of these parameters
- their lower bound, most likely value and upper bound assessment of M_u .

Also included in the figures are the values of the frequencies of exceedance and the corresponding return periods at m_0 and m_1 based on the most likely values and bounds for $f(m_0)$, $f(m_1)$ and M_D . These figures provided the opportunity to compare their assessments of the frequencies of exceedance to the recorded historical data (in terms of the historical data in the catalog chosen by the S-expert) for both the data corrected for incompleteness and uncorrected data.

Another figure included a plot of an estimate of the frequency of exceedance versus magnitude curve based on the historical data in the catalog. To estimate the frequency versus magnitude curve it is necessary to 'correct the data for incompleteness.' Our method for correcting incompleteness is based on assuming a model for the 'probability of detection'. It is similar to the method developed by Veneziano for the EPRI hazard project (EPRI, 1989). The term 'probability of detection' refers to the likelihood, as a function of magnitude and time, given an earthquake occurred, it is detected, is published, and has been recorded in the catalog. In this analysis the basic model for the probability of detection is an exponential model of the form

$$\pi(t,m) = \exp[-\nu h(m)t^r]$$

where t is time counted backwards from the most recent time in the catalog (1985) and

$$h(m) = \max\{0, (M_D - m)^c\}$$

with M_D being the smallest magnitude for which detection is certain for all times and m denotes magnitude. The symbols r , c , and ν are model parameters. In our application of the model to estimating the frequency versus magnitude relation, we have specified values for r , c , and M_D and used the data to estimate the 'rate' parameter ν for each zone. The curves plotted in the figures are based on

$$r = 1.93, c = 1.0, M_D = 5.0$$

i.e., the curves assume that a magnitude 5.0 (or the equivalent intensity) earthquake would have been detected and been recorded in the catalog throughout

the period covered by the catalog, i.e., back to 1700. The values of r , c represent the fall-off in the probability of detection with time and magnitude.

As an example Figs. 4.2, and 4.3 show some detection probability curves for the zone 1 of expert's 1 zonation Fig. 4.4 shows the probability of detection which was developed as a default when data was not sufficient.,

Also included in the figures provided to the experts were:

- the historical data, in log frequency of exceedance per year, corrected for incompleteness
- the frequency of exceedance curve based on their 'most likely' estimates of recurrence rates and the upper magnitude cutoff.

This plot provides a comparison of their 'most likely' assessment of the frequency of exceedance with the "corrected" historical data.

When using the recorded historical earthquake data to estimate the frequency of exceedance versus magnitude it is recognized that the predicted values of frequency are subject to uncertainties. The choice of catalog and the model and method of correcting for incompleteness are just two factors which contribute to uncertainty in predicting frequencies. Another source of potential significant uncertainty is the fact that the observed earthquakes within the period covered by catalog, approximately 1700 to 1985, represents only a *sample* of overall earthquake history. If we conceptually imagine repeating the geologic conditions of this period, we could expect to realize a different set of earthquakes (i.e., earthquake generation is a stochastic process). Another realization of earthquakes would result in a change in the predicted frequencies. This variability in predicted frequencies, due to the use of a sample of earthquakes, we refer to as 'sampling uncertainty': To provide the S-experts with some measure of the sampling uncertainty, we have applied the technique of resampling to quantify the uncertainty in estimating frequencies of exceedance using LLNL catalog.

In quantifying the sampling uncertainty we emphasize that this is only *one* source of uncertainty associated with using historical data to estimate frequency. Thus, it

represents a minimal level of uncertainty. Other uncertainties, including choice of catalog, incompleteness method and mathematical model representing the stochastic process of earthquake generation, all add to the uncertainty in predicting frequencies. Again, only sampling uncertainty is represented in the results of the resampling process.

Resampling the Historical Data. To assess the sampling uncertainty in estimating the frequencies of earthquakes, within a source zone, based on the recorded earthquakes within a catalog we have applied a resampling technique. This is a method, based on using the realized earthquake magnitudes in the original catalog, to generate a collection of 'new' catalogs (or sets of magnitudes) representing a possible sampling of catalogs one could expect to get if we were able to 'replicate the past earthquake history.' The variation in the estimated frequencies derived from this collection of catalogs represents the sampling uncertainty due to using the historical earthquake data to estimate frequency.

Since the catalog can be thought of as a sample of size one of the total number of recorded earthquakes and since it is not realistic to consider resampling a sample of one, it is necessary to impose an additional assumption to implement the resampling process. We have done this in two ways by making different assumptions about the 'random process' generating earthquakes. One view is based on a parametric assumption about the number of recorded events while the alternate view is based on a nonparametric assumption about the rate of earthquake occurrences. Specifically, the two are:

- Option 1: The *total number of recorded events* within a zone (over all time and magnitudes) is modeled as an approximate Poisson random variable. The Poisson parameter, the expected number of recorded events in a zone, is set equal to the number of recorded events in the catalog.
- Option 2: The total number of events occurring (over all zones and magnitudes), as predicted by correcting the recorded events for incompleteness, is modeled as a stationary random process over time. The rates per year for the corrected catalog for 15 time periods (over the 258 years in the catalog) is modeled as a random sample of size 15 of the stationary random variable, the rate per year of earthquake occurrences.

Since the number of recorded events per magnitude (we actually work with half unit magnitude bins) over all time is the variable of interest for estimating frequencies, the resampling process involves resampling a total number of events (recorded events for Option 1 and actual occurrences recorded or not for Option 2) and then resampling that number of magnitudes from the magnitudes in the original catalog to generate 'new' catalogs. Option 1 is based on sampling from an appropriate Poisson distribution whereas Option 2 is based on sampling *with replacement* from the set $[\lambda_{t1}, \lambda_{t2} \dots \lambda_{t15}]$, where λ_t denotes the rate of earthquake occurrences (based on the number of recorded events) in the j th time interval, and adjusting this to generate a resampled number of recorded events for each zone. Given a resampled total number of recorded events per zone, the resampled magnitudes are generated by resampling *with replacement*¹ from the magnitudes (in each zone) in the original catalog. The resampling process is iterated 1,000 times to generate 1,000 resampled catalogs for recorded magnitudes. Each resampled catalog of recorded magnitudes is corrected for incompleteness and used to estimate the frequency of exceeding a magnitude as a function of magnitude. This is based on modeling the magnitude distribution as a truncated exponential distribution on the range $(3.75, M_U)$, where M_U is the most likely value of the upper magnitude cutoff. Finally, 1,000 sampled predicted frequencies are accumulated at m_0 and m_1 . The distribution of these frequencies represents the sampling distribution of the estimated frequency. The variation in the sampled frequencies represents the sampling variability in estimating frequencies based on a sample of earthquake history as represented by the original catalog. As discussed earlier, the range of values of the sampled frequencies represents the minimal uncertainty in assessing frequencies if one relies on the historical data as a primary source of information in formulating one's opinion about the frequencies. An abbreviated illustration of the resampling process is presented in Figure 4.5.

Summaries of the results of the resampling process are presented in tables to summarize the 5th quantile, mean, median (50th quantile) and 95th quantile of the sampling distribution of the estimated frequency for the two magnitudes m_0 , m_1 based on the models for Options 1 and 2 respectively. The correction for incompleteness is based on modeling the 'probability of detection' by an exponential model similar to Equation 3.2. In one case, an empirical model for

the probability of detection which assumes a magnitude 5 earthquake occurring any time over the period of the catalog would be identified and ultimately be recorded in the catalog. This model attempts to represent the probability of detection for area that have been well populated, elg., New England and the Atlantic Seaboard, during the entire period of the catalog. Plots of the probability of detection as a function of time (back from 1985) for magnitudes 4 and 4.5. Other cases represent to variability in the probability of detection.

Plots of the probability of detection as a function of time for several magnitudes are shown to the S-experts. One case is an attempt to approximate the probability of detection in areas surrounding the cities in the midwest, e.g., Chicago, St. Louis. Another case attempts to approximate the probability of detection for the 'unpopulated' areas of the EUS. Plots of the estimated log number of exceedances versus magnitude based on the three models for the probability of detection are shown to the experts. Also included is the uncorrected data for 284 years. These plots provide a comparison of the effects of the models of probability of detection on the estimated number and a comparison of each model with the (uncorrected) data.

4.2.3.3 Comparative Assessment of Historic Seismicity

The historic earthquake catalog is the principal source of information used to evaluate the rate of earthquake occurrences in the eastern U.S. The degree to which a seismicity expert utilizes the historic record varies from expert-to-expert and location-to-location. To facilitate the experts development of seismicity models in the vicinity of the SRS, this section describes the procedure to estimate earthquake occurrence rates from the earthquake catalog. The approach involves a nonparametric evaluation which includes an estimate of the uncertainty in the rate of occurrence. The uncertainty (variation in the estimated rate of occurrence) is attributed primarily to the length of the historic period and the variability in estimates of earthquake magnitude.

Limitations of earthquake catalogs are well documented (Stepp et al., 1965 and EPRI, 1987) and include incompleteness, limited period of record, and the non homogeneity of earthquake magnitude assessments. These sources of variation are considered directly in the historic analysis.

Bootstrap Simulation. To estimate the historic rate of earthquake occurrences and its uncertainty (statistical error of estimation), the bootstrap resampling method is used as shown in Fig. 4.6. The bootstrap method is carried out in the following manner. Given an earthquake catalog for the EUS, an estimate of the rate of occurrence of events of magnitude m or greater $v_H(M>m)$, can be determined (number of events divided by the period of record). The subscript H is used to denote the historic seismicity assessment. In addition, we would like to know the statistical uncertainty in the estimated rate. To do this, a sample of $v_H(M>m)$ estimates is required. The bootstrap resampling method provides the opportunity to generate an empirical sample of $v_H(M>m)$ that can be used to derive an empirical distribution and to estimate the standard error.

Let the original (observed) earthquake catalog be denoted,

$$EQ = \{e_1, e_2, \dots e_i, \dots e_n\}$$

when e_i is the i^{th} event in the catalog, which is defined in terms of its date of occurrence, magnitude (or Modified Mercalli Intensity (MMI)), and location. There are n events in the catalog.

Given the catalog, a random sample of earthquakes is taken. The events are sampled independently with replacement (an event that is selected is returned to the original catalog for the subsequent samples) and with equal probability. Due to replacement, an event can be selected in subsequent sampling. This process is repeated until a catalog has been generated that has the same number of events, n , as the original catalog. This constitutes one resampling of the earthquake catalog. Based on the type of problem, the resampling is repeated a sufficient number of times. The bootstrap simulation produces a set of earthquake catalogs, each based on a random selection of earthquakes from the original catalog. This set of earthquake catalogs can be denoted:

$$EBS = \{EBS_1 \dots EBS_j \dots EBS_N\}$$

where N is the number of catalogs that were generated. Each catalog, EB_{Sj} , is a complete catalog of events, such that each sampled event in the catalog is defined in terms of its size (date, magnitude, epicentral location, etc.).

For each resampled catalog the number of events above a given magnitude that have occurred in a region can be determined and a rate of occurrence estimated. This can be denoted,

$$\nu_H(M > m, R)_j = \frac{N(M > m, R)_j}{T}$$

where j corresponds to the resampled catalog, EB_{Sj} , and

$N(M > m, R)$ = number of events of magnitude greater than m that occurred in a region R

T = time period in years

Based on the set of resampled catalogs, EB_S a total of N estimates of $\nu_H(M > m, R)$ are made (N being the number of resampled catalogs). The set of $\nu_H(M > m, R)_j$ values provide a statistical sample that can be used to determine a nonparametric, empirical distribution. This distribution provides a measure of the uncertainty of $\nu_H(M > m, R)$ (or statistical error of estimation) given the length of the historic record. Figure 4.7 shows an illustration of a cumulative probability distribution function (CDF) on the rate of earthquake occurrences that can be obtained.

To account for incompleteness in the earthquake catalog, the probability of earthquake detection (P_D) was used. (P_D) is estimated as a function of earthquake magnitude, location and time period. Accounting for incompleteness, an equivalent period of earthquake completeness (complete reporting) in a region is determined according to,

$$T_E(m) = \sum_j P_D(m, t_j) T_j$$

where m is earthquake magnitude, t_j is the index on the reporting time period, and T_j is the length of a reporting time period in years, respectively. The "corrected" rate of earthquake occurrences is,

$$v_H(M > m_i, R) = \frac{N(M > m_i, R)}{T_E(m_i)}$$

This relationship is used in the historic seismicity evaluation.

Application. In performing the historic seismicity assessment, there are a number of choices to be made. These include the earthquake catalog to use, the estimation of earthquake magnitude for non-instrumentally recorded events, consideration of the variability in earthquake magnitude estimates, and the estimation of P_D . These are discussed next.

The historic seismicity assessment is performed using two earthquake catalogs. They are:

- EPRI earthquake catalog updated to 1988, and
- Earthquake catalog compiled by LLNL for use in the SRS seismic hazard study (referred to hereafter as the LLNL catalog).

EPRI Earthquake Catalog. In the EPRI seismic hazard study (1988) methods and procedures were developed to generate an earthquake catalog in which main and secondary events were identified and magnitude was defined on a uniform scale. As part of the development of a uniform measure of earthquake magnitude, the variability in instrumental and non-instrumental magnitude estimates and its relationship to the assessment of earthquake occurrence rates was considered. The study concluded that in order to obtain an unbiased estimate of occurrence rates, the variability in magnitude must be considered. To account for this variability, each event was assigned a "uniform" magnitude, denoted m_b^* . The uniform magnitude is based on the best estimate of the magnitude of an event, whether instrumentally recorded or determined from an MMI- m_b conversion, and its variability. It has the desirable property that it provides an unbiased estimate

of earthquake occurrence rates. Therefore, to perform the historic seismicity assessment using the EPRI catalog, the uniform magnitude is used.

As part of the EPRI study, the incompleteness of the earthquake catalog was also evaluated. The EPRI P_D values were determined as a function of earthquake magnitude, time period and location.

LLNL Earthquake Catalog. To perform the SRS seismic hazard assessment, LLNL compiled an earthquake catalog from available sources, including the EPRI catalog and the catalog compiled by Bollinger and others as part of Southeastern U.S. Seismicity Network (SEUSSN). In the SRS hazard study, the catalog was not processed in the manner of the EPRI study to assign a uniform magnitude to each event. The assessment of magnitude was left to the seismicity expert, who could specify an MMI- m_b relationship to determine a magnitude for historical events.

In using the LLNL earthquake catalog to perform the historic seismicity assessment, the magnitude of each earthquake was assumed to be a random variable. For historical events the distribution on m_b was determined from a statistical analysis that was performed with the LLNL catalog to develop an MMI- m_b conversion. The expected value of m_b is given by,

$$E(m_b) = 1.32 + 0.48 \cdot \text{MMI}$$

The standard deviation from m_b is 0.62. The variability in earthquake magnitude is defined by a Normal probability distribution. The magnitude of instrumentally recorded events is also assumed to be normally distributed with a standard deviation of 0.30. In the bootstrap resampling, as an event is selected from the catalog, a magnitude is randomly chosen from the normal distribution, which is truncated at ± 3 standard deviations.

To account for the incompleteness of the earthquake catalog, LLNL has made two estimates of P_D for the SRS region. The LLNL P_D values vary with magnitude and time period and are applicable to the entire study region. The LLNL P_D estimates, which tend to bracket the EPRI values, are given in Appendix B.

In the bootstrap resampling using the LLNL catalog, an additional variable was considered. Since the occurrence of earthquakes is a stochastic process, the number of events that occur in a given time period is random. This is to say that the total number of events that occurred is simply a realization of the stochastic process of earthquake generation. Assuming stationarity, the number of events that occur in a comparable time period is likely to be different. With this in mind, the number of earthquakes in a sampled catalog is considered a random variable. As part of the bootstrap simulation, when a catalog is generated, the total number of events in the catalog is simulated as a Poisson variable. (Note, sensitivity studies indicate that this variable does not contribute to the overall uncertainty in the estimated rate of occurrence).

Evaluations. The historic seismicity assessment is performed for two regions around the SRS. The first is a large region, $6^\circ \times 6^\circ$ around the site. Within each region the rate of occurrence of earthquakes above three magnitudes are considered. They are 3.75, 5.0 and 6.0. In all, three historical seismicity assessments are performed. The first is performed using the EPRI catalog and the others are based on the LLNL catalog using the two estimates of P_D .

An initial insight to the seismicity of the region is obtained by considering the events that are located in the two regions. Examples of the format of information given to the S-experts is shown Table 4.1, Figures 4.8 and 4.9.

4.2.4 Documentation

One of our guiding principles in designing the elicitation process was to make sure that all experts had complete flexibility to develop their resources and opinions independent of the other panelists. We wanted everyone to function independently in formulating their opinions and have the flexibility to use analytical methods as well as personal intuition and insight to the degree they felt appropriate.

In the following describing our philosophy of eliciting opinions, we did not neglect the need to assure the quality of the experts' responses. We introduced several quality measures into the elicitation process:

- In the initial choice of experts for inclusion as panelists

- As part of the development of the questionnaires used to elicit the expert's opinions, careful consideration was given to the structure of the questions.
- By interacting with individuals to clarify potential misunderstandings.
- By having group discussions after the initial elicitation.
- By introducing qualitative and quantitative comparisons of the expert's inputs with available earthquake data, with subsequent clarification of significant discrepancies, and generally using data diagnostic techniques to identify experts' input with required additional scrutiny.
- By performing follow-up interviews with those experts for whom issues had been raised.
- Requiring from the experts a detailed account, in written form, of the logic they used to develop their input, the data they used, the assumptions they made, and more generally document their answers, so that an external reviewer could follow and understand their arguments and support for any particular parts of their subjective opinions expressed by their answers to our questions.
- One practical detail worth mentioning is that all interviews were audio-taped and the workshops were documented in detail, leading to exhaustive account of their content.
- In addition, the workshop on ground motion G-KDW was videotaped.

We are confident that these measures can assure the quality of the final seismicity inputs and the applicability of the resulting estimated seismic hazard.

4.2.5 Summary of the Seismicity Elicitation for the SRS-SHC

The seismicity elicitation comprised five phases:

Phase 1: S-experts respond to written questionnaires to elicit:
Upper magnitude M_u , preferred value and its uncertainty
(range 5-95 percentile and distribution shape, one of 7 shapes)

a and b values, preferred values, uncertainty (5-95 range, and
one of 7 distribution shapes) and type of correlation between a
and b (one of 3 models)

Note: also, recurrence model can be bi-linear and/or
characteristic model.

Phase 2: Update of seismicity input by written questionnaire elicit rates
of events $f(m)$ for several magnitudes one of them being 3.75
and the other magnitude M_1 is a magnitude as large as possible
consistent with the upper magnitude cutoff M_u .

$f(m = 3.75)$, $f(m_1)$ preferred values
5-95 percentile ranges, and of 7 shapes

For bilinear and characteristic models a third value is also
elicited.

Phase 3: Review by LLNL team, interaction with experts.

Phase 4: Preliminary hazard calculations by the LLNL team, preparation
of feedback meeting, development of DDT's.

Phase 5: Final feedback – one on one interview, documentation

5. Elicitation of the Ground Motion Attenuation Models

5.1 Standard methodology for ground motion modeling

Given the state of knowledge about ground motion in the EUS, the approach to
deriving ground motion information for the EUS Seismic Hazard Characterization
Project and for the first phase of the SRS-SHC project was to elicit ground motion

descriptions from experts on ground motion. The approach was based on assuming

- The ground motion parameter, e.g., PGA, is a lognormal stochastic variable
- The natural logarithm of the median of a ground motion parameter (mean of the natural logarithm of the ground motion parameter) is a function of the earthquake magnitude m and distance r and other source and travel path parameters as described by a ground motion model.
- The variability of the ground motion is quantified by the standard deviation, $\sigma_{\ln}$, of the natural logarithm of the ground motion parameter.

Given these assumptions, the elicitation of ground motion information for the EUS Study was based on asking the ground motion experts to

- Assign relative weights to a set of ground motion models such that the weights represent their assessments of the adequacy of the models to estimate the expected value of the logarithm of the ground motion parameter
- Assess, with uncertainty, the value of the standard deviation, $\sigma_{\ln}$, representing the level of random variation in ground motion.

5.2 Panel on Elicitation of Experts' Judgments

5.2.1 Role and Composition of the Panel

Recognizing that the quality of the information received from eliciting experts is heavily influenced by the structure of the questions asked and the elicitation process, a panel of experts on expert elicitation was convened to review the elicitation process and make recommendations for improving the elicitation of ground motion information.

The panelists included:

- George Apostolakis, UCLA
- Robert Clemen, University of Oregon
- Stan Kaplan, Pickard, Lowe and Garrick (PLG)
- Ralph Kenney, USC and Pros and Cons Consulting
- Peter Morris, Advanced Decision Analysis (ADA)
- Robert Winkler, Duke University and Risk Assessment Consulting

A workshop with the panel was held at LLNL on May 27, 1992. The primary purpose of the workshop was to discuss ways to elicit the information needed, particularly the ground motion information, for seismic hazard analyses. Combination and aggregation of the information derived from the seismicity and ground motion experts was a second topic of interest.

After a presentation on the description of seismic hazard analyses, the role of experts' interpretations in developing the seismicity and ground motion inputs and a chronology of LLNL's previous efforts in eliciting ground motion information, the workshop discussion concentrated on several topics, briefly described in Sections 5.2.2, 5.2.3 and 5.2.4.

5.2.2 Type of Ground Motion Information to be Elicited:

Two concepts of the ground motion information to be elicited emerged from the discussion:

- Personal probability distributions of the ground motion given an earthquake of magnitude m at a distance r from the site. This distribution would reflect an individual's relative likelihood that, given an (m, r) earthquake, the level of the appropriate ground motion parameter is less than (or exceeds) a given value over a range of possible values. This is very much an individual

expression that would reflect the individual's perception and interpretation of the available (historical) evidence combined with one's state of knowledge about earthquake coupling, seismic wave attenuation and the effects of local soil conditions at a site. Uncertainty in one's judgment and/or in one's ability to express his/herself probabilistically would be reflected by having the expert provide an uncertainty distribution over a range of probability distributions.

- Recognizing that the ground motion at a site could be the result of an (m,r) earthquake at an infinity of different locations (source conditions), involves different seismic wave travel paths and different sections of the local site, estimates of the frequency distribution of the ground motion given an earthquake of magnitude m at a distance r from the site. Uncertainty in one's estimate would be reflected by having the expert provide an uncertainty distribution over a range of estimates of the frequency distribution.

The two concepts are identical if the frequency distribution could be known since the personal probability distribution of a well-calibrated expert would be the known frequency distribution. The panel recommended that the former concept should be used for ground motion elicitation, i.e., each experts' personal probability distribution of the appropriate ground motion parameters should be elicited.

5.2.3 Method and Format of Elicitation:

Although there are several elicitation methods, e.g., questionnaire, personal interview, group interaction, the panel strongly recommended that one-on-one personal interviews be used for the elicitation of both seismicity and ground motion information. Feedback with group interactions was also suggested as integral elements of an overall elicitation process. Assuming personal probability distributions are elicited, the panel recommended the distribution be elicited directly by eliciting fractiles, i.e., the 10th, 20th, ... percentiles, of the distribution. This is preferred in contrast to eliciting expected values, standard deviations, etc.,

which are artificial mathematical concepts often misunderstood and difficult to relate to the physical processes.

5.2.4. Aggregation of Experts' Judgments and Combining Seismicity and Ground Motion Inputs for Seismic Hazard Assessment

For the SRS-SHC Study, uncertainty distributions for the seismic hazard were developed by combining the seismicity information from each seismicity expert with the ground motion information from each ground motion expert. Because of the potential dependencies between the information derived from the experts within a panel, it was recommended by the panel on expert elicitations that the seismicity and ground motion be aggregated separately before combining the two types of information to assess seismic hazard. It was pointed out to the panel that, although not impossible, this would be extremely difficult and time and resource intensive and, thus, not possible for the current project. Recognizing that limitation, the panel recommended that the ground motion probability distributions be combined into an aggregate probability distribution before combining the aggregate ground motion distribution with each of the seismicity expert's inputs to assess the seismic hazard. There are several methods for aggregating the experts' ground motion personal probability distributions. No single optimum method was identified by the panel. Their recommendation was to try several methods and assess the sensitivity of the results to the different aggregated probability distributions.

5.2.5 Summary of Recommendations

The following are a summary of the panel's recommendations relevant to ground motion distribution elicitation and development.

1. The information elicited should be an expert's personal probability distributions for the appropriate ground motion parameters.
2. The experts' personal probability distributions should be elicited directly rather than indirectly in terms of ground motion models and other distributional parameters; uncertainties can be included in terms of uncertainty distributions for fractiles.

3. Elicitations should be based on individual interviews with feedback and re-elicitation.
4. Documentation of the resources and reasoning used by the experts in formulating their probability distribution is important.
5. The individual probability distributions should be combined into an aggregate probability distribution.
6. Aggregation within a panel involves analytical methods based on weights; no set of weights is "best" and equal weighting is one useful aggregation.
7. No specific aggregation method is recommended but the sensitivity of the seismic hazard results to aggregation methods should be investigated and reported.
8. Dependencies among experts and differences in the level of uncertainty between experts should be recognized and aggregation methods based on these should be considered.
9. The aggregated ground motion probability distribution should be combined with the seismicity inputs to estimate seismic hazard.

5.3. Ground Motion Workshop, Elicitations and Feedback

A ground motion information dissemination workshop, experts' judgments elicitation and a feedback workshop were combined in a meeting with the ground motion panel at LLNL on August 17–20, 1992. The ground motion panel present were:

K. Aki
G. Bollinger/M. Chapman
D. Boore
K. Campbell

J. Fletcher
R. Herrmann
M. Trifunac

The purposes of the meeting were (1) to disseminate information on current activities relevant to ground motion modeling, (2) to elicit the panel members' ground motion personal probability distributions and (3) to feedback interpretations of the results of the elicitations to the panel for their discussion, consideration, and possible revision of their inputs.

5.3.1 Ground Motion Information Dissemination Workshop

The primary purpose of the Information Dissemination Workshop was to disseminate information about current activities relevant to ground motion modeling and to have the expert's participate in open interchange of information about ground motion. In addition, the panel was given an overview of the SRS-SHC Project, the results of that study, its critique and review and the purpose of the EUS Update Study. Finally, the experts were introduced to the elicitation process, its purpose, the information to be elicited and the format for the elicitation sessions.

The topics presented for discussion during the Information Dissemination Workshop included:

- EUS magnitude scales and relationships between scales
- Uncertainties associated with ground motion modeling
- Regionalization of Q and modeling of differences in attenuation between regions

5.3.2 Ground Motion Probability Distribution Elicitations

The ground motion elicitations for the original EUS Seismic Hazard Characterization Project were based on having the experts assign relative weights to a collection of ground motion models and to estimate, with uncertainty, the

logarithmic standard deviation of the random variation in ground motion at a site given an earthquake of magnitude m at distance r from the site. This information was used to estimate ground motion frequency distributions that were used for the seismic hazard calculations. Based on the recommendations of the Panel on Expert Elicitations, the goal of the EUS Update Study elicitation was to elicit experts' ground motion personal probability distributions directly rather than inferring such through weights associated with ground motion models. However, it was quickly recognized that the experts were unprepared to provide such information in the form desired, i.e., as direct personal probability distributions. Thus, it was necessary to change the format of the information elicited.

The elicitation teams were based on personal interviews with the experts. Two LLNL elicitation teams were used:

- J. Savy/A. Boissonnade
- R. Mensing/D. Bernreuter

The interviews were designed to be informal to allow the experts to provide the desired information in a form they felt most comfortable with, yet were intended to have sufficient structure to assure that all the needed information was accumulated. The structure of the interviews varied considerably among the experts.

Since the experts were accustomed to thinking in terms of ground motion models, the elicitation was based on deriving information that could be derived from ground motion models. This information was transformed into estimates of ground motion frequency distributions that can be viewed as approximations to ground motion probability distributions.

Based on the recommendations of the panel on expert elicitation, the elicitation was originally designed to elicit personal probability distributions for the ground motion parameters for a selected set of magnitudes and distances. The recommended format was to elicit fractiles of the probability distributions directly. As indicated, the experts were unprepared to provide ground motion information in the designed format.

As an alternative, the experts seemed to be comfortable with providing uncertainty estimates (or a process to derive estimates) of the logarithmic mean and standard deviation of the ground motion parameter. This is the format ultimately used to elicit ground motion information. Given the ground motion frequency distribution family or 'shape', e.g., the lognormal distribution, estimates of the mean and standard deviation are sufficient to develop uncertain estimates of the ground motion frequency distributions.

Based on the accepted notion that rational well-calibrated experts would use the frequency distribution, if it were known, as his/her personal probability distribution, we believe the estimated frequency distributions derived from the elicitations can be regarded as approximations to the experts' personal probability distributions of the ground motion parameters given (m,r).

In summary, the information elicited is:

- The distribution family of the ground motion parameter frequency distribution, given (m,r). All the experts considered this to be the lognormal distribution.
- An estimate of the median (50th fractile) of the ground motion parameter including uncertainty. This was either provided directly or by outlining a process by which LLNL could assess an uncertainty distribution for the median. Most experts provided a process such as weights on existing ground motion models or computer codes involving physical models of ground motion. Uncertainty was expressed empirically or analytically and frequently limitations were imposed on the range of applicability of some models and/or on the level of the ground motion to allow for saturation.
- Estimates on the 5th and 95th fractiles of the ground motion parameter including uncertainty. Again, these were either provided directly or through a process by which LLNL could assess the appropriate uncertainty distributions. Most experts provided this input in terms of uncertainty distributions for the standard deviation of the logarithm of the ground motion parameter. This was unfortunate since it involves providing

estimates of a mathematical concept and was considered one of the problem areas in the previous elicitation.

Based on the elicited information, a family (with personal probabilities) of ground motion frequency distributions was developed for each of the ground motion experts.

5.3.3 Feedback

The final session of the ground motion workshop was a group feedback meeting with all the experts.

The purpose of this session was to provide to the experts a summary of their inputs, to encourage a discussion and interaction of the experts and to have the experts make any desired changes in their initial inputs.

The presentation provided the experts with a view of how their assessments of ground motion, expressed in terms of the median ground motion level and, generally, the standard deviation of the logarithm of the ground motion, translates into ground motion frequency distributions. This feedback and the subsequent discussions led several experts to reconsider their inputs and to make some revisions, including revisions in their concepts for estimating the medians, putting limitations on the applicability of some models and reducing the uncertainty in their estimates.

5.3.4 Summary of Final Ground Motion Inputs

The elicitation was performed for 6 ground motion measures. The ground motion measures considered are the peak ground acceleration (PGA) and spectral velocities at 1, 2.5, 5, 10, and 25 Hz. For each of the six ground motion measures, the experts provided information to develop personal probability (uncertainty) distributions for the parameters of the ground motion frequency distribution for 16 magnitude/distance pairs, 5.0/10, 5.0/50, 5.0/100, 5.0/250, 6.25/10, 6.25/50, 6.25/100, 6.25/250, 7.5/10, 7.5/50, 7.5/100, 7.5/250, 8/10, 8/50, 8/100, and 8/250.

Seven experts in ground motion modeling were selected to provide their assessments of the parameters of the conditional ground motion frequency distribution, given (m,r). The elicited information was limited to ground motion at a hard rock site in Southeast U.S. The parameters elicited were:

1. Median ground motion, i.e., the 50% frequency of exceedance ground motion level.

2. Either

- 2a 5% and 95% frequency of exceedance ground motion levels

or

- 2b Shape of the ground motion frequency distribution (Note: the only distribution selected was the lognormal distribution) with an estimate of the random variability of the ground motion, i.e., the standard deviation of the logarithm of the ground motion for the lognormal distribution.

3. Ground motion saturation level, if appropriate.

In all cases, the experts were asked to provide bounds and the most likely value of the median and logarithmic standard deviation and select a shape (from a collection of 7 families of distributions) for their uncertainty distribution.

Only one expert provided the median, 5% and 95% levels of ground motion (Items 1 and 2a). All other experts felt more comfortable giving methods on how to obtain uncertainty distributions for the medians and, assuming the lognormal ground motion frequency distribution, the standard deviation of the logarithm, $\sigma_{\ln}$. Thus, they provided, for each ground motion measure and magnitude/distance pair, a selection of attenuation models with associated weights to represent their belief that any one of these models might best represent the median ground motion (i.e., the ground motion estimate at the 50 percent exceedance probability level, g_{50}). In addition, bounds for g_{50} (or methods to calculate these) were provided as well as the shape of their uncertainty distribution that represents their uncertainty in estimating g_{50} . In preparation for

the interviews, the experts were provided a description of the models presently available in the EUS and Southeast U.S. studies. Tables 5.1 and 5.2 summarize those models.

It is interesting to note that in many instances experts elected to provide inputs as a function of magnitude and distance, which is quite different from previous elicitation results. In previous elicitations, where the experts had to provide a set of ground motion models applicable over all magnitudes and distances, they were limited to a choice of models that could best represent the ground motion without being able to specify peculiarities. In contrast, in this elicitation the experts were able to provide their best assessment on a magnitude/distance basis.

As indicated earlier, everyone that chose to use 2b as an input selected the lognormal distribution to represent the random variation of ground motion, given (m,r). Generally, the triangular distribution was chosen to represent the experts' uncertainty distributions. Again, the current approach of eliciting information about the ground motion frequency distribution for several (m,r) provides more flexibility. The experts used this flexibility as several experts provided uncertainty distributions for σ_{ln} which were a function of magnitude in contrast to the previous elicitations when only a single uncertainty distribution for σ_{ln} , applicable over all (m,r), was elicited.

The final input elicited from the ground motion experts were either absolute saturation levels for ground motion or limits on the range of values of the fractiles, e.g., median ground motion, of the ground motion frequency distribution. The former results is a truncation of the ground motion frequency distribution while the latter does not necessarily truncate the frequency distribution but only limits the location (range of the median ground motion) and/or the 'shape' (limits the range of σ_{ln}) of the lognormal frequency distribution.

In the previous LLNL studies, including the 1989 study, the knowledge base of the ground motion experts covered a variety of approaches. Some experts based their knowledge on empirical considerations and estimated their uncertainties on the uncertainty they observe in the data only. With this approach they often did

not try to identify the physical significance of this uncertainty, neither did they attempt to determine its origins.

Other experts separated the various components of the uncertainty and estimated that uncertainty which they believed was the appropriate one to use in the hazard model.

It is now customary to distinguish two distinct types of variabilities in the estimate of the ground motion. One type is due to the inherent physical randomness in the multitude of physical processes leading to the ground motion at one site. This variability, often called the random uncertainty is generally represented by a simple log normal distribution with median value equal to the value obtained from a standard attenuation curve for a set of given earthquake parameters, such as magnitude and distance, and with standard deviation equal to a value σ , generally estimated from existing data. The more data we collect, the better we can determine the parameters of the probability distribution function of the ground motion for a given set of earthquake parameters but the random uncertainty distribution function of the ground motion for a given set of earthquake parameters but the random uncertainty will not be reduced.

On the other hand the second type of variability, also called the knowledge uncertainty, is due to the lack of perfect knowledge in our understanding of the earthquake process. Additional studies or additional data will help improve our understanding and will lead to a reduction of the knowledge uncertainty. For example, when considering a set of median ground motion attenuation curve for the prediction of the ground motion at a particular site, additional geological, geophysical and strong motion data will likely reduce the range between the highest and lowest prediction.

In previous studies such as the LLNL 1989 study or the LLNL NPR 1992 study, an effort was made to properly characterize the two types of uncertainties but that effort showed to be insufficient when considering the range of values given by the ground motion experts for the random uncertainty. The range of estimates shown in Figure 2.1 is representative of the results obtained in one of these studies and does not in our opinion accurately represents the present state of knowledge. In our opinion, the large variability that we observe in Fig. 2.1 is a result of the

different approaches, the different physical interpretations and the different levels of knowledge of the experts with the specific issue at hand.

This important drawback in the ground motion expert elicitation methodology was identified early enough in the study for the SR-site that two sets of results were obtained. In the first set, the estimates of the ground motion uncertainty given by the experts (Fig. 2.1), and used as their estimates of the random uncertainty, were used. In the second set, we the LLNL analyst team used the experts inputs and our understanding of their actual meaning to derive a probability distribution function for the value of sigma to be used for all ground motion expert's models. The median value was equal to 0.5, the 2.5-th percentile equal to .3 and the 97.5-th percentile equal to .8 on the natural logarithm base scale.

5.4 Composite Ground Motion Uncertainty Distribution

Based on the recommendations of the panel on expert elicitation to aggregate the elicited ground motion probability distributions prior to combining the ground motion distributions with the seismicity information to estimate seismic hazard, the issue of developing an aggregated uncertainty estimate of the ground motion frequency distribution was investigated. One model of an aggregated ground motion frequency distribution is a weighted average of ground motion frequency distributions from all the experts. Since each expert has provided an uncertainty distribution of the ground motion frequency distribution, this approach results in an uncertainty distribution of the aggregated ground motion frequency distribution. Equal weights are frequently used. Two shortcomings of this concept are (1) using equal weights makes the aggregated frequency distribution sensitive to extremes and (2) the diversity in assessed ground motion between experts is lost in the 'averaging' process. The former drawback can be overcome by using other weights but the selection of weights can be a difficult and sensitive issue. Since any weighted combination of this type is an averaging process, the loss of diversity still exists. This is a major concern since this is contradictory to the stated strong desire, from some experts on elicitation, to have the final seismic hazard results reflect the diversity of opinions among the seismicity and ground motion experts.

In an attempt to be sensitive to the need to retain the diversity of the experts' interpretations of ground motion and still combine the individual frequency distributions into a "group" frequency distribution, a "composite" uncertainty distribution was developed, based on the joint mixture distribution of the experts' uncertainty distributions for the logarithmic mean and standard deviation of the ground motion parameter, the two parameters used by the experts to describe their assessment of ground motion. A value for the logarithmic mean and standard deviation, taken from the joint mixture distribution, identifies one of the ground motion frequency distributions provided by the experts through their uncertainty distributions. The range of possible ground motion frequency distributions covered by the composite uncertainty distribution is equivalent to that covered by the range of individual uncertainty distributions provided by the experts.

5.4.1 Composite Ground Motion Uncertainty Distribution Methodology

The experts suggested the lognormal family of distributions as the appropriate description of the ground motion parameter (e.g., PGA) frequency distribution. The inputs received from the experts were (1) a procedure for developing an uncertainty distribution for the median ground motion level, g_{50} and (2) an uncertainty distribution for the standard deviation of the logarithm of the ground motion, σ_{ln} . Uncertainty distributions for these parameters defines an uncertainty distribution over the space of ground motion frequency distributions.

The experts' assessments of the ground motion, based on their interpretation of the available ground motion data and models, were elicited for combinations of four magnitudes and four distances, $m = 5, 6.25, 7.5, 8$ and $r = 10, 50, 100, 250$ (km). For each (m,r) , the inputs received from the experts were translated into uncertainty distributions for g_{50} and σ_{ln} . The composite ground motion uncertainty distribution, for a given (m,r) , is the joint uncertainty distribution for (g_{50}, σ_{ln}) based on a Monte Carlo simulation of the experts' uncertainty distributions. The composite uncertainty distribution is expressed in terms of:

- The empirical uncertainty distribution for g_{50} , given in terms of the fractiles $g_{50, \min}, g_{50,5}, g_{50,10}, \dots, g_{50,90}, g_{50, \max}$.

- Empirical conditional uncertainty distributions for σ_{ln} , given each of the fractiles, actually considered to be the same over the range ($g_{50,a-2.5}$, $g_{50,a+2.5}$) for $a = \min, 5, 10, \dots, 90, 95, \max$; these distributions are approximated by beta (s_l, s_u, p, q) distributions, where (s_l, s_u) represents the range of σ_{ln} and p, q are the parameters of the beta distribution.

5.5 Results

The composite ground motion uncertainty distributions were developed for the 16 magnitude/distance pairs specified in Section 5.3.4. Extrapolation of the composite uncertainty distributions to unelicited magnitudes and distances are based on performing regression analyses over magnitude and distance for each fractile for the median ground motion and for the bounds and parameters of the beta distributions for σ_{ln} .

Figures 5.1, 5.2 and 5.3 are examples of the resulting composite model.

Figure 5.1 gives a summary of the uncertainty in the median ground motion attenuation models for magnitude 5 and 7, obtained as composite of the input by the 7 ground motion experts.

Figure 5.2 shows the 50th percentile median curve (dashed line). The other curves show the dispersion due to randomness (assuming a σ of 0.6), and for a magnitude of 6.0.

Figure 5.3 shows the 85th percentile of the median curve (dashed line). The other curves show the dispersion due to randomness (assuming $\sigma = 0.6$) and a magnitude of 6.0.

Similar results not shown here were developed for the 5 spectral velocities of the study.

6. Site Characterization of SRS, Site Amplification

6.1 Geotechnical Characterization of the SRS

The Savannah River Site (SRS) is located on the Atlantic Coast Plain, which is an essentially flat-lying unconsolidated marine and fluvial sediments. The sediments are mainly sandy soils interbedded with clay and silt layers. There are about 600 to 1200 feet of Coastal Plain sediment at SRS. At the proposed New Production Reactor (NPR) site at SRS, a metamorphosed basement of crystalline rock occurs at approximately 1,100 feet below ground surface. This basement rock surface slopes gently to the southeast.

Many geotechnical investigations have been performed previously within the Savannah river Plant area, including those conducted for the Defense Waste Processing Facility (DWPF) about 4 miles from the NPR site (D'Appolonia, 1982), for the proposed Away From Reactor-Spent Fuel Storage Facility (AFR-SFSF) in the vicinity of the proposed NPR site (D'Appolonia, 1980), in L-area (Geotechnical Engineers, Inc., 1984, GEI Consultants, Inc., 1989), in F-area (Geotechnical Engineers, Inc., 1983, WSRC-RP-575, 1990), and in K-area (GEI Consultants, Inc., 1991). These investigations conducted borings of up to a maximum depth of about 350 feet, standard penetration tests (SPT), cone penetration tests (CPT), seismic refraction surveys, borehole geophysical logging, down-hole and cross-hole wave velocity measurements, piezometer installation, undisturbed soil sampling, laboratory testing, including soil classification tests, consolidation tests, and static and dynamic property tests, and liquefaction potential evaluation.

Under the New Production Reactor project (NPR) and continuing in this project, a site amplification working group was formed consisting of Professors Wayne Clough, Carl Constantino, Ricardo Dobry, I. M. Idriss, Dr. Walter Silva and Richard Woods. An extensive review of geotechnical data available within the SRS plant area was conducted. A workshop of local site amplification study was conducted with participation of the DOE-DP staff, SRS site characterization staff, LLNL team, and the working group members. In the meeting, we introduced the overview of LLNL seismic hazard analysis methodology. We also presented our proposed approach for the correction of local site effects on seismic ground motion. The approach which was approved by the panel members, has been used to study the local site effect for seismic hazard characterization of 69 nuclear plant sites east of the Rocky Mountains, Bernreuter and others (1989). For long term study, the working group also recommended to install instrumentation packages in

a deep hole at the site. To demonstrate our methodology, the site amplification factors were calculated on the basis of the shear wave velocity profile at the Away From Reactor (AFR) spent fuel storage facility site. The dynamic properties given at the L-area were used in that preliminary calculation. The results were presented and discussed at the workshop.

A Geotechnical investigation program was performed at SRS. The technical assistance was provided by the designer, Ebasco Service, Inc. and Lawrence Livermore National Laboratory (LLNL). This geotechnical investigation program consisted of the following three phases:

1. Phase I: The purpose of the Phase I geotechnical study which was performed under the New Production Reactor project (NPR), was to provide site selection information used to evaluate the relative merits of the Candidate Plant Islands within the NPR circle. The technical specifications were provided by Ebasco. Law Environmental, Inc. and Law Engineering, Inc. (LAW) were selected by WSRC as the Phase I geotechnical consultants. The preliminary report was delivered to WSRC in April and the final report was given in June of 1991.
2. Phase II: Phase II geotechnical investigation was confined exclusively to the defined candidate plant island. The investigation specified by Ebasco and reviewed by LLNL emphasizes on site investigations and soil characterizations for the depth less than 500 ft. from the ground surface primarily for the purpose of foundation design of the plant structure. The contract was awarded to Dames and Moore Consultant, Inc. and scheduled to finish the investigation by May of 1992.
3. Phase III: This is a separate site investigation and soil characterization for the deeper part of the site. The main purpose is to provide the required geotechnical data for studying site effects to be incorporated in seismic hazard assessment at the SR-NPR site. The investigation also includes the seismic instrumentation and in-situ shear wave and damping measurements in a deep hole down to the bedrock at the depth of approximately 1100 ft. from ground surface. The technical specifications were provided by LLNL. The contract was awarded to LAW. Site

investigation was scheduled to be completed in January of 1992. The installation of an instrumentation package in in-situ shear wave measurements were also planned to be completed in May of 1992.

While the geotechnical investigation was ongoing, the complete site specific geotechnical data would not be available until the completion of the site investigation program scheduled in May of 1992. The details of the site investigation and the related site amplification study is being documented in a separate report, Chen, et al., (1992).

In April of 1991, the completion of Phase I investigation provided a substantial amount of shear wave velocity data the NPR-site to the depth of about 270 ft. from the surface. The specific subsurface conditions down to 270 ft. became more clearly defined. This information was used to model the upper part of the soil column and data from the literature was used to model the deeper part of the site. Since there was no dynamic soil tests conducted on the Phase I investigations, the dynamic characteristics of the NPR soils were assumed the same as those available from the K-reactor site. (Note that the K-reactor site is about 4 miles from the NPR site). The preliminary site amplification factors were developed based on those only available data. The amplification factors were incorporated in the preliminary PGA hazard curves and uniform hazard spectra.

6.2 Correction factors for the NPR Site

The NPR site investigations and the site specific geotechnical data being available, the site amplification analysis are preliminary in nature, and can only be made by using best estimated geotechnical properties based on the available data. A generalized site profile was therefore developed for the preliminary site amplification study based on the data available as of January 1, 1992.

A generalized soil stratigraphical profile for the NPR site is presented in Figure 6.1. It formed the basis for developing the correction factors to be used in the SHA.

In developing these correction factors, the uncertainties in the geometry, stratigraphy and material properties were included. Figures 6.2 and 6.3 give the strain degradation curves uncertainty used in the analysis.

The correction factors were calculated by using the Shake computer program, and the uncertainty was obtained by using a Monte Carlo simulation technique where the geometry and material properties were taken as the uncertain variables.

The final correction factors used in the SHA analysis of the NPR site is presented in Figure 6.4, for a peak ground acceleration of 0.3 g. The figure shows the median correction factor for each and the 16th and 84th percentiles for each frequency. The correction factor displayed in the figure is the ratio of the peak spectral velocity (5% damped): Surface/bedrock.

6.3 Use of the Correction Factors in the Hazard Analysis

The correction factor is defined as the ratio a ground motion parameter value for a given type of site conditions to some reference site conditions case. In the present calculations, the reference case was selected to be a rock outcropping at the site. The parameter of interest is the peak of the acceleration (PGA) or the response spectral velocity (PSV) at a given frequency.

Let us imagine that for a given earthquake we have a site (located at some distance from the epicenter of the earthquake) where two different site geologies reside at the same location.

On geology A, the site appears to be a rock site on geology B, the site appears to be something else. For that earthquake, the peak of the acceleration recorded on geology A is $PGA(A)$ and it is $PGA(B)$ on geology B. The response spectral velocities for frequency f are $PSV(A,f)$ and $PSV(B,f)$. The correction factor as we define it for the amplification of the peak acceleration is:

$$r_{PGA} = \frac{PGA(B)}{PGA(A)}$$

and for a frequency f , the correction factor is:

$$r(f) = \frac{PSV(B,f)}{PSV(A,f)}$$

Let us assume that we can calculate the ground motion at a site for a given site geology reference case. For example: by using an attenuation curve, where the variables are the magnitude of the earthquake (M) and the distance from the earthquake (d). The predicted ground motion at a hypothetical reference site is:

$$\begin{aligned} g_1(M,d) \text{ for } PGA \\ g_2(M,d,f) \text{ for } PGV \text{ at frequency } f \end{aligned} \quad (6.1)$$

The predicted ground motion at the site for which the correction factors would be $r(PGA)$ and $r(f)$ would then be

$$\begin{aligned} g_1(m,d) \cdot r_{PGA} \\ g_2(m,d,f) \cdot r(f). \end{aligned} \quad (6.2)$$

The same calculations are performed in the hazard analysis. The ground motion attenuation relationship is first calculated for the reference case using equation 6.1 and then it is modified as shown by equation 6.2 to include the site specificity which is directly included in the calculation of the hazard as described in Section 3.3.2. In these calculations, the uncertainty in the correction is also included by assigning a probability distribution to $r(PGA)$ or $r(f)$ the parameter of which are determined by a statistical analysis on the simulation calculation described in Section 6.2.

7. Results and Comparisons with other Studies

7.1 Estimates of the Seismic Hazard at the SRS

Figure 7.1 shows the probabilistic estimates of the seismic hazard for the SRS using the latest data available to LLNL. the hazard is expressed in terms of the annual probability of exceedance of the peak ground acceleration (PGA, in

cm/sec/sec). The three unmarked curves on Figure 7.1 represent three percentiles of the probability distribution of the hazard. The lowest curve represents the 15th percentile, the middle curve represents the 50th (median) and the upper one represents the 85th percentile. The curve labeled "a" is an estimate of the mean.

In the calculation summarized in Figure 7.1 all earthquakes greater or equal to magnitude 5.0 were considered, and all sources of variability were included (i.e., Random variability, uncertainty, and diversity of opinions). The ground motion models aggregation used the composite model described in Section 5.

The median 10,000 yr. return period PGA is .14 g and the mean 10,000 yr. PGA is 0.31 g. For 3,000 yr. return period these numbers are 0.08 g and 0.19 g respectively. The ratio of mean to median hazard varies from approximately 4.2 for 0.05 g to 10 at 0.3 g and 12 at 0.5 g.

The ratios of the 10,000 yr. return period PGA values between mean and median is 2.3, and the ratio of 85th to median is 2.0. For the 3,000 yr. return period case, these ratios are 2.6 and 2.4 respectively. These results are summarized in table 7.1.

Similarly, Figure 7.2 shows the 10,000 yr. return period uniform hazard spectra for the 15, 50 and 85th percentile hazard estimates and for the mean hazard. (Curve labeled "a"), which falls right on the 85th percentile Uniform Hazard Spectrum (UHS), for frequencies higher than 1 Hz (i.e. 2.5, 5.0, 10.0 and 25 Hz. The ratio of the mean to median 10,000 yr. return period spectral values is

2.2	at	1 Hz
2.7	at	2.5 Hz
2.4	at	5 Hz
2.0	at	10 Hz
3.0	at	25 Hz

The amount of uncertainty is thus approximately constant over all frequencies with perhaps more at the highest frequencies.

7.2 Comparison with Previous Results

7.2.1 Previous Results for the SRS

The PGA hazard results obtained at the end of the NPR project are shown in Figure 7.3 and in Figure 7.4. The seismicity models have been updated, but not finalized since the final feedback described in Section 3 is not finished, and the ground motion models have been entirely overhauled, but still used as separate models in the hazard calculations. (i.e., not aggregated into a composite model).

For this case, the values in the ground motion random uncertainty was set at .5 with a range of .37 to .65 for all ground motion experts. This is lower than the estimates obtained in the 1992 re-elicitation. Thus we can observe that the median values are those between the NPR and SRS 93 values but the uncertainties are larger in the latest 1992 estimates (Fig. 7.2). The previous (1991) results are summarized in Table 7.2.

We notice very little differences between the results presented in Figures 7.1, 7.3 and 7.4.

7.2.2 Comparison with the Estimates of PSH at Vogtle

To provide some insights in the evolution of the seismic hazard estimates since they were provided in the first comprehensive studies of the Eastern U.S., we show some comparisons for the results obtained at a Nuclear Plant nearby, practically on the boundary of the SRS.

Figure 7.5 shows the mean hazard estimates for the EUS Study performed for NRC and published in 1989. (Curve L89), for the EUS 1993 Study (L93) and for the EPRI Study (E89) published in 1989.

Figure 7.6 shows the median hazard curves for the same studies.

The main observation is that the total uncertainty on the estimate of the hazard have decreased substantially. Table 7.3 summarizes the results for the 1989 LLNL study.

7.2.3 Sensitivity Analyses.

7.2.3.1 Effect of using $M_0 = 3.75$ as Minimum Magnitude

Fig. 7.7 shows the results for using $m_0 = 3.75$. The median hazard is practically equal to the case of $m_0 = 5.0$ for PGA values greater than 0.3g, or equivalently for values of the yearly probability of exceedance smaller than 10^{-5} , for the mean hazard, the minimum difference is around .4g. For both curves, the difference at low PGA is approximately a factor of 2 in the probability of exceedance.

7.2.3.2 Effects of Upgrading the Seismicity Input

Since the seismicity upgrading between the 1992 study (NPR) and 1993 study (SRS-SHC) was very minimal, there is practically no differences between the two cases. A better measure of the overall upgrading of seismicity input is obtained by comparing the results of the 1989 study (figs. 7.5 and 7.6) with the final 1993 results (Figs. 7.1 and 7.2).

7.2.3.3. Effect of Upgrading the Ground Motion Models

Fig. 7.8 show results obtained with the ground motion attenuation composite model. Comparing with fig. 7.1 show that the composite model lead to practically the same results as by using a set of separate independent ground motion attenuation models (Fig. 7.1). In the case of the spectra (Fig. 7.9) it appears that the uncertainty obtained from the experts and combined in the composite model leads to higher uncertainty. The median UHS are approximately the same.

At this point we cannot compare the effect of upgrading only the ground motion models between 1989 and 1993. We can however compare the results for the 1992 NPR results and the 1993 SRS results since the seismicity input has practically not changed between these two cases. By comparing fig. 7.3 with fig. 7.1 it can be seen that the two set of ground motion attenuation models do not lead to substantially different results.

8. Conclusions and Recommendation for Finalizing the Seismic Hazard Characterization of the SRS

8.1 Summary of the Present Status

Seismicity Modeling:

The feedback process of all the S-experts elicitation is the most important task remaining in the finalizing of seismicity modeling. At this point, the feedback material needs only minimal effort to be complete. We have performed the feedback for 3 out of the 9 S-experts. The written documentation needs to be completed as well. It will be updated as we complete the remaining feedback elicitations which are one-on-one interviews.

The three S-experts who participated in feedback are:

- The Site Team (Dale Stephenson)
- W. Lettis
- J. Litehiser

There have been no major changes in the zonation and seismicity modeling from these experts, just minor re-arrangements of the weights of alternative maps or alternative boundaries, and a set of more detailed explanations in the development of the documentation. Minor updates of upper magnitude cutoffs and some seismicity rates updates.

Ground Motion Modeling:

The modeling of ground motion using the composite model approach has demonstrated its stability and usefulness. It allows to reach the same level of accuracy in the calculation of percentile values of the hazard with a minimum of computational effort. It also leads to a single model which embodies the total uncertainty in the process of developing ground motion models.

The initial, basic standard ground motion models used in the derivation of the composite can be considered final at this point.

The estimation of the random uncertainty, expressed by σ , is not considered final. In the results presented in this report, we made a judgment on which range of values was the most appropriate for σ and selected it without the benefit of a full review by individuals who would be considered experts in evaluating random

uncertainty (not necessarily all our G-experts would qualify!). Thus, the random uncertainty part of the ground motion model is still to be finalized.

Site Specific Condition, Amplification:

The results presented here rely on geotechnical data available on January 1, 1993, mostly for the NPR site. More data for the site at large, have been, and are still being collected and analyzed.

8.2 Recommendation for Additional Tasks for Completion of the Study

- (1) Complete the feedback one-on-one elicitation for the remaining 6 S-experts.
- (2) Perform all the DDT's applicable to S-experts data, review and finalize.
- (3) Develop an approach for finalizing the model of the ground motion random uncertainty. Possibly a combination of workshop analysis and additional elicitation.
- (4) Finalize the ground motion composite model.
- (5) Review the ground motion model, perform all the DDT's, peer review.
- (6) Collect and finalize all remaining pertinent new geotechnical data.
- (7) Select several site locations at the SRS, establish their local site correction/amplification factors.
- (8) Perform all the hazard calculations, provide results of sensitivity analyses, results, deaggregations, etc.

Several of the above tasks will require contributions from the substantive experts (S and/or G-experts) and/or from normative experts. Several of these tasks could

also be dependent on findings from other ongoing projects, such as the DOE/NRC/EPRI "Resolution" project described in Section 1.

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Table 3.1.
SRS Zonation and Seismicity Panel Members
(SRS S-Panel, List of S-experts)

(1, 2, & 4)	• Professor Gilbert A. Bollinger	University of Virginia
(1,2 & 3)	• Mr. Richard J. Holt	Weston Geophysical Co.
(2 & 3)	• Dr. Alan Kafka	Weston Observatory
(3)	• Dr. William Lettis	Consultant
(3)	• Dr. Joe Litehiser	Bechtel Company
(2 & 3)	• Professor L. Tim Long	Georgia Tech.
	• Professor Pradeep Talwani	University of South Caroling (Columbia)
(1, 2 & 3)	• Professor M. Nafi Toksöz	M.I.T.
	• Site Team; Dale Stephenson	Westinghouse-SRS

Note:

- (1) Also participated in the SEP Panels.
- (2) Also participated in the EUS NRC/LLNL 1989 study.
- (3) Also participated in the EPRI EUS study (1985, 1988).
- (4) Also member of the Ground Motion Panel (Table 3-2).

Table 3.2
SRS Ground Motion Panel Members
(SRS G-panel, List of G-experts)

	• Professor Keiiti Aki	USC
(1)	• Professor John G. Anderson	University of Nevada, Reno
(2)	• Professor Gil Bollinger/ Professor Martin Chapman	University of Virginia, (now retired) University of Virginia
(1)	• Dr. David Boore	USGS
(1)	• Dr. Kenneth Campbell	EQE Consultants
	• Professor Robert Herrmann	St. Louis University
(1)	• Professor Mihailo Trifunac	USC
	• Site Team: Dr. Joe Fletcher	USGS

Note: (1) Participated in the NRC/LLNL EUS 1989 study.
(2) Also member of SRS S-expert panel.

Table 5.1

Model #	ID in Q3 - SRS	Description
1	RV-6A-1	Aki's RV model - Uses $f_{\max} = 40$ Hz - Power of 4 exponent of f for f_c vs M_o means increasing stress drop - $Q = 1000 f^{.3}$
2	RV-6A-2	Aki's RV model applying to Charleston, i.e., large distant earthquakes - Same as RV-6A-1, but used decreasing $f_{\max}$ from 40 Hz for $m \leq 5$ to 10 Hz $m \geq 6.5$
3	RV-6A-3	Bollinger-Chapman's RV model, 100 bars - Uses Boore-Atkinson 1987 source spectrum and f_c , M_o scaling - Stress parameter ($\Delta \sigma$) = 100 bars - $Q = 811 f^{.42}$ - $F_{\max} = 50$ Hz - Uses m_{bLg} - M_o as shown in Fig. 1
4	RV-6A-4	Bollinger-Chapman's RV model: 500 bars - Same as RV-GA-3 but uses different stress parameter (500 bars) and different m_{bLg} - M_o relationship (see Fig. 1)
5	RV-1A	Boore-Atkinson's RV model uses original 1987 BSSA m_{bLg} - M_o relationship through moment magnitude: $M = 2.715 - .277 m_{bLg} + .125 m_{bLg}^2$ stress parameter: 100 bars and $f_{\max} = 50$ Hz

6	RV-2A	Toro McGuire's RV model using: stress parameter = 100 bars $\kappa = .004 \text{ sec}$, $Q = 560 f^{.65}$ and same $m_b L_g - M_o$ relationship as model #5
7	COMB-1A	Veneziano's model. Intensity based (1986) regression model
8	RV-1A	Boore-Atkinson's RV model, same as model #5 except for $M = 2.69 - .25 m_b L_g$ $+ .127 m_{bLg}^2$
9	SE-2A	Nuttli's 1986 semi empirical model (see Questionnaire Q3-SRS) $M_o - f_c$ slope of 3 (constant stress drop) Using: $Q = 100 f^{.3}$ $\log(a) = 1.22 + .375 m_b - 0.83 \log(R^2 + h^2)^{1/2}$ $-.0012R$ where h is depth and R is distance to epicenter
10	DR-4A-1	Boore-Atkinson model described in Spectra, 1990 (Vol. 6., No. 1, pp 15-35) Uses constant stress drop of 100 bars $f_{\max} = 40 \text{ Hz}$
11	RV-6A-5	Campbell's RV model. Same as RV-2A (#6) except uses the $M_o -$ $m_b L_g$ relationship described at the NPR ground motion workshop, April 24-26, 1990: $\log_e M_o = 35.783 + 4.37 m_{blg} - .0544 m_{bLg}^2$ $-.0939 m_{bLg}^3 + .0128 m_{bLg}^4$
12	DR-4A-2	Campbell's RV model, same as #8 (RV- 1A) scaled by a multiplicative factor of 1.7

13	RV-6A-6	Same as #11 (RV-6A-5), scaled by a multiplicative factor of 1.7
14	RV-3A	Fletcher's RV model, using same parameters as #8 (RV-1A) but with Nuttli's $M_O - m_{bLg}$ relationship: $\text{Log } M_O = 2 m_b + 13.2$ and $(m_b \sim m_{bLg})$
15	RV-4A	Fletcher's RV model, using same parameters as #6 (RV-2A) but with Nuttli's $M_O - m_{bLg}$ relationship (same as above)
16	RV-5A	Fletcher's RV model using same parameters as Boore-Atkinson RV-1A, $M = 2.715 - .227 m_{bLg} + .127 m_{bLg}^2$ and a stress parameter of 200 bars
17	A1-G17	Region specific intensity attenuation law from Bollinger (dominated by Charleston data) and Trifunac 1976 for PGA vs I_s
18	A7-G17	Trifunac, intensity to ground motion, and using Veneziano's attenuation of intensity
19	RV-6A-8	Herrmann's RV model using stress parameter of 100 bars Nuttli (1984) $Q = 400 f^{-4}$ $Kappa = 0.025$ Toro-McGuire model of random process is used and a m_{bLg} is calculated for each run (Herrmann 1987, Herrmann and Kijko)
20	RV-6A-9	Same as #19 for 200 bars
21	RV-6A-7	Same as #19 for 50 bars

Table 5.2

Model #	ID in Q3 - SRS	Description
1	RV-6S-1	Aki's RV model - Uses $f_{\max} = 40$ Hz - Power of 4 exponent for f_c vs M_0 means increasing stress drop - $Q = 1000 f \cdot 3$
2	RV-6S-2	Aki's RV model applying to Charleston, i.e., large distant earthquakes - Same as RV-6A-1, but used decreasing $f_{\max}$ from 40 Hz for $m \leq 5$ to 10 Hz $m \geq 6.5$
3	RV-1S	Boore-Atkinson's RV model uses original 1987 BSSA $m_{bLg} - M_0$ relationship through moment magnitude: $M = 2.715 - .277 m_{bLg} + .125 m_{bLg}^2$ stress parameter: 100 bars and $f_{\max} = 50$ Hz
4	DR-4S	Atkinson empirical, 1990
5	RV-6S-3	Bollinger-Chapman's RV model, 100 bars - Uses Boore-Atkinson 1987 source spectrum and f_c , M_0 scaling - Stress parameter ($\Delta \sigma$) = 100 bars - $Q = 811 f \cdot 42$ - $F_{\max} = 50$ Hz - Uses $m_{bLg} - M_0$ as shown in Fig. 1
6	RV-6S-4	Bollinger-Chapman's RV model: 500 bars - Same as RV-6S-3 but uses different stress parameter (500 bars) and different $m_{bLg} - M_0$ relationship
7	RV-1S (modified)	Boore-Atkinson's RV model, same as model #7 except for $M = 2.69 - .25 m_{bLg} + .127 m_{bLg}^2$

8	RV-2S (modified as noted)	Toro McGuire's RV model using: stress parameter = 100 bars $\kappa = .004$ sec, $Q = 560$ f.65 and same m_{bLg} - M_0 relationship as model #7
9	DR-4S-1	Boore-Atkinson model described in Spectra, 1990 (Vol. 6., No. 1, pp 15-35) Uses constant stress drop of 100 bars $f_{max} = 40$ Hz
10	RV-2S (modified)	Campbell's RV model. Same as RV-2S (Toro-McGuire Model) except uses the M_0 - m_{bLg} relationship described at the NPR ground motion workshop, April 24-26, 1990: $\log_e M_0 = 35.783 + 4.37 m_{bLg} - .0544 m_{bLg}^2$ $- .0939 m_{bLg}^3 + .0128 m_{bLg}^4$
11	DR-4S-2	Campbell's RV model, same as #8 (RV- 1A) scaled by a multiplicative factor of 1.7
12	RV-6S-6	Same as #10 (RV-2S), scaled by a multiplicative factor of 1.7
13	RV-3S	Fletcher's RV model, using same parameters as #3 (RV-1S) but with Nuttli's M_0 - m_{bLg} relationship: $\log M_0 = 2 m_b + 13.2$ and ($m_b \sim m_{bLg}$)
14	RV-4S	Fletcher's RV model, using same parameters as #8 (RV-2S) but with Nuttli's M_0 - m_{bLg} relationship (same as above)
15	RV-5S	Fletcher's RV model using same parameters as Boore-Atkinson RV-1S, $M = 2.715 - .227 m_{bLg} + .127 m_{bLg}^2$ and a stress parameter of 200 bars

16		Lee 87, IV 2.2, Trifunac attenuation Is
17		Lee 87, IV 2.2, Veneziano attenuation Is
18		Lee 87, III 2.2, Trifunac attenuation
19		Lee 87, III 2.2, Veneziano attenuation

Table 7.1

Summary of 1993 SRS Results for PGA

	10000 yr RP		3000 yr RP	
	PGA	ratio with median	PGA	ratio with median
Median Hazard	.14 g	1.0	.08 g	1.0
Mean Hazard	.31 g	2.2	.21 g	2.6
85th Percent	.29 g	2.1	.19 g	2.4

Table 7.2

Summary of 1992 NPR Results for PGA

	10000 yr RP		3000 yr RP	
	PGA	ratio with median	PGA	ratio with median
Median Hazard	.14 g	1.0	.08 g	1.0
Mean Hazard	.29 g	2.1	.17 g	2.1
85th Percent	.29 g	2.1	.18 g	2.3

Table 7.3

Summary of 1989 Vogtle Results for PGA
for the LLNL Study

	10000 yr RP		3000 yr RP	
	PGA	ratio with median	PGA	ratio with median
Median Hazard	.19 g	1.0	.11 g	1.0
Mean Hazard	.67 g	3.5	.39 g	3.5
85th Percent	.47 g	2.5	.27 g	2.5

Fig. 2-1 Estimates of Dispersion in Ground Motion Predictions

Figure E3-1 LLNL PSHA Methodology Outline

Figure E3-1 LLNL PSHA Methodology Outline (cont'd)

AIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910

301/587-8202

Centimeter

Inches

MANUFACTURED TO AIM STANDARDS
BY APPLIED IMAGE, INC.

2 of 3

Figure E3-1 LLNL PSHA Methodology Outline (cont'd)

Seismicity and Ground Motion Descriptions Derived from Substantive Experts

Fig. 3-2

Need to elicit descriptions from a range of experts to cover the diversity of interpretations and judgements

In the revised approach, the experts are asked to characterize directly the frequency of occurrence of earthquakes greater than several magnitudes (m_0 and m_1) rather than to give estimates of the a and b — values of a Gutenberg - Richter Model.

The expert is asked:

- (a) To give a preferred value of $N(m_0)$ and $N(m_1)$
- (b) Give a 95% percentile confidence interval, and
- (c) Give a shape of the probability distribution for $N(m_0)$ and $N(m_1)$

Fig. 4.1 Revised Approach to Frequency Occurrence Modeling

Fig. 4.2 Computed Probabilities for Magnitudes 6, 5, & 4

Fig. 4.3 **Computed Probabilities for Magnitudes 4.5 & 4.0**

Fig. 4.4 **Empirical Probabilities for Magnitudes 4.5 & 4.0**

Fig. 4.5

Resampling Process

Fig. 4.6 Overview of the seismicity evaluation

Fig. 4.7 Illustration of a sample cumulative probability distribution on the rate of earthquake occurrences within a specified region.

Fig. 4.8 Comparison of the EPRI and LLNL historic seismicity and the seismicity estimated by Litehiser. Shown are the cumulative probability distribution function on the rate of occurrence of earthquakes of magnitude 5 or greater in Region 2.

SRS Historic Seismicity
Region: $2^{\circ} \times 2^{\circ}$; $m > 3.75$

Fig. 4.9 Comparison of the EPRI and LLNL historic seismicity and the seismicity estimated by Litehiser. Shown are the cumulative probability distribution function on the rate of occurrence of earthquakes of magnitude 3.75 or greater in Region 2.

Fig. 5.1 Comparison of Selected Composite Uncertainty Fractiles of the Median Ground Motion for Magnitudes 5.0 and 7.0 for PGA

Fig. 5.2 Plot of the Composite Uncertainty Fractiles, as a Function of Distance for Magnitude 6.0, of the Median Ground Motion for PGA

Fig. 5.3

Plot of the Composite Uncertainty Fractiles, as a Function of Distance for Magnitude 6.0, of the 85th Frequency Fractile g_{85} of Ground Motion for PGA: $\sigma_{ln} = 0.6$

Fig. 6.1 Generalized soil stratigraphical profile at the NPR site

Fig. 6.2 Soil damping ratios in F-area, L-area, and K-area at SRS used for evaluation of the overall COV of SRS soils.

Fig. 6.3 Shear modulus degradation relations based on data from K-area.

Fig. 6.4 Median 16-th, and 84-th percentiles of SR-NPR site correction factors for shaking level of 0.3g at adjacent rock outcrop.

percentiles = 15., 50. and 85.
 arithmetic means
 hazard curves using S & G experts

SRP site

Fig. 7.1

SRS, 1992 Seismicity & Composite g.m.
 9Sxpert, Mo > 5.00

10000.-year return period constant percentile spectra:
percentiles = 15., 50. and 85.

Fig. 7.2

SRP site

SRS, 1992 Seismicity & Composite g.m.
95xpert, Mo > 5.00

SRP-NPR : 8 G and 9 S experts
frequency case $M_0 > 5.00$ $G-X_{\sigma} = .3, .5, .8$

Fig. 7.3 Arithmetic mean hazard curve (AMHC) for the SRP-NPR site using a common sigma for all G-experts.
 $\sigma = .37$ to $.65$. $m_0 \geq 5$

Fig. 7.4 15-th, 50-th, and 85-th percentile hazard curves for the SRP NPR site using a common sigma for all G-experts, $\sigma = .37$ to $.65$. $m_0 \geq 5$

Fig. 7.5 Comparison of EUS 1989 and 1993 LLNL (L89, L93) and EUS EPRI (E89) Mean Hazard Curves

Fig. 7.6 Comparison of EUS 1989 and 1993 LLNL (L89, L93) and EPRI (E89) Median Hazard Curves

percentiles = 15., 50. and 85.
arithmetic means
hazard curves using S & G experts

SRP site

Fig. 7.7

SRS-Benchmark: 8 G / 9 S experts
frequency case, Mo>3.75, Experts' sigma

Fig. 7.8

SRP site

SRS, 1992 Seismicity & Attenuation models
 7G-95 Expert, Mo > 5.00 Experts' sigma

10000.-year return period constant percentile spectra:
percentiles = 15., 50. and 85.

Fig. 7.9

SRP site

SRS, 1992 Seismicity & Attenuation models
6G-9S experts/Mo > 5.00 Experts' sigma

Appendix A

A.1. SRS Regional seismic environment

A.2 S-experts zonation maps

Fig. 1.1 Location of the SRP

Fig. 1.2 Tectonic provinces in the southeastern U.S. A denotes the Valley and Ridge and Blue Ridge, B is the Piedmont, and C is the Coastal Plain (from Bollinger et al., 1989)

Fig. 1.3 Isoseismal map of the Charleston, South Carolina earthquake, September 1, 1886 (after Bollinger, 1977)

Fig. 1.4 Epicentral area maps for the 1886 Charleston, South Carolina earthquakes. (A) Dashed contour encloses intensity X effects. Dutton's (1889) map (B) and Sloan's map (C) show contours enclosing the highest intensity zone, although neither Dutton nor Sloan labeled his contours (after Bollinger, 1977)

Fig. 1.5 Local area seismicity map

Fig. 1.6 Location of Pen Branch fault at SRP with phase 1 shallow coring locations shown as large filled circles. Two other possible north-south trending faults were thought to intersect the Pen Branch fault.

Fig. 2.1(a) Primary zonation model for Bollinger

Fig. 2.1(a) Primary zonation model for Bollinger (cont)

Fig. 2.1(a) Primary zonation model for Bollinger (cont)

Fig. 2.1(b) Alternative zonation for Bollinger

Fig. 2.1(b)

Alternative zonation for Bollinger (cont)

Fig. 2.1(b)

Alternative zonation for Bollinger (cont)

Fig. 2.2(a) Primary zonation model for Holt

Fig. 2.2(a) Primary zonation model for Holt (cont)

Fig. 2.2(a)

Primary zonation model for Holt (cont)

Fig. 2.2(b) Alternative zonation for Holt

Fig. 2.2(b) Alternative zonation for Holt (cont)

Fig. 2.3(a) Primary zonation model Kafka

Fig. 2.3(a) Primary zonation model Kafka (cont)

Fig. 2.3(a) Primary zonation model Kafka (cont)

Fig. 2.3(b) Alternative zonation for Kafka

Fig. 2.3(b) **Alternative zonation for Kafka (cont)**

Fig. 2.4(a) Primary zonation model for Lettis

Fig. 2.4(a) **Primary zonation model for Lettis (cont)**

Fig. 2.4(a) **Primary zonation model for Lettis (cont)**

Fig. 2.4(a) Primary zonation model for Lettis (cont)

Fig. 2.4(a) Primary zonation model for Lettis (cont)

Fig. 2.4(a) Primary zonation model for Lettis (cont)

Fig. 2.4(b) Alternative zonation for Lettis

Fig. 2.4(b) Alternative zonation for Lettis (cont)

Fig. 2.4(b) Alternative zonation for Lettis (cont)

Fig. 2.4(b) Alternative zonation for Lettis (cont)

Fig. 2.4(b) Alternative zonation for Lettis (cont)

Fig. 2.4(b) Alternative zonation for Lettis (cont)

Fig. 2.5(a) Primary zonation model for Litehiser

Fig. 2.5(a) Primary zonation model for Litehiser (cont)

NOTE: UNLABELLED ZONES ARE: 13

Fig. 2.5(a) Primary zonation model for Litehiser (cont)

Fig. 2.6(a) Primary zonation model for Long

Fig. 2.6(a) Primary zonation model for Long (cont)

Fig. 2.6(a) Primary zonation model for Long (cont)

Fig. 2.6(b) Alternative zonation for Long

Fig. 2.6(b) Alternative zonation for Long (cont)

Fig. 2.6(b) Alternative zonation for Long (cont)

Fig. 2.7(a) Primary zonation model for Talwani

Fig. 2.7(a) Primary zonation model for Talwani (cont)

Fig. 2.7(a) Primary zonation model for Talwani (cont)

Fig. 2.7(b) Alternative zonation for Talwani

Fig. 2.7(b) **Alternative zonation for Talwani (cont)**

Fig. 2.7(b) Alternative zonation for Talwani (cont)

Fig. 2.8(a) Primary zonation model for Toksöz (cont)

Fig. 2.8(a) Primary zonation model for Toksöz (cont)

Fig. 2.8(b) **Alternative zonation for Toksöz**

Fig. 2.8(b) Alternative zonation for Toksöz (cont)

Fig. 2.8(b) Alternative zonation for Toksöz (cont)

Fig. 2.9(a) Primary zonation model for Site Team
(D. Stephenson)

Fig. 2.9(a) Primary zonation model for Site Team
(D.Stephenson) (cont)

Fig. 2.9(a) Primary zonation model for Site Team
(D. Stephenson) (cont)

Fig. 2.9(b) Alternative zonation for Site Team
(D.Stephenson)

Fig. 2.9(b) Alternative zonation for Site Team
(D.Stephenson) (cont)

Appendix B

S-experts' Seismicity Parameters

Fig. 2.9(b) Alternative zonation for Site Team
(D.Stephenson) (cont)

seismicity data for Bollinger
S-Expert Number: 1

Expert's Zone Name	Style/Scale/ Zone/ Mag/ Index	Upper Mag/Int Cutoff			a-b values				frequency estimates								
		Int	lower value	pref. value	upper value	a values		b values		f (m0)				ml		f (ml)	
						Lower	Prefer'd	Upper	Lower	Prefer'd	Upper	Lower	Prefer'd	Upper	Lower	Prefer'd	Upper
zone R21	1	mag	7.15	7.35				-0.955	-0.910	-0.865	0.440	0.8100	1.470	6.00	0.00320	0.00720	0.01660
zone R22	2	mag	6.45	6.70				-0.910	-0.880	-0.850	0.910	1.3500	2.000	6.00	0.00810	0.01410	0.02450
zone R23	3	mag	6.05	6.30			7.05	-0.720	-0.640	-0.560	0.010	0.0350	0.123	6.00	0.00020	0.00130	0.00680
zone R24	4	mag	6.20	6.45			7.20	-0.940	-0.900	-0.860	0.133	0.2400	0.420	6.00	0.00100	0.00220	0.00490
zone R25	5	mag	5.75	6.00			6.75	-0.850	-0.820	-0.790	0.078	0.1160	0.173	5.00	0.00680	0.01100	0.01780
zone R26	6	mag	6.15	6.40			7.15	-0.700	-0.640	-0.580	0.018	0.0460	0.119	5.50	0.00100	0.00350	0.01150
zone L21	7	mag	6.65	6.90			7.65	-0.850	-0.770	-0.690	0.016	0.0580	0.163	6.00	0.00020	0.00110	0.00460
zone L22	8	mag	5.75	6.00			6.75	-0.860	-0.780	-0.700	0.007	0.0260	0.092	5.00	0.00060	0.00280	0.01230
zone L23	9	mag	5.75	6.00			6.75	-0.850	-0.800	-0.750	0.034	0.0720	0.154	5.00	0.00300	0.00720	0.01780
zone L24	10	mag	6.00	6.25			7.00	-0.860	-0.810	-0.760	0.019	0.0350	0.063	5.00	0.00160	0.00340	0.00710
zone L26	11	mag	6.25	6.50			7.25	-0.880	-0.800	-0.720	0.006	0.0220	0.078	5.00	0.00050	0.00220	0.00980
zone L25	12	mag	5.75	6.00			6.75	-0.850	-0.800	-0.750	0.023	0.0500	0.106	5.00	0.00200	0.00500	0.01230
zone C21	13	mag	5.50	5.75			6.50	-0.850	-0.800	-0.750	0.070	0.1585	0.361	5.00	0.00600	0.01600	0.04200
zone R24 (altzais)	14	mag	7.15	7.35			8.10	-0.940	-0.900	-0.860	0.133	0.2400	0.420	6.00	0.00100	0.00220	0.00490
zone L26 w/ L23 ac	15	mag	5.75	6.00			6.75	-0.850	-0.800	-0.750	0.000	0.0009	0.002	5.00	0.00004	0.00009	0.00022
zone L22 w/ L23 ac	16	mag	5.75	6.00			6.75	-0.850	-0.800	-0.750	0.002	0.0037	0.008	5.00	0.00016	0.00037	0.00092

Bollinger - corrected CZ ** Aug. 26
S-Expert Number: 1

Expert's Zone Name	Sfile Zone Index	Scale Mag/ Int	Upper Mag/Int Cutoff			a-b values						frequency estimates								
			lower value	pref. value	upper value	a values			b values			f(m0)			m1	f(m1)				
						Lower	Prefer'd	Upper	Lower	Prefer'd	Upper	Lower	Preferred	Upper		Lower	Preferred	Upper		
zone R21	1	mag	7.15	7.35	8.10				-0.955	-0.910	-0.865	0.440	0.8100	1.470	6.00	0.00320	0.00720	0.01660		
zone R22	2	mag	6.45	6.70	7.45				-0.910	-0.880	-0.850	0.910	1.3500	2.000	6.00	0.00810	0.01410	0.02450		
zone R23	3	mag	6.05	6.30	7.05				-0.720	-0.640	-0.560	0.010	0.0350	0.123	6.00	0.00020	0.00130	0.00680		
zone R24	4	mag	6.20	6.45	7.20				-0.940	-0.900	-0.860	0.133	0.2400	0.420	6.00	0.00100	0.00220	0.00490		
zone R25	5	mag	5.75	6.00	6.75				-0.850	-0.820	-0.790	0.078	0.1160	0.173	5.00	0.00680	0.01100	0.01780		
zone R26	6	mag	6.15	6.40	7.15				-0.700	-0.640	-0.580	0.018	0.0460	0.119	5.50	0.00100	0.00350	0.01150		
zone LZ1	7	mag	6.65	6.90	7.65				-0.850	-0.770	-0.690	0.016	0.0580	0.163	6.00	0.00020	0.00110	0.00460		
zone LZ2	8	mag	5.75	6.00	6.75				-0.860	-0.780	-0.700	0.007	0.0260	0.092	5.00	0.00060	0.00280	0.01230		
zone LZ3	9	mag	5.75	6.00	6.75				-0.850	-0.800	-0.750	0.034	0.0720	0.154	5.00	0.00300	0.00720	0.01780		
zone LZ4	10	mag	6.00	6.25	7.00				-0.860	-0.810	-0.760	0.019	0.0350	0.063	5.00	0.00160	0.00340	0.00710		
zone LZ6	11	mag	6.25	6.50	7.25				-0.880	-0.800	-0.720	0.006	0.0220	0.078	5.00	0.00050	0.00220	0.00980		
zone LZ5	12	mag	5.75	6.00	6.75				-0.850	-0.800	-0.750	0.023	0.0500	0.106	5.00	0.00200	0.00500	0.01230		
zone CZ1	13	mag	5.50	5.75	6.50				-0.850	-0.800	-0.750	0.070	0.1585	0.361	5.00	0.00600	0.01600	0.04200		
zone R24(altzsis)	14	mag	7.15	7.35	8.10				-0.940	-0.900	-0.860	0.133	0.2400	0.420	6.00	0.00100	0.00220	0.00490		
zone LZ6 w/ LZ3 ac	15	mag	5.75	6.00	6.75				-0.850	-0.800	-0.750	0.000	0.0009	0.002	5.00	0.00004	0.00009	0.00022		
zone LZ2 w/ LZ3 ac	16	mag	5.75	6.00	6.75				-0.850	-0.800	-0.750	0.002	0.0037	0.008	5.00	0.00016	0.00037	0.00092		

seismicity data for Holt
S-Expert Number: 2

Expert's Zone Name	Sfile Zone Index	Scale Mag/ Int	Upper Mag/Int Cutoff			a-b values						frequency estimates								
			lower value	pref. value	upper value	a values			b values			f (m0)			m1	f (m1)				
						Lower	Prefer'd	Upper	Lower	Prefer'd	Upper	Lower	Preferred	Upper						
																Lower	Preferred	Upper		
zone R-1	1	mag	6.80	7.20	7.40				-0.950	-0.900	-0.800	0.100	0.5000	0.700	7.20	0.00020	0.00100	0.00200		
zone R1-1	2	mag	6.80	7.20	7.40				-0.940	-0.900	-0.860	0.200	0.4000	1.000	7.20	0.00020	0.00100	0.00200		
zone OSZ-1	3	mag	5.30	5.50	5.80	0.000	0.100	3.000	-0.900	-0.500	0.000									
zone OSZ-2	4	mag	5.30	5.50	5.80	0.000	0.100	3.000	-0.900	-0.500	0.000									
zone OSZ-3	5	mag	5.30	5.50	5.80	0.000	0.100	3.000	-0.900	-0.500	0.000									
zone R-3	6	mag	5.30	5.50	5.80				-0.900	-0.810	-0.750	0.040	0.1000	0.400	5.50	0.00020	0.00100	0.00200		
zone R-2	7	mag	7.00	7.20	7.60				-0.920	-0.860	-0.740	1.000	2.0000	2.000	7.20	0.00020	0.00100	0.00200		
zone R2-1	8	mag	7.00	7.20	7.60				-0.930	-0.850	-0.750	0.500	0.7000	1.000	7.20	0.00010	0.00200	0.00400		
zone R-4	9	mag	5.80	6.00	6.20				-0.820	-0.810	-0.680	0.200	0.3000	1.000	6.00	0.00020	0.00060	0.00200		
zone R-5	10	mag	5.30	5.50	5.70				-0.950	-0.940	-0.930	0.030	0.0800	0.300	5.60	0.00020	0.00100	0.00200		
zone R-6	11	mag	6.40	6.80	7.20				-1.000	-0.900	-0.830	0.070	0.4000	2.000	6.80	0.00010	0.00050	0.00100		
zone R-7	12	mag	6.80	7.20	7.40				-0.900	-0.790	-0.400	0.400	0.8000	3.000	7.20	0.00060	0.00100	0.00400		
zone R-8	13	mag	5.80	6.00	6.20				-0.950	-0.900	-0.850	0.600	0.7000	10.000	6.00	0.00020	0.00100	0.00300		
zone RC-2	14	mag	6.80	7.20	7.40				-0.900	-0.850	-0.800	0.010	0.1000	4.200	7.20	0.00020	0.00050	0.00100		
zone RC-1	15	mag	5.80	6.20	6.40				-1.000	-0.920	-0.800	1.000	2.0000	2.000	7.20	0.00020	0.00050	0.00100		
fault OS-1	16	mag	5.30	5.50	5.80	0.000	0.100	3.000	-0.900	-0.500	0.000									
fault OS-2	17	mag	5.30	5.50	5.80	0.000	0.100	3.000	-0.900	-0.500	0.000									
fault OS-3	18	mag	5.30	5.50	5.80	0.000	0.100	3.000	-0.900	-0.500	0.000									
fault OS-4	19	mag	5.30	5.50	5.80	0.000	0.100	3.000	-0.900	-0.500	0.000									
fault OS-5	20	mag	5.30	5.50	5.80	0.000	0.100	3.000	-0.900	-0.500	0.000									
fault OS-6	21	mag	5.30	5.50	5.80	0.000	0.100	3.000	-0.900	-0.500	0.000									
dummy zone- no act	22	mag	5.30	5.50	5.80	-9.990	-9.000	-8.000	-0.900	-0.500	-0.400

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Centimeter

Inches

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3 of 3

seismicity data for Kafka
S-Expert Number: 3

Expert's Zone Name	File Index	Upper Mag/Int Cutoff			a-b values			frequency estimates					
		Scale	Mag	Int	a values		b values		f (m0)		ml	f (ml)	
					Lower	Upper	Lower	Upper	Lower	Upper		Lower	Upper
zone R1	1	mag	7.60	8.20	8.40		-1.100	-0.860	-0.700	0.200	0.700	4.50	0.05000
zone R2	2	mag	7.60	8.20	8.40		-1.100	-0.860	-0.700	0.400	0.900	4.50	0.06000
zone R3	3	mag	6.00	7.60	8.40		-1.100	-0.860	-0.700	0.001	0.0070	4.10	0.00050
zone R4	4	mag	7.60	8.20	8.40		-1.100	-0.860	-0.700	0.043	0.1400	4.10	0.03400
zone R5	5	mag	6.00	7.60	8.40		-1.100	-0.860	-0.700	0.001	0.0028	4.10	0.00028
zone R6	6	mag	6.00	7.60	8.40		-1.100	-0.860	-0.700	0.020	0.1000	4.10	0.01600
zone R7	7	mag	7.60	8.20	8.40		-1.100	-0.860	-0.700	0.100	0.3800	4.40	0.06900
zone R8	8	mag	7.60	8.20	8.40		-1.100	-0.860	-0.700	0.100	0.2200	4.30	0.04300
zone R9	9	mag	8.10	8.30	8.40		-1.100	-0.860	-0.700	0.300	0.5600	4.40	0.06900
zone R10	10	mag	7.60	8.20	8.40		-1.100	-0.860	-0.700	0.290	0.5200	4.50	0.03400
zone R11	11	mag	7.60	8.20	8.40		-1.100	-0.860	-0.700	0.010	0.0400	4.10	0.00400
zone R12	12	mag	5.00	6.00	8.40		-1.100	-0.860	-0.700	0.001	0.0028	4.10	0.00028
zone R13	13	mag	7.60	8.20	8.40		-1.100	-0.860	-0.700	0.100	0.2500	4.30	0.03800
zone R14	14	mag	6.00	7.60	8.40		-1.100	-0.860	-0.700	0.003	0.0170	4.10	0.00100
zone R15	15	mag	7.60	8.20	8.40		-1.100	-0.860	-0.700	0.050	0.1400	4.20	0.02200
zone R16	16	mag	7.60	8.20	8.40		-1.100	-0.860	-0.700	0.500	1.1400	4.50	0.10700
zone R17	17	mag	6.00	7.60	8.40		-1.100	-0.860	-0.700	0.010	0.0500	4.10	0.00700
zone R18	18	mag	7.60	8.20	8.40		-1.100	-0.860	-0.700	0.800	1.1400	4.50	0.10000
zone R19	19	mag	7.60	8.20	8.40		-1.100	-0.860	-0.700	0.170	0.4000	4.50	0.04300
zone R20	20	mag	6.00	7.60	8.40		-1.100	-0.860	-0.700	0.007	0.0230	4.10	0.00260
zone R21	21	mag	6.00	7.60	8.40		-1.100	-0.860	-0.700	0.005	0.0160	4.10	0.00300
zone R22	22	mag	6.00	7.60	8.40		-1.100	-0.860	-0.700	0.002	0.0120	4.10	0.00100
zone R23	23	mag	6.00	7.60	8.40		-1.100	-0.860	-0.700	0.050	0.1000	4.10	0.02200
zone R24	24	mag	6.00	7.60	8.40		-1.100	-0.860	-0.700	0.160	0.3600	4.40	0.02900
zone R25	25	mag	6.00	7.60	8.40		-1.100	-0.860	-0.700	0.050	0.1400	4.10	0.03400
zone RC1	26	mag	6.00	7.60	8.40		-1.100	-0.860	-0.700	0.500	1.0500	4.40	0.10700
zone RC2	27	mag	5.00	6.00	8.40		-1.100	-0.860	-0.700	0.250	0.5300	4.10	0.13800
zone RC3	28	mag	5.00	6.00	8.40		-1.100	-0.860	-0.700	0.250	0.5300	4.10	0.13800
zone RC4	29	mag	7.60	8.20	8.40		-1.100	-0.860	-0.700	1.900	2.5800	4.830	0.06900
zone RC5	30	mag	7.60	8.20	8.40		-1.100	-0.860	-0.700	0.089	0.2100	4.30	0.02100
zone RC6	31	mag	7.60	8.20	8.40		-1.100	-0.860	-0.700	1.500	3.1000	4.500	0.06900
zone RC7	32	mag	7.60	8.20	8.40		-1.100	-0.860	-0.700	0.089	0.2100	4.40	0.05400
zone RC8	33	mag	6.00	7.60	8.40		-1.100	-0.860	-0.700	0.500	1.0500	4.50	0.10700
zone RC9	34	mag	5.00	6.00	8.40		-1.100	-0.860	-0.700	0.050	0.1100	4.10	0.02900
zone RC10	35	mag	5.00	6.00	8.40		-1.100	-0.860	-0.700	0.250	0.5300	4.10	0.13800
zone RC11	36	mag	7.60	8.20	8.40		-1.100	-0.860	-0.700	0.004	0.0128	4.10	0.00300
zone RC12	37	mag	7.60	8.20	8.40		-1.100	-0.860	-0.700	0.004	0.0128	4.10	0.00300
zone RC13	38	mag	6.00	7.60	8.40		-1.100	-0.860	-0.700	0.000	0.0001	4.10	0.00001
zone RC14	39	mag	6.00	7.60	8.40		-1.100	-0.860	-0.700	0.000	0.0003	4.10	0.00002
zone RC15	40	mag	6.00	7.60	8.40		-1.100	-0.860	-0.700	0.000	0.0000	7.00	0.00000

seismicity data for Lettis
S-Expert Number: 5

Expert 's Zone Name	Sfile Zone Index	Scale Mag/ Int	Upper Mag/Int Cutoff			a-b values						frequency estimates								
			lower value	pref. value	upper value	a values			b values			f(m0)			m1	f(m1)				
						Lower	Prefer'd	Upper	Lower	Prefer'd	Upper	Lower	Preferred	Upper		Lower	Preferred	Upper		
zone R2b	1	mag	6.00	6.50	7.00				-1.270	-0.800	-0.700	0.007	0.0260	0.066	5.00	0.00030	0.00260	0.00690		
zone R4	2	mag	7.40	7.50	7.60				-1.160	-0.690	-0.660	0.059	0.1771	0.347	6.00	0.00230	0.00500	0.00710		
zone R5	3	mag	6.25	6.50	7.50				-1.200	-1.010	-0.860	0.066	0.1215	0.226	5.00	0.00350	0.00660	0.00970		
zone R6	4	mag	6.25	6.50	7.50				-1.130	-0.970	-0.820	0.069	0.1319	0.174	5.00	0.00520	0.00800	0.01040		
zone L5	5	mag	6.00	6.25	7.60				-0.880	-0.640	-0.510	0.004	0.0097	0.035	5.00	0.00030	0.00160	0.00350		
zone L7	6	mag	6.00	6.50	7.60				-1.110	-0.580	-0.510	0.002	0.0024	0.016	5.00	0.00010	0.00050	0.00160		
zone L13	7	mag	7.30	7.60	8.00				-1.090	-0.910	-0.840	0.066	0.4167	0.660	6.00	0.00040	0.00380	0.00630		
zone L14	8	mag	5.50	6.50	7.60				-1.110	-0.580	-0.510	0.002	0.0024	0.016	5.00	0.00010	0.00050	0.00160		
zone L15	9	mag	5.50	6.50	7.60				-1.110	-0.580	-0.510	0.002	0.0024	0.016	5.00	0.00010	0.00050	0.00160		
zone L17	10	mag	6.50	7.00	7.60				-1.090	-0.910	-0.840	0.066	0.4167	0.660	6.00	0.00040	0.00380	0.00630		
zone L18	11	mag	5.50	6.50	7.00				-1.300	-1.040	-0.970	0.049	0.0972	0.132	5.00	0.00230	0.00490	0.00630		
zone L19	12	mag	6.50	7.00	7.60				-1.410	-0.960	-0.880	0.016	0.0712	0.104	5.00	0.00070	0.00450	0.00690		
zone R9a	13	mag	7.20	7.60	8.00				-1.430	-1.010	-0.650	0.036	0.0710	0.090	6.00	0.00024	0.00036	0.00140		
zone L8	14	mag	5.50	6.50	7.60				-1.180	-1.070	-0.820	0.021	0.0451	0.104	5.00	0.00100	0.00210	0.00690		
zone R3	15	mag	7.20	7.60	8.00				-1.060	-0.860	-0.760	0.156	0.4514	0.625	6.00	0.00140	0.00520	0.00760		
zone R11	16	mag	5.50	6.00	7.60				-1.180	-1.030	-0.850	0.062	0.1007	0.208	5.00	0.00350	0.00520	0.01740		
zone R12	17	mag	6.00	6.50	7.00				-1.400	-1.040	-0.600	0.017	0.0694	0.167	5.00	0.00210	0.00350	0.00800		
zone R13	18	mag	6.00	6.50	7.00				-1.400	-1.040	-0.960	0.104	0.1389	0.312	5.00	0.00240	0.00690	0.01040		
zone R14	19	mag	6.00	6.50	7.00				-1.360	-1.060	-1.030	0.208	0.5903	0.799	5.00	0.01040	0.02780	0.03470		
zone R10 **	20	mag	5.80	6.00	7.20				-1.200	-0.800	-0.780	0.142	0.2083	0.399	5.00	0.01010	0.02080	0.03120		
zone R15 **	21	mag	5.80	6.00	7.20				-1.300	-0.830	-0.780	0.066	0.2257	0.451	5.00	0.00490	0.02080	0.03120		
zone R16 **	22	mag	5.80	6.00	7.20				-1.190	-0.920	-0.830	0.104	0.6944	0.938	6.00	0.00170	0.00590	0.01150		
zone R17	23	mag	6.00	7.00	7.75				-1.260	-1.070	-0.960	0.122	0.4861	0.972	6.00	0.00140	0.00190	0.00970		
zone R19	24	mag	5.50	6.00	7.00				-0.910	-0.780	-0.640	0.014	0.0694	0.174	5.00	0.00330	0.00730	0.01700		
zone R18b	25	mag	6.00	6.25	7.00				-1.250	-0.870	-0.740	0.049	0.1076	0.201	5.00	0.00380	0.00870	0.01740		
zone R20b	26	mag	5.50	6.25	7.50				-1.360	-0.870	-0.840	0.028	0.0972	0.191	5.00	0.00260	0.00800	0.01840		
zone R21b	27	mag	6.75	7.00	7.50				-1.210	-0.690	-0.640	0.008	0.0451	0.278	5.00	0.00100	0.00630	0.01840		
zone R22b	28	mag	6.00	6.50	7.75				-1.100	-0.910	-0.600	0.031	0.0660	0.111	5.00	0.00150	0.00490	0.01080		
zone R24b	29	mag	6.00	6.50	7.00				-1.150	-0.970	-0.850	0.003	0.0160	0.023	5.00	0.00030	0.00100	0.00170		
zone R25	30	mag	6.50	7.50	7.75				-1.300	-0.960	-0.880	0.122	0.2951	0.521	6.00	0.00020	0.00210	0.00310		
zone R26	31	mag	6.50	7.50	7.75				-1.000	-0.840	-0.670	0.208	0.3819	0.521	6.00	0.00180	0.00490	0.00780		
zone R27	32	mag	7.30	7.50	8.00				-1.460	-0.850	-0.800	0.233	0.4167	0.729	6.00	0.00040	0.00500	0.00690		
zone R28	33	mag	7.00	7.50	8.00				-1.060	-0.950	-0.760	0.139	0.2778	0.365	6.00	0.00100	0.00200	0.00310		
zone R29	34	mag	7.30	7.50	8.00				-1.270	-0.940	-0.850	0.208	0.6944	0.903	6.00	0.00210	0.00520	0.01010		
zone R30	35	mag	6.50	7.00	8.00				-1.150	-0.980	-0.920	0.330	0.7639	1.146	6.00	0.00160	0.00490	0.00660		
zone RC2	36	mag	5.50	6.00	6.50				-1.130	-0.750	-0.650	0.066	0.1354	0.156	5.00	0.00520	0.01530	0.01560		
zone RC1	37	mag	5.50	6.00	6.50				-1.300	-1.020	-0.950	2.083	5.2083	5.903	5.00	0.14930	0.27780	0.31250		
fault L1b Belai	38	mag	6.00	6.25	6.75	-0.720	0.170	0.320	-1.100	-1.000	-0.810									
fault L1a Belai	39	mag	6.00	6.25	6.75	-0.720	0.170	0.320	-1.100	-1.000	-0.810									
fault L2c E. P1	40	mag	6.00	7.00	7.60	-0.220	0.160	0.320	-1.100	-1.000	-0.800									
fault L2a E. P1	41	mag	6.00	7.00	7.60	-0.220	0.160	0.320	-1.100	-1.000	-0.800									
fault L4a Mille	42	mag	6.00	6.25	7.60	-0.900	0.110	0.260	-1.100	-1.000	-0.800									
fault L6a State	43	mag	5.50	6.00	6.50	-0.650	0.130	0.280	-1.100	-1.000	-0.200									
fault L9a Helen	44	mag	5.50	6.00	7.00	0.130	0.280	0.480	-1.100	-1.000	-0.810									
fault S1	45	mag	6.00	7.00	7.60	-0.220	0.160	0.320	-1.100	-1.000	-0.800									
fault S4a Penbra	46	mag	6.00	7.00	7.60	-0.970	0.270	0.480	-1.100	-1.000	-0.800									
fault S5a	47	mag	5.00	5.50	6.00	-0.100	0.110	0.150	-1.100	-1.000	-0.800									
fault S6a	48	mag	5.00	6.00	6.50	-0.590	0.210	0.660	-1.100	-1.000	-0.800									

seismicity data for Lettis
S-Expert Number: 5
(continued)

Expert's Zone Name	Sfile Zone Index	Scale Mag/ Int	Upper Mag/Int Cutoff			a-b values						frequency estimates								
			lower value	pref. value	upper value	a values			b values			f (m0)			m1	f (m1)				
						Lower	Prefer'd	Upper	Lower	Prefer'd	Upper	Lower	Preferred	Upper		Lower	Preferred	Upper		
fault S7a	49	mag	5.00	5.50	6.00	-0.100	0.110	0.150	-1.100	-1.000	-0.800									
zone R9b	50	mag	7.20	7.60	8.00				-1.430	-1.010	-0.650	0.054	0.1060	0.135	6.00	0.00036	0.00054	0.00216		
Dummy zone , no se	51	mag	5.20	5.60	6.00				-1.430	-1.010	-0.650	0.000	0.0000	0.000	6.00	0.00000	0.00000	0.00000		

seismicity data for Litehiser
S-Expert Number: 6

Expert's Zone Name	Sfile Zone Index	Scale Mag/ Int	Upper Mag/Int Cutoff			a-b values						frequency estimates						
			lower value	pref. value	upper value	a values			b values			f(m0)			m1	f(m1)		
						Lower	Prefer'd	Upper	Lower	Prefer'd	Upper	Lower	Preferred	Upper		Lower	Preferred	Upper
zone 30	1	mag	7.40	7.50	7.50				-0.950	0.000	0.000	0.302	0.4740	0.743	5.50	0.00654	0.01020	0.01610
zone 31	2	mag	5.40	5.90	6.60				-0.760	0.000	0.000	0.116	0.1850	0.249	5.00	0.01300	0.02060	0.03290
zone 13	3	mag	5.40	5.90	6.60				-0.660	0.000	0.000	0.067	0.1600	0.382	5.00	0.00388	0.00922	0.02190
zone F	4	mag	5.40	5.90	6.60				-0.810	0.000	0.000	0.124	0.2750	0.612	5.00	0.01160	0.02590	0.05750
zone G	5	mag	5.40	5.90	6.60				-0.870	0.000	0.000	0.078	0.1740	0.386	5.00	0.00635	0.01410	0.03140
zone N3	6	mag	6.80	7.30	7.40				-1.000	0.000	0.000	0.082	0.1240	0.188	5.00	0.00460	0.00695	0.01050
zone H	7	mag	6.80	7.30	7.40				-1.050	0.000	0.000	0.076	0.1150	0.174	5.00	0.00380	0.00574	0.00866
zone 24	8	mag	5.70	6.20	6.60				-0.860	0.000	0.000	0.075	0.1060	0.148	5.00	0.00612	0.00859	0.01200
zone 25	9	mag	5.40	5.90	6.60				-1.200	0.000	0.000	0.073	0.1230	0.208	5.00	0.00236	0.00398	0.00669
zone B20	10	mag	5.70	6.20	6.60				-0.870	0.000	0.000	0.640	0.9030	1.270	5.00	0.05360	0.07560	0.10700
zone B21	11	mag	5.40	5.90	6.60				-1.150	0.000	0.000	0.063	0.1380	0.300	5.00	0.00222	0.00485	0.01060
zone B24	12	mag	6.80	7.30	7.40				-1.090	0.000	0.000	0.133	0.2010	0.304	5.00	0.00591	0.00892	0.01350
zone B25	13	mag	5.70	6.20	6.60				-0.920	0.000	0.000	0.580	0.8760	1.320	5.00	0.04080	0.06160	0.09310
zone B26	14	mag	6.00	6.50	6.60				-1.010	0.000	0.000	4.510	7.4200	12.200	5.50	0.07420	0.12200	0.20100

seismicity data for Long
S-Expert Number: 7

Expert's Zone Name	Sfile Zone Index	Scale Mag/ Int	Upper Mag/Int Cutoff			a-b values						frequency estimates								
			lower value	pref. value	upper value	a values			b values			f(m0)			m1	f(m1)				
						Lower	Prefer'd	Upper	Lower	Prefer'd	Upper	Lower	Preferred	Upper		Lower	Preferred	Upper		
zone A1(A1.1)	1	mag	7.20	7.50	7.50				-1.150	-1.000	-0.920	0.500	1.4000	3.000	7.00	0.00024	0.00100	0.00500		
zone A2(A2.1)	2	mag	7.20	7.50	7.50				-1.110	-1.000	-0.850	0.020	0.0500	0.200	7.00	0.00003	0.00010	0.00050		
zone A3(A3.1)	3	mag	7.20	7.50	7.50				-1.150	-1.000	-0.920	0.040	0.1000	0.200	7.00	0.00001	0.00010	0.00050		
zone B1.1-alternat	4	mag	6.80	7.00	7.20				-1.100	-1.000	-0.900	0.040	0.1000	0.200	6.50	0.00002	0.00020	0.00100		
zone A4(A4.1)	5	mag	7.20	7.50	7.50				-1.150	-1.000	-0.900	0.005	0.0200	0.050	7.00	0.00000	0.00003	0.00010		
zone B1.2(B1.2.1)	6	mag	6.80	7.00	7.20				-1.100	-1.000	-0.750	0.050	0.1000	0.500	6.50	0.00010	0.00040	0.01000		
zone B1.3(B1.3.1)	7	mag	6.80	7.00	7.20				-1.100	-1.000	-0.900	0.100	0.2000	0.400	6.50	0.00010	0.00030	0.00200		
zone B1.4	8	mag	6.80	7.00	7.20				-1.200	-1.000	-0.900	0.002	0.0100	0.020	6.50	0.00000	0.00003	0.00010		
zone B1.5(B1.5.1)	9	mag	6.80	7.00	7.20				-1.200	-1.000	-0.900	0.010	0.0500	0.100	6.50	0.00001	0.00010	0.00050		
zone C2.1	10	mag	5.30	5.50	5.90				-1.300	-1.200	-1.100	0.025	0.1000	0.200	5.00	0.00020	0.00300	0.01000		
zone C2.2	11	mag	5.30	5.50	5.90				-1.100	-1.000	-0.900	0.050	0.1300	0.250	5.00	0.00200	0.00500	0.02000		
zone C2.3	12	mag	5.30	5.50	5.90				-1.300	-1.200	-1.100	0.100	0.2500	0.400	5.00	0.00100	0.01000	0.02000		
zone C2.4	13	mag	5.30	5.50	5.90				-1.300	-1.200	-1.100	0.010	0.0200	0.050	5.00	0.00020	0.00080	0.00300		
zone C1.1 shallow	14	mag	5.30	5.50	5.90				-1.150	-1.100	-1.000	1.000	1.5000	2.000	5.00	0.03000	0.06000	0.13000		
zone B2.1 deep bac	15	mag	6.80	7.00	7.20				-1.150	-1.100	-1.000	1.000	1.5000	2.000	7.00	0.00030	0.00050	0.00300		
zone A4/background	16	mag	6.80	7.00	7.20				-1.150	-1.100	-1.000	0.006	0.0087	0.012	7.00	0.00000	0.00000	0.00002		
zone B1.4/backgrou	17	mag	6.80	7.00	7.20				-1.150	-1.100	-1.000	0.000	0.0007	0.001	7.00	0.00000	0.00000	0.00000		

seismicity data for Street
S-Expert Number: 8

Expert's Zone Name	Sfile Zone Index	Scale Mag/ Int	Upper Mag/Int Cutoff			a-b values						frequency estimates						
			lower value	pref. value	upper value	a values			b values			f (m0)			m1	f (m1)		
						Lower	Prefer'd	Upper	Lower	Prefer'd	Upper	Lower	Preferred	Upper		Lower	Preferred	Upper
zone 1-1	1	mag	5.80	6.00	6.20	3.700	3.920	4.100	-1.150	-1.120	-0.900							
zone 1-2	2	mag	5.80	6.00	6.20	3.000	3.200	3.400	-0.700	-0.510	-0.500							
zone 1-4	3	mag	6.50	6.70	7.00	3.200	3.420	3.600	-0.700	-0.560	-0.500							
zone 1-3	4	mag	5.80	6.00	7.00	2.600	4.000	4.000	-1.000	-0.800	-0.600							
zone 1-5	5	mag	7.30	7.40	7.50	4.800	4.920	5.100	-1.000	-0.920	-0.850							
zone 1-6	6	mag	5.80	6.00	6.20	2.800	2.870	3.400	-0.950	-0.780	-0.700							
zone 2-1	7	mag	5.80	6.00	6.20	3.400	3.600	3.800	-0.700	-0.500	-0.500							
zone 2-2	8	mag	5.60	5.80	6.00	2.600	3.400	3.400	-0.900	-0.590	-0.500							
zone CZ	9	mag	0.00	0.00	0.00	2.600	2.600	2.600	-1.200	-1.100	-0.900							

seismicity data for Taiwan
S-Expert Number: 9

Expert's Zone Name	Sfile Zone Index	Scale Mag/ Int	Upper Mag/Int Cutoff			a-b values						frequency estimates								
			lower value	pref. value	upper value	a values			b values			f (m0)			m1	f (m1)				
						Lower	Prefer'd	Upper	Lower	Prefer'd	Upper	Lower	Preferred	Upper		Lower	Preferred	Upper		
zone R2	1	mag	7.80	8.00	8.50				-1.010	-0.910	-0.810	0.600	0.8000	1.000	5.25	0.02500	0.03300	0.05000		
zone R3	2	mag	7.80	8.00	8.50				-0.980	-0.880	-0.780	1.000	1.3300	1.670	5.25	0.05000	0.06700	0.10000		
zone R4	3	mag	5.50	5.80	6.00				-0.910	-0.810	-0.710	0.050	0.1000	0.200	4.75	0.01000	0.02000	0.03000		
zone R5	4	mag	5.50	6.00	6.00				-0.920	-0.820	-0.720	0.030	0.0700	0.100	4.75	0.01500	0.02000	0.03500		
zone R6	5	mag	5.50	5.80	6.00				-1.000	-0.900	-0.800	0.100	0.1500	0.250	4.75	0.03000	0.04000	0.06000		
zone R25	6	mag	5.50	6.00	6.00				-0.920	-0.820	-0.720	0.200	0.2500	0.330	4.75	0.04000	0.05000	0.07000		
zone L1	7	mag	6.80	7.00	7.50				-0.800	-0.700	-0.600	0.080	0.1800	0.220	5.25	0.01300	0.01800	0.03000		
zone L2	8	mag	6.80	7.00	7.50				-0.800	-0.700	-0.600	0.100	0.2000	0.250	5.25	0.01500	0.02000	0.03300		
zone L3	9	mag	4.50	5.00	5.50				-0.930	-0.780	-0.630	0.080	0.1000	0.150	4.75	0.02000	0.02500	0.03300		
zone L4	10	mag	4.50	5.00	5.50				-0.930	-0.780	-0.630	0.010	0.0200	0.030	4.75	0.00500	0.01000	0.01500		
zone L5	11	mag	4.50	5.00	5.50				-0.960	-0.810	-0.630	0.010	0.0200	0.030	4.75	0.00500	0.01000	0.01500		
zone RC1	12	mag	4.80	5.00	5.20				-1.200	-1.000	-0.850	2.000	2.5000	3.000	4.75	0.20000	0.25000	0.33000		
zone RC1 alternat	13	mag	4.80	5.00	5.20				-1.200	-1.000	-0.850	2.000	2.5000	3.000	4.75	0.20000	0.25000	0.33000		
fault F01	14	mag	3.00	3.50	4.00				-1.200	-1.000	-0.800	0.001	0.0010	0.002	4.75	0.00005	0.00010	0.00015		
fault F02	15	mag	4.00	4.50	5.00				-1.200	-1.000	-0.800	0.005	0.0100	0.015	4.75	0.00050	0.00100	0.00150		
fault F03	16	mag	3.50	4.00	4.50				-1.200	-1.000	-0.800	0.001	0.0050	0.010	4.75	0.00010	0.00050	0.00100		
fault F11.1	17	mag	4.00	4.50	5.00				-1.200	-1.000	-0.800	0.002	0.0032	0.005	4.75	0.00016	0.00032	0.00048		
fault F11.2	18	mag	4.00	4.50	5.00				-1.200	-1.000	-0.800	0.001	0.0017	0.003	4.75	0.00009	0.00017	0.00026		
fault F11.3	19	mag	4.00	4.50	5.00				-1.200	-1.000	-0.800	0.001	0.0014	0.002	4.75	0.00007	0.00014	0.00021		
fault F11.4	20	mag	4.00	4.50	5.00				-1.200	-1.000	-0.800	0.001	0.0021	0.003	4.75	0.00011	0.00021	0.00032		
fault F11.5	21	mag	4.00	4.50	5.00				-1.200	-1.000	-0.800	0.001	0.0017	0.003	4.75	0.00009	0.00017	0.00026		
fault F04	22	mag	4.25	4.50	4.60				-1.200	-1.000	-0.800	0.005	0.0100	0.015	4.75	0.00050	0.00100	0.00150		

seismicity data for Toksoz ck davis
S-Expert Number: 10

Expert's Zone Name	Sfile Zone Index	Scale Mag/ Int	Upper Mag/Int Cutoff			a-b values						frequency estimates						
			lower value	pref. value	upper value	a values			b values			f(m0)			m1	f(m1)		
						Lower	Prefer'd	Upper	Lower	Prefer'd	Upper	Lower	Preferred	Upper		Lower	Preferred	Upper
zone R1	1	mag	5.80	6.30	6.80				-0.900	-0.850	-0.800	0.180	0.2100	0.220	5.60	0.00300	0.00600	0.00700
zone R2	2	mag	7.80	8.30	8.80				-0.920	-0.880	-0.850	0.160	0.1800	0.200	5.10	0.00900	0.01200	0.01400
zone R3	3	mag	7.80	8.30	8.80				-0.950	-0.930	-0.910	1.170	1.3300	1.440	6.10	0.00700	0.00900	0.01000
zone R4	4	mag	5.20	5.70	6.20				-1.000	-0.940	-0.700	0.240	0.6400	0.650	5.10	0.01900	0.03400	0.05200
zone R6	5	mag	5.80	6.30	6.80				-1.250	-1.250	-1.100	0.150	0.2500	0.430	5.00	0.00300	0.00700	0.01000
zone R5	6	mag	5.80	6.30	6.80				-1.100	-1.000	-0.900	0.300	0.4300	0.720	5.80	0.00300	0.00400	0.00900
zone R8	7	mag	5.00	5.50	6.00				-1.140	-0.970	-0.910	0.100	0.1400	0.150	5.00	0.00800	0.00900	0.01000
zone R7	8	mag	5.10	5.60	6.10				-1.250	-1.100	-1.100	0.140	0.2800	0.460	5.10	0.00300	0.00500	0.00900
zone R9	9	mag	5.20	5.70	6.20				-1.590	-1.590	-1.370	0.180	0.2400	0.250	5.00	0.00200	0.00200	0.00300
zone R10	10	mag	5.80	6.30	6.80				-0.610	-0.540	-0.540	0.009	0.0100	0.040	4.60	0.00200	0.00400	0.00700
zone R11	11	mag	5.80	6.30	6.80				-0.820	-0.710	-0.710	0.220	0.2900	0.390	5.80	0.00500	0.01000	0.01000
zone R12	12	mag	5.80	6.30	6.80				-1.000	-0.970	-0.890	0.170	0.2300	0.360	5.00	0.00700	0.01400	0.02200
zone R13	13	mag	6.10	6.60	7.10				-1.060	-0.930	-0.890	0.170	0.2500	0.360	5.10	0.00600	0.01300	0.03100
zone R14	14	mag	6.10	6.60	7.10				-1.420	-1.060	-0.800	0.760	1.1400	1.700	5.00	0.01700	0.05200	0.15500
zone R15	15	mag	5.20	5.70	6.20				-0.930	-0.880	-0.760	0.038	0.0640	0.110	5.10	0.00200	0.00400	0.00700
zone R16	16	mag	6.60	7.10	7.60				-1.010	-0.950	-0.830	0.250	0.5000	1.000	5.80	0.00300	0.00600	0.01200
zone R17	17	mag	5.10	5.60	6.10				-1.450	-1.220	-1.220	0.410	0.7500	1.500	5.10	0.00900	0.01700	0.03400
zone R18	18	mag	6.70	7.20	7.70				-0.560	-0.550	-0.400	0.080	0.1800	0.400	6.60	0.00200	0.00500	0.01200
zone L1	19	mag	5.00	5.50	6.00				-1.160	-0.600	-0.500	0.010	0.0200	0.040	5.00	0.00200	0.00400	0.00700
zone L2	20	mag	5.00	5.50	6.00				-0.700	-0.600	-0.500	0.030	0.0600	0.120	5.00	0.00500	0.01100	0.02100
zone L3	21	mag	6.40	6.90	7.40	0.995	1.421	1.421	-0.878	-0.748	-0.748							
(Bi-Linear Model)						-3.604	-2.432	-2.432	-0.060	-0.060	-0.057							
zone L10	22	mag	6.40	6.90	7.40				-0.920	-0.840	-0.810	0.100	0.2700	0.670	5.40	0.00400	0.01100	0.02800
zone RC1	23	mag	5.00	5.50	6.00				-1.270	-1.180	-1.160	1.800	3.1500	5.250	5.60	0.01200	0.02100	0.03400
zone RC2{be}	24	mag	6.00	6.50	7.00				-0.640	-0.600	-0.540	0.310	0.5800	0.970	6.10	0.01300	0.02200	0.03800
zone RC2{altz}	25	mag	6.00	6.50	7.00				-0.640	-0.600	-0.540	0.310	0.5800	0.970	6.10	0.01300	0.02200	0.03800

seismicity data for SR-Site Team
S-Expert Number: 11

Expert's Zone Name	Sfile Zone Index	Scale Mag/ Int	Upper Mag/Int Cutoff			a-b values						frequency estimates								
			lower value	pref. value	upper value	a values			b values			f (m0)			m1	f (m1)				
						Lower	Prefer'd	Upper	Lower	Prefer'd	Upper	Lower	Preferred	Upper						
																Lower	Preferred	Upper	Lower	Preferred
zone L01	1	mag	4.80	5.50	6.00				-0.870	-0.820	-0.770	0.030	0.1000	0.300	5.50	0.00080	0.00100	0.00600		
zone L02	2	mag	5.00	6.00	6.50				-0.820	-0.790	-0.760	0.050	0.1000	0.200	6.00	0.00100	0.00200	0.00300		
zone R01	3	mag	4.80	5.50	6.00				-0.850	-0.800	-0.750	0.003	0.0180	0.075	5.30	0.00100	0.00500	0.01700		
zone R07	4	mag	4.80	5.50	6.00				-0.850	-0.800	-0.750	0.040	0.0600	0.300	5.30	0.00100	0.00500	0.01800		
zone R02	5	mag	7.10	7.50	7.80				-0.860	-0.780	-0.700	0.002	0.0200	0.050	6.80	0.00000	0.00110	0.00200		
zone R03	6	mag	5.20	6.00	6.90				-0.930	-0.890	-0.850	0.200	0.3000	0.700	6.00	0.00080	0.00150	0.00300		
one R04	7	mag	4.80	5.50	6.00				-0.740	-0.680	-0.620	0.020	0.1500	0.300	6.00	0.00080	0.00150	0.00300		
zone R08	8	mag	5.20	6.00	6.80				-0.700	-0.640	-0.580	0.020	0.1500	0.300	6.00	0.00100	0.00500	0.01500		
zone R06	9	mag	8.00	8.40	8.70				-0.910	-0.880	-0.850	0.600	1.2500	2.000	7.50	0.00080	0.00100	0.00300		
zone R05	10	mag	7.60	8.00	8.30				-0.890	-0.860	-0.830	0.060	0.2500	0.400	6.50	0.00500	0.01000	0.03000		
zone RC1	11	mag	4.50	5.00	5.50				-0.850	-0.820	-0.790	0.080	0.4000	0.800	5.50	0.00600	0.01400	0.30000		
fault f01	12	mag	5.00	5.50	5.75				-0.700	-0.600	-0.500	0.000	0.0000	0.000	5.50	0.00000	0.00000	0.00001		
fault f02	13	mag	5.00	5.50	5.75				-0.700	-0.600	-0.500	0.000	0.0000	0.000	5.50	0.00000	0.00000	0.00001		
fault f03	14	mag	5.00	5.50	5.75				-0.700	-0.600	-0.500	0.000	0.0000	0.000	5.50	0.00000	0.00000	0.00001		
fault f04	15	mag	5.00	5.50	5.75				-0.700	-0.600	-0.500	0.000	0.0000	0.000	5.50	0.00000	0.00000	0.00001		
fault f05	16	mag	5.00	5.50	5.75				-0.700	-0.600	-0.500	0.000	0.0000	0.000	5.50	0.00000	0.00000	0.00001		

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